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(54) **THREE-DIMENSIONAL MEMORY DEVICE INCLUDING CONTACT VIA STRUCTURES THAT EXTEND THROUGH WORD LINES AND METHOD OF MAKING THE SAME**

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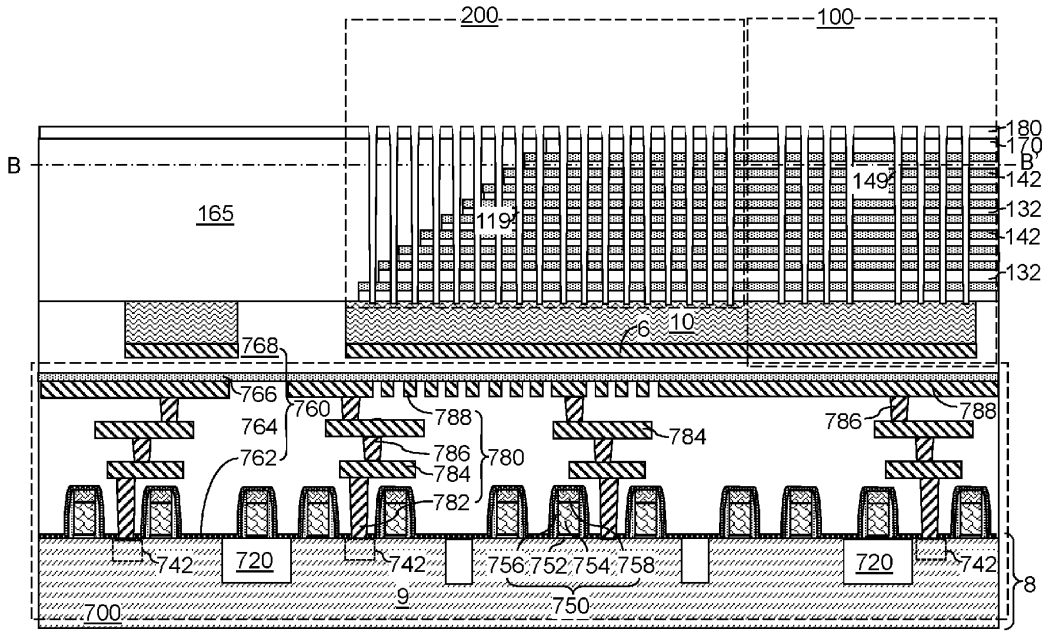
H01L 27/11526	(2006.01)
H01L 27/11548	(2006.01)
H01L 27/11573	(2006.01)
H01L 27/11575	(2006.01)
H01L 27/11582	(2006.01)
H01L 23/522	(2006.01)
H01L 21/768	(2006.01)

(52) **U.S. Cl.**

CPC .. ***H01L 27/11556*** (2013.01); ***H01L 27/11526*** (2013.01); ***H01L 27/11548*** (2013.01); ***H01L 27/11573*** (2013.01); ***H01L 21/76877*** (2013.01); ***H01L 27/11582*** (2013.01); ***H01L 23/5226*** (2013.01); ***H01L 21/76816*** (2013.01); ***H01L 27/11575*** (2013.01)

(57) **ABSTRACT**

A three-dimensional memory device includes semiconductor devices located on a semiconductor substrate, lower interconnect level dielectric layers embedding lower interconnect structures, an alternating stack of insulating layers and electrically conductive layers overlying the lower interconnect level dielectric layers and including stepped surfaces, memory stack structures vertically extending through the alternating stack, and contact via structures extending downward from the stepped surfaces through underlying portions of the alternating stack to the lower interconnect structures. Each of the contact via structures laterally contacts an electrically conductive layer located at the stepped surfaces, and provides electrical interconnection to an underlying semiconductor device. A top portion of each contact via structures contacts an electrically conductive layer, and is electrically isolated from other underlying electrically conductive layers.



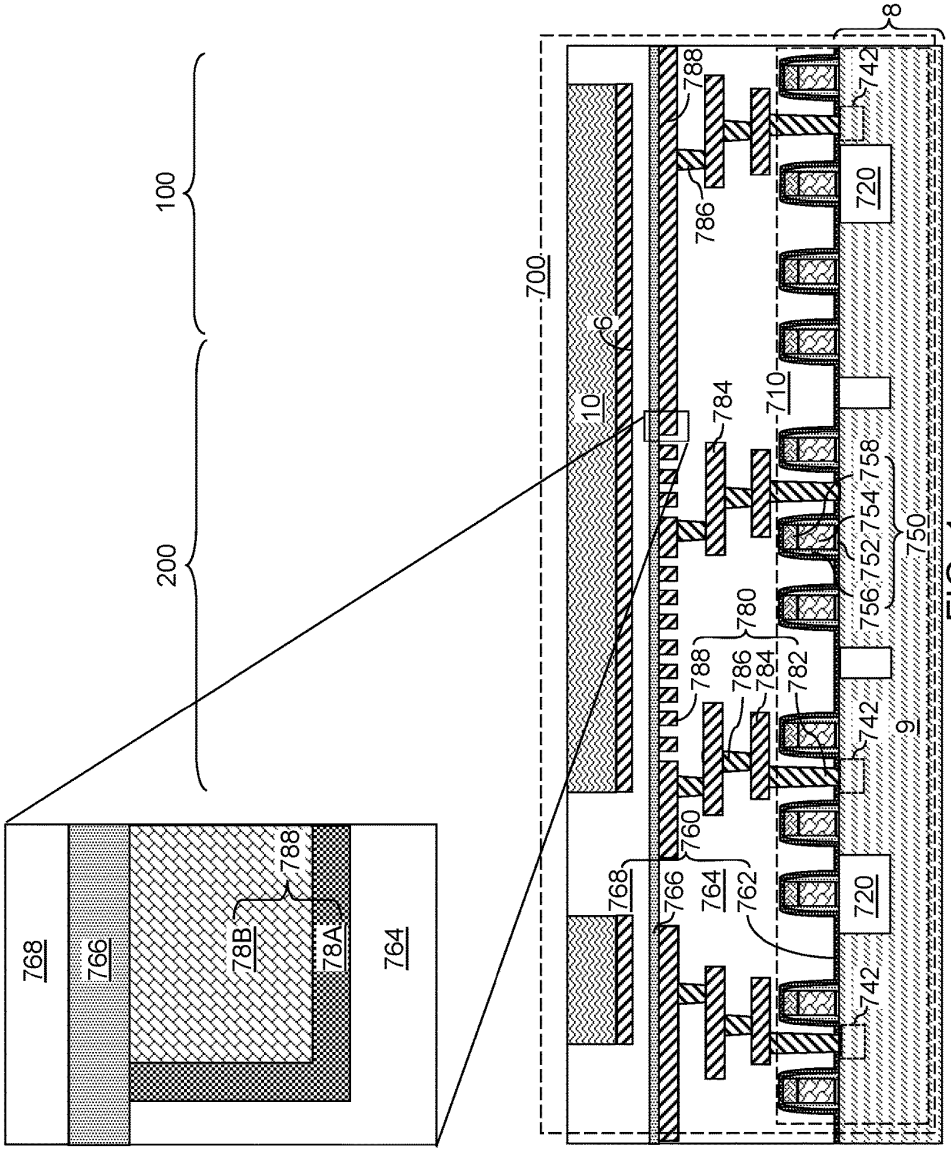

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FIG. 1

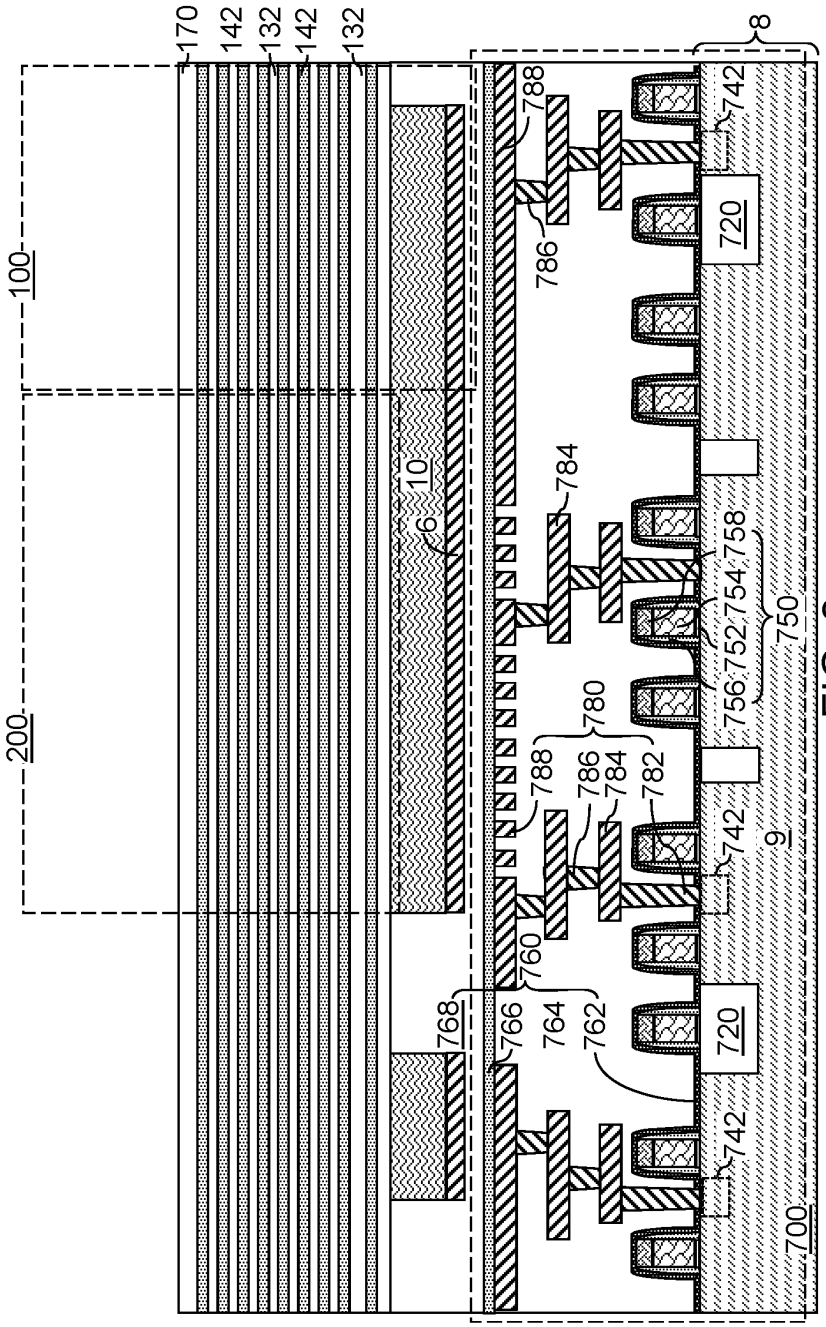
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FIG. 2

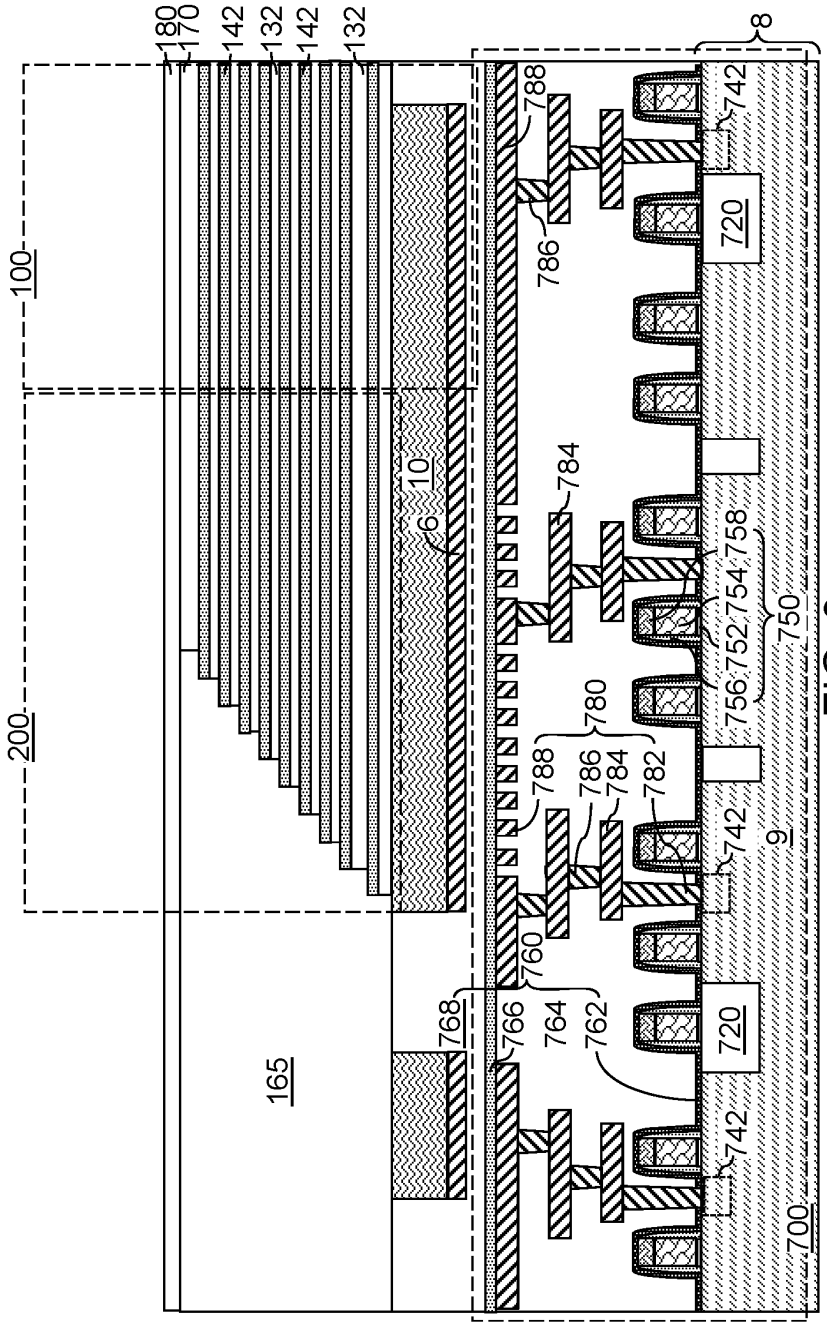
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FIG. 3

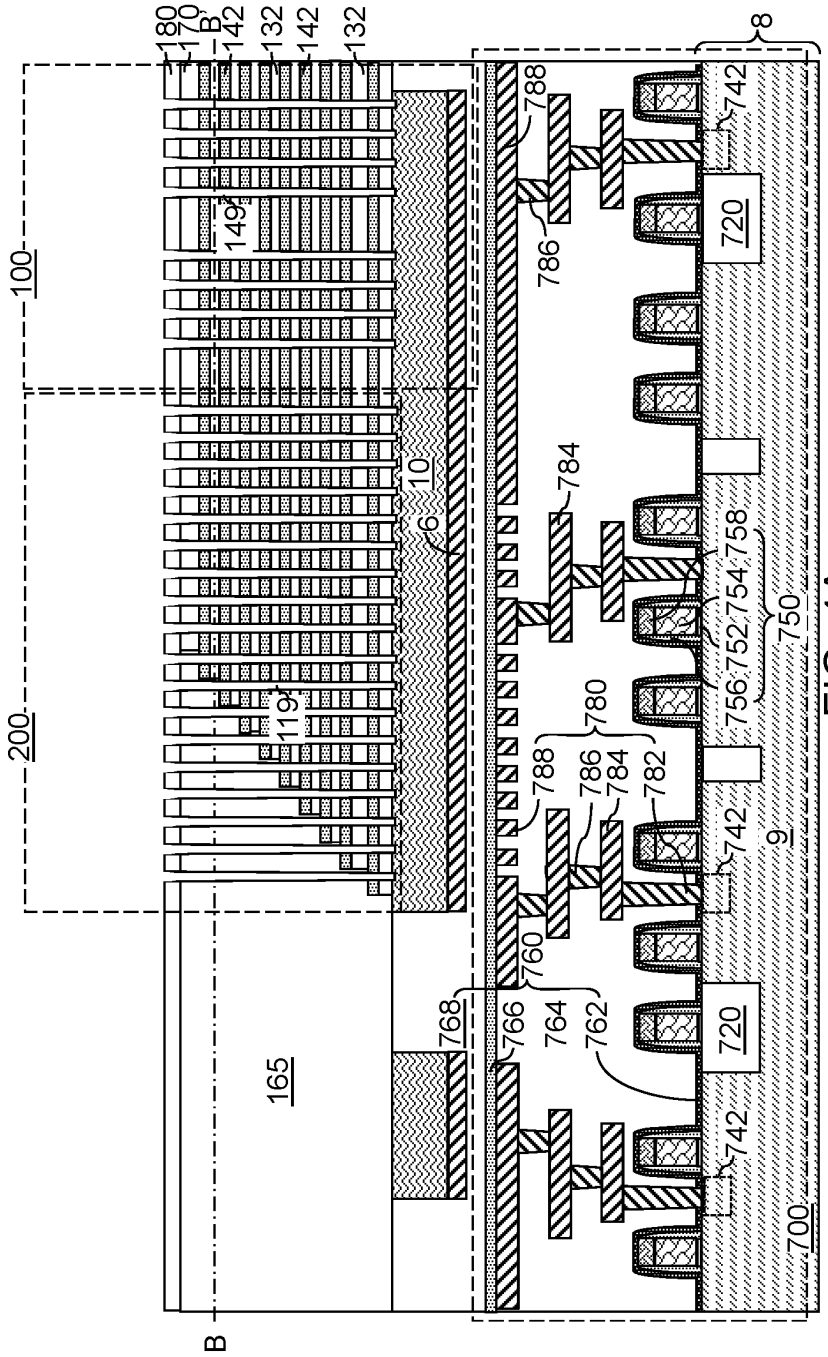
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FIG. 4A

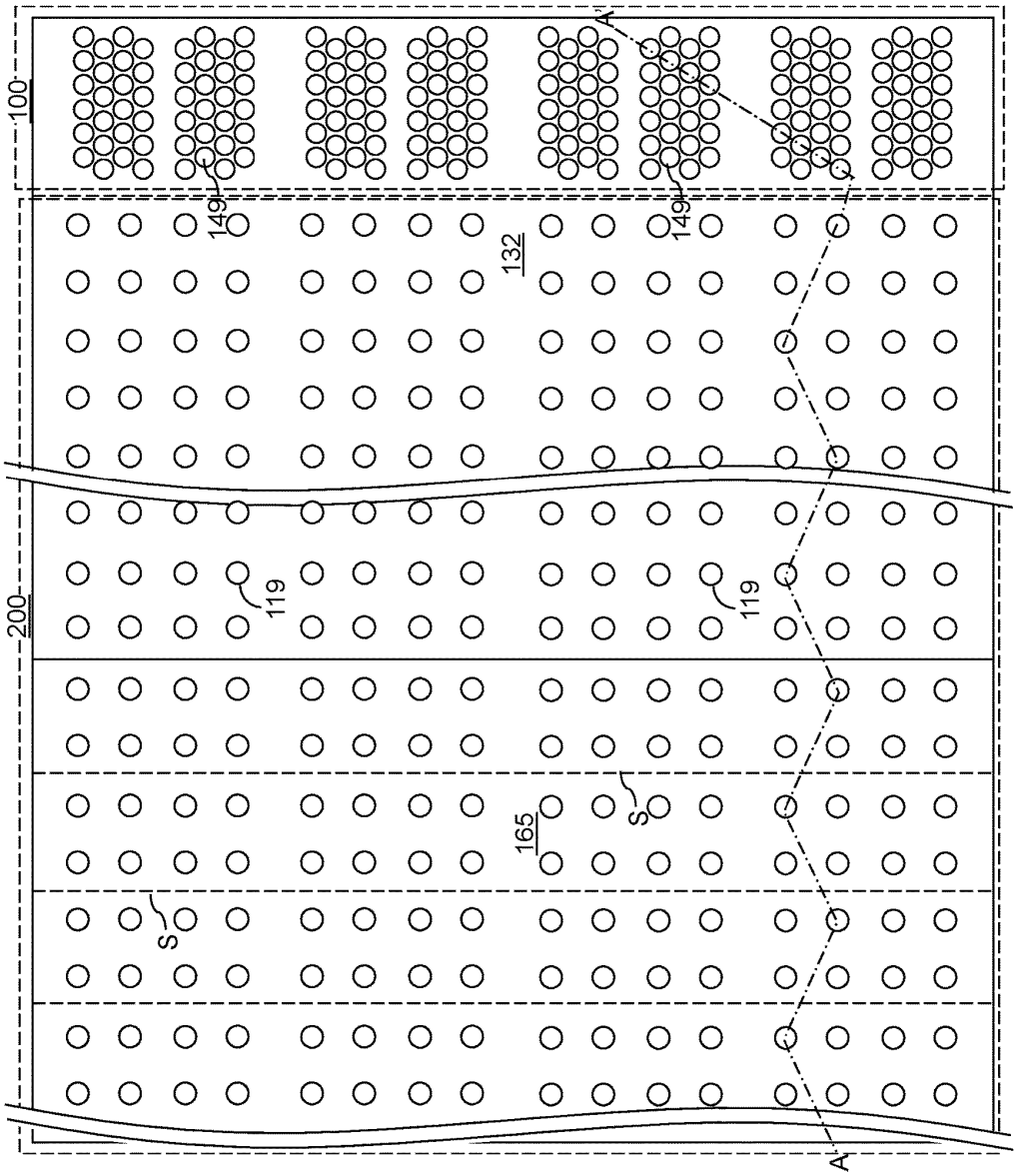

FIG. 4B

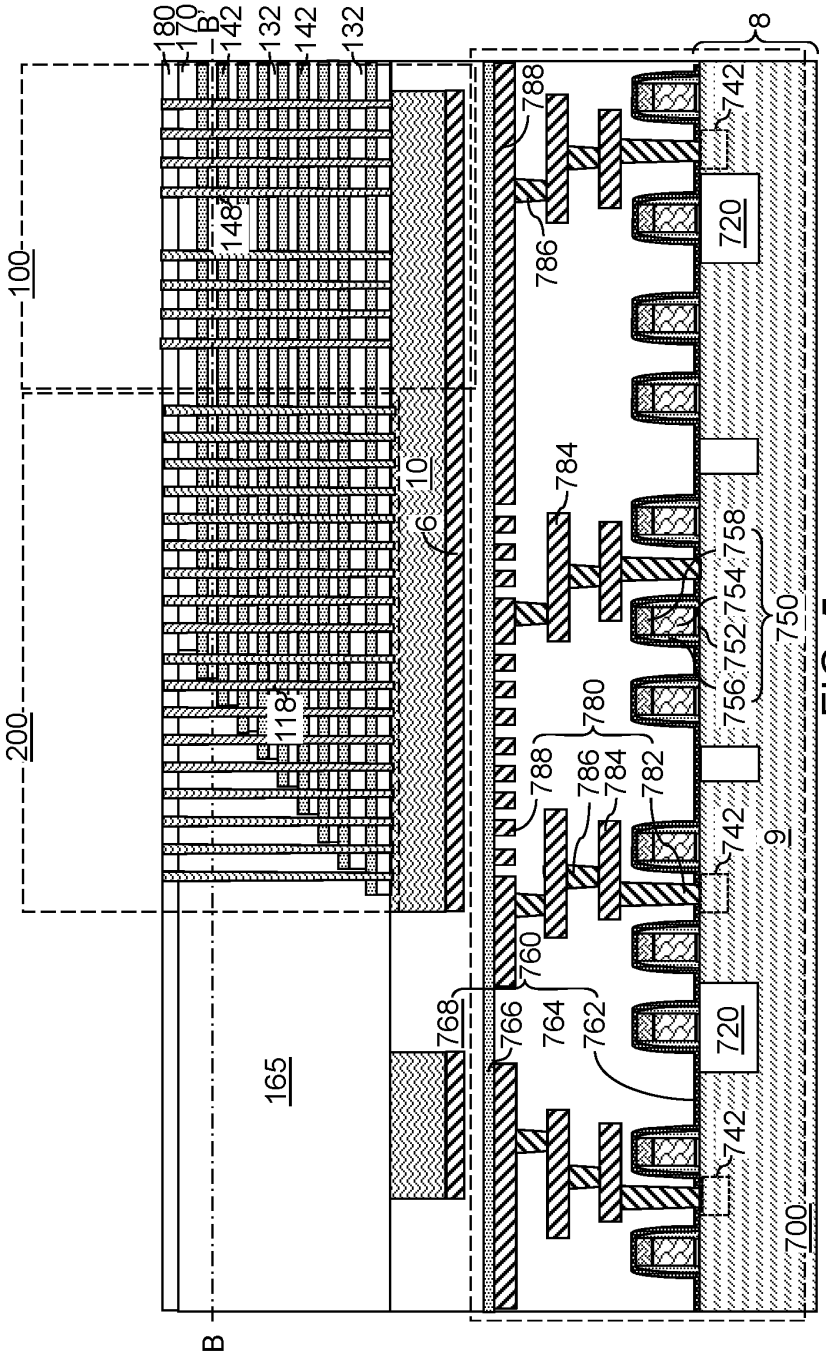
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FIG. 5

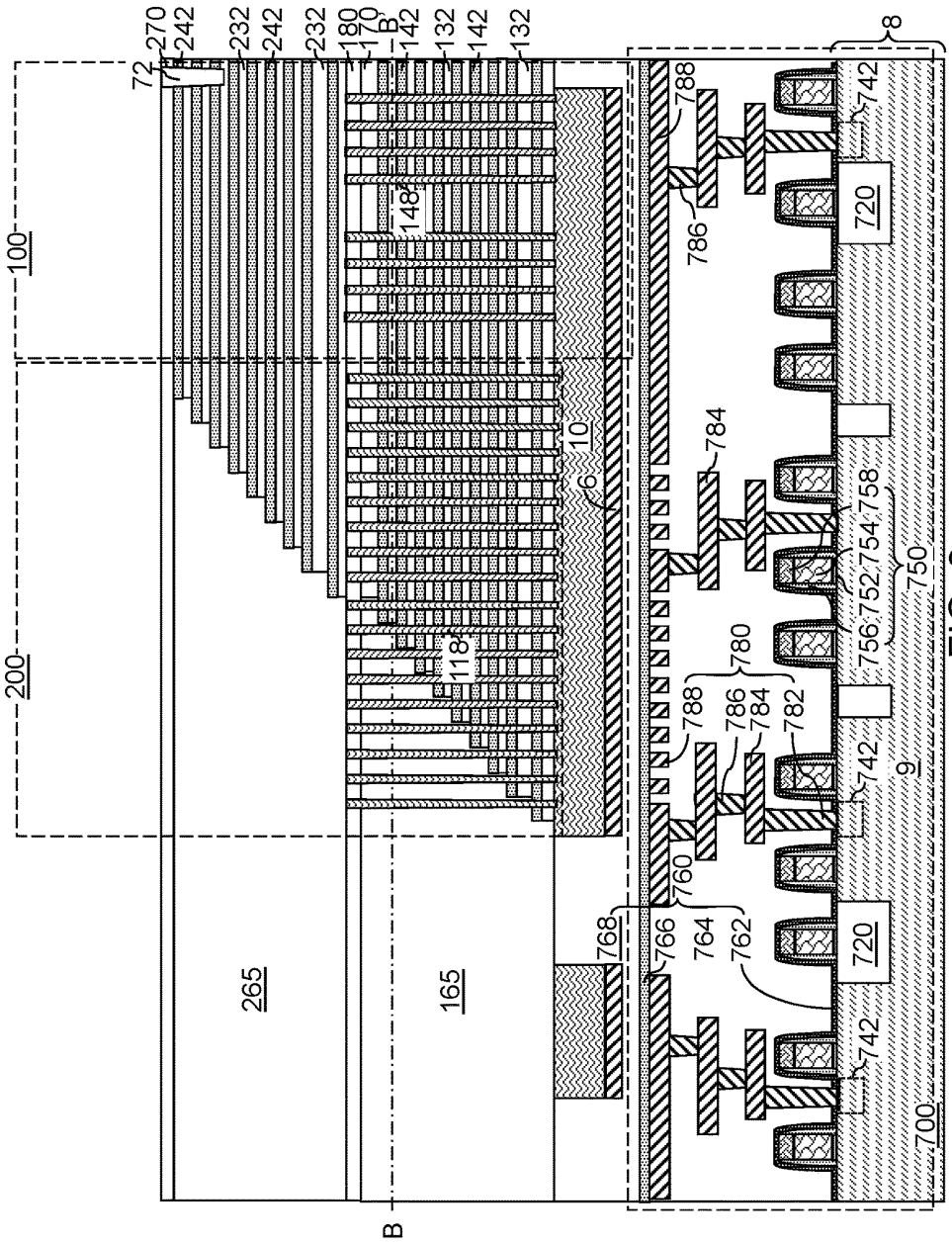
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FIG. 6

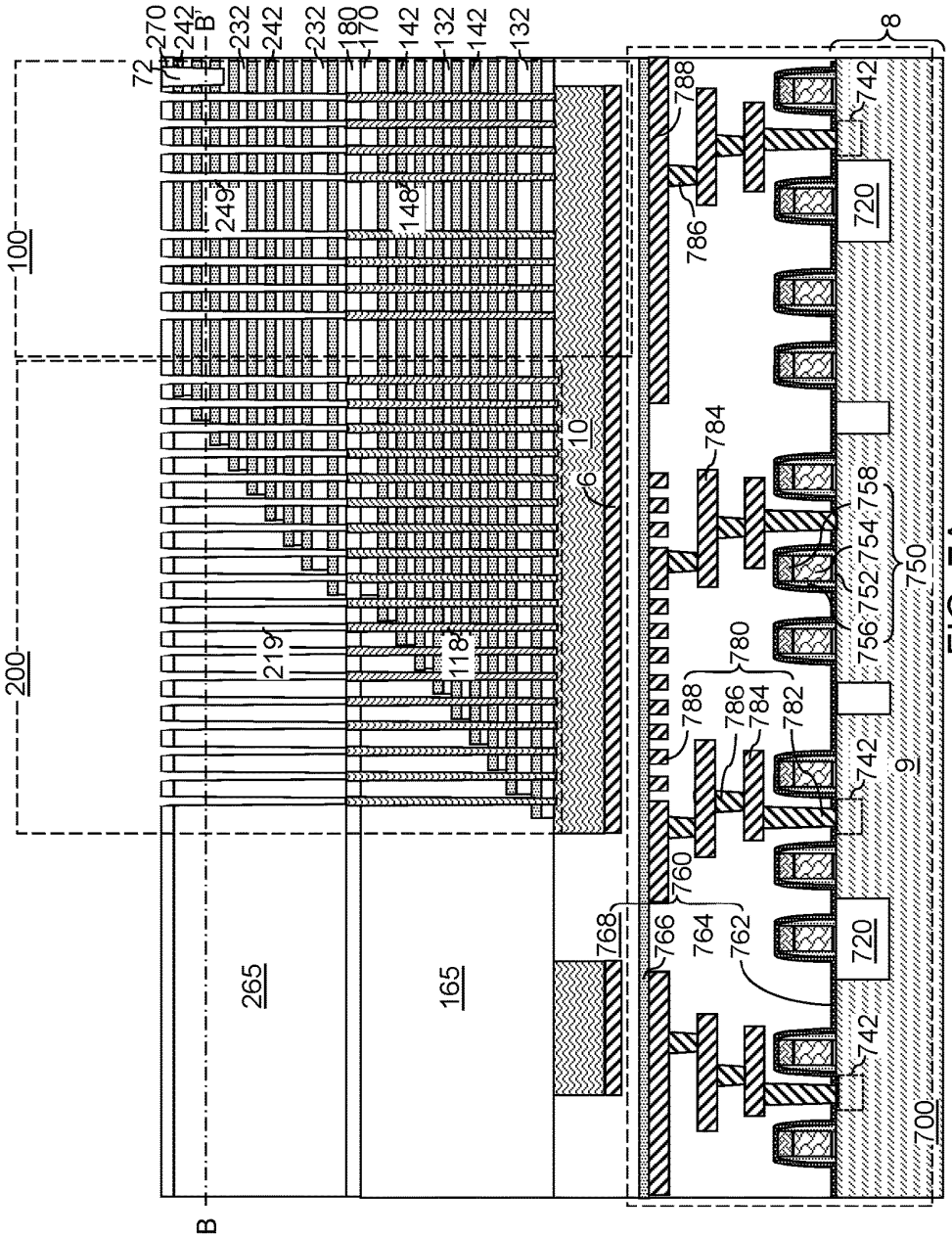

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FIG. 7A

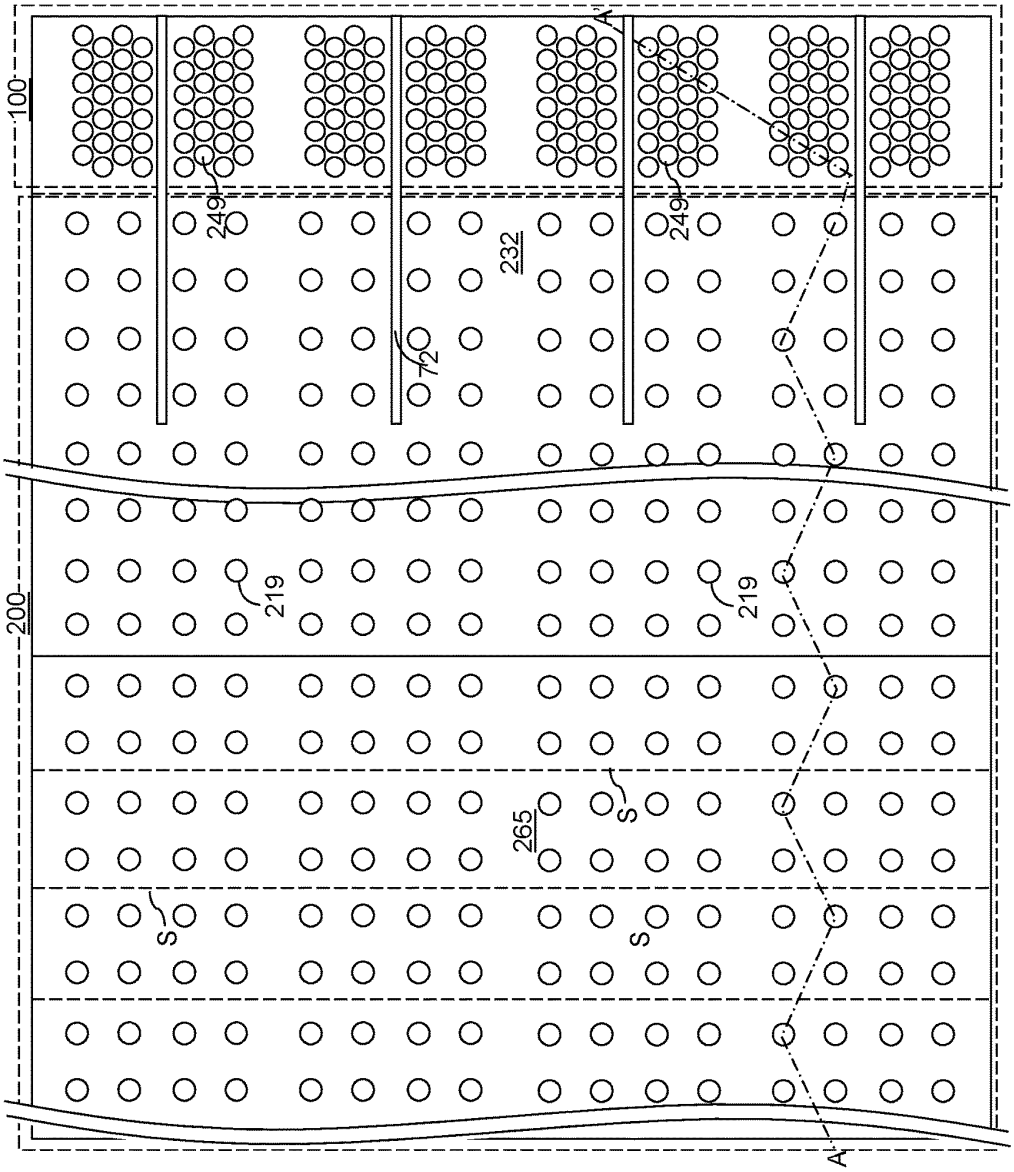

FIG. 7B

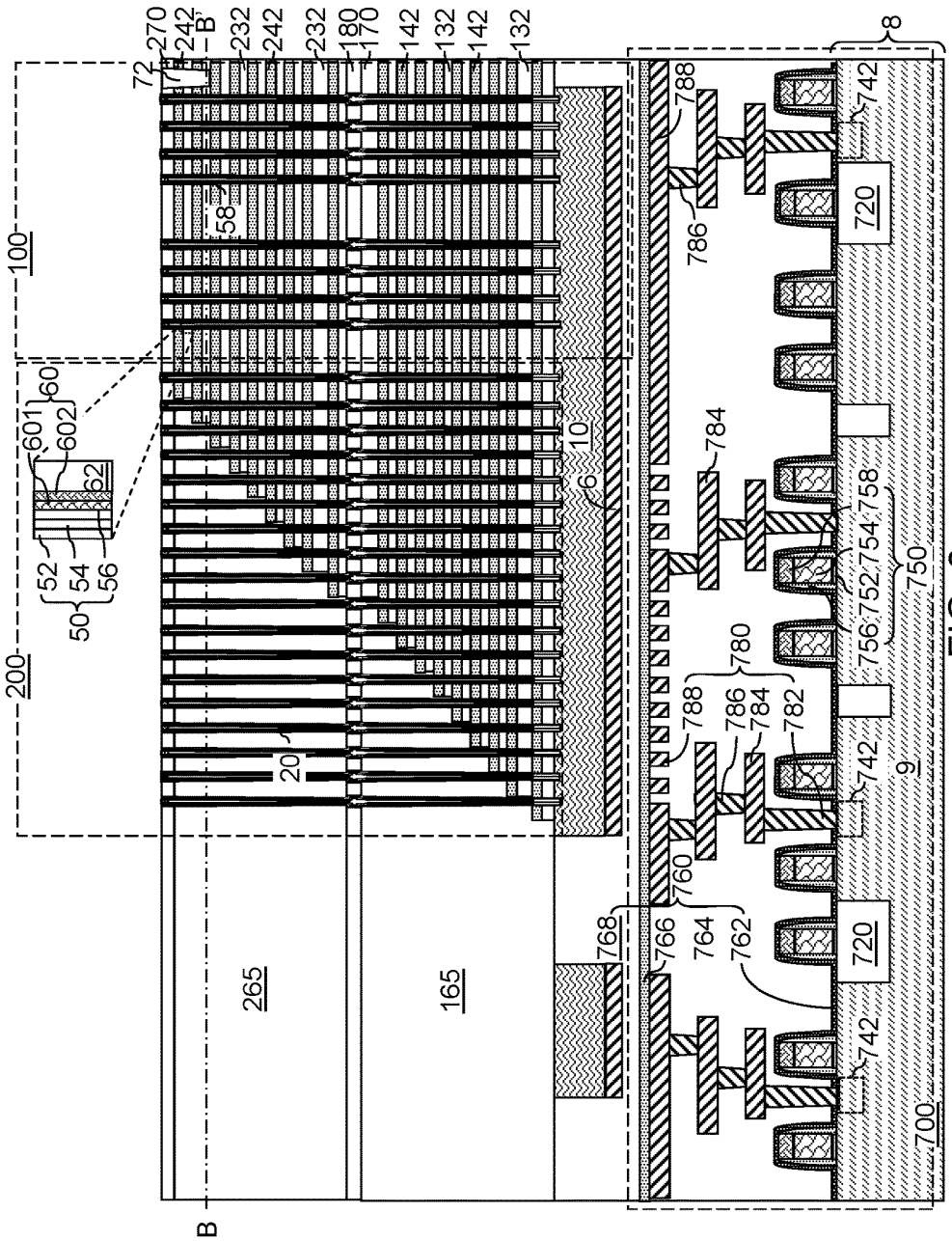
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FIG. 8

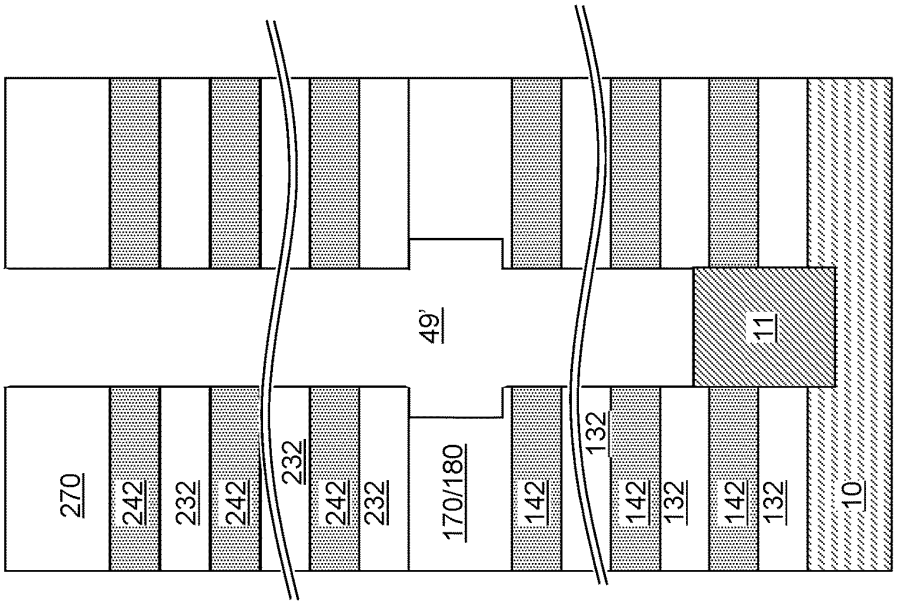
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FIG. 9B

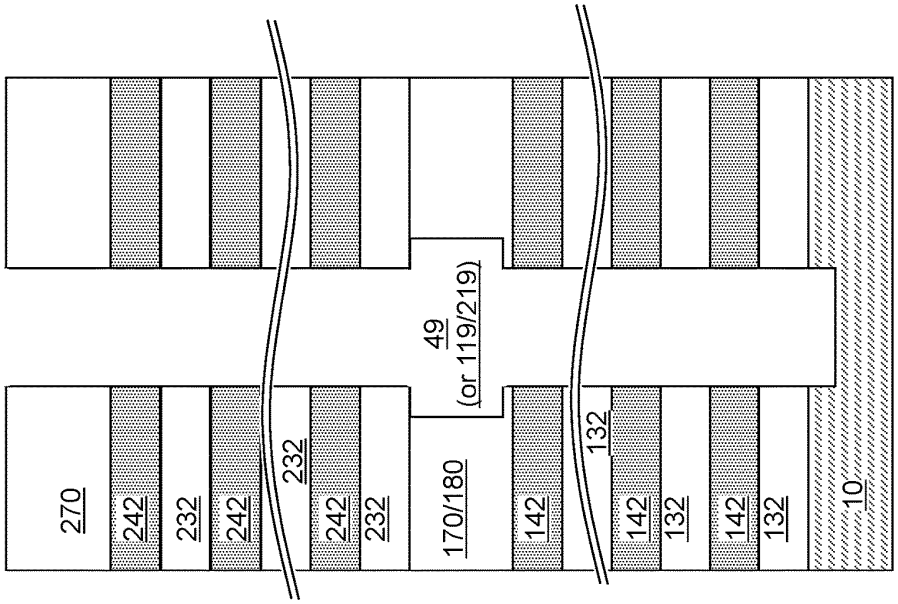
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FIG. 9A

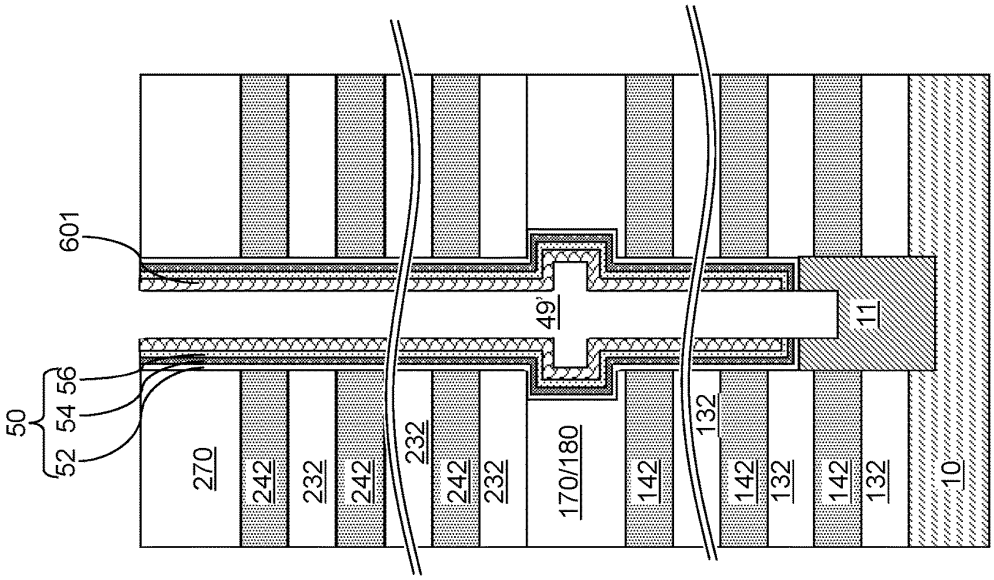
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FIG. 9D

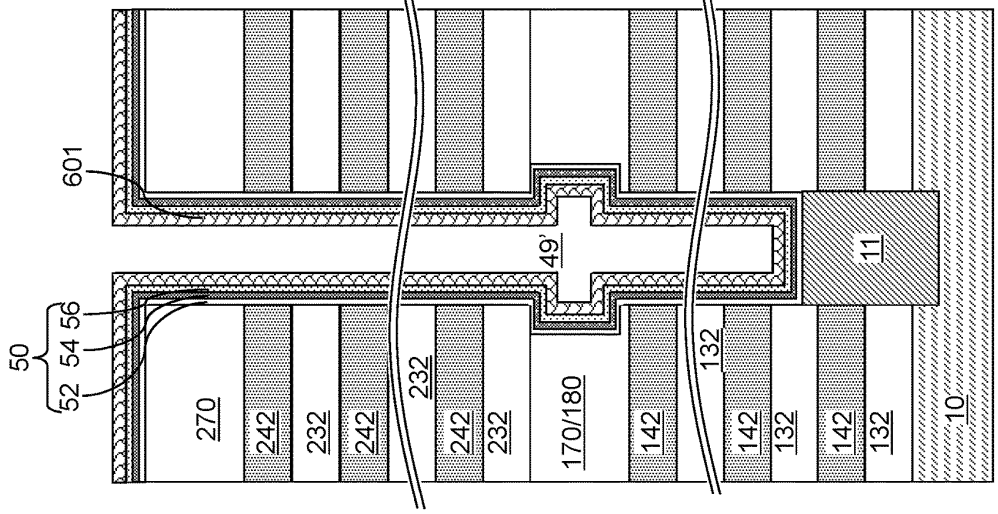
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FIG. 9C

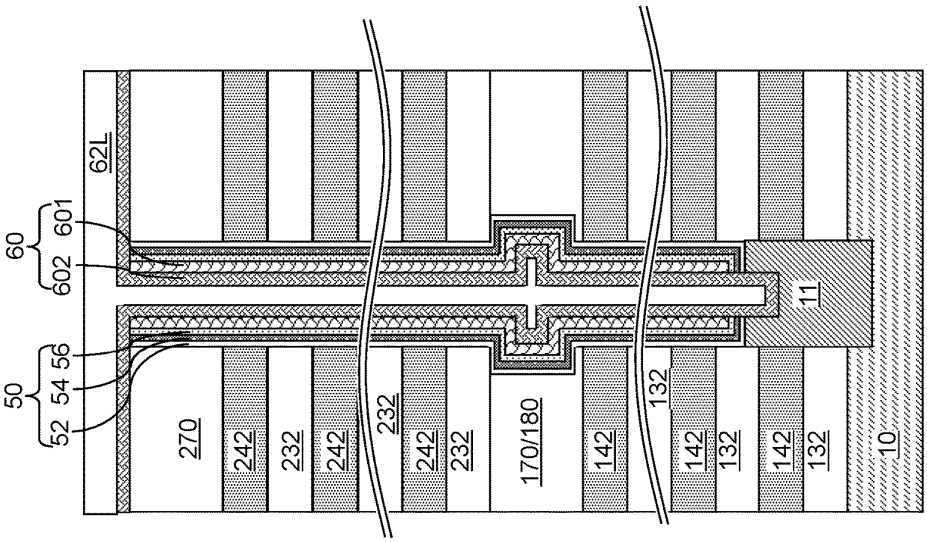
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FIG. 9F

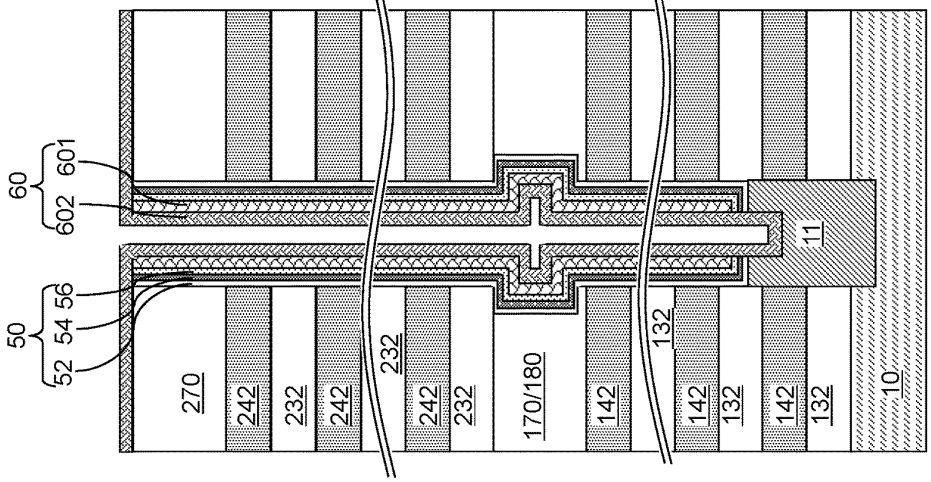
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FIG. 9E

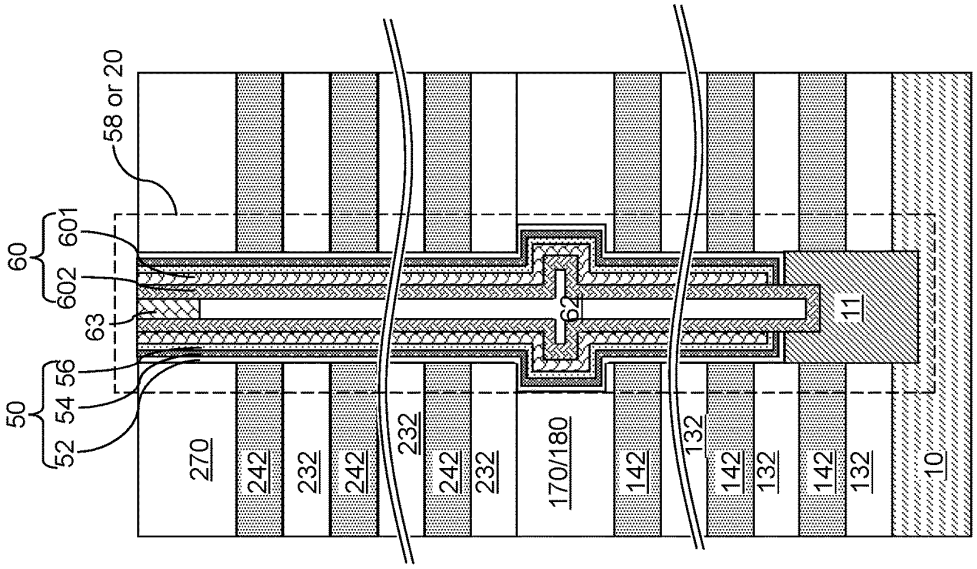
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FIG. 9H

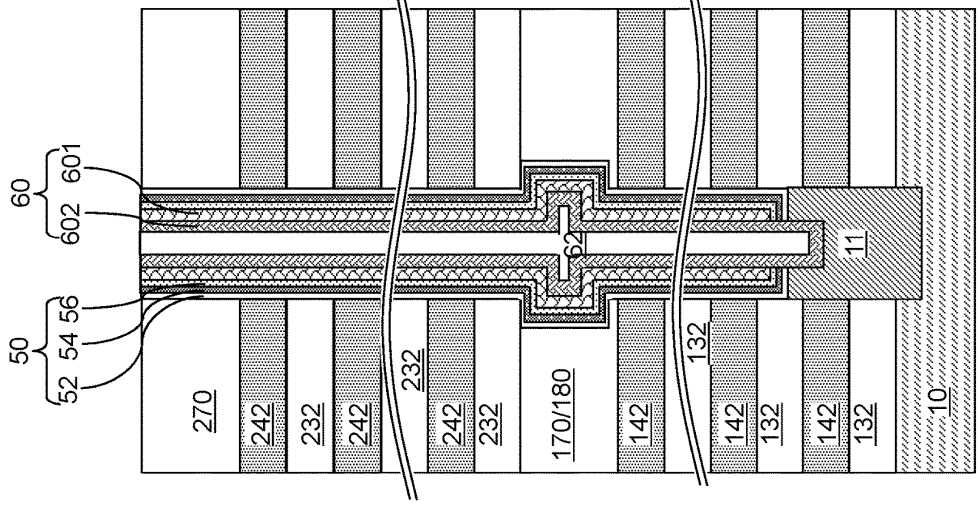
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FIG. 9G

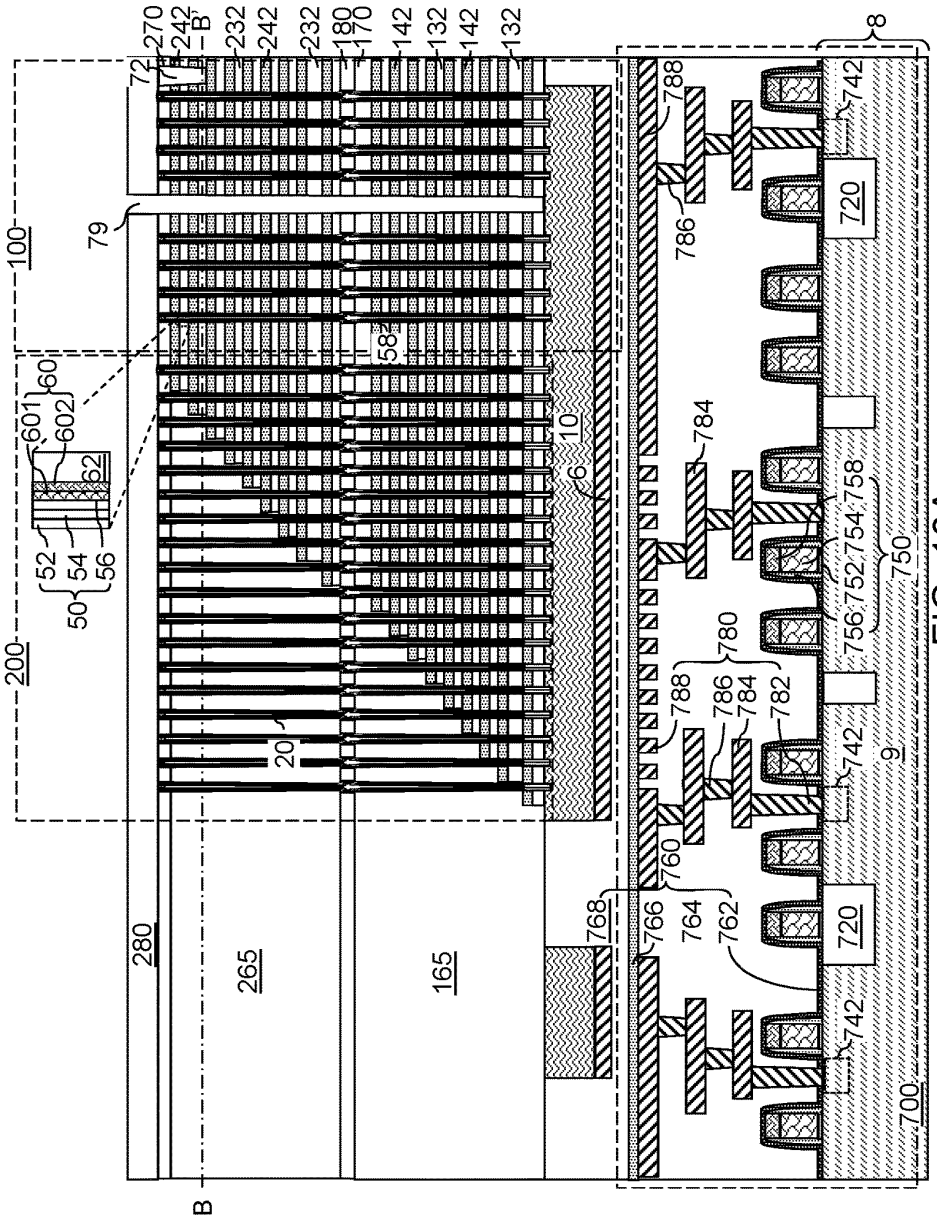
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FIG. 10A

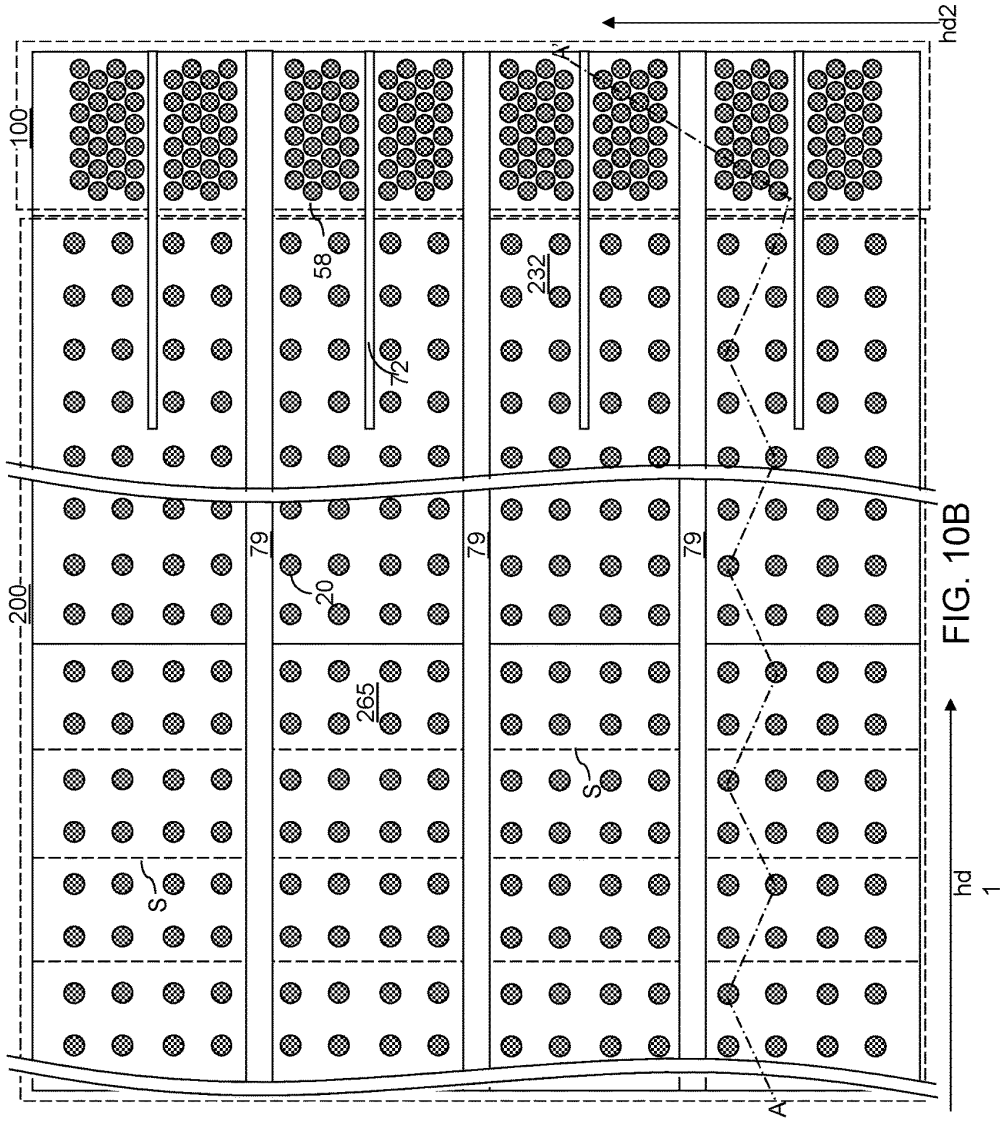

FIG. 10B

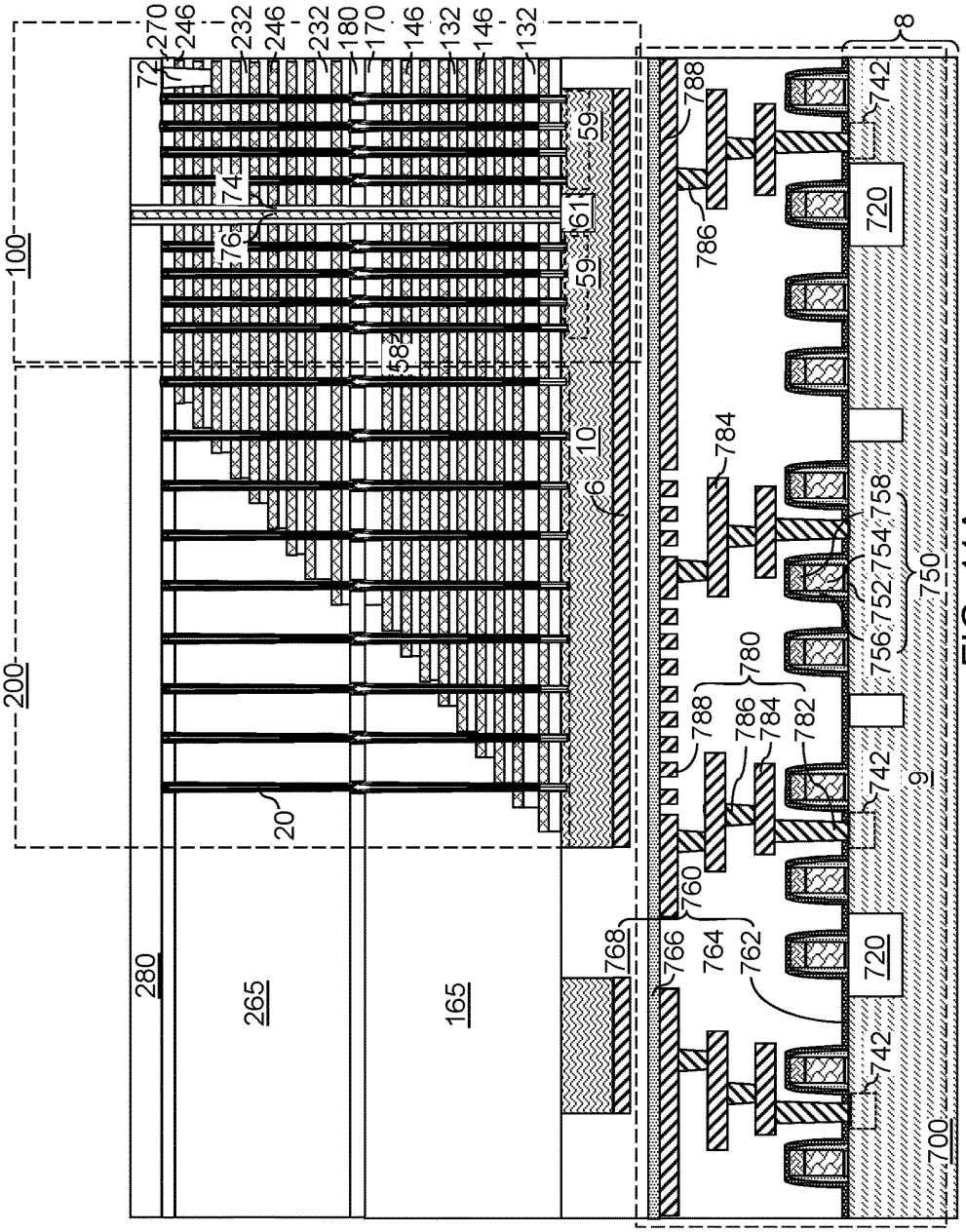
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FIG. 11A

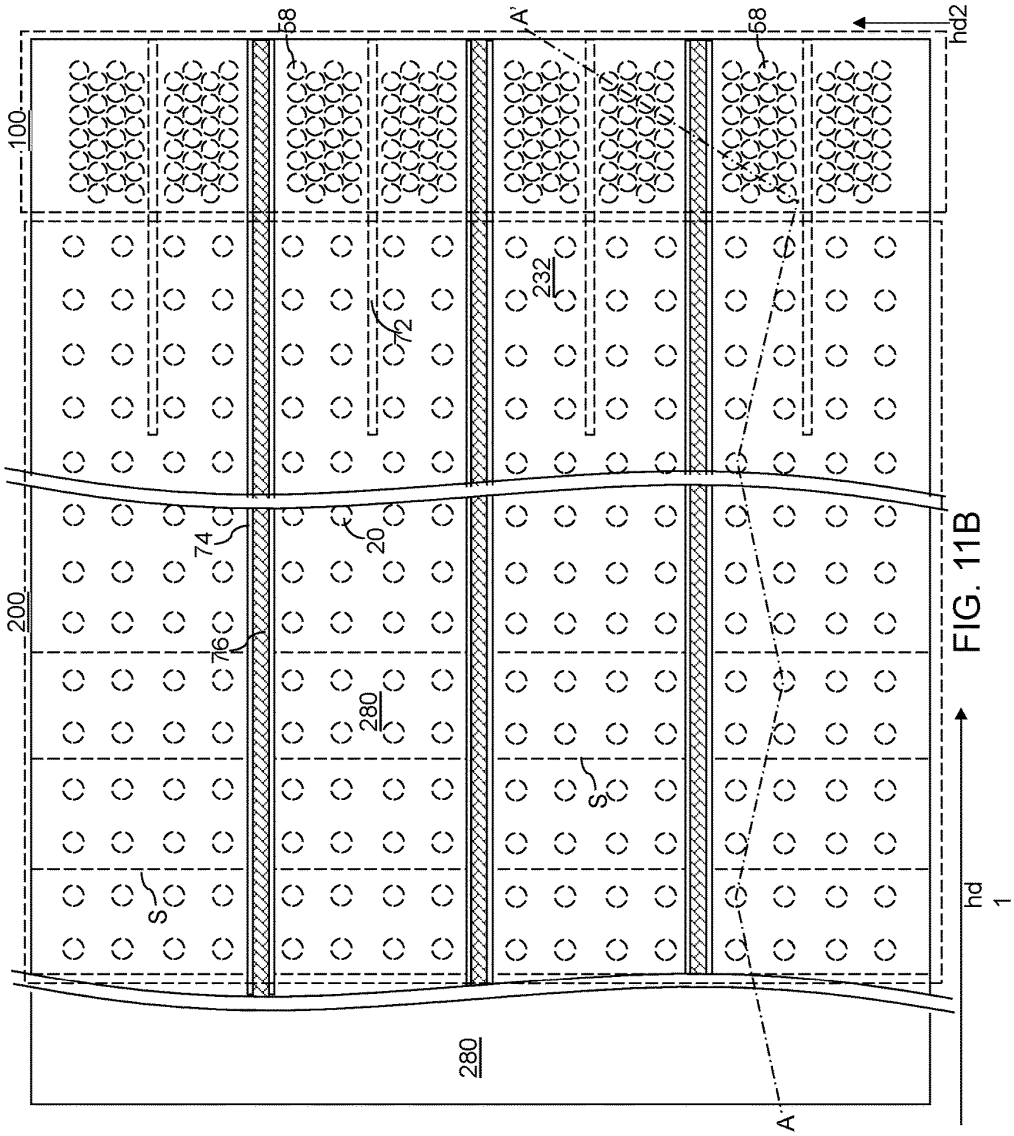

FIG. 11B

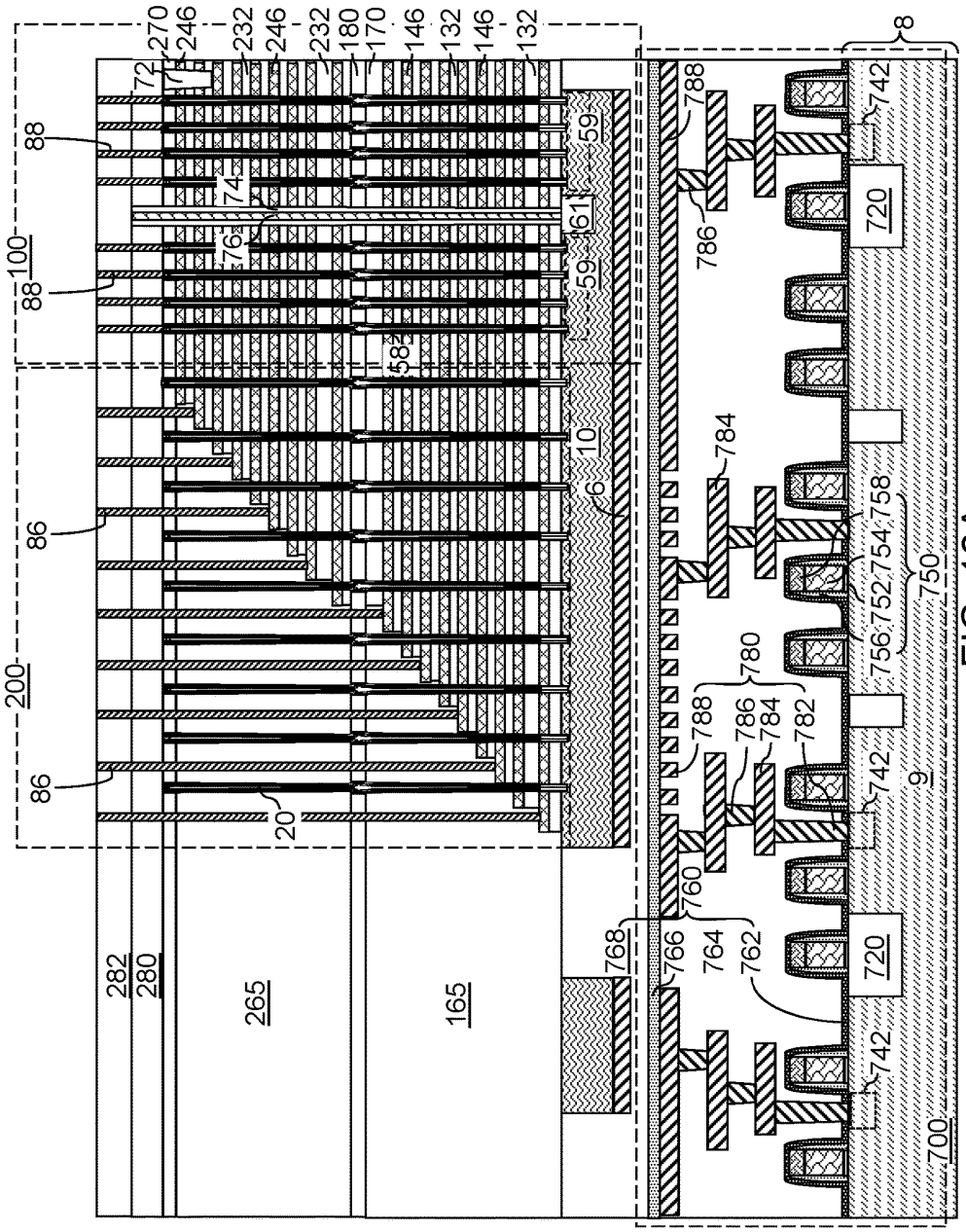
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FIG. 12A

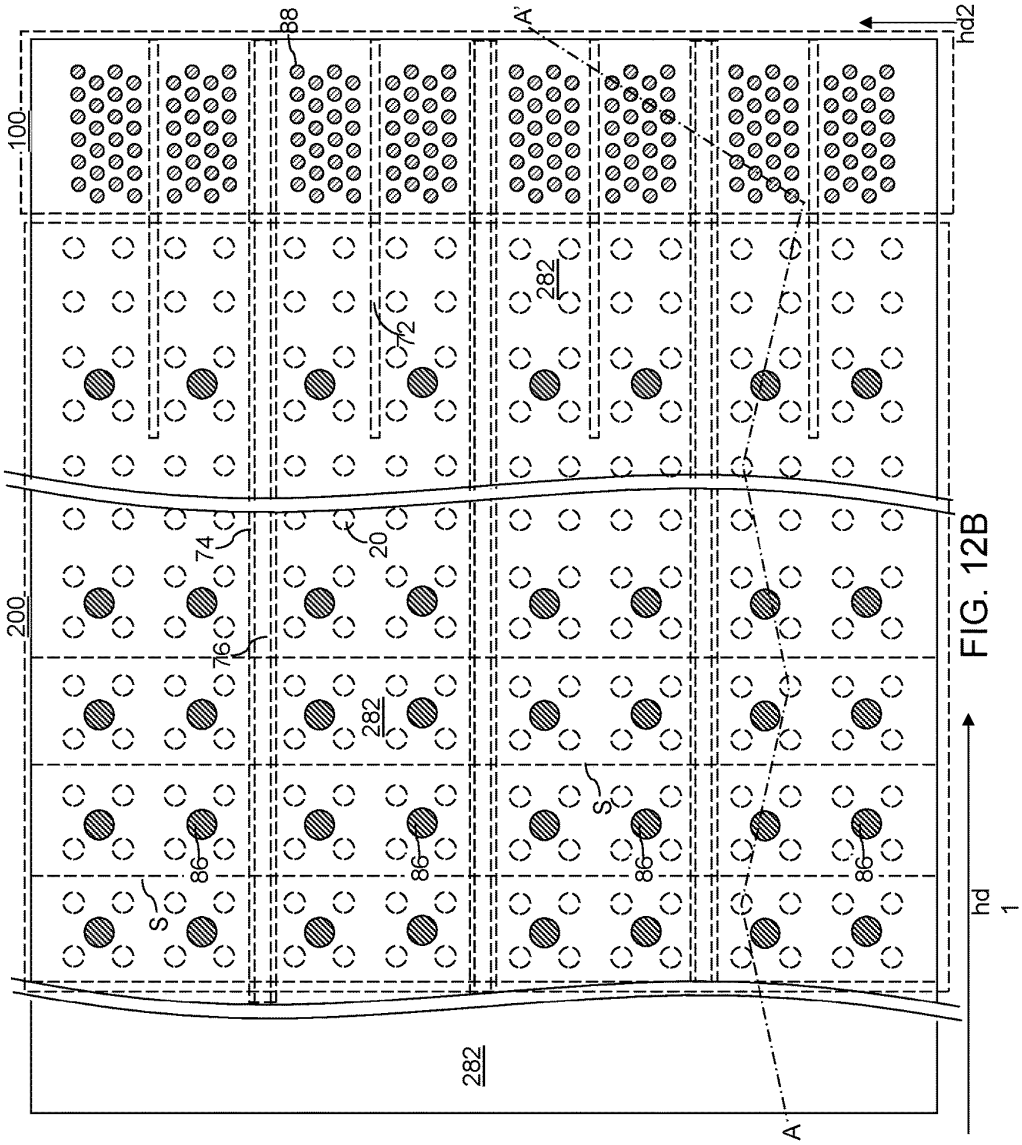

FIG. 12B

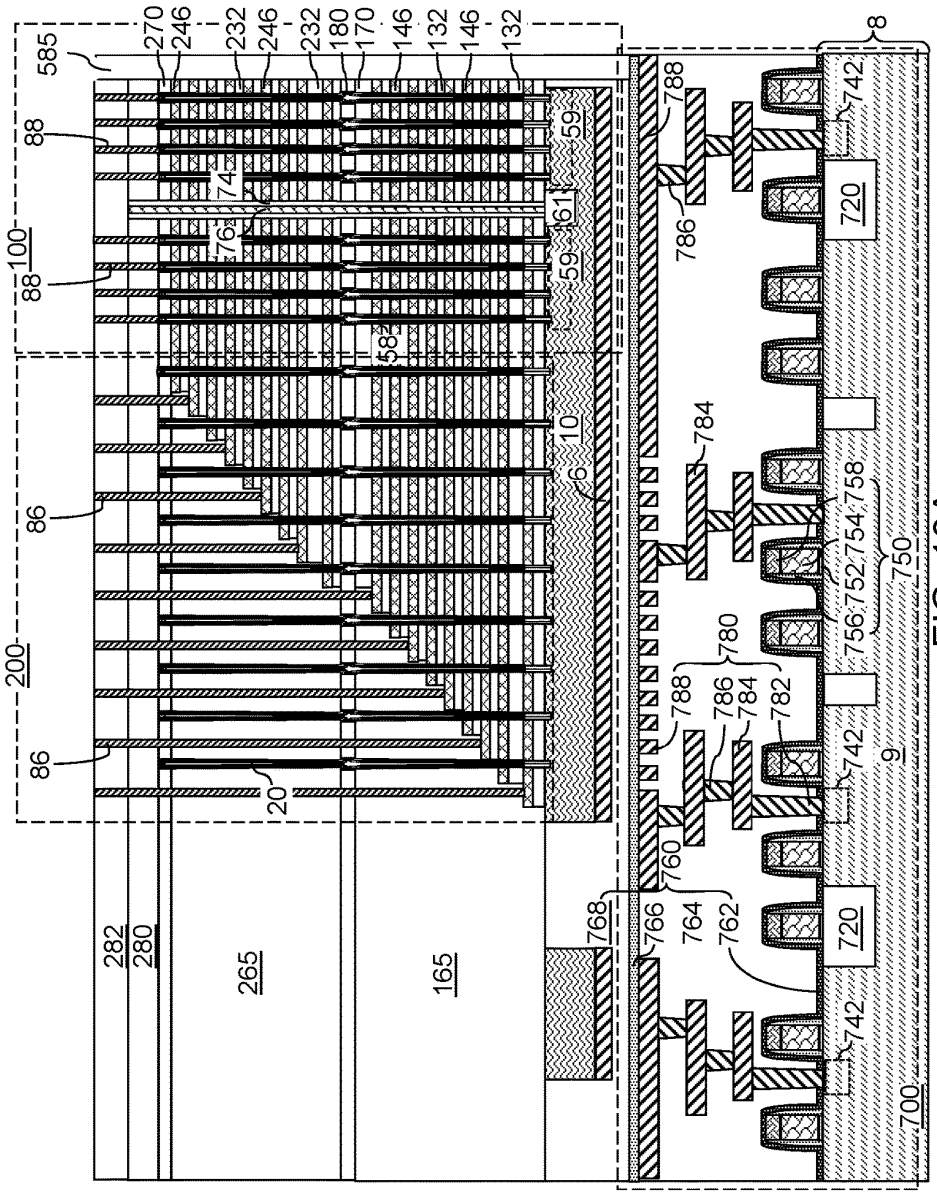
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FIG. 13A

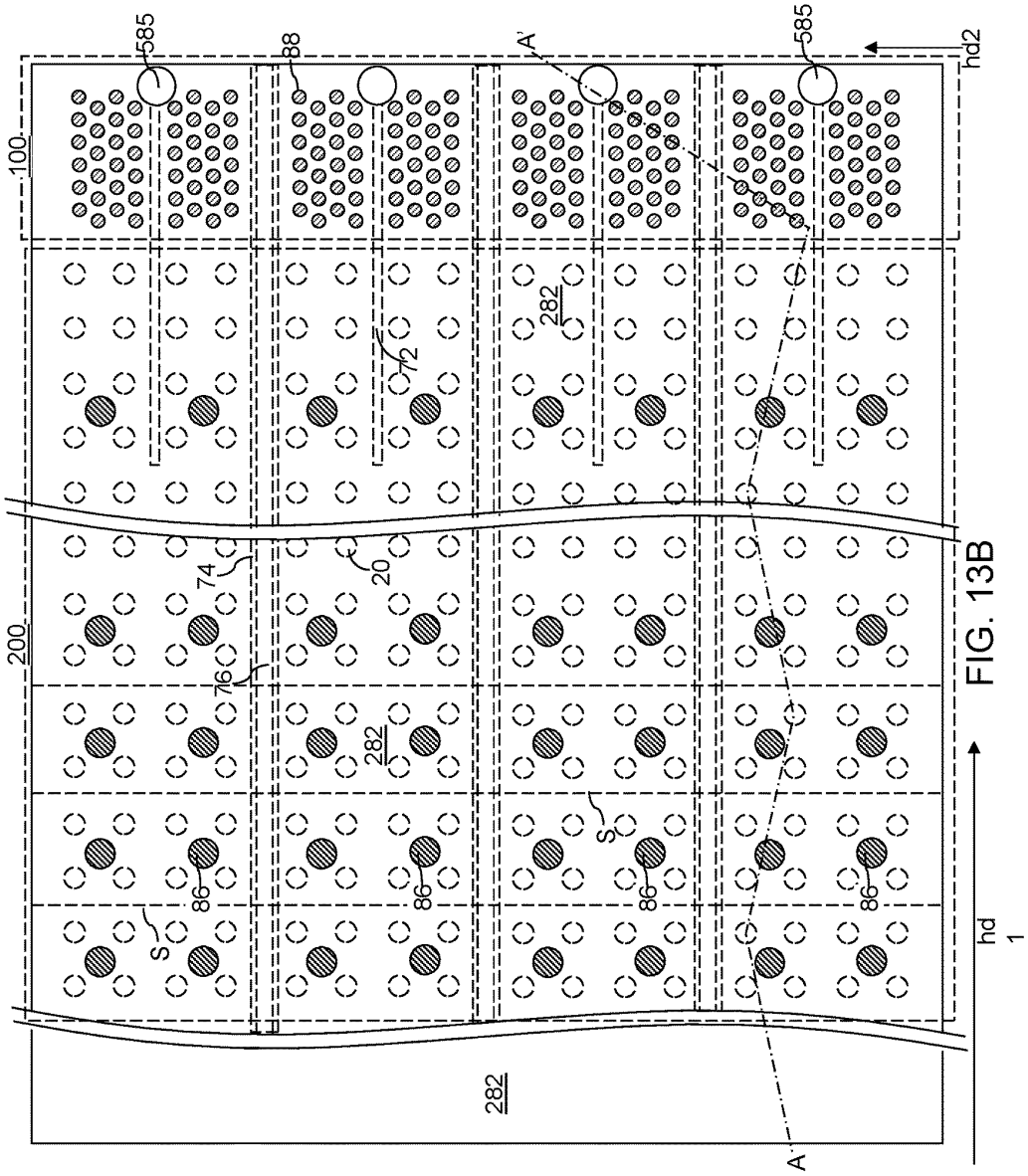

FIG. 13B

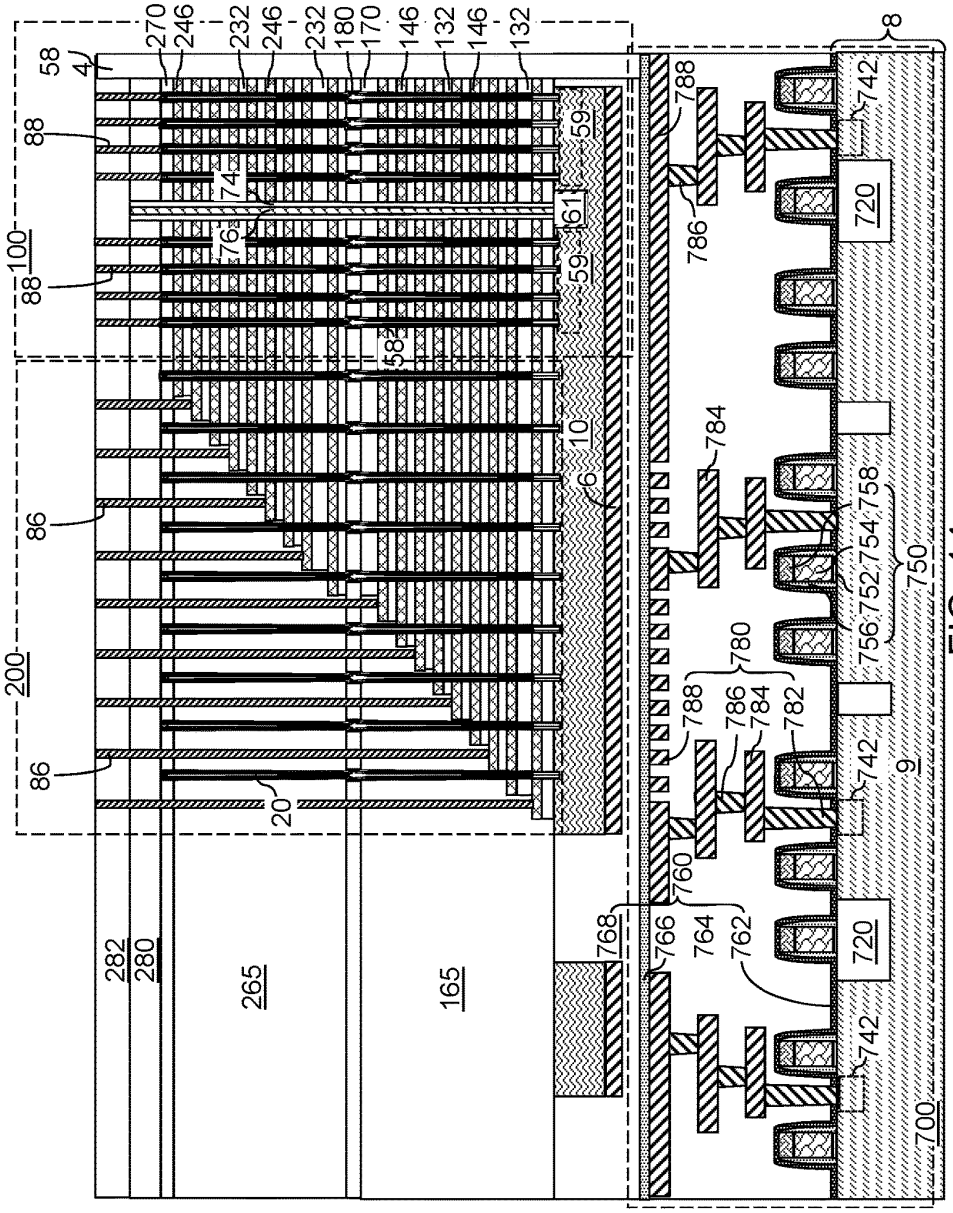
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FIG. 14

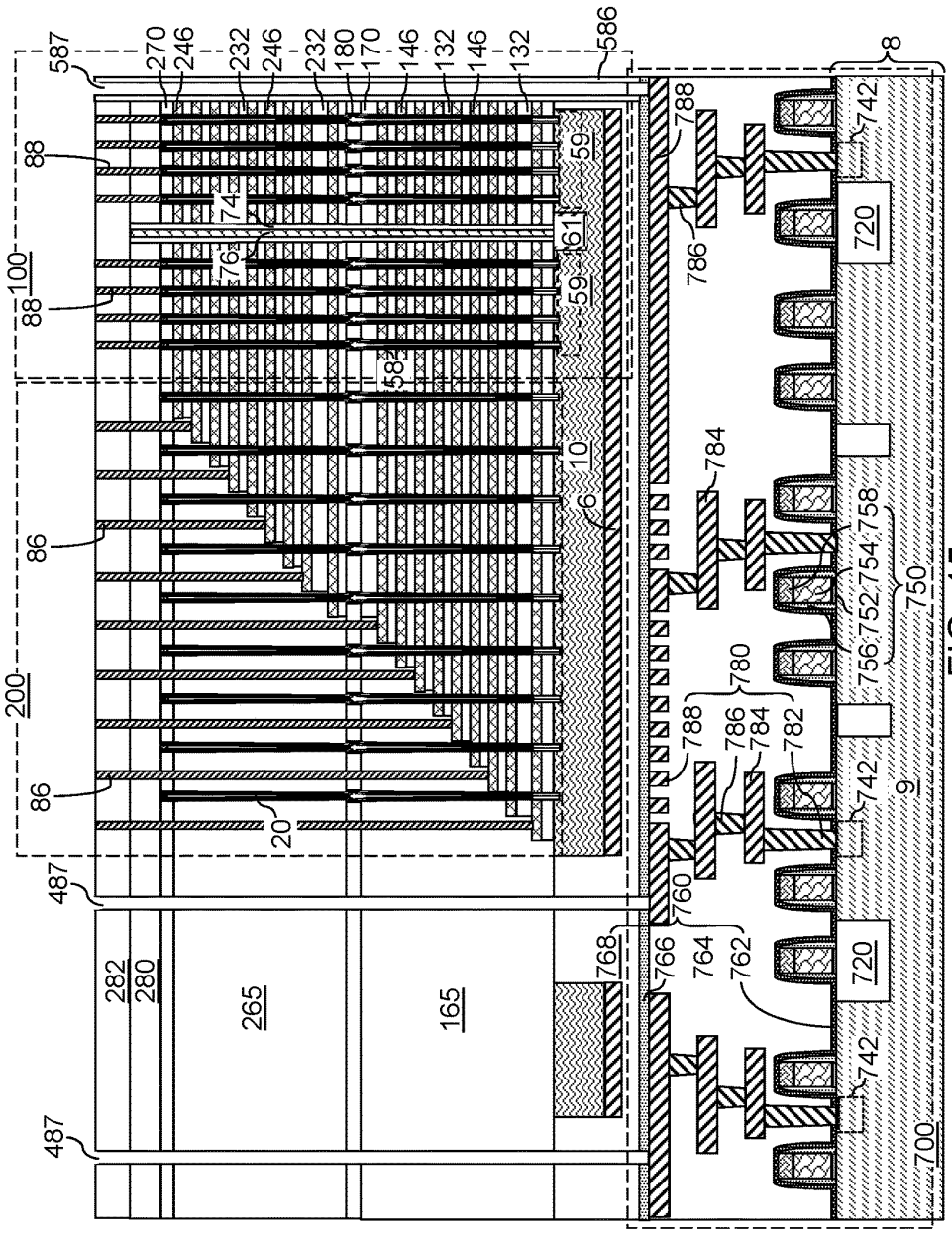
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FIG. 15

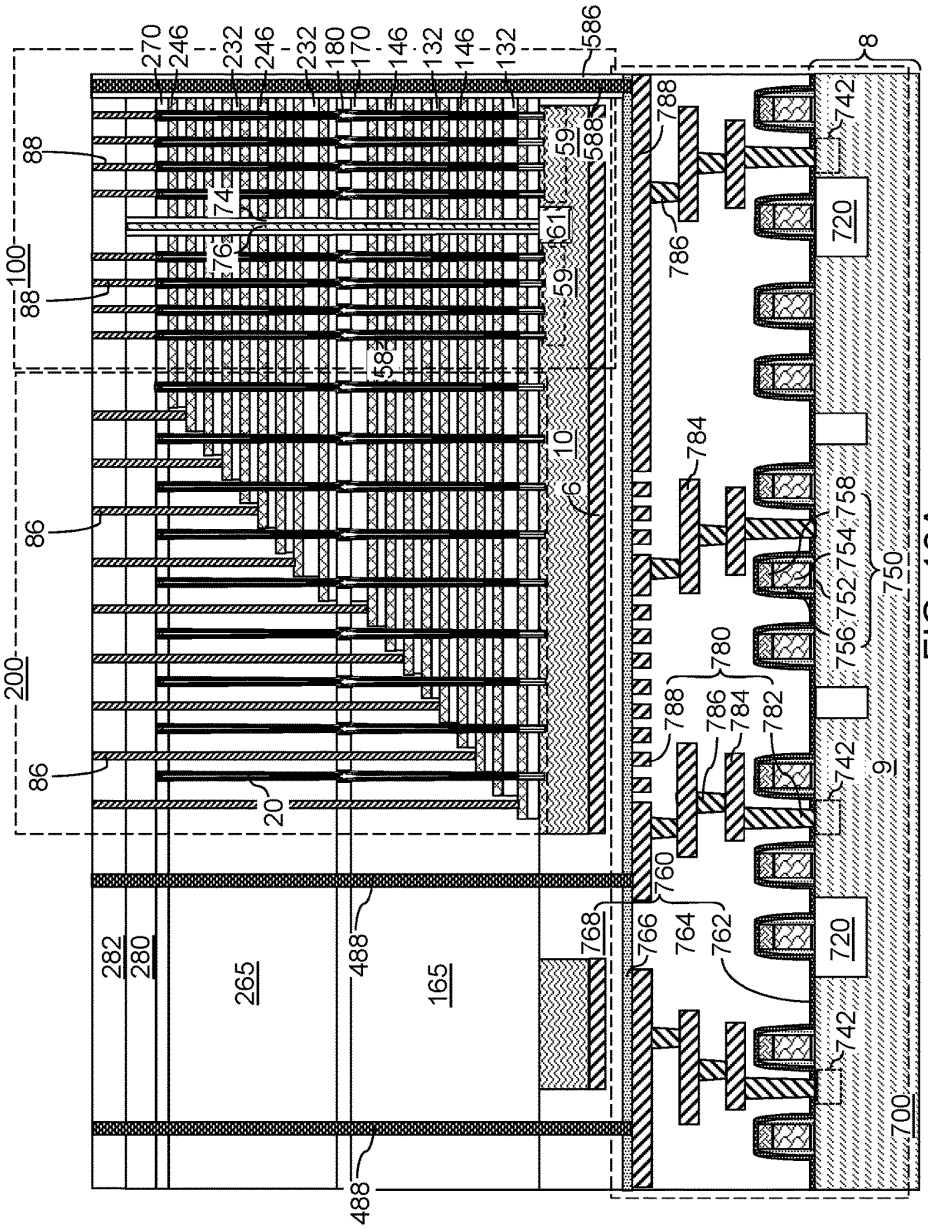
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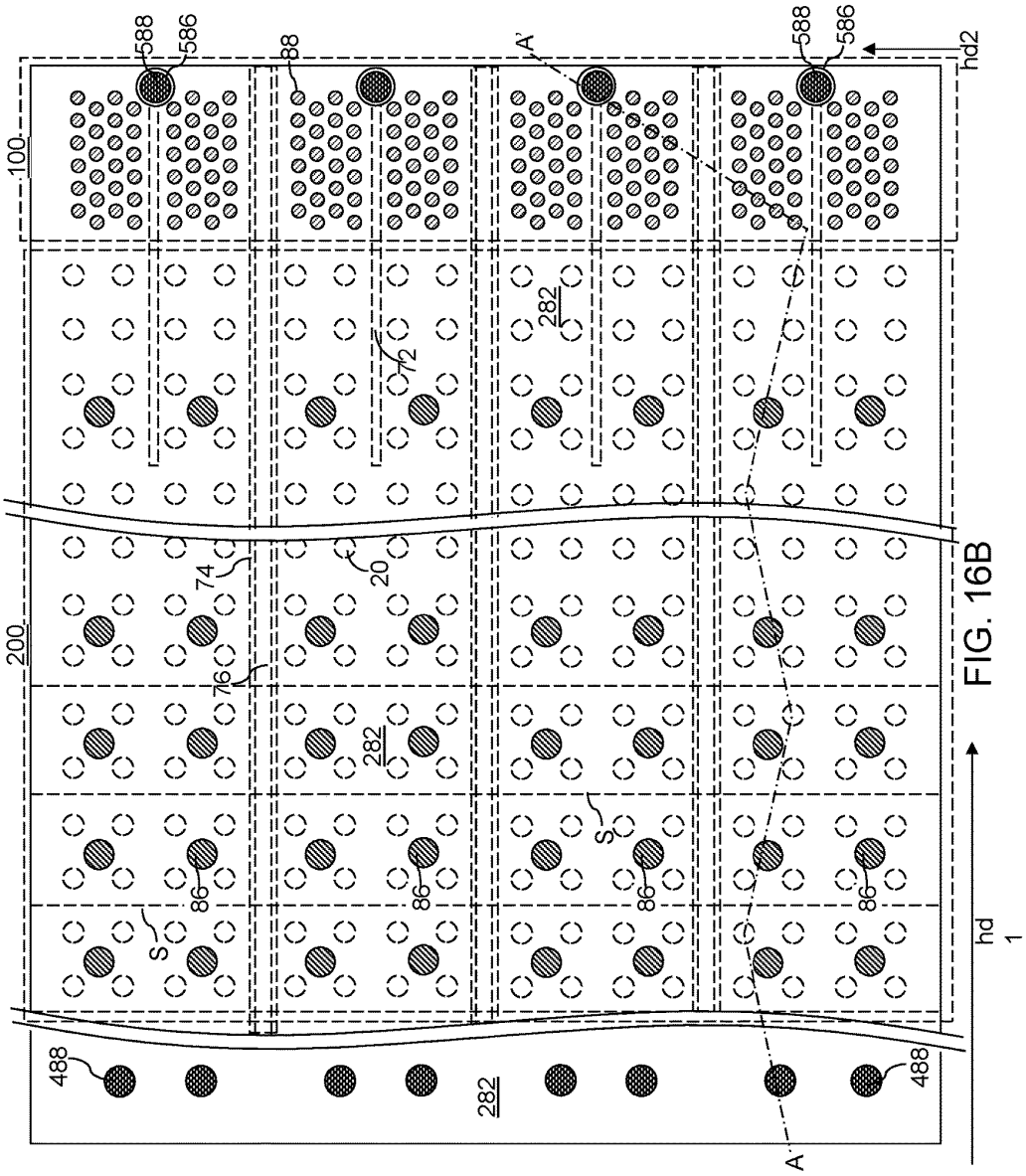
FIG. 16A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A

FIG. 16B

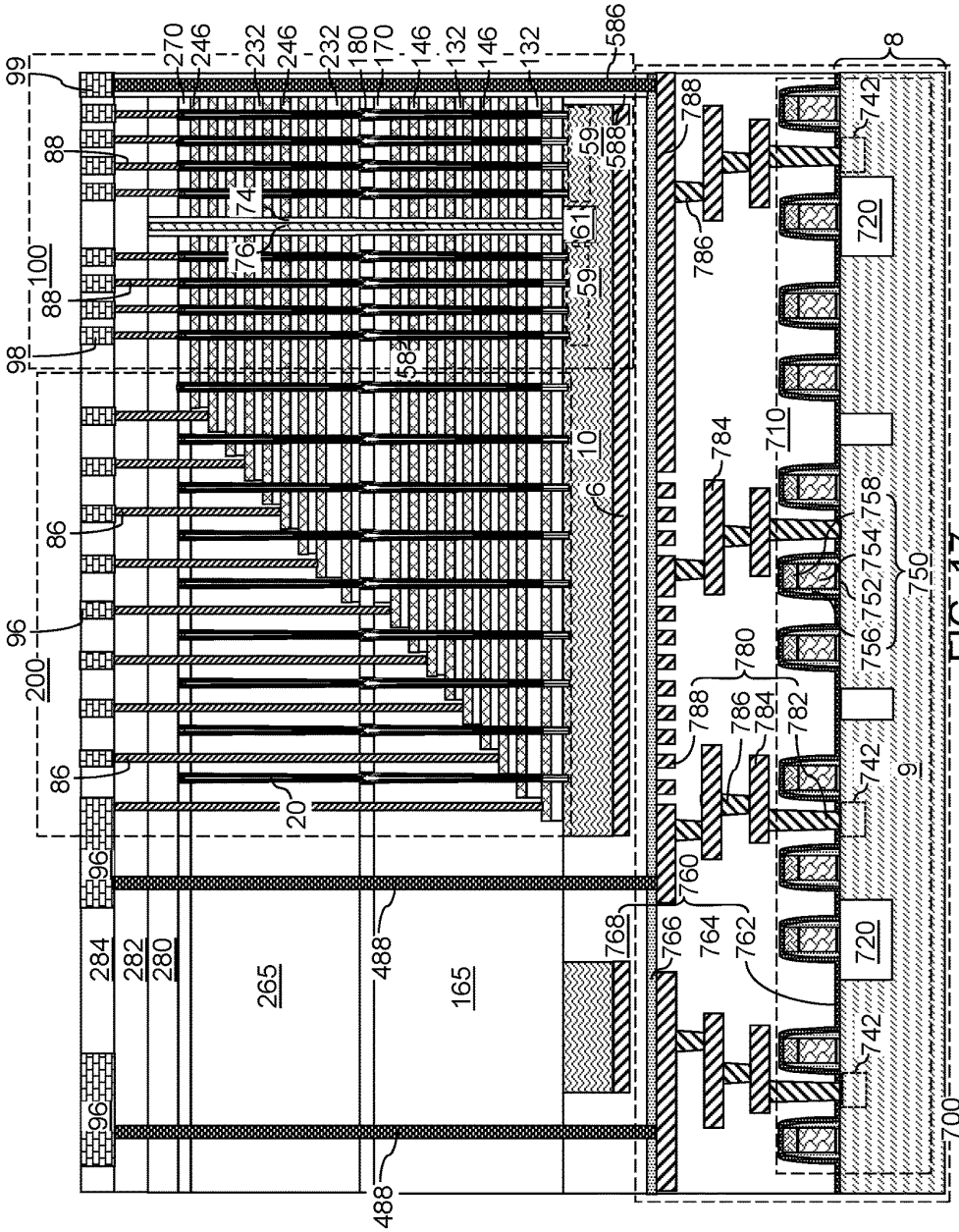
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FIG. 17

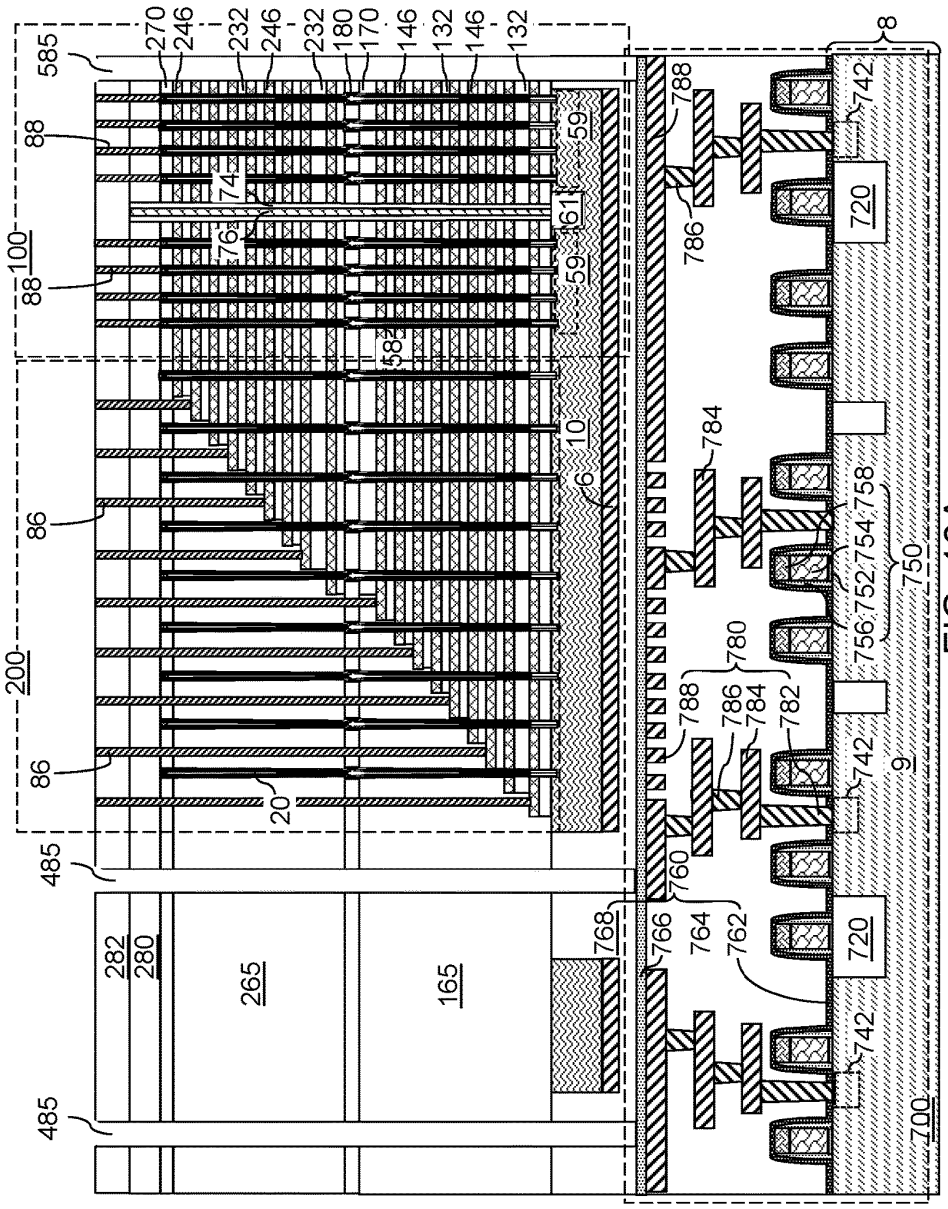
585
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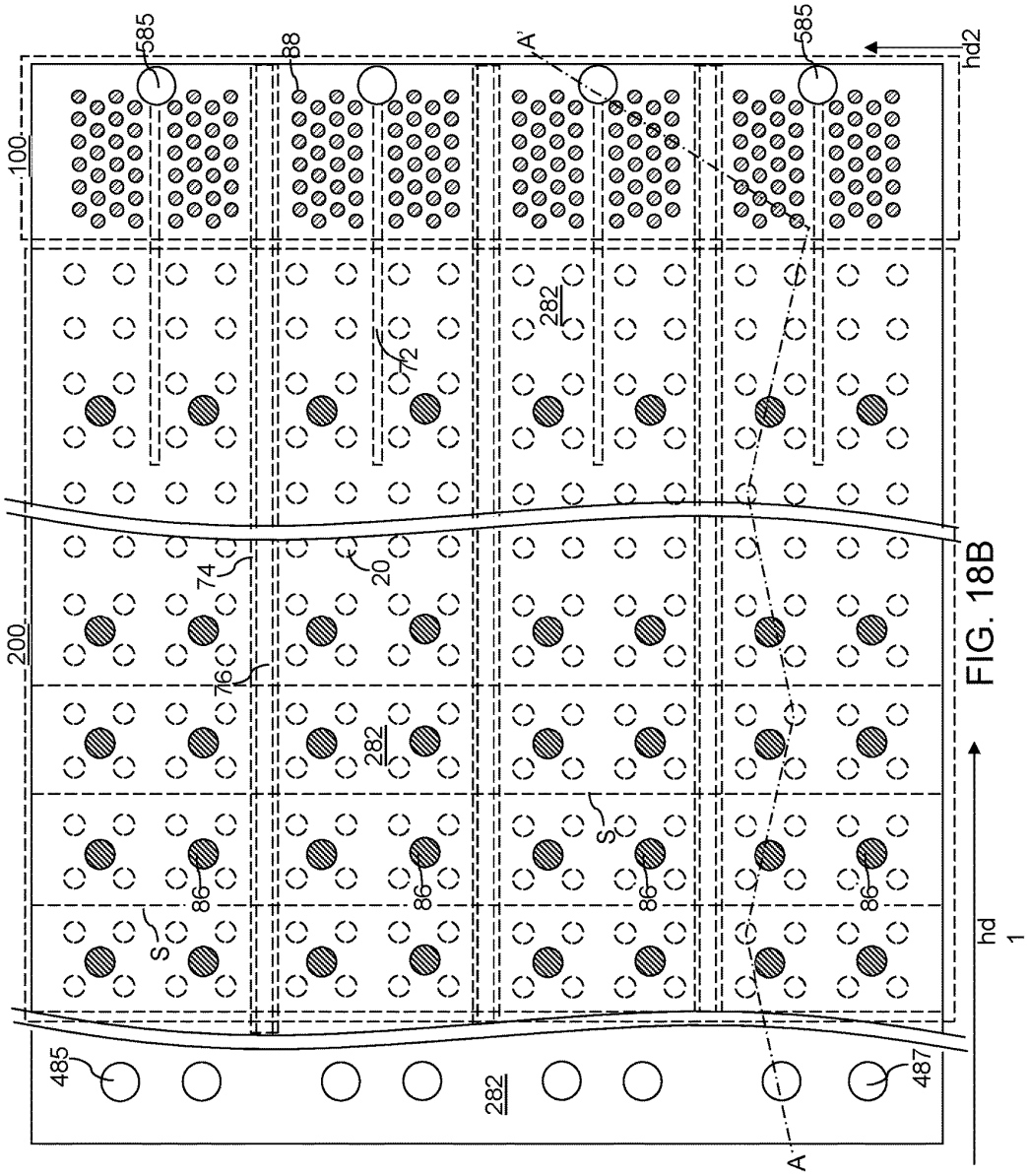
FIG. 18A


585
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487
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FIG. 18B

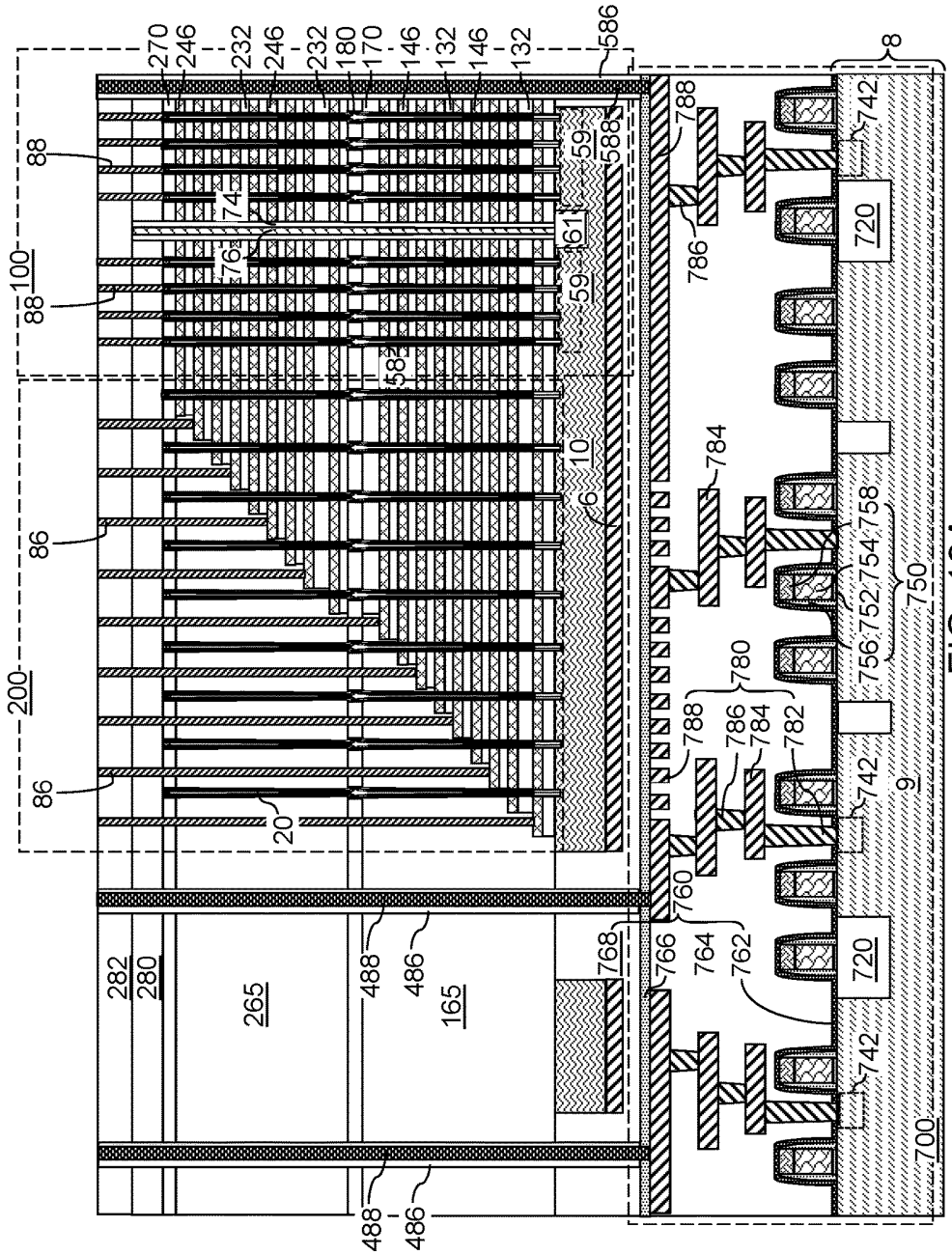
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FIG. 19A

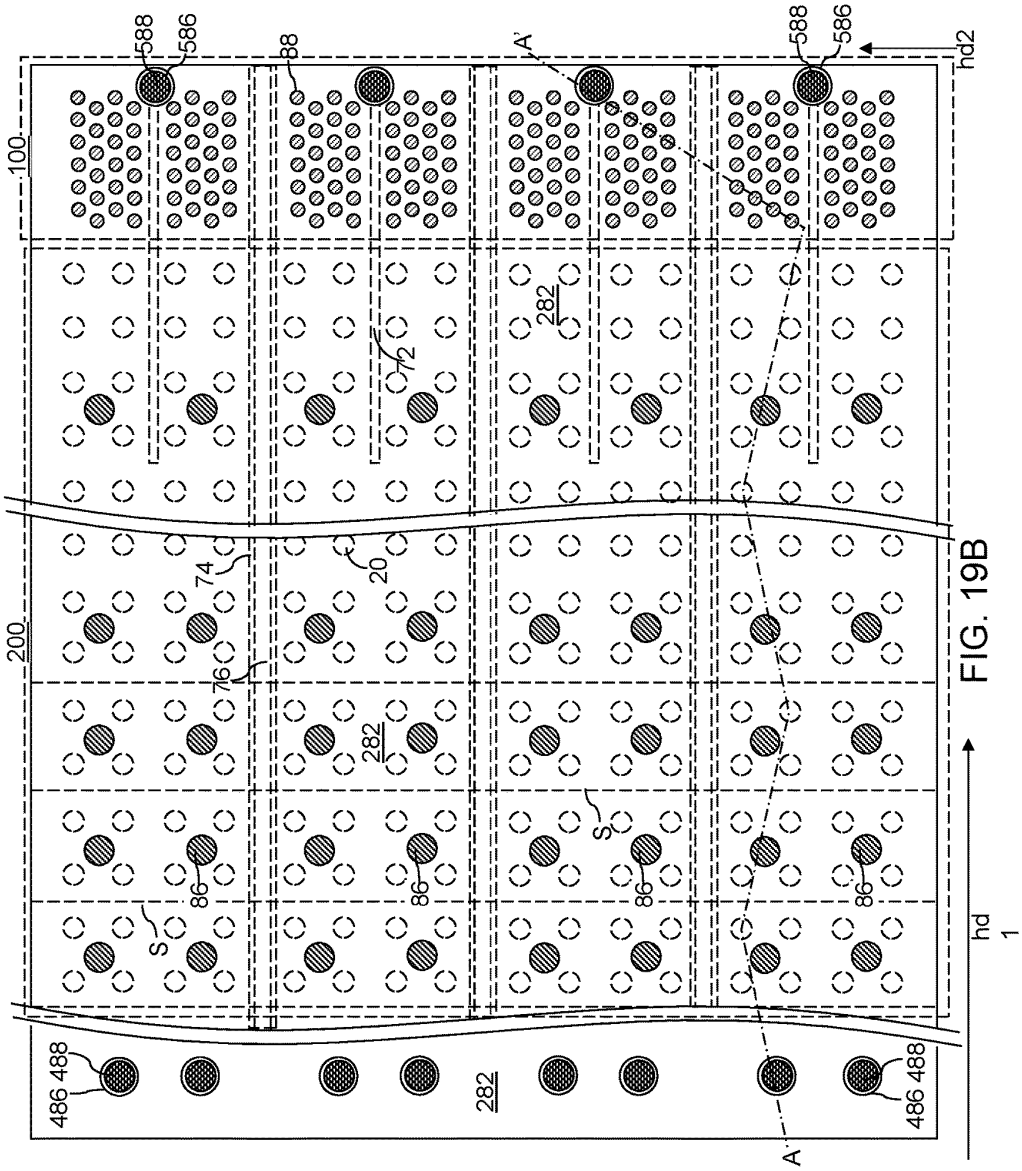

FIG. 19B

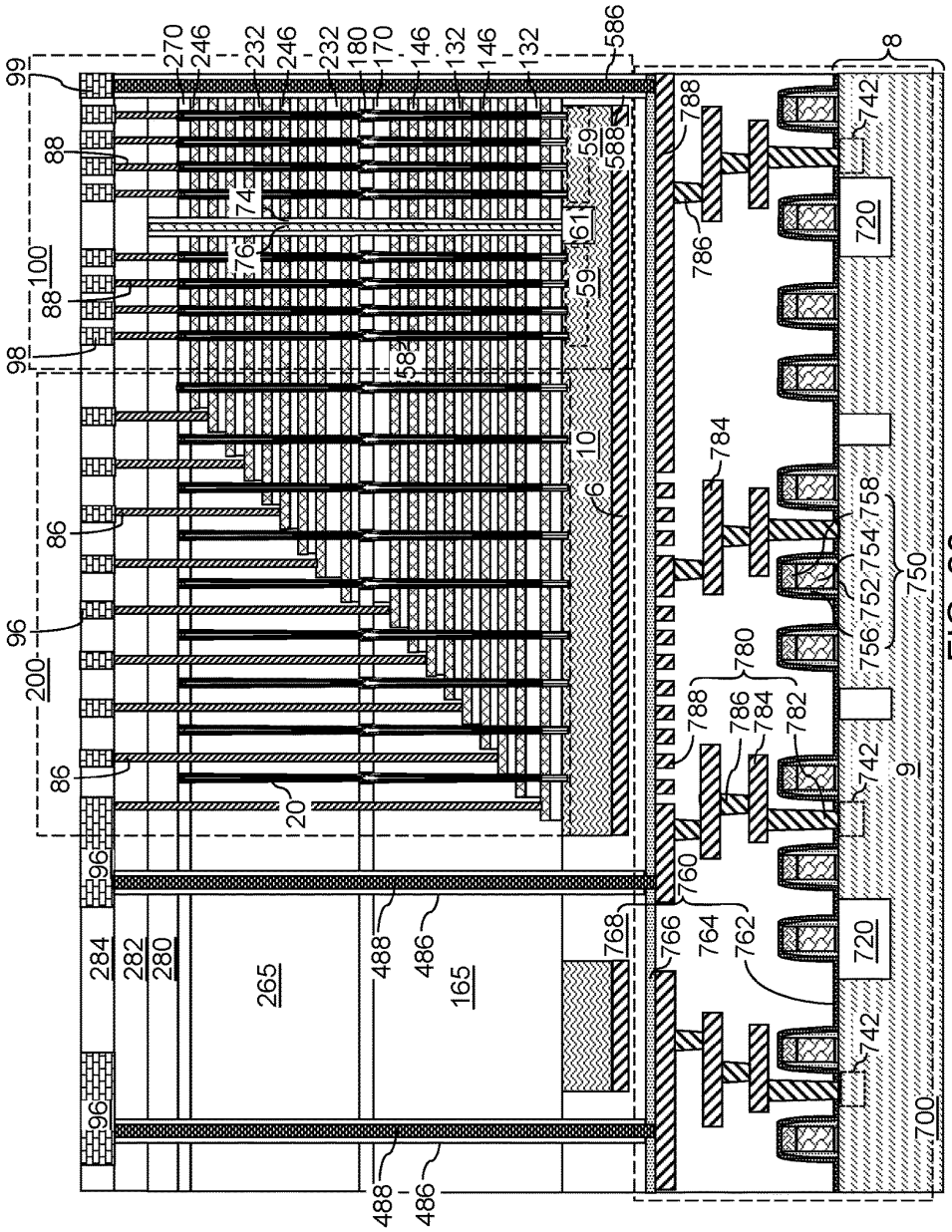
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FIG. 20

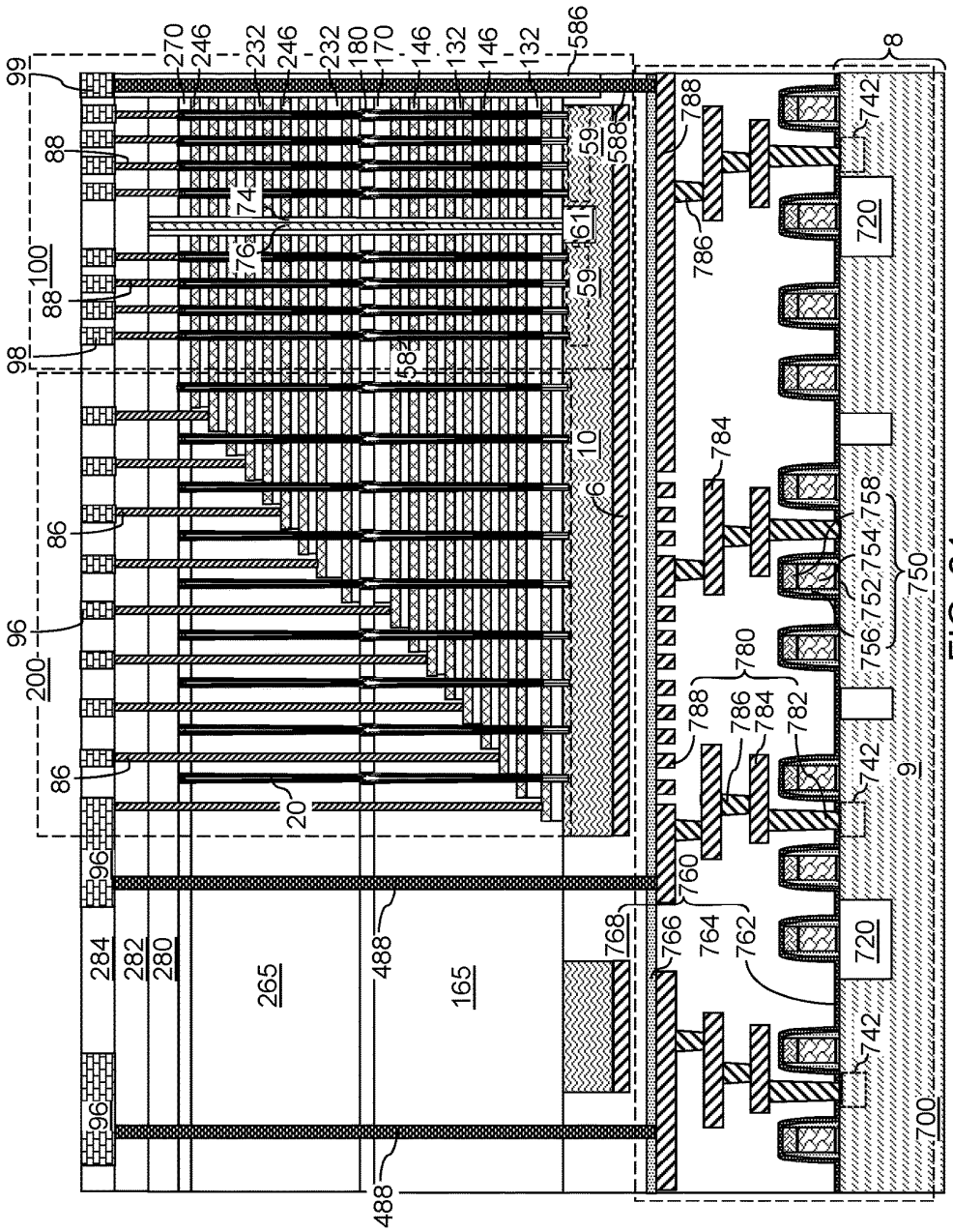
99
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FIG. 21

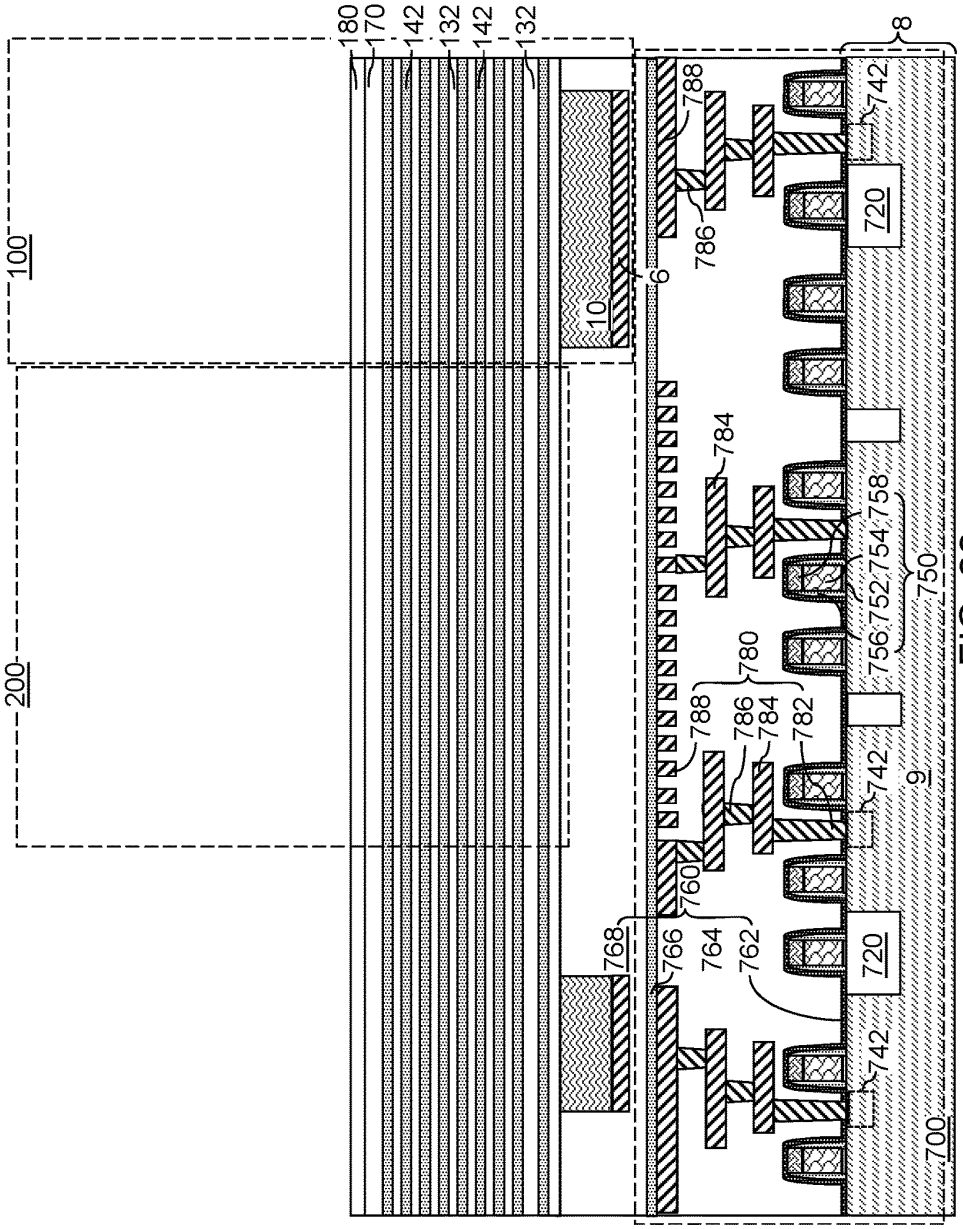
180
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FIG. 22

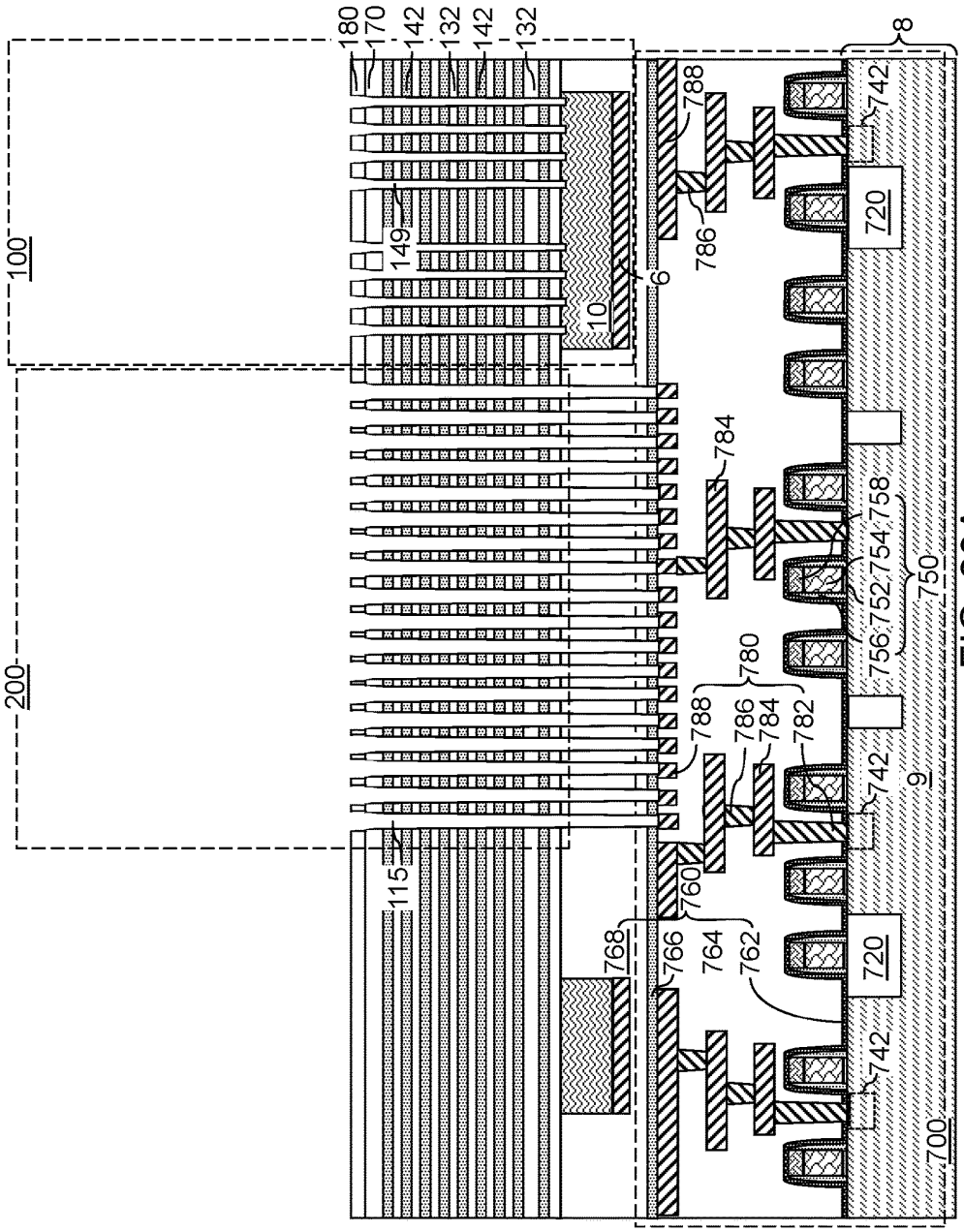
180
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FIG. 23A

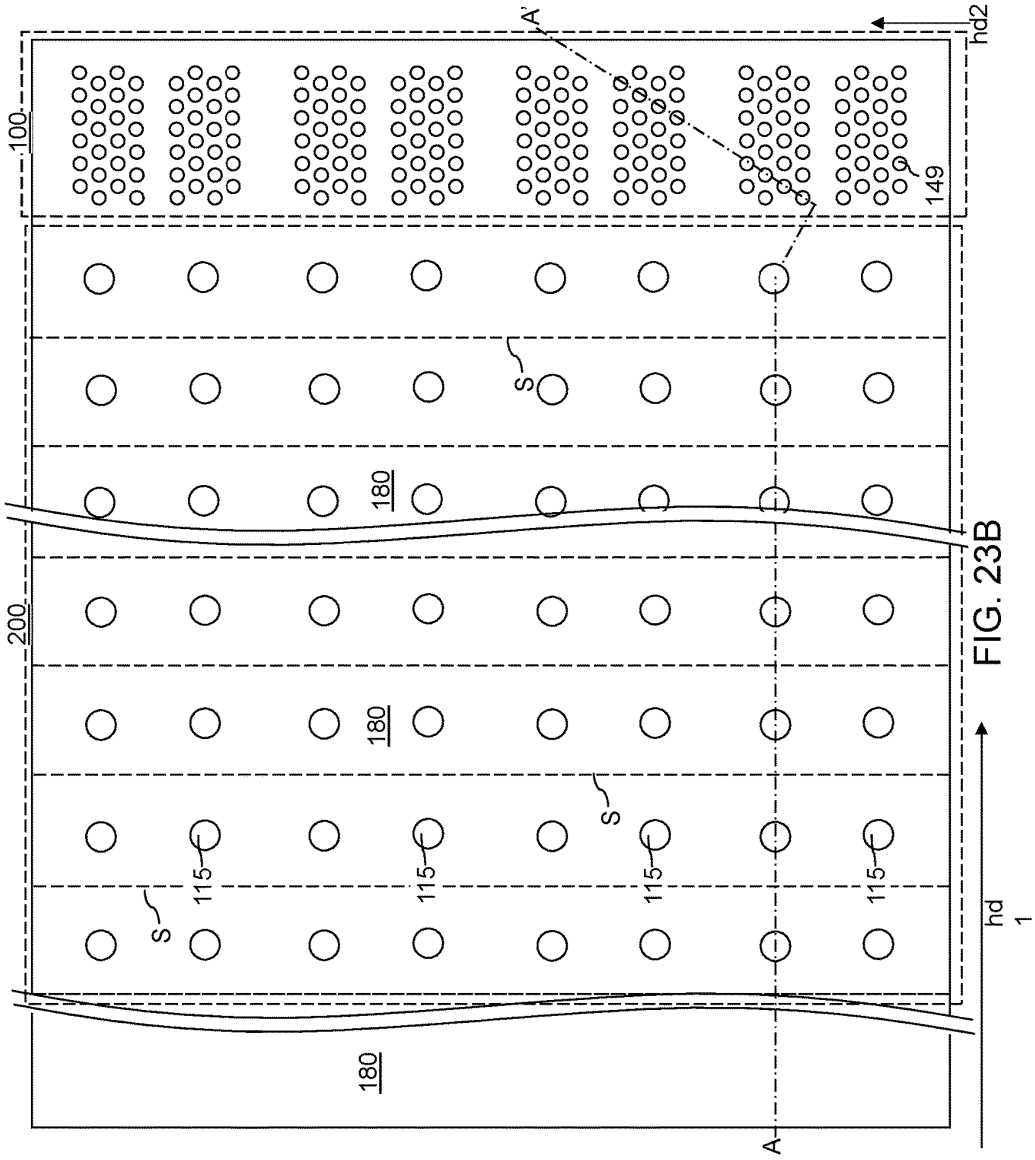

FIG. 23B

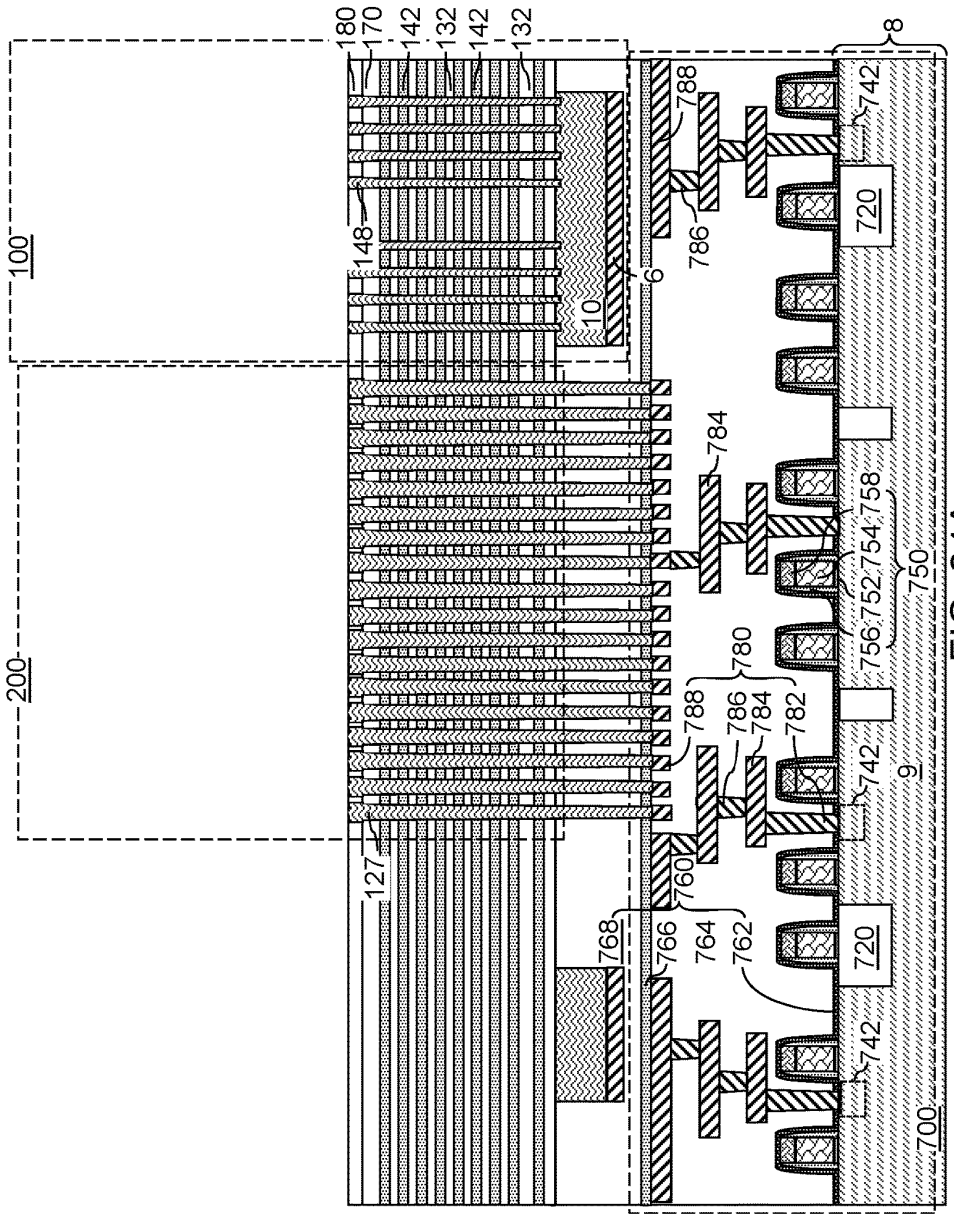
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FIG. 24A

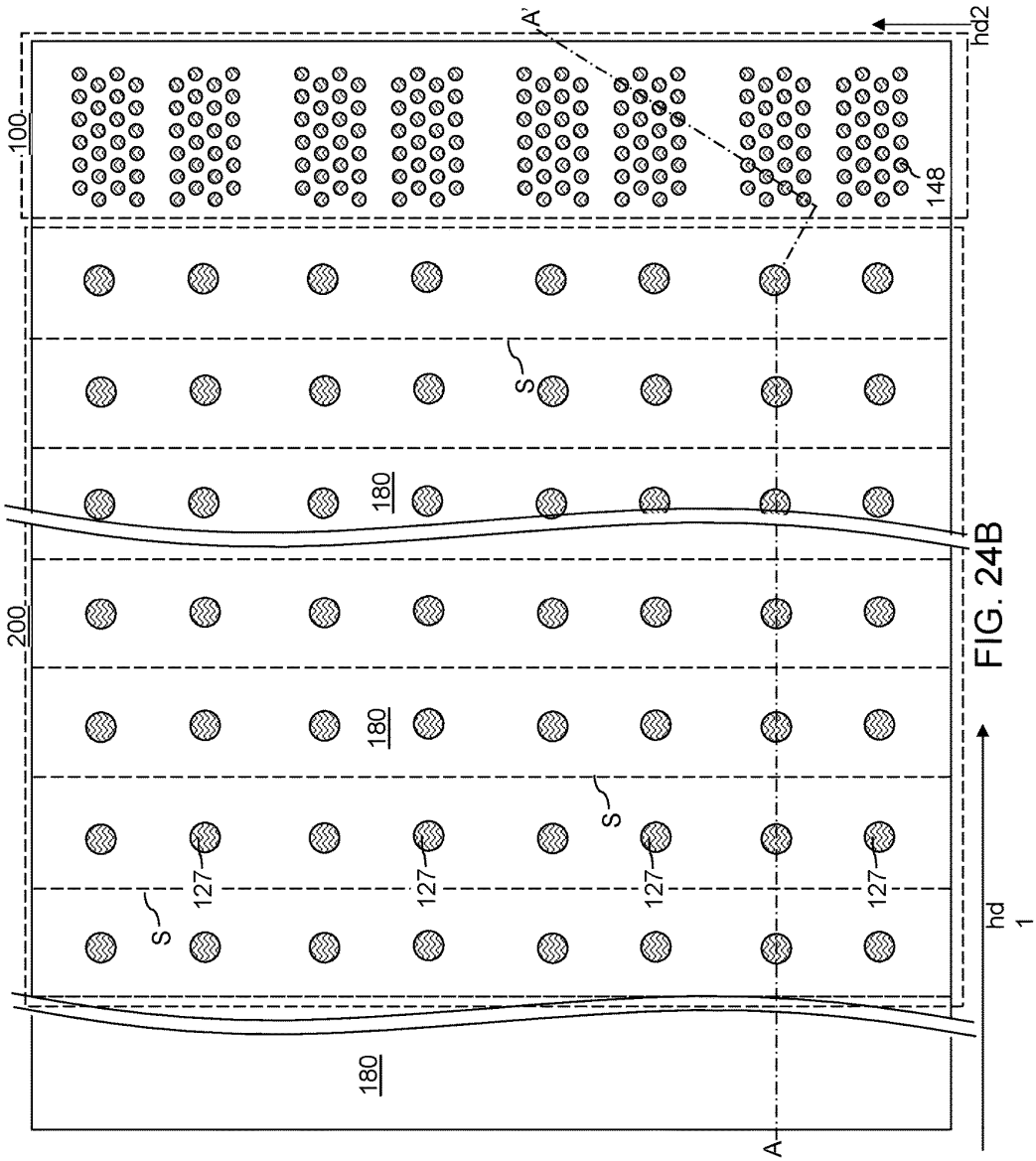

FIG. 24B

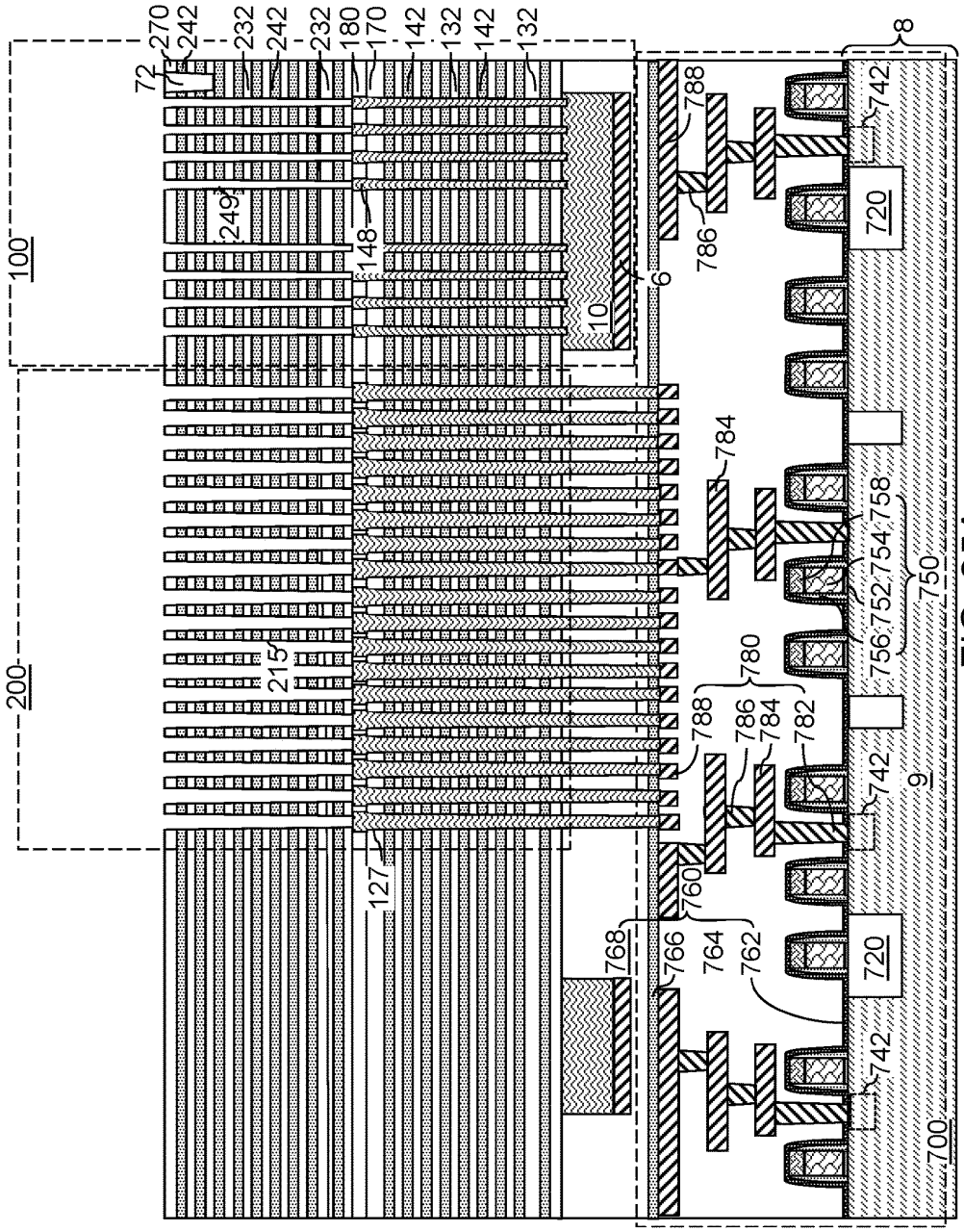
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FIG. 25A

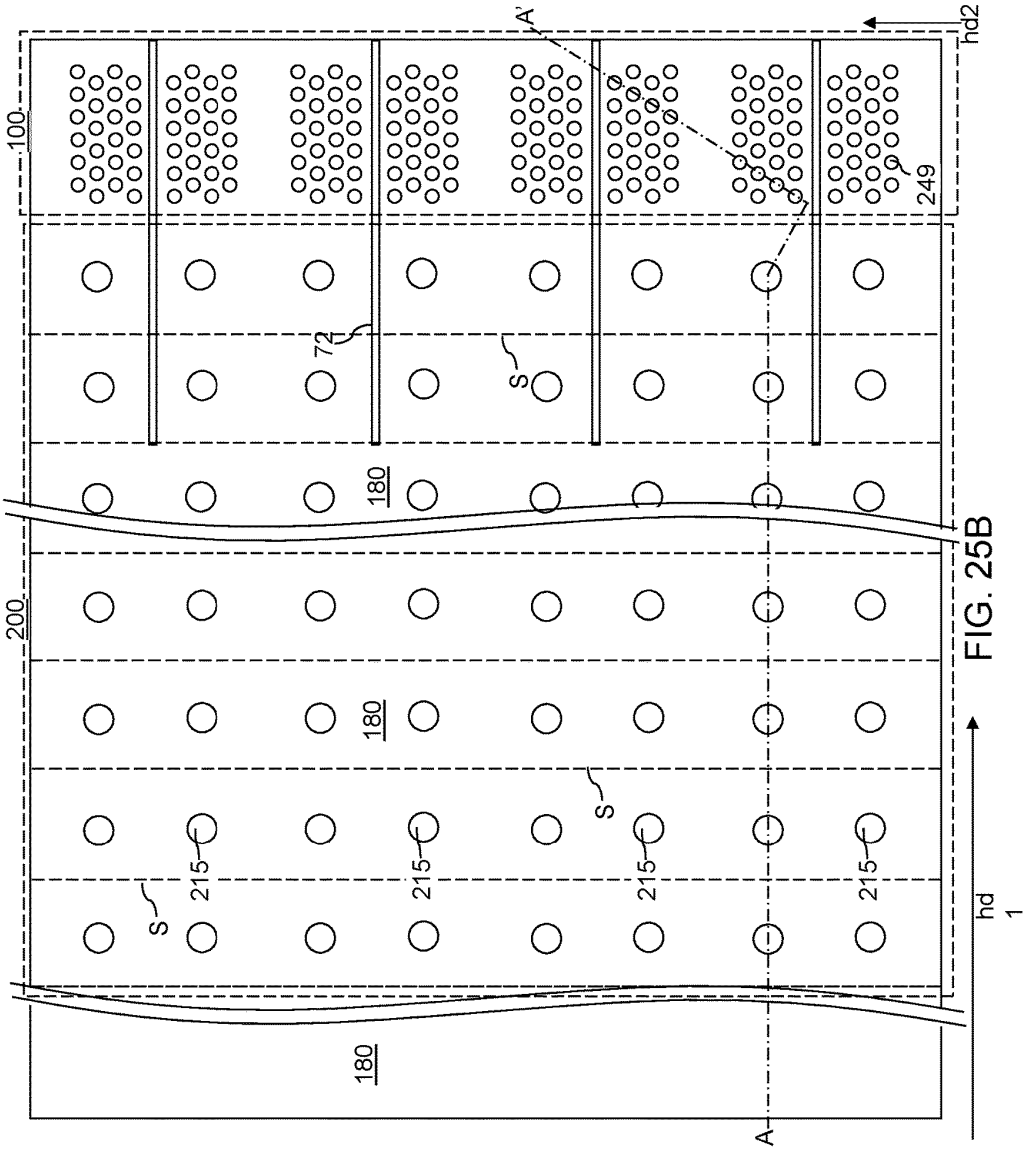

FIG. 25B

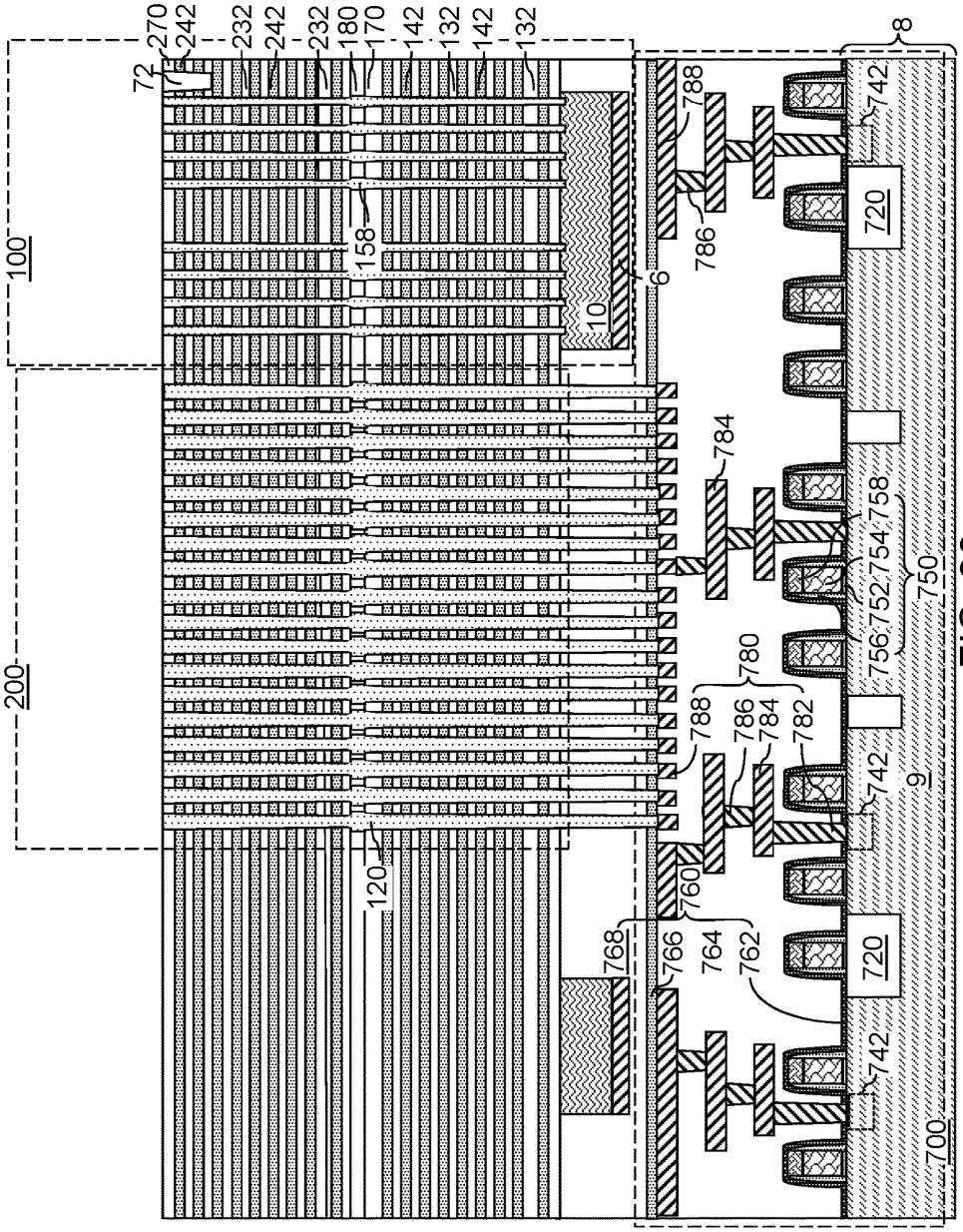
100
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FIG. 26

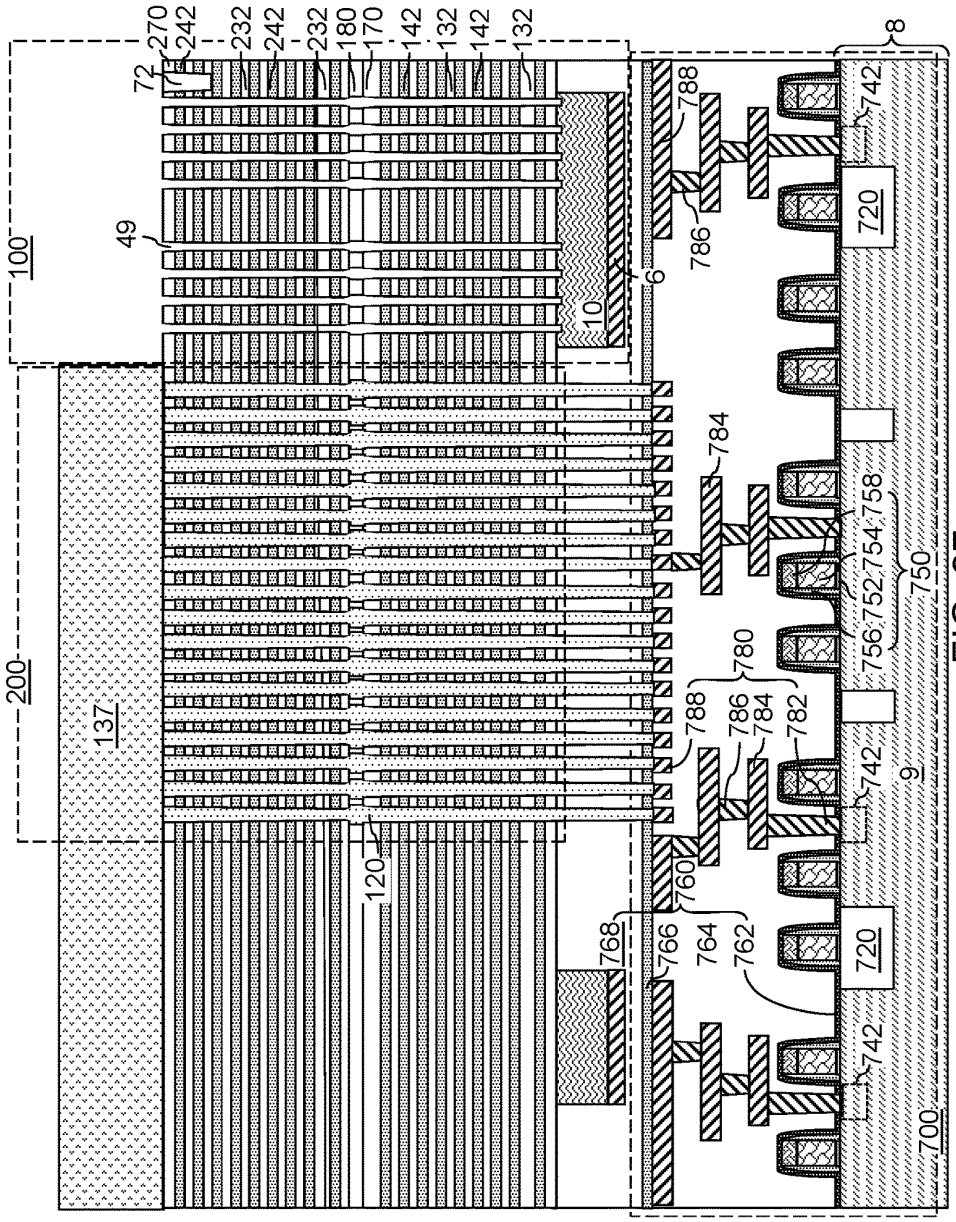
270
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FIG. 27

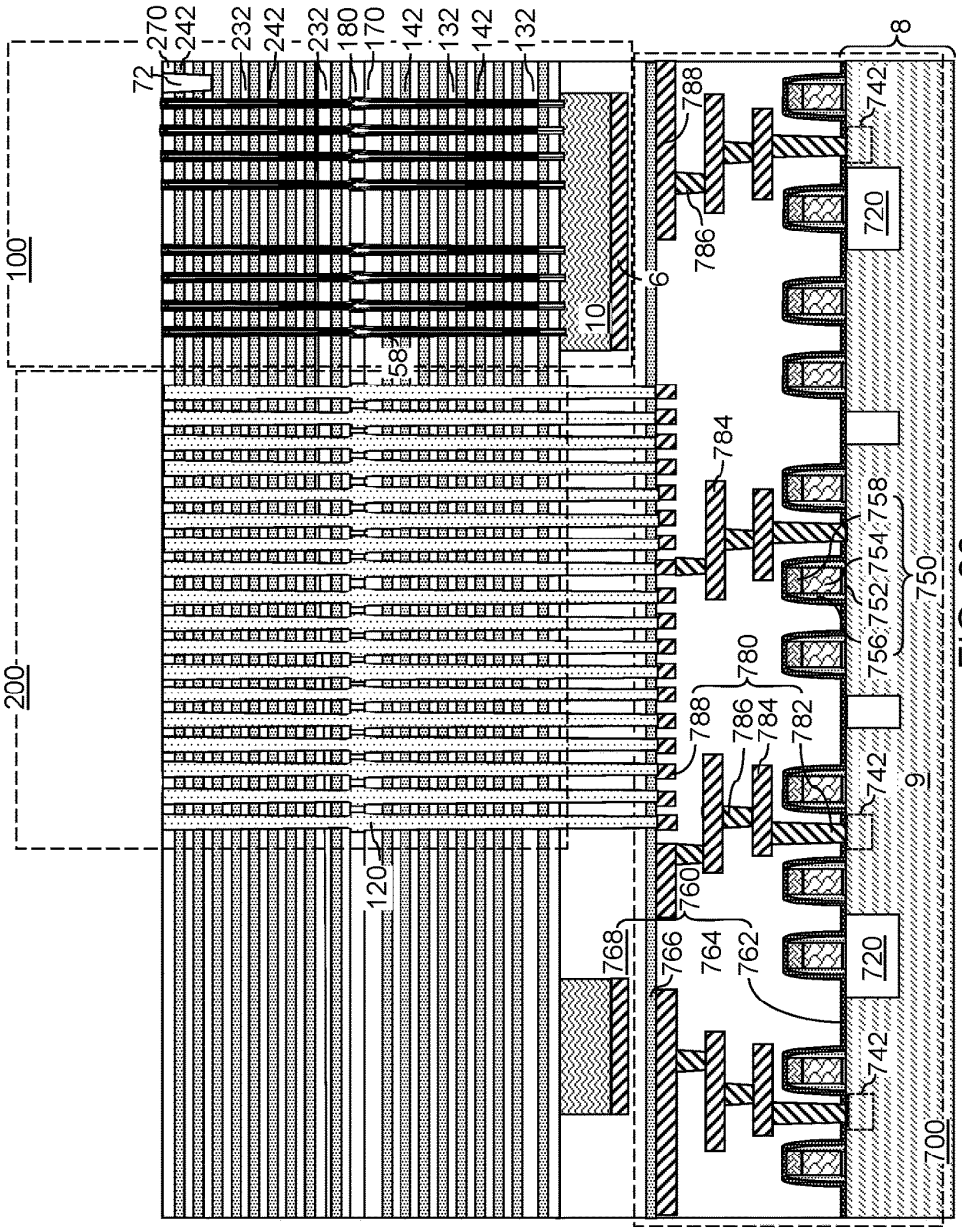
270
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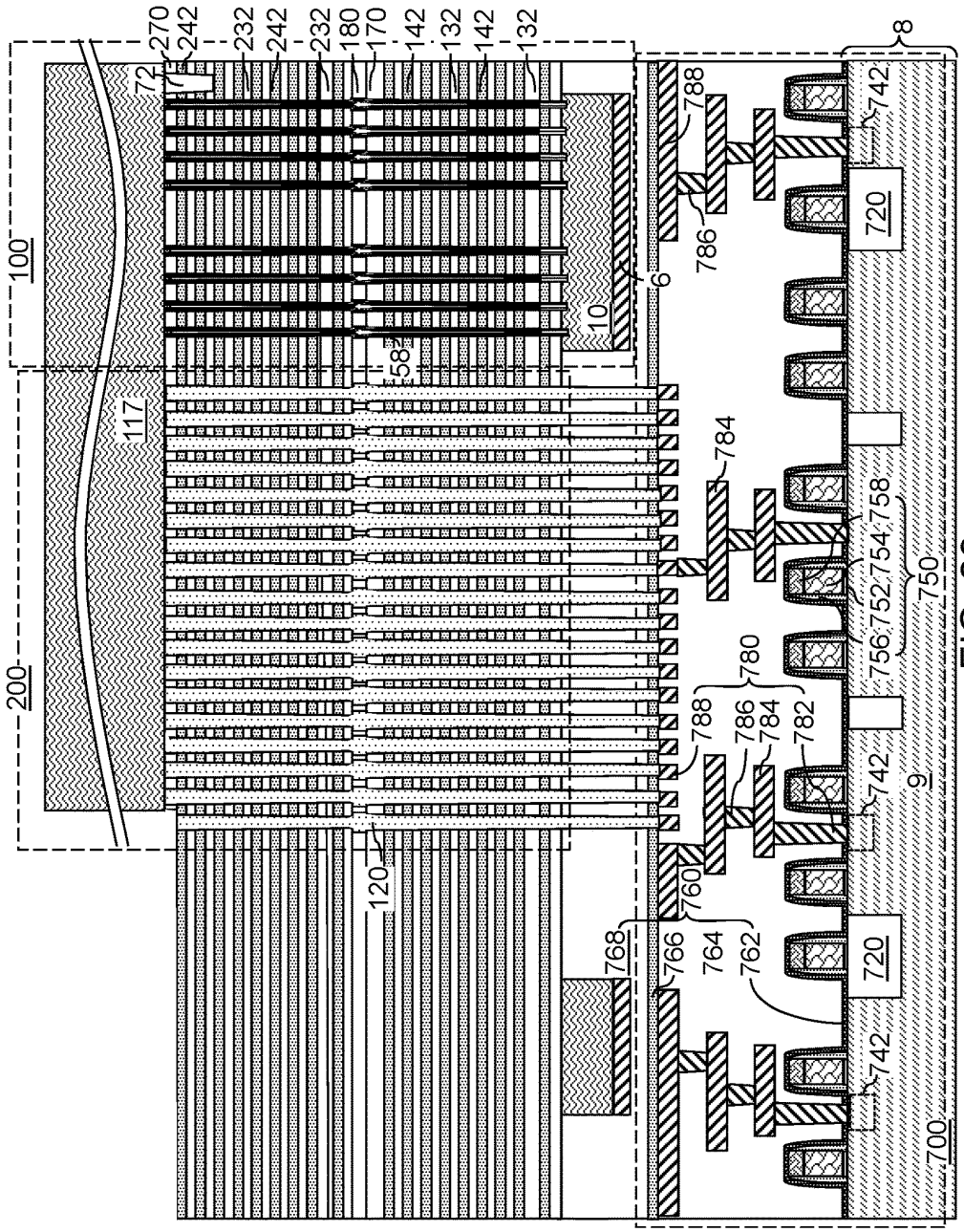
FIG. 28


270
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9
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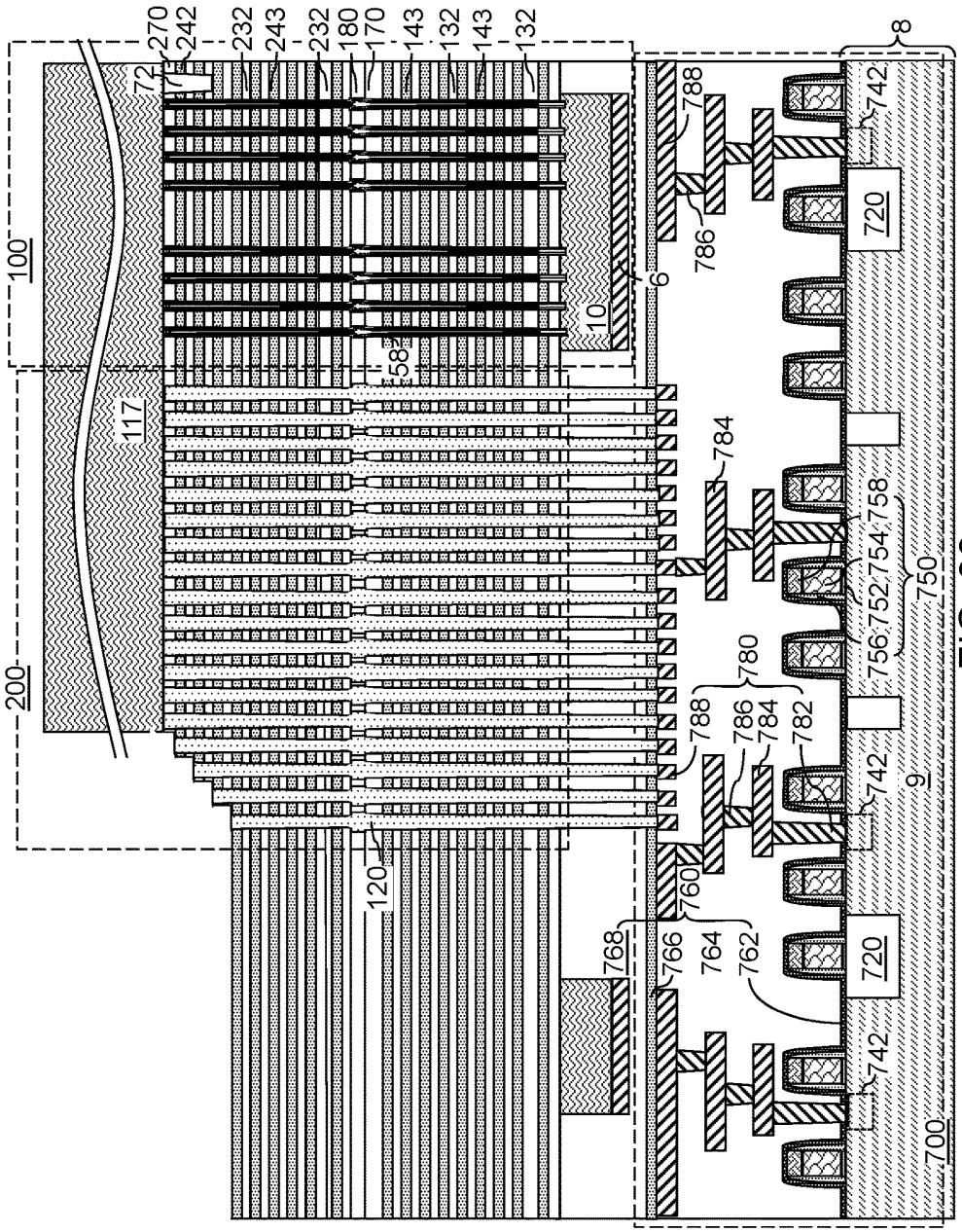
FIG. 29


270
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756
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754
758
9
8
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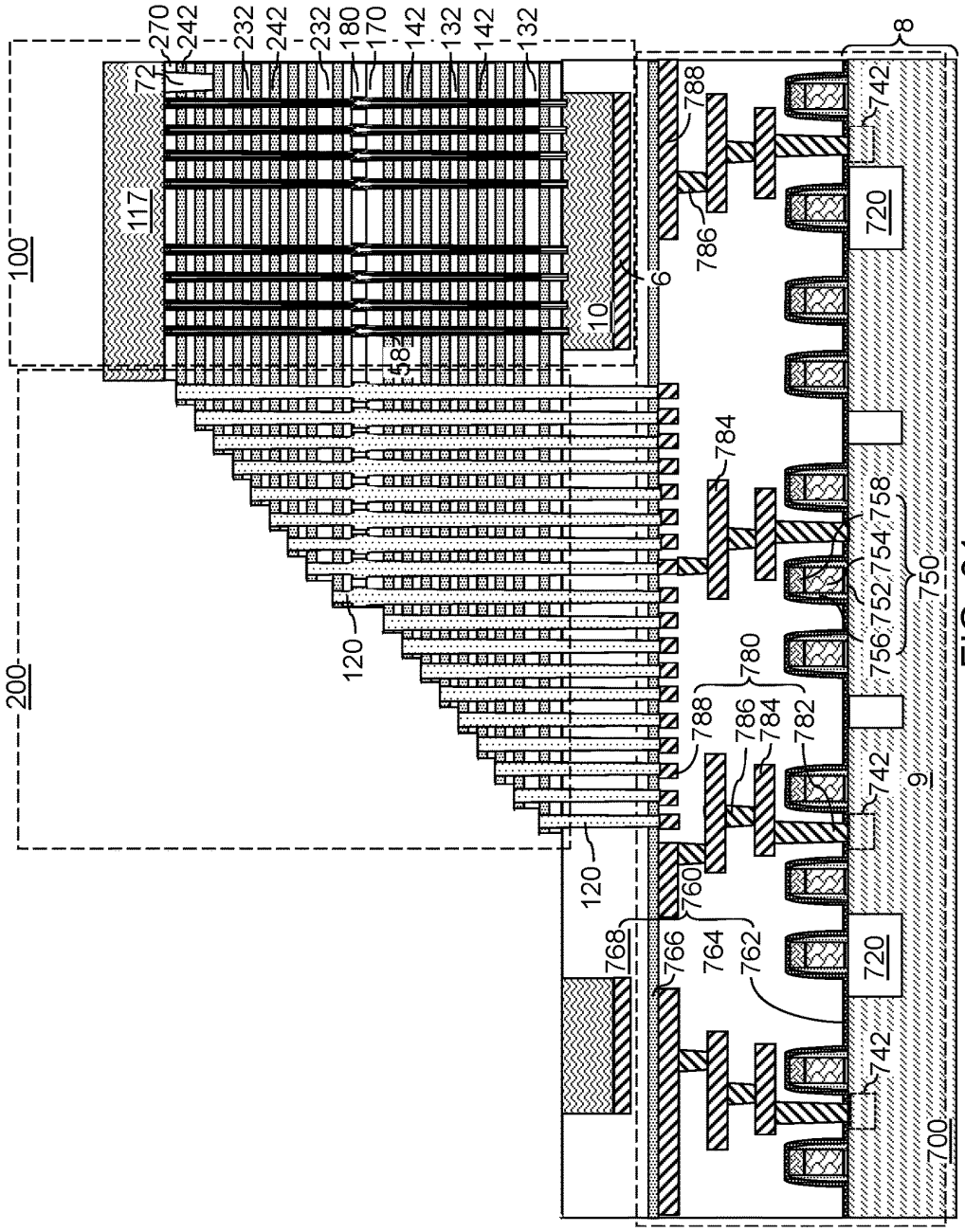
FIG. 30


100
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270
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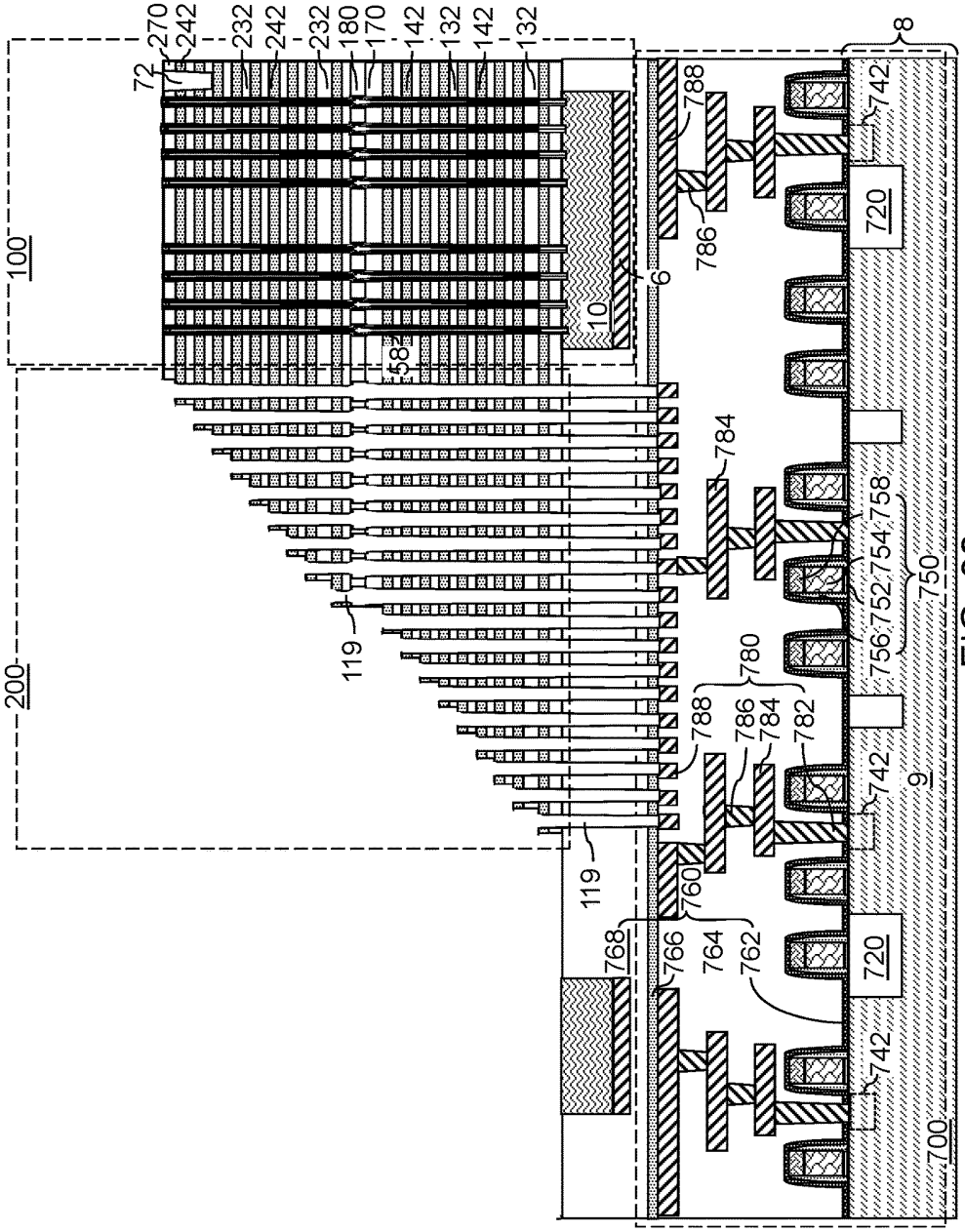
FIG. 31


100
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762
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742
720
720
758
754
752
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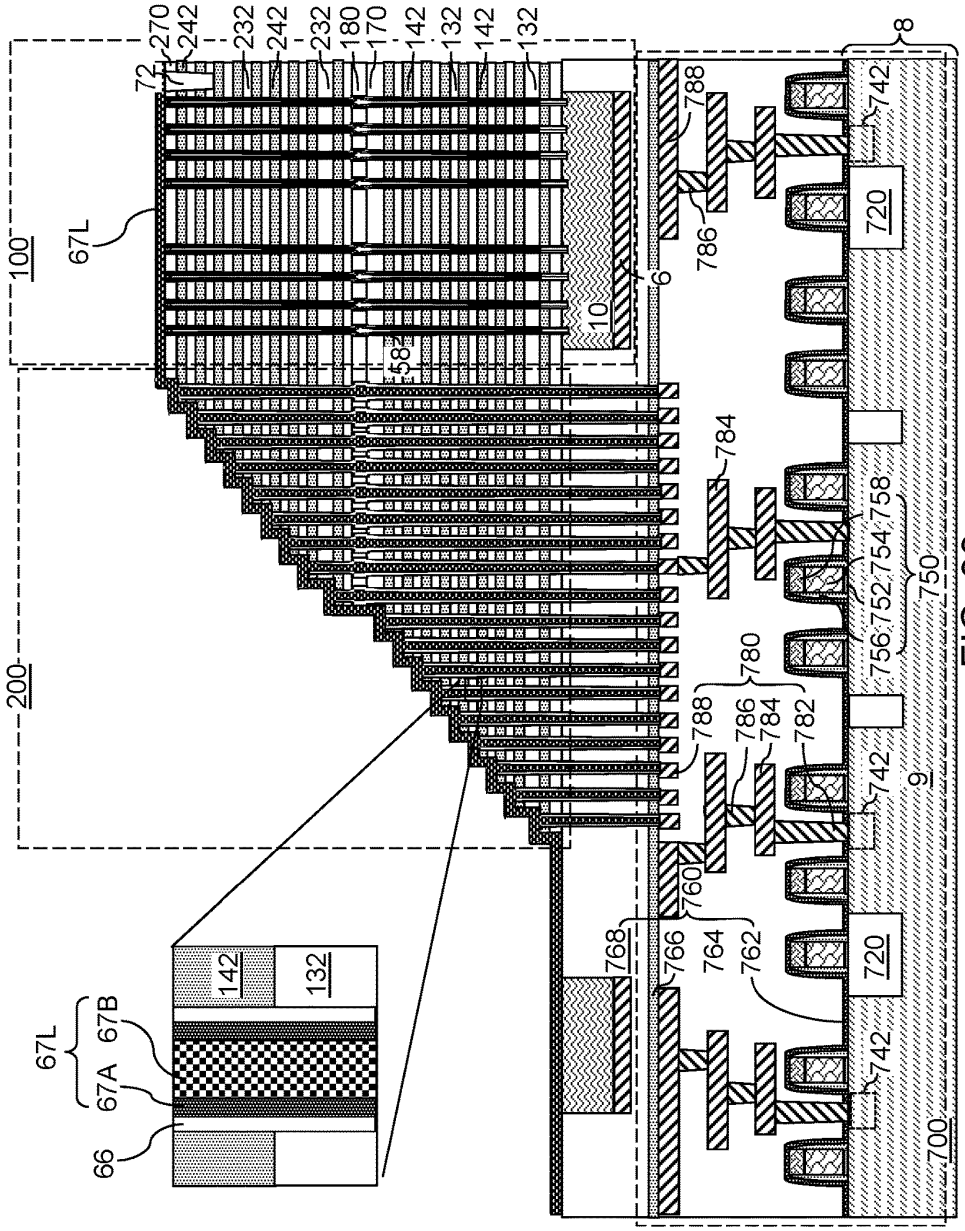
9
8
700

FIG. 32


100
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67L
67B
67A
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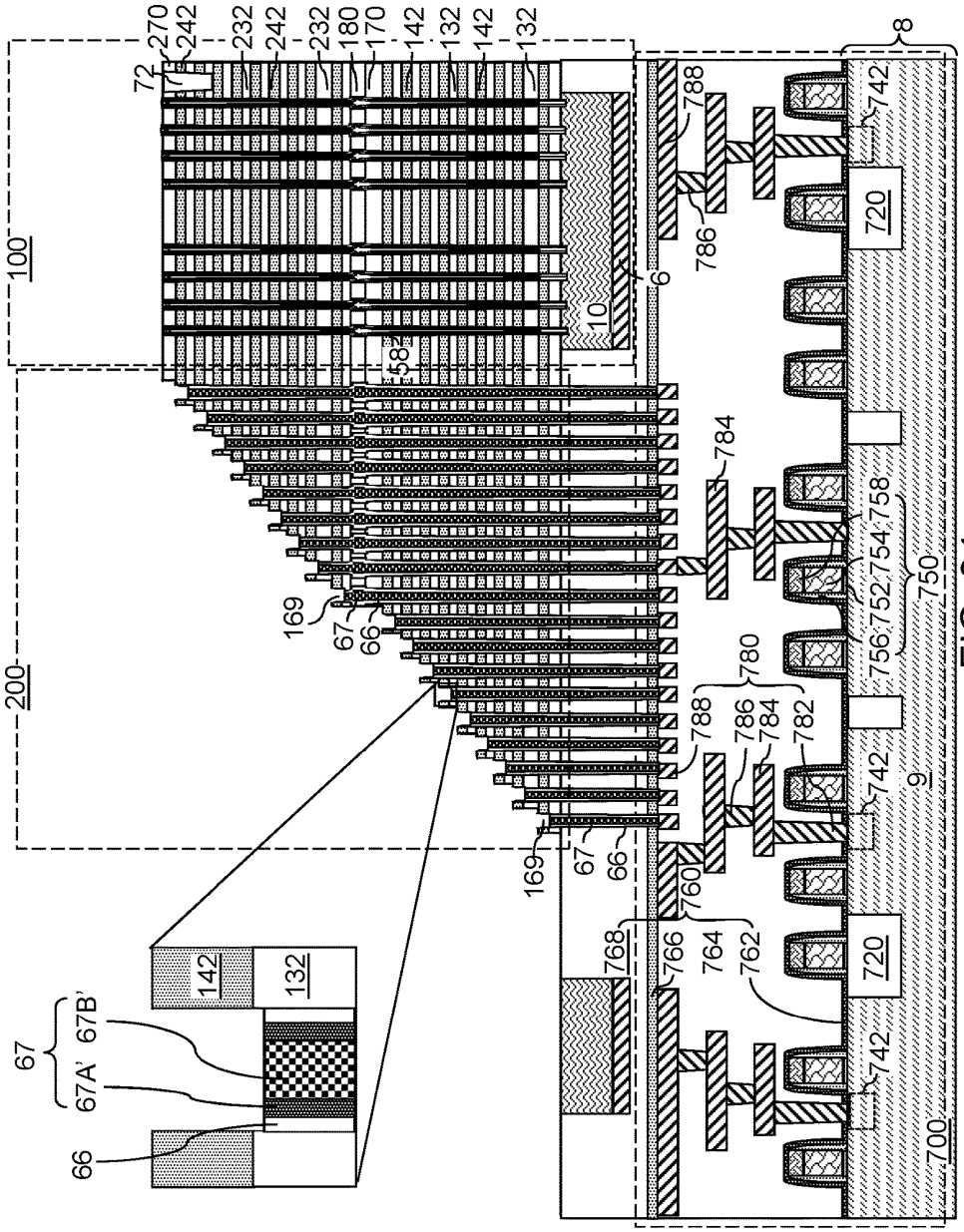
142
132

FIG. 33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67A'
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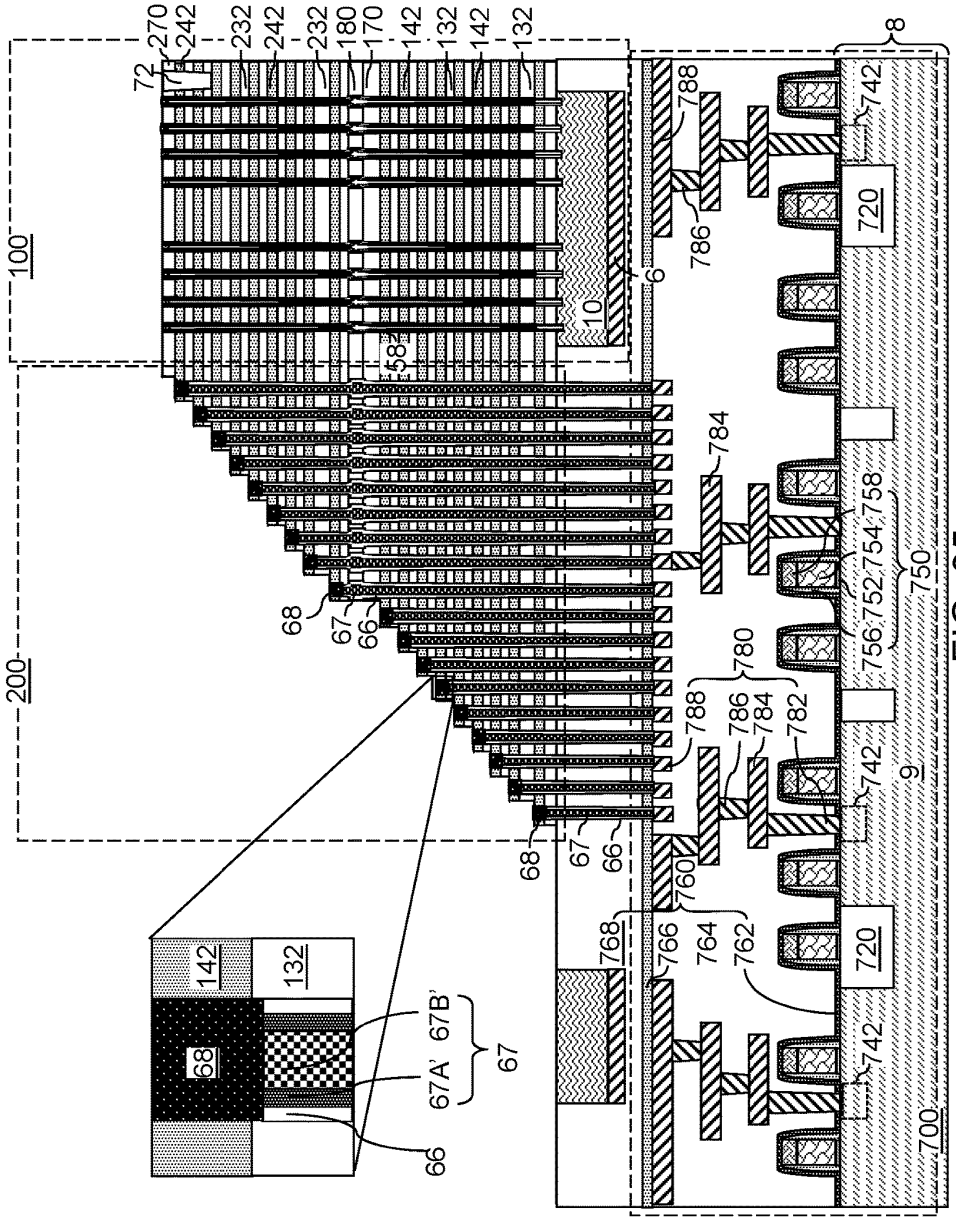
FIG. 34


100
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766
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754
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8
700
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67
66
67A'
67B'
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FIG. 35

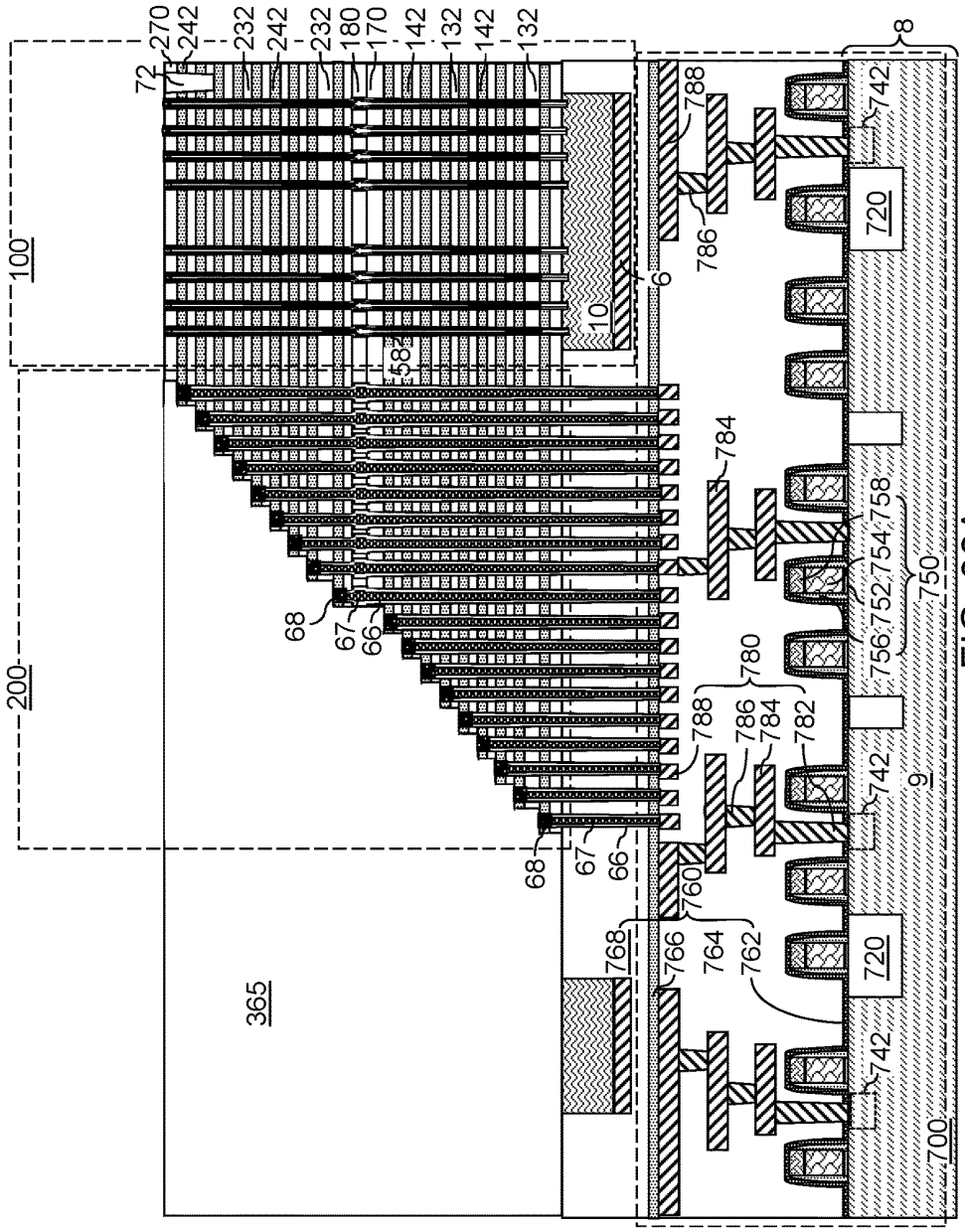
270
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FIG. 36A

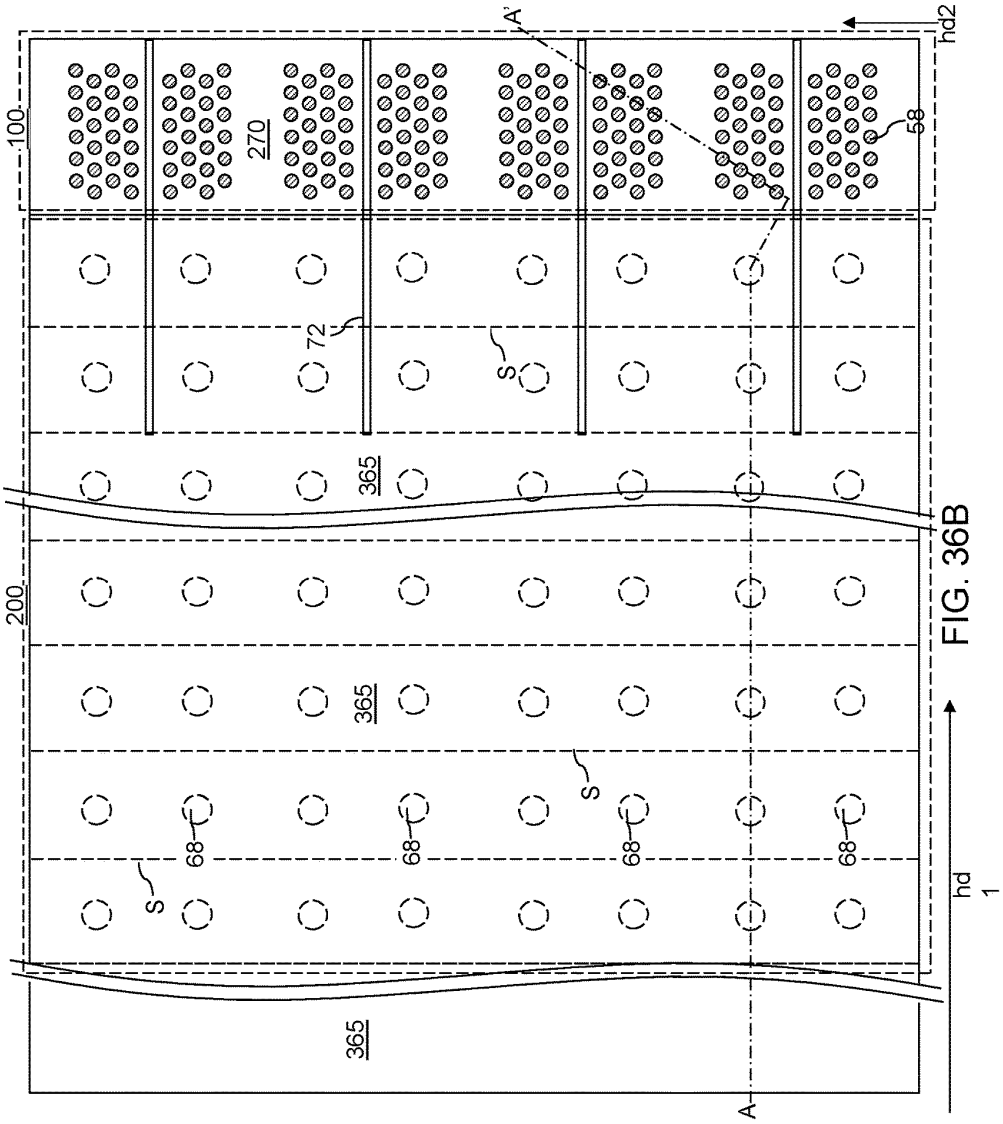

FIG. 36B

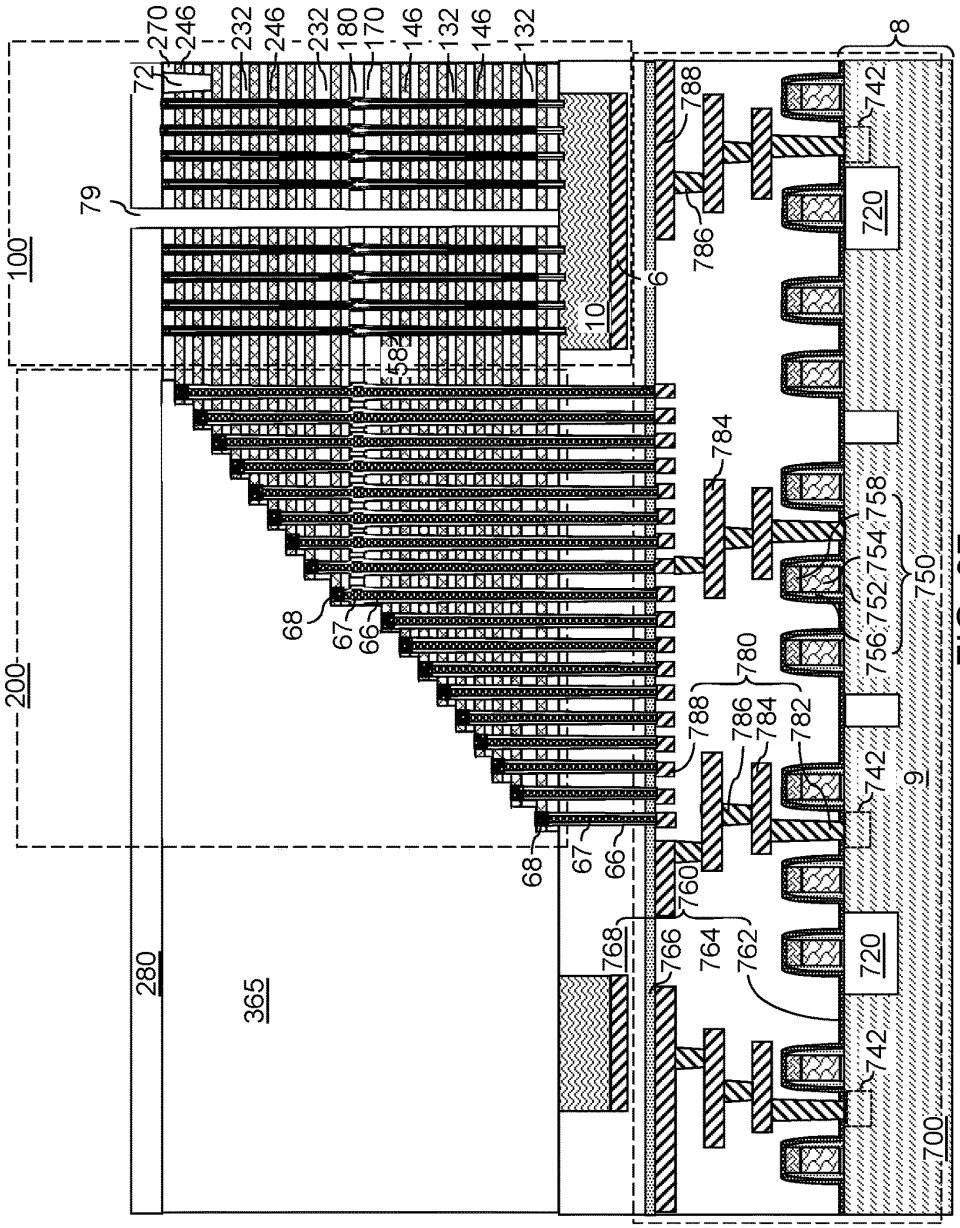
270
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FIG. 37

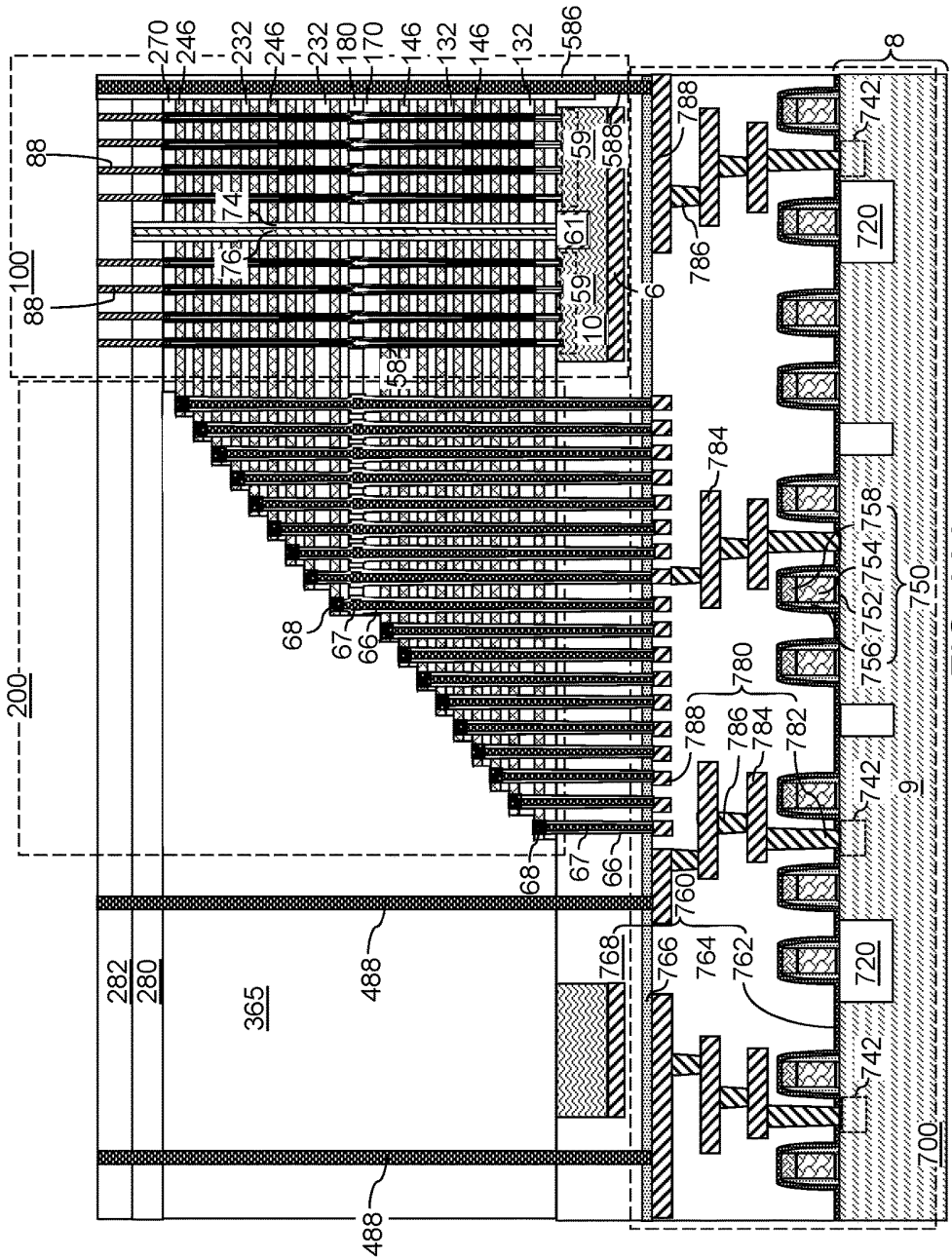
270
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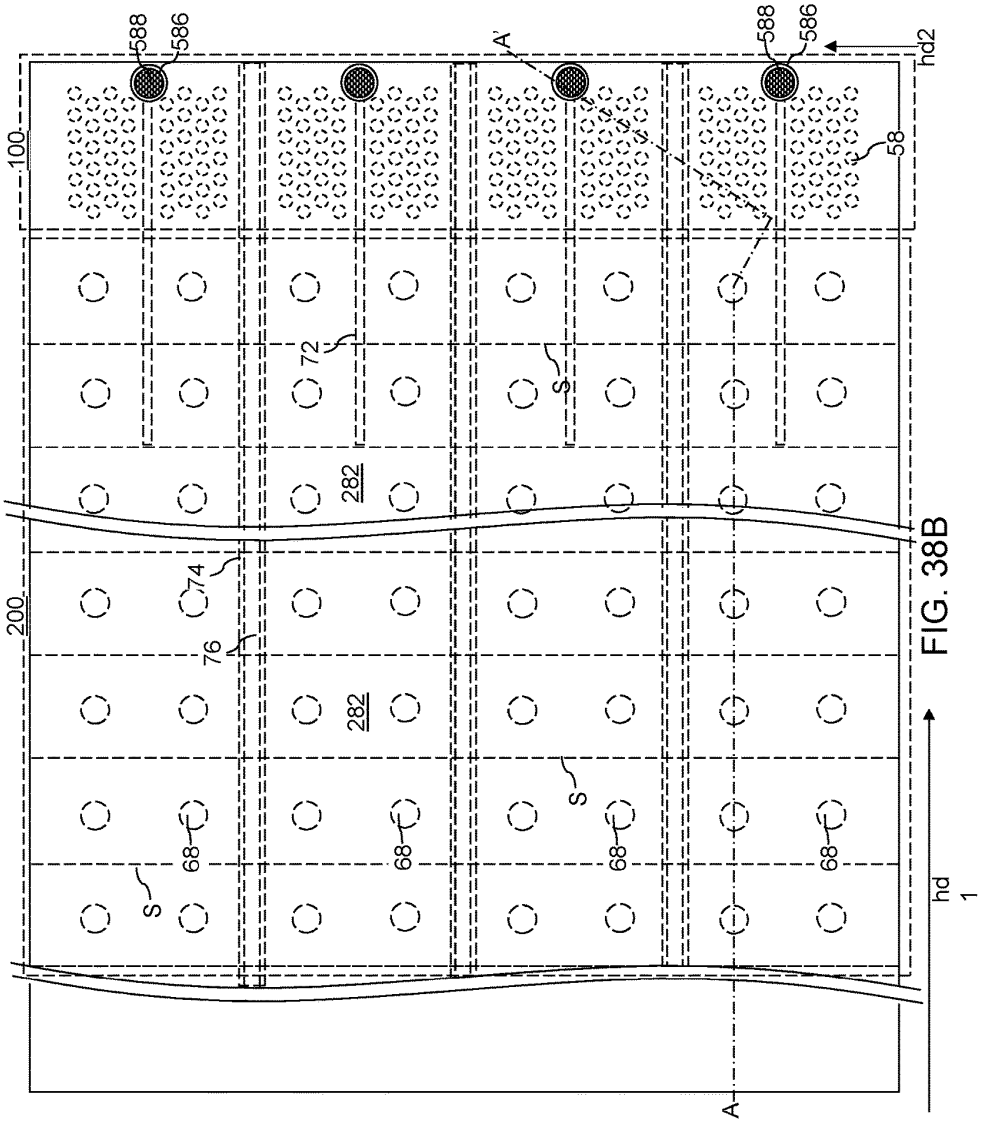
FIG. 38A


588
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A'
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586
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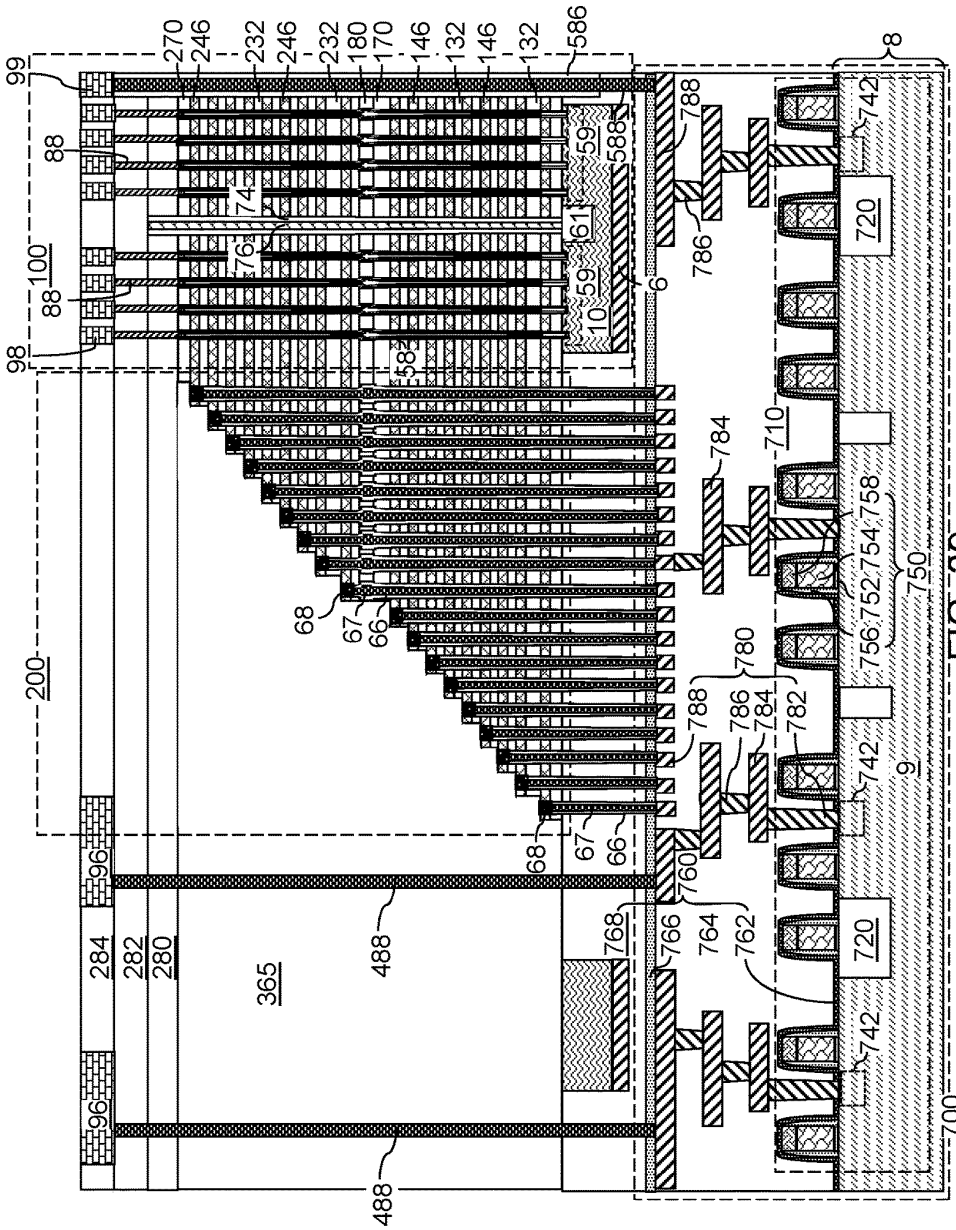
hd
1
A

FIG. 38B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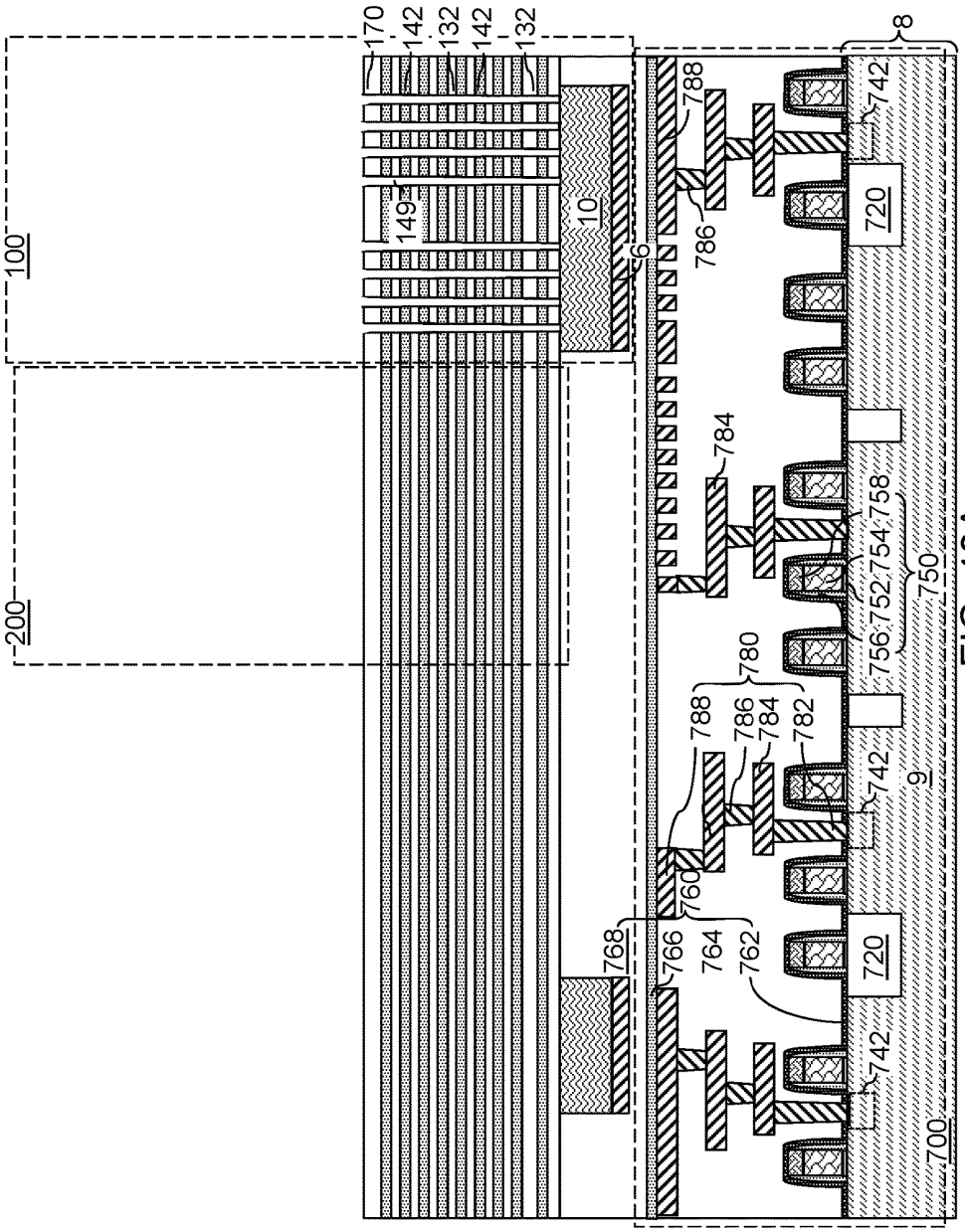
700

FIG. 39


100
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742
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FIG. 40A

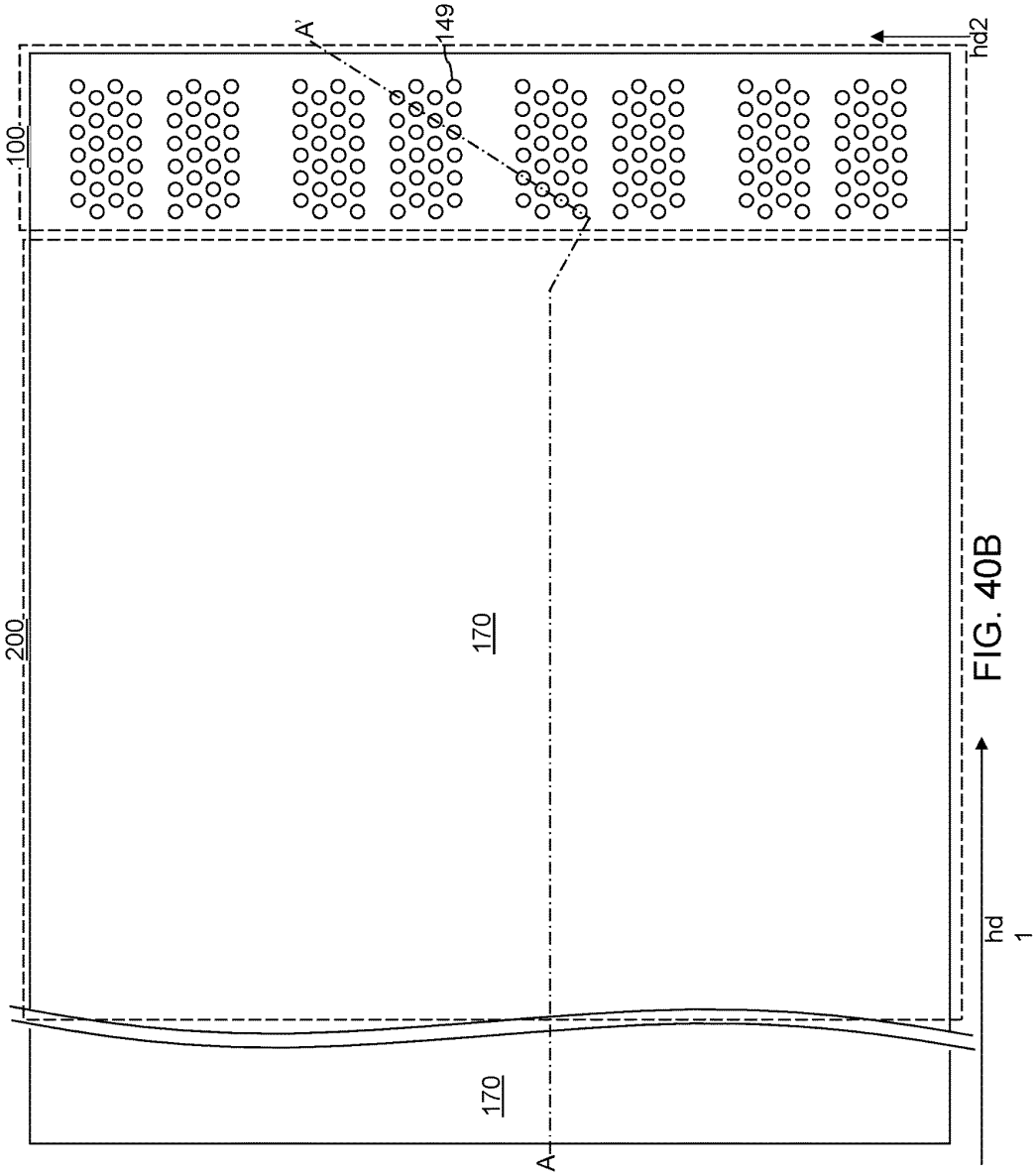

FIG. 40B

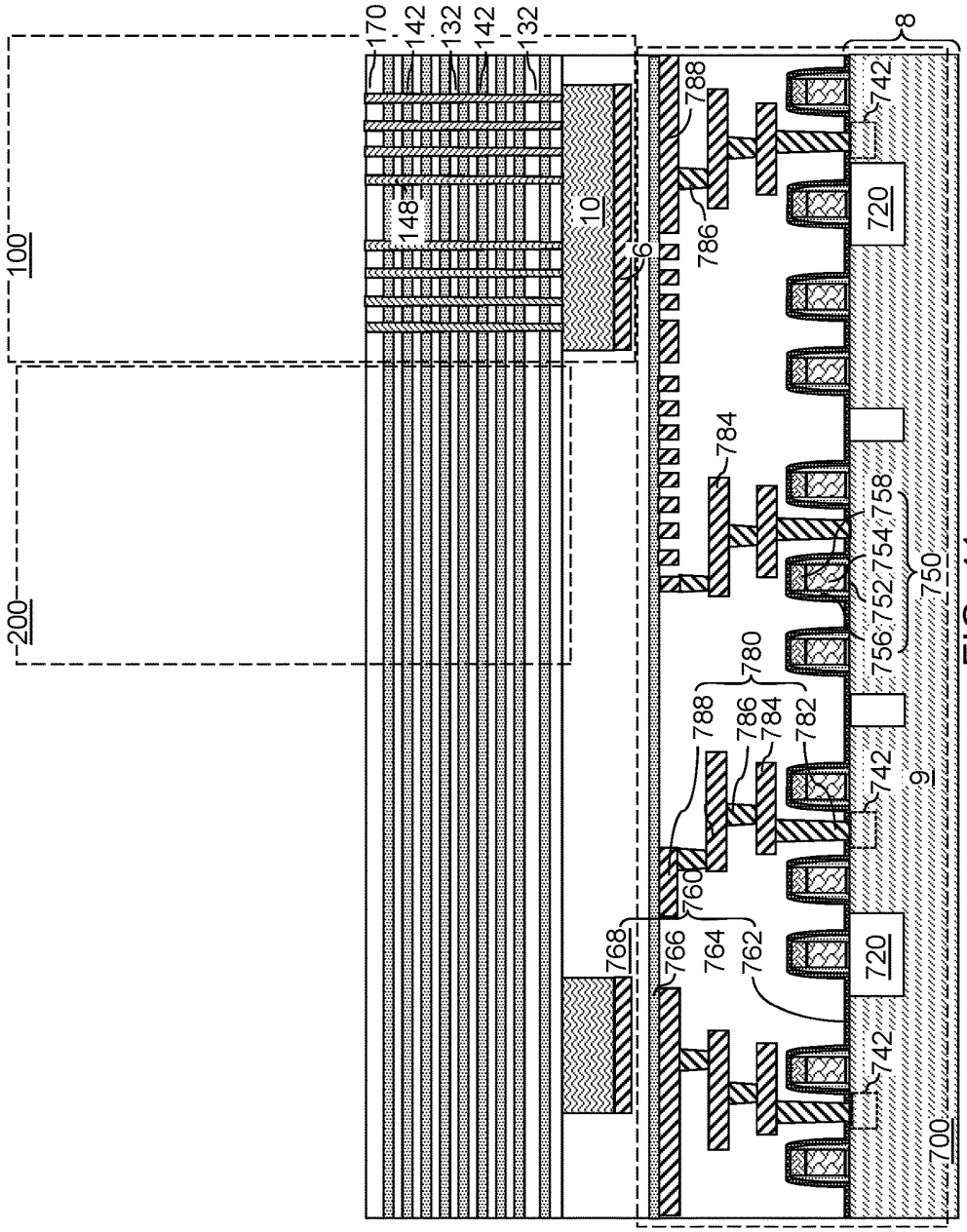
170
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FIG. 41

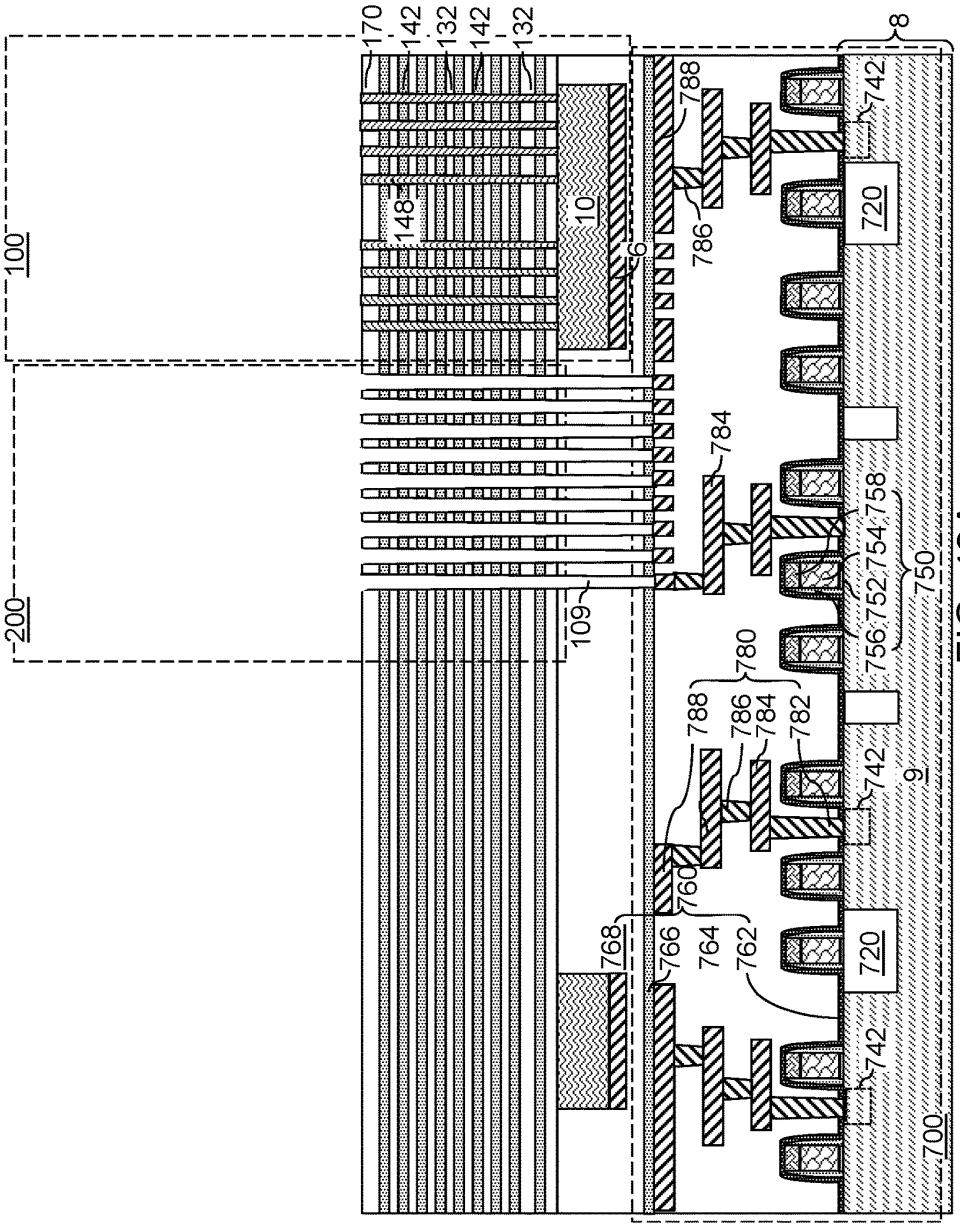
170
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FIG. 42A

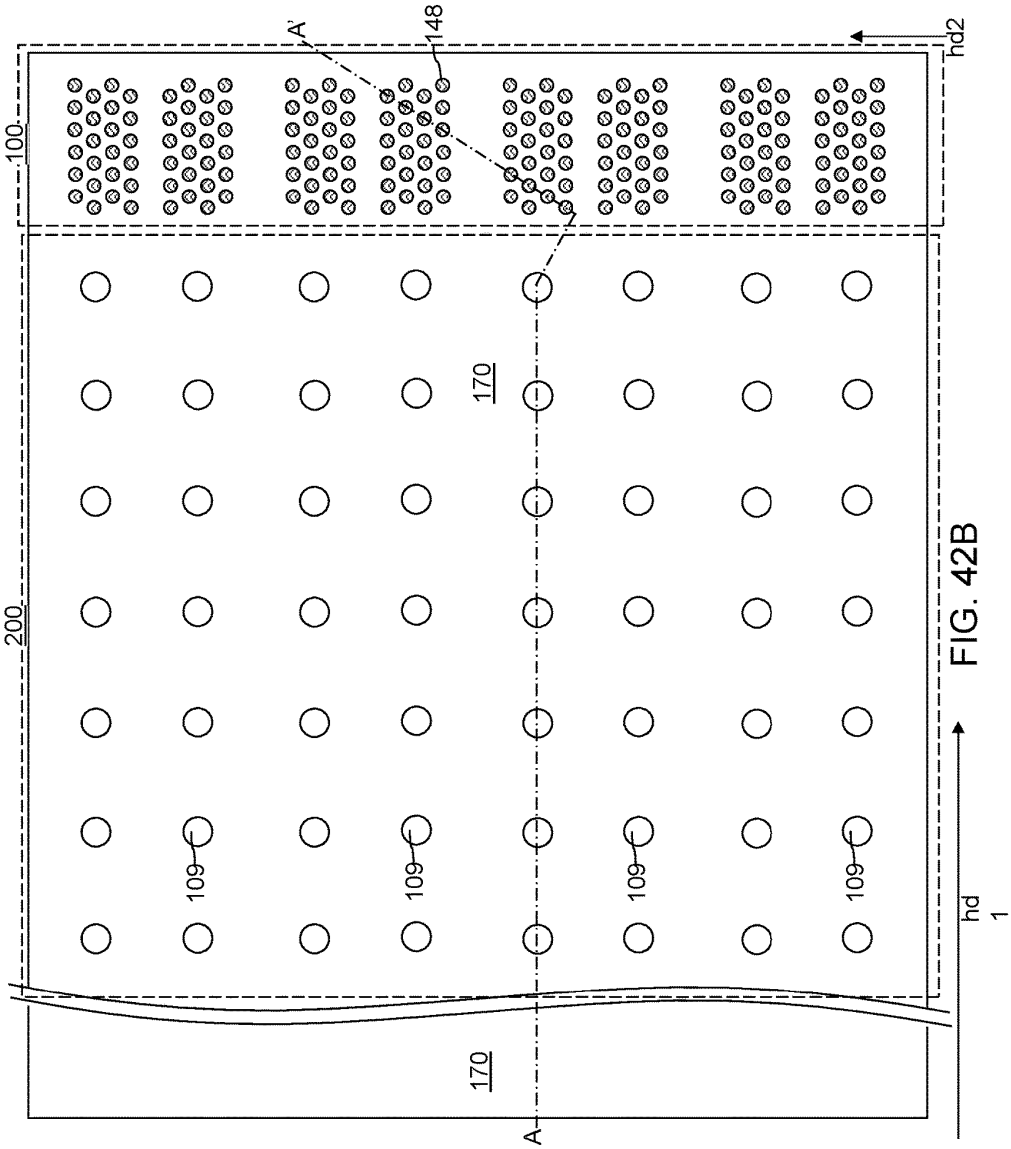

FIG. 42B

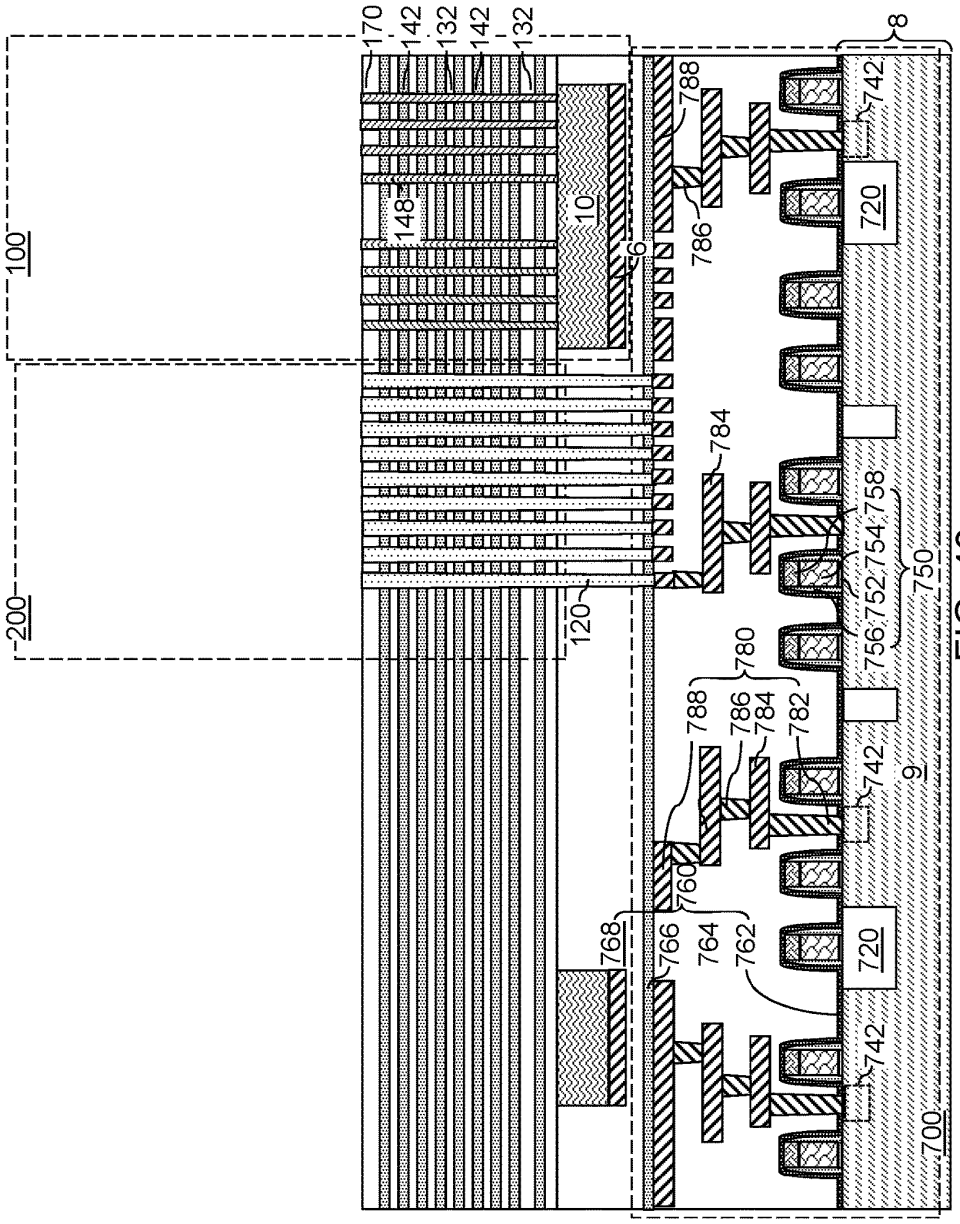
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FIG. 43

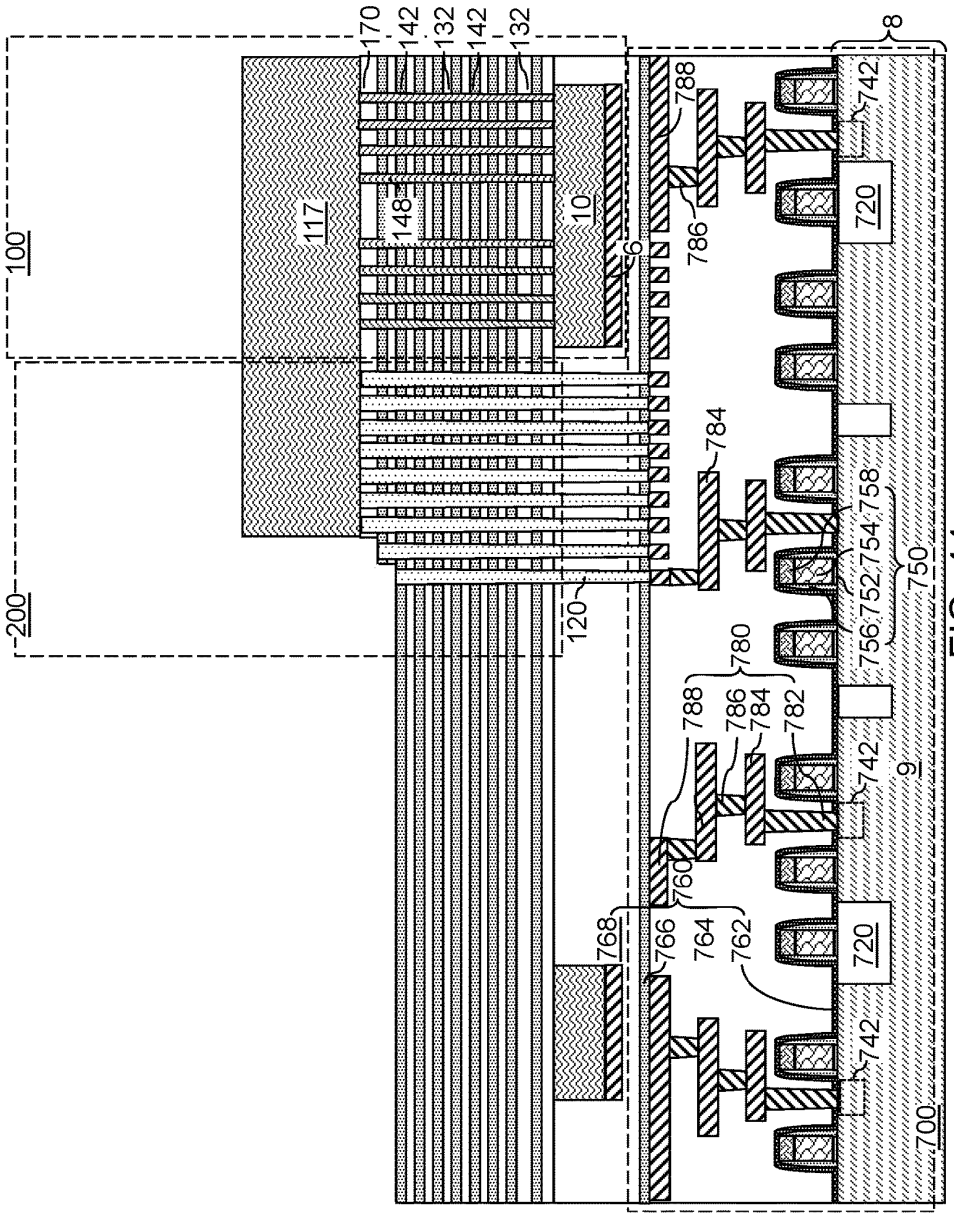
100
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FIG. 44

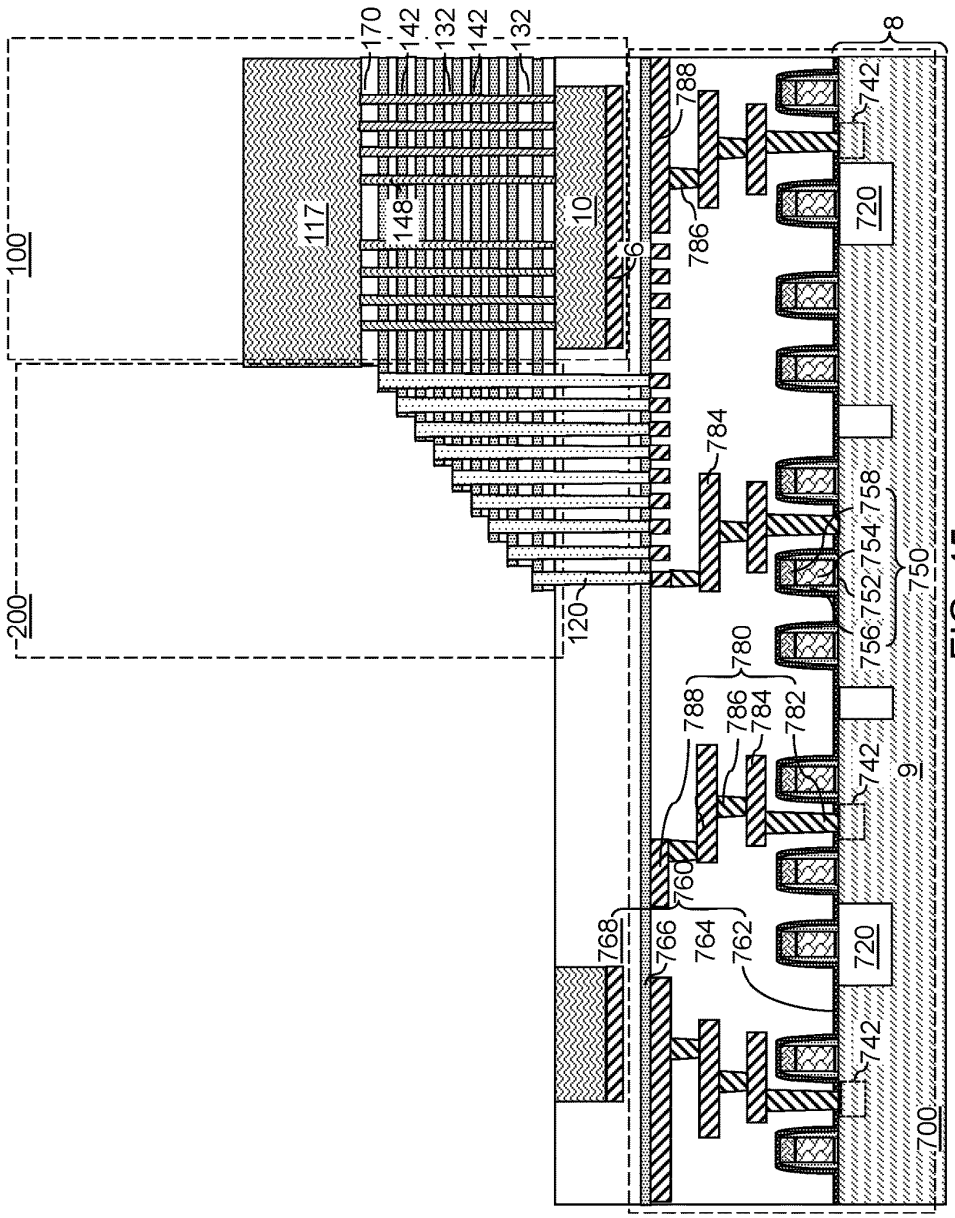
100
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FIG. 45

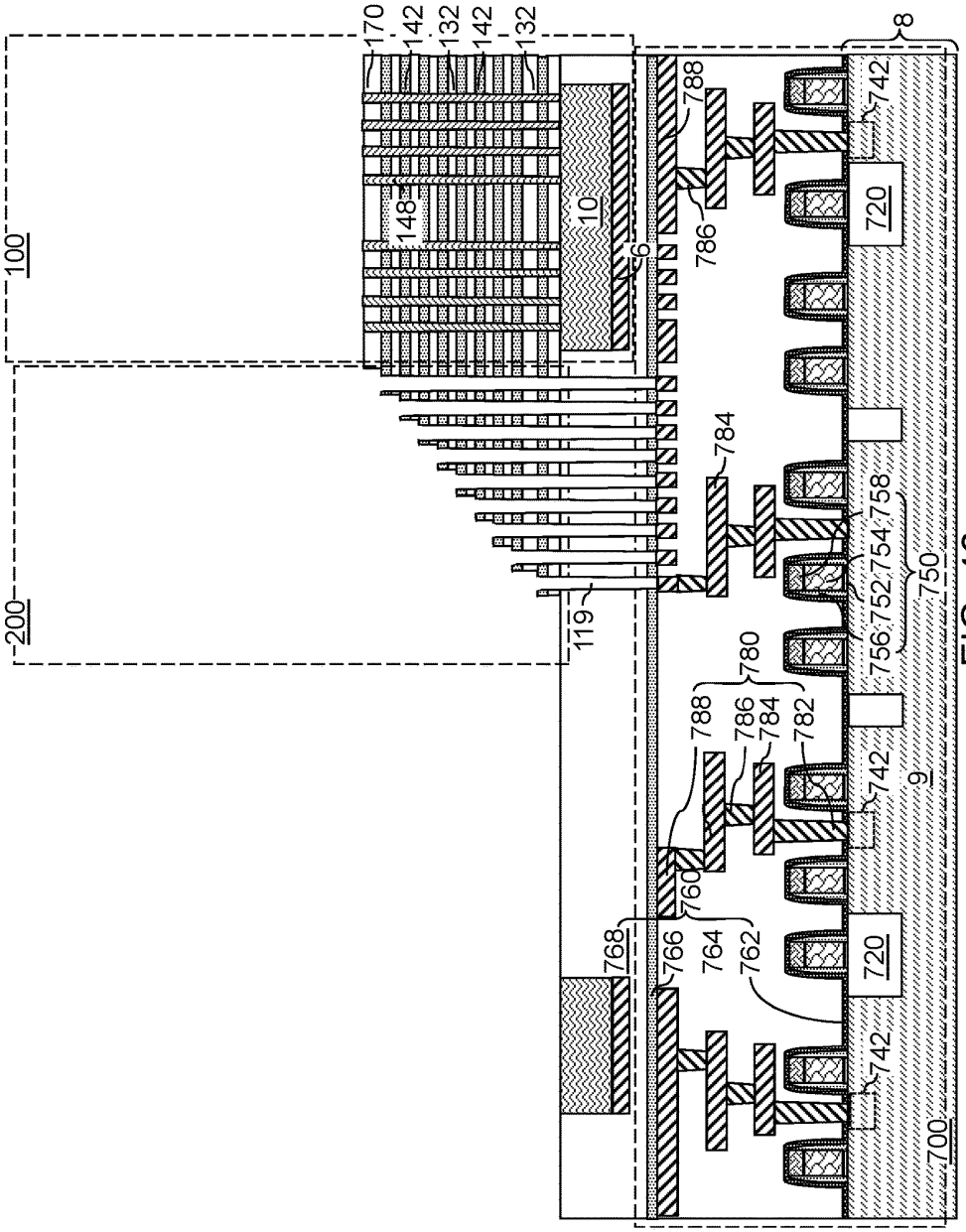
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FIG. 46

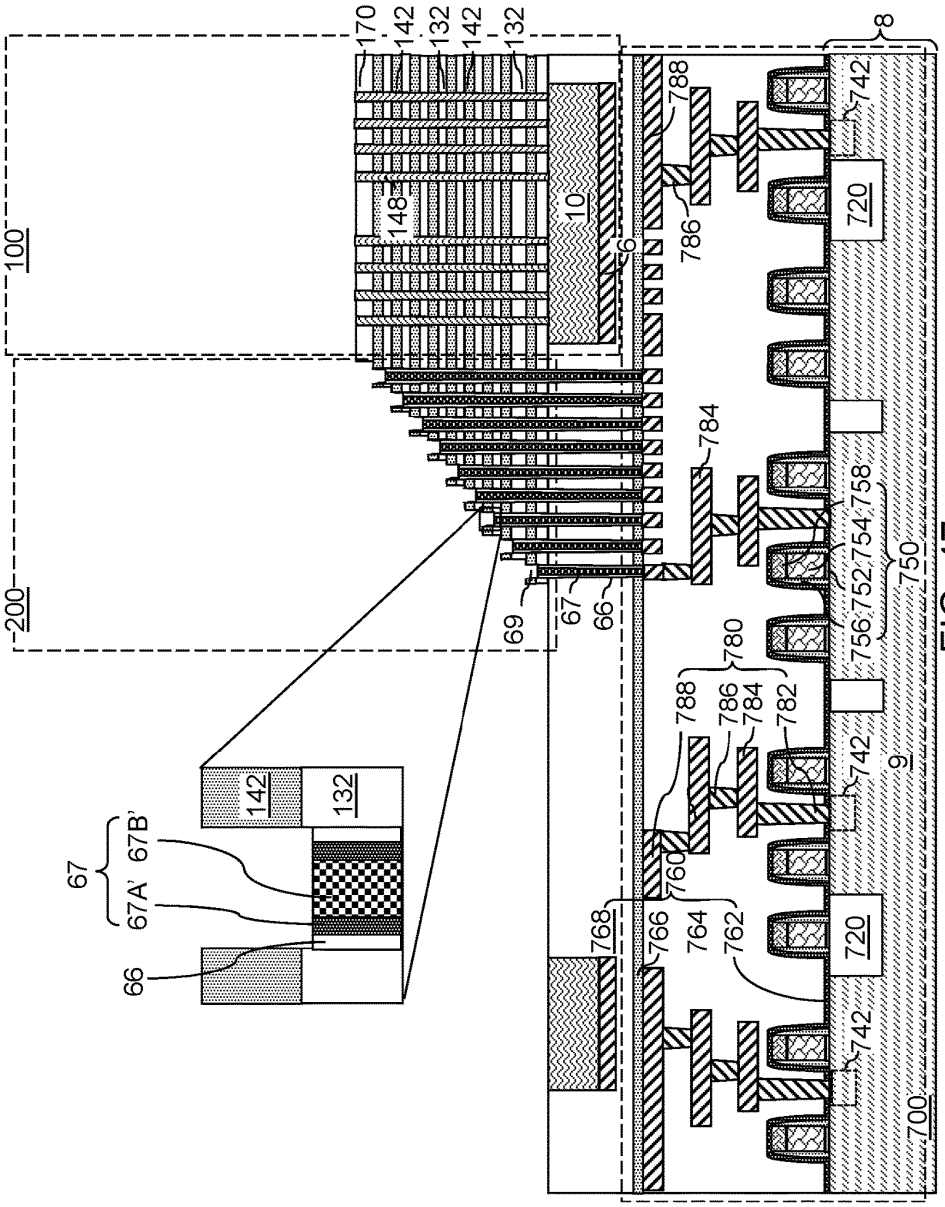
100
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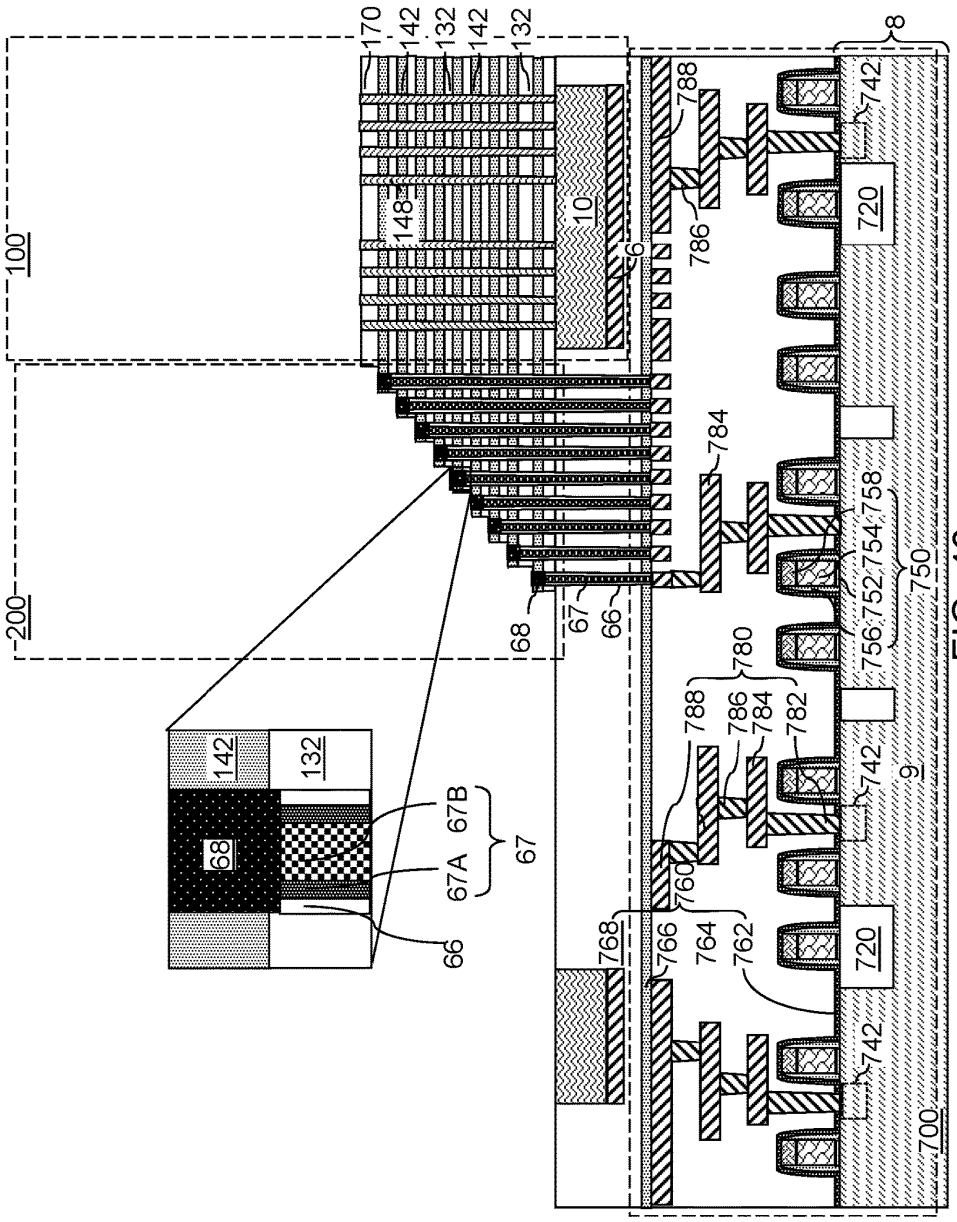
FIG. 47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67B
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FIG. 48

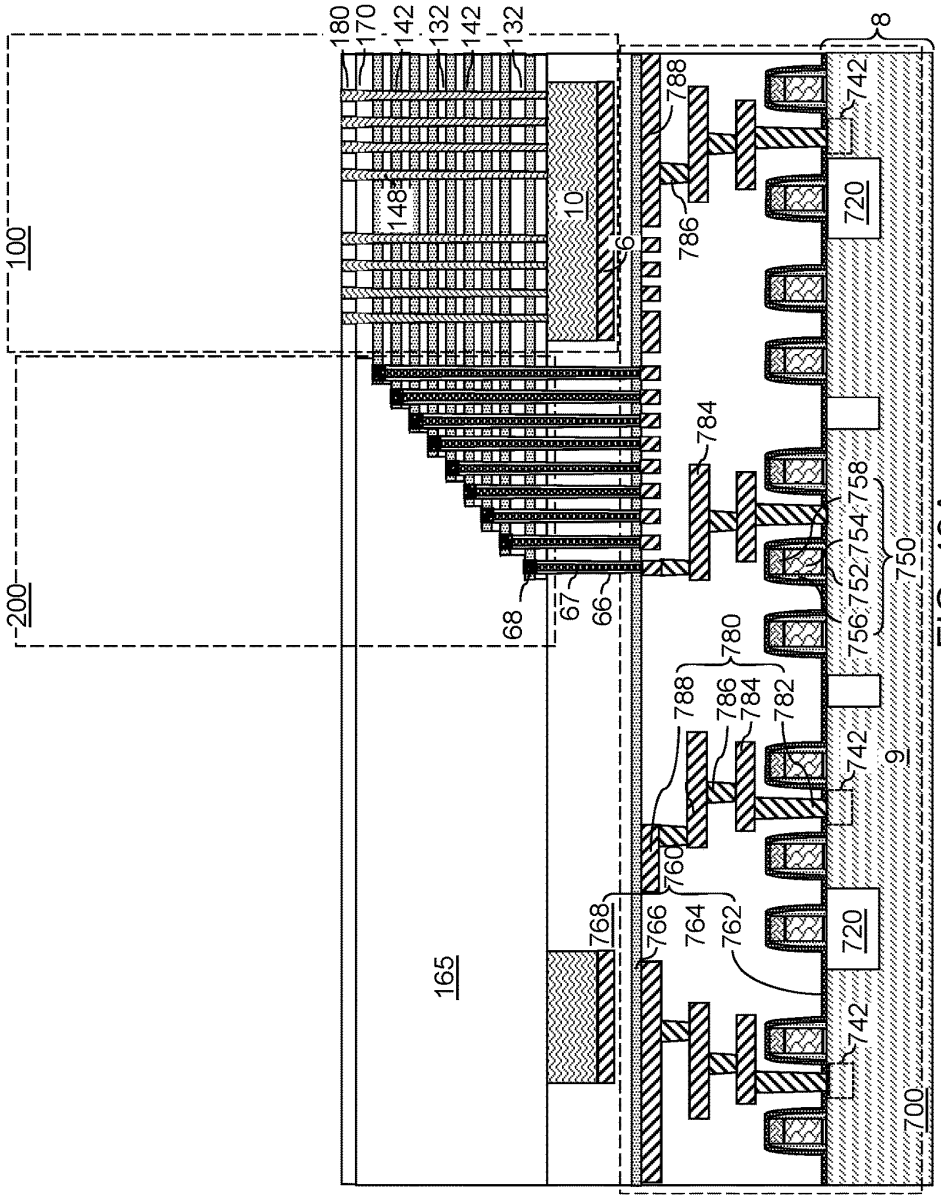
180
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FIG. 49A

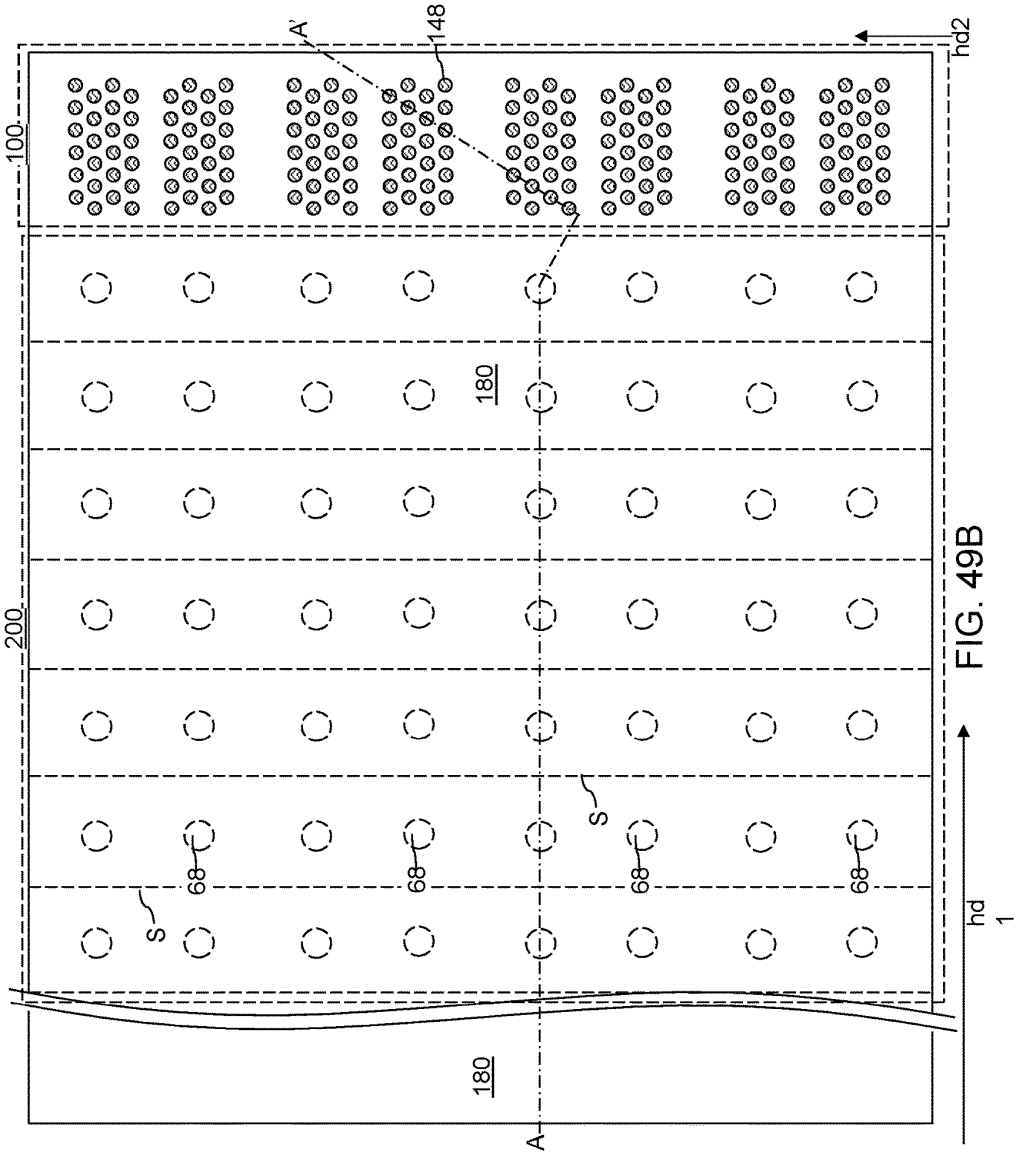

FIG. 49B

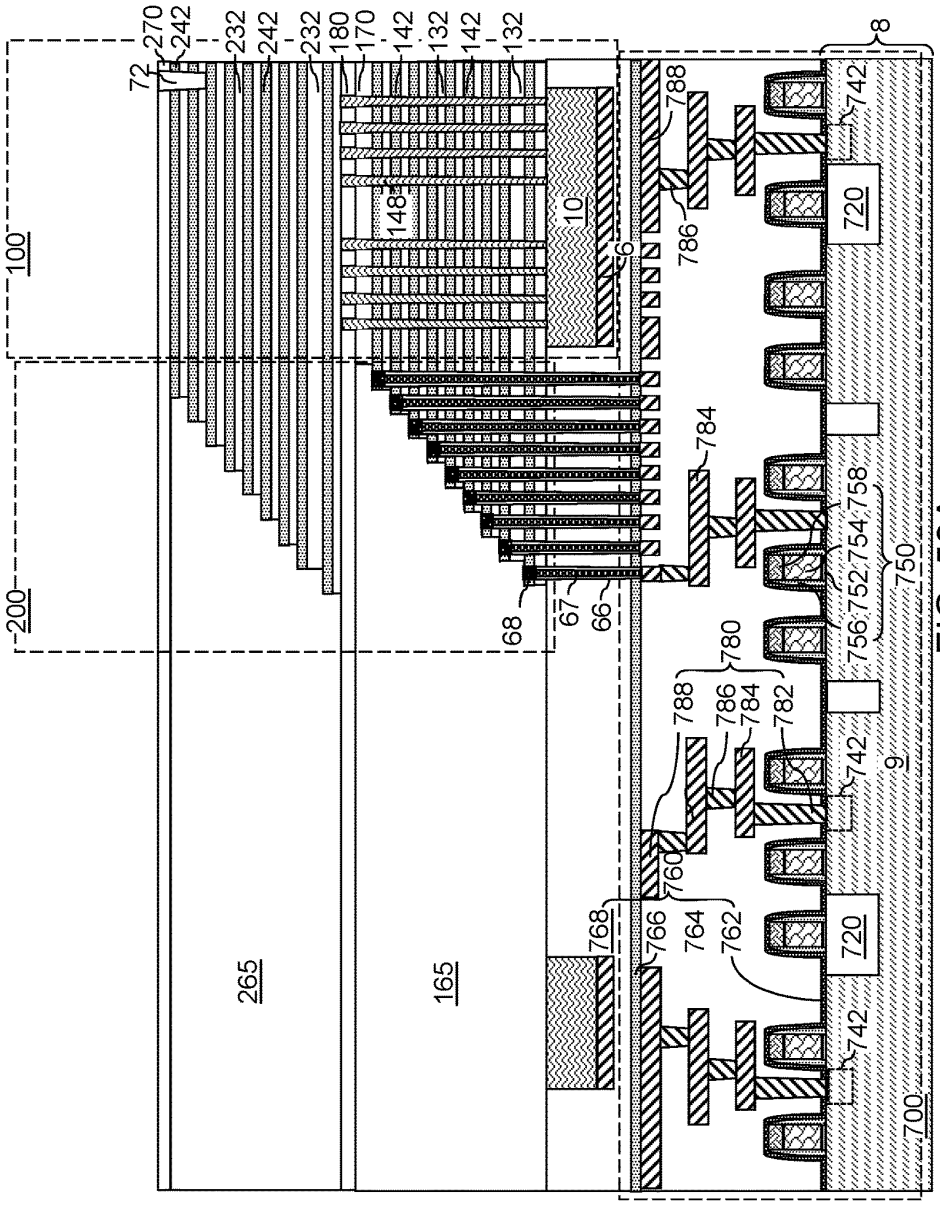
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FIG. 50A

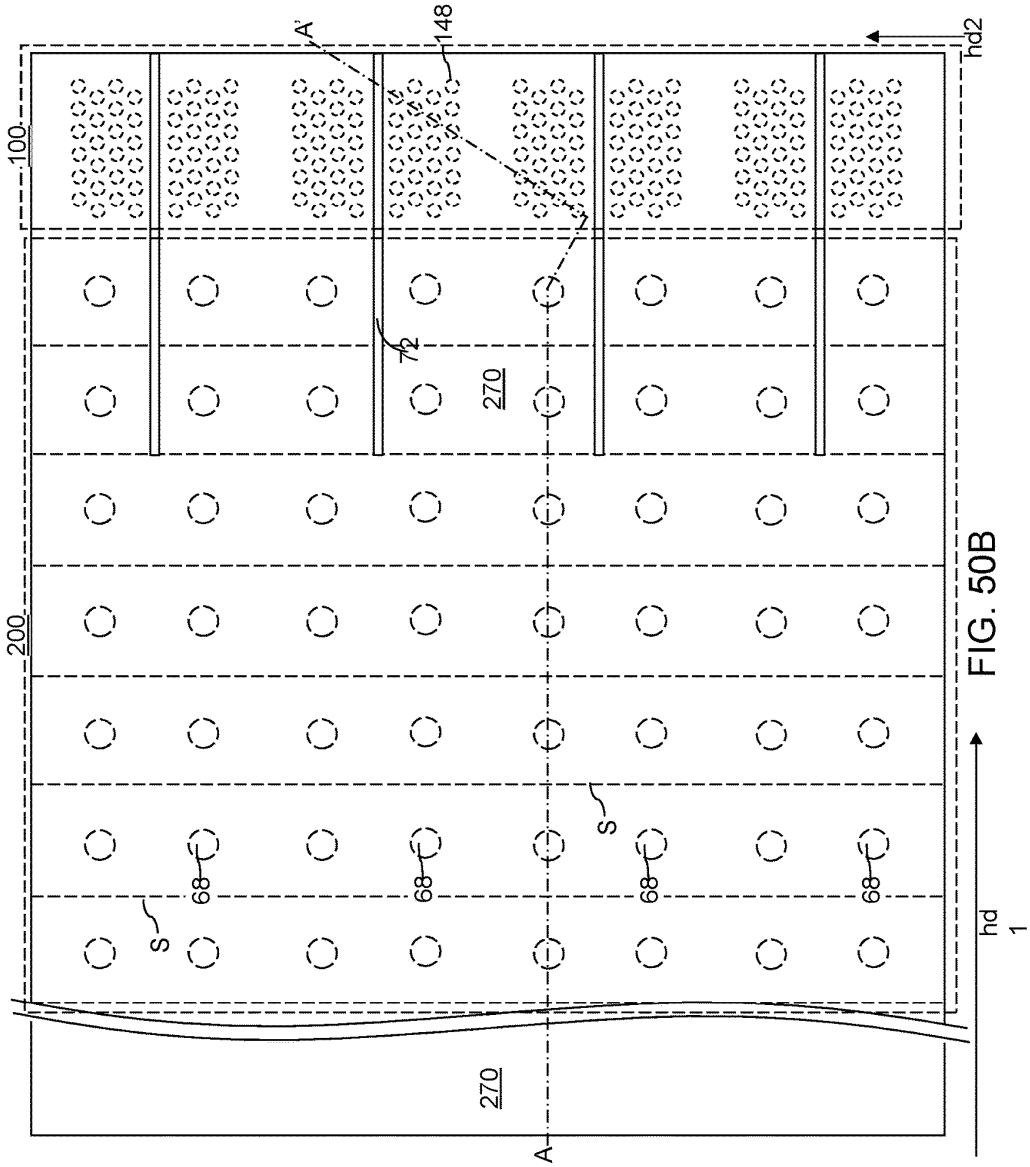

FIG. 50B

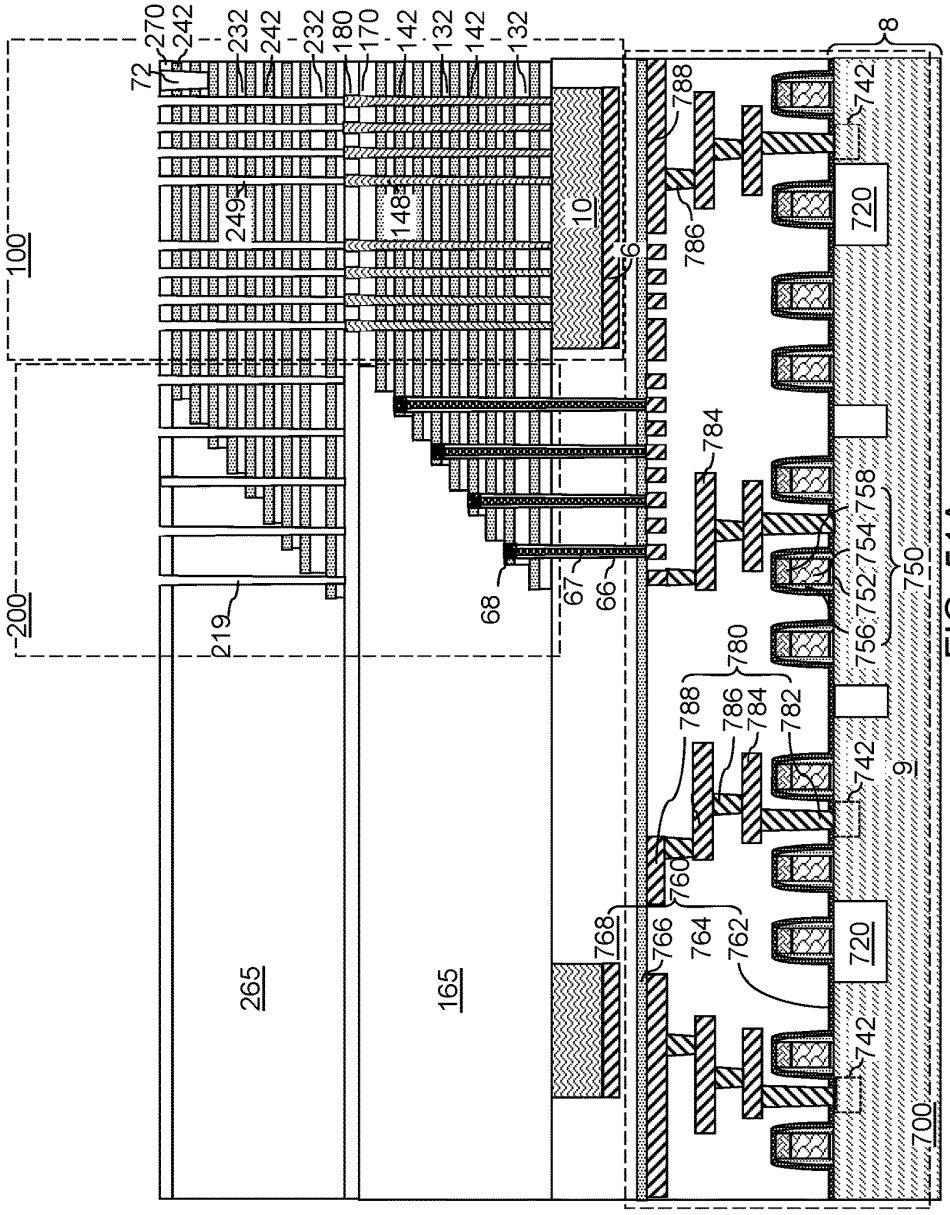
100
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FIG. 51A

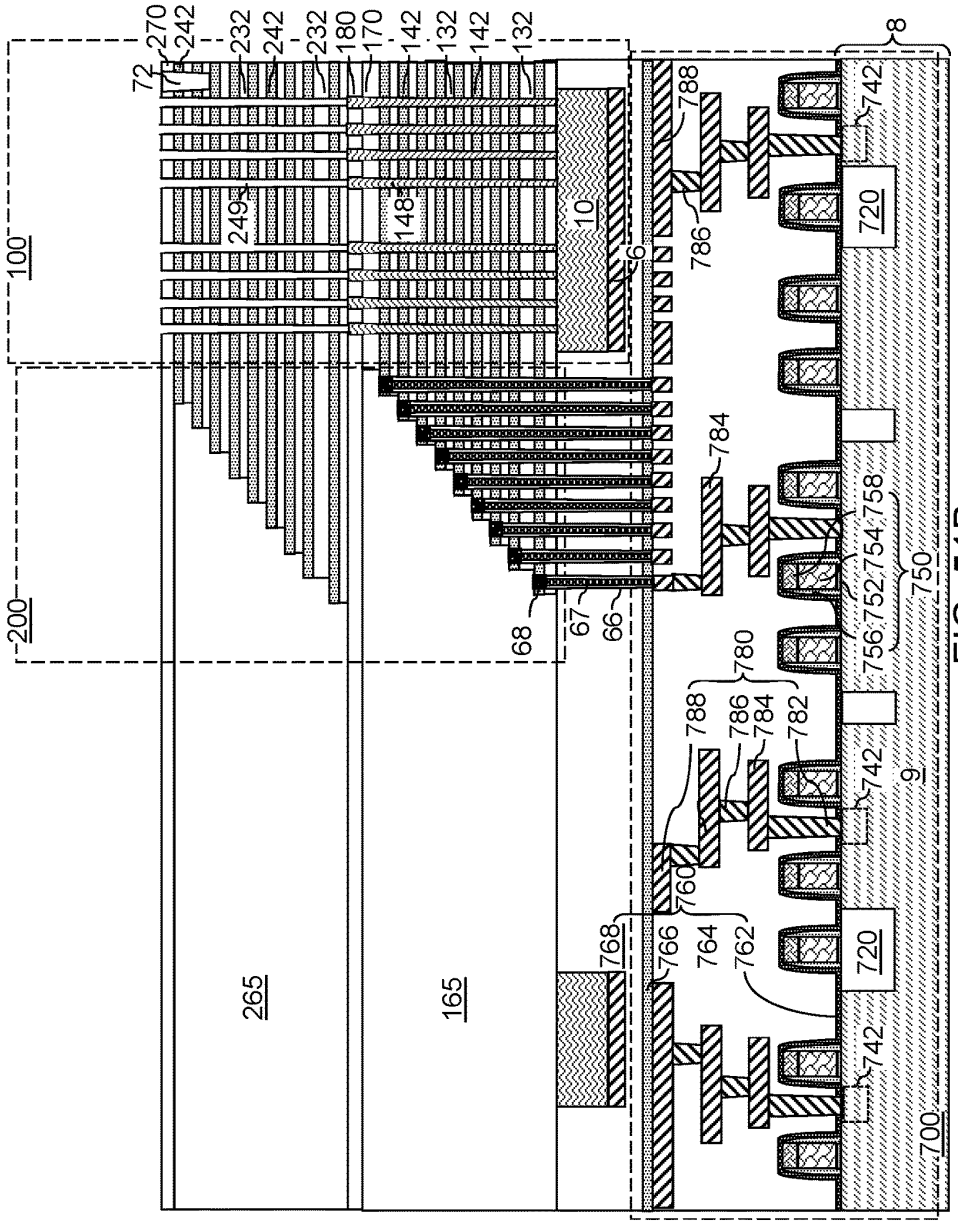
100
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FIG. 51B

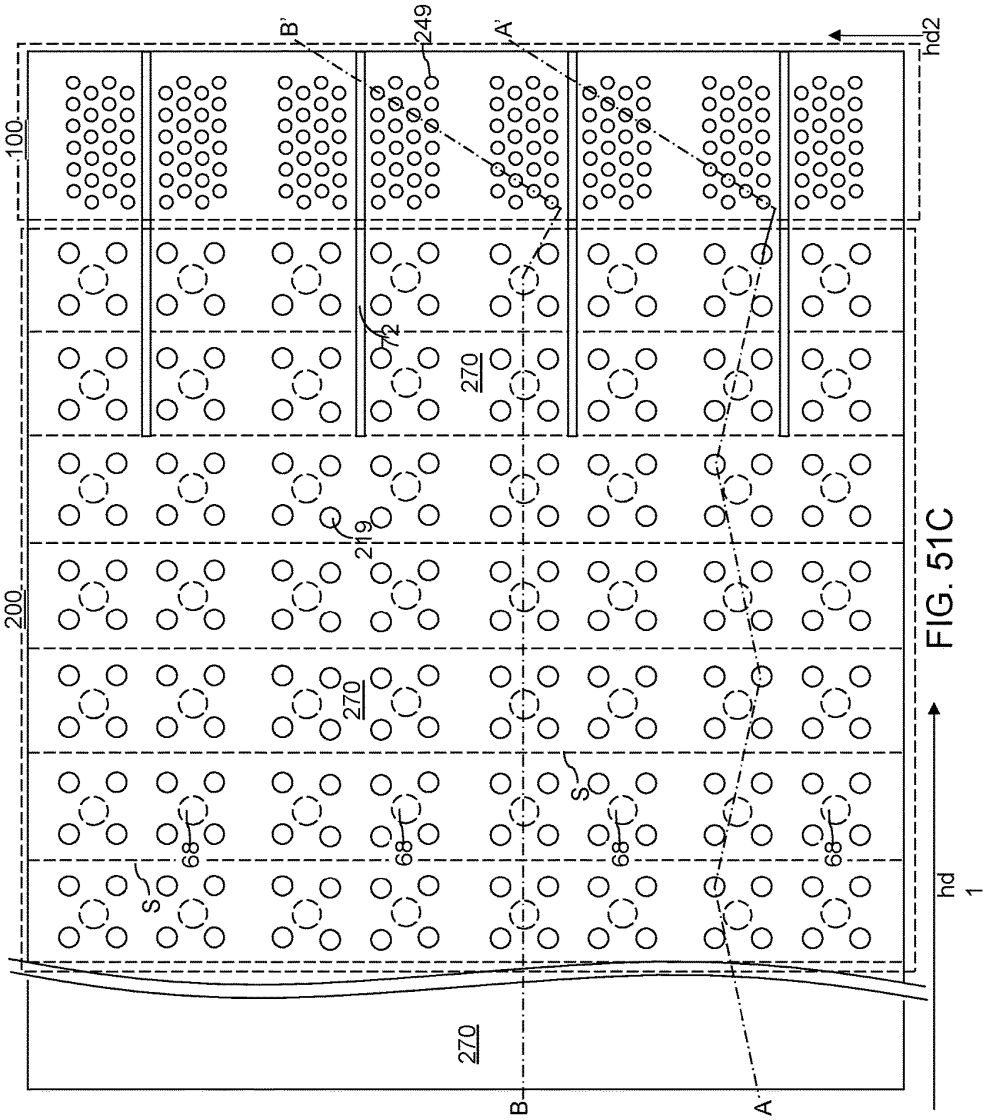
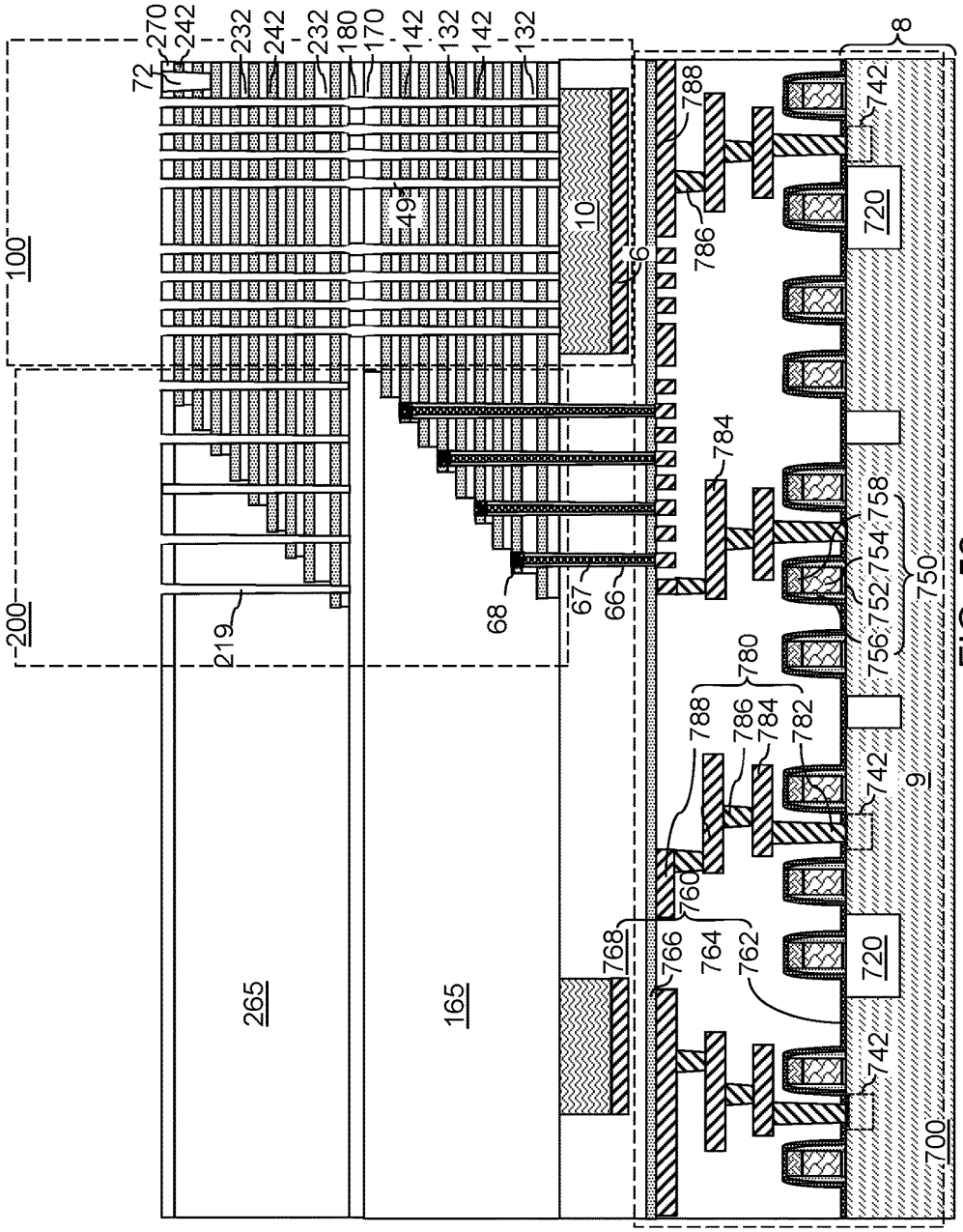


FIG. 51C


100
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142
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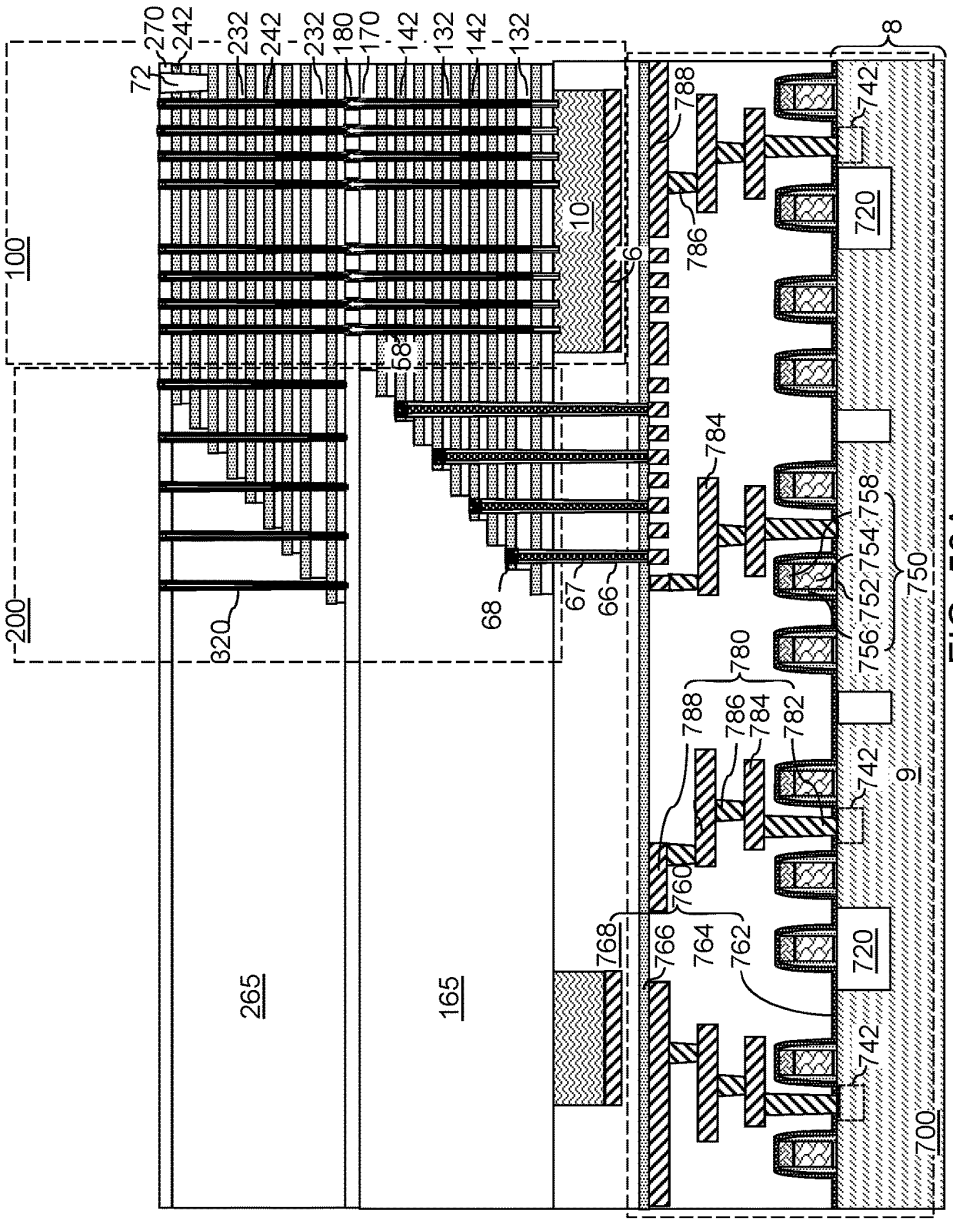
FIG. 52


100
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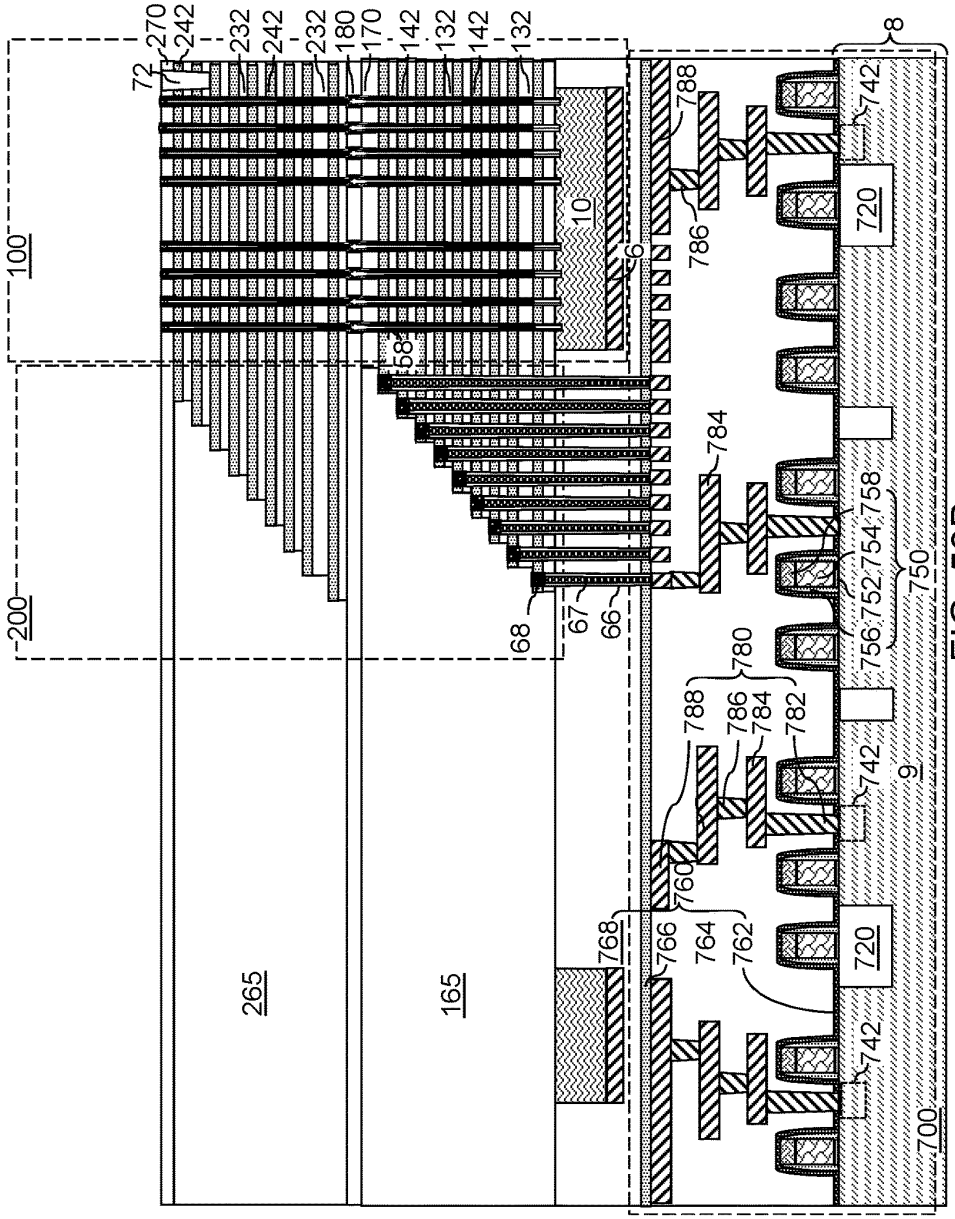
758
750

FIG. 53A


100
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720
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FIG. 53B

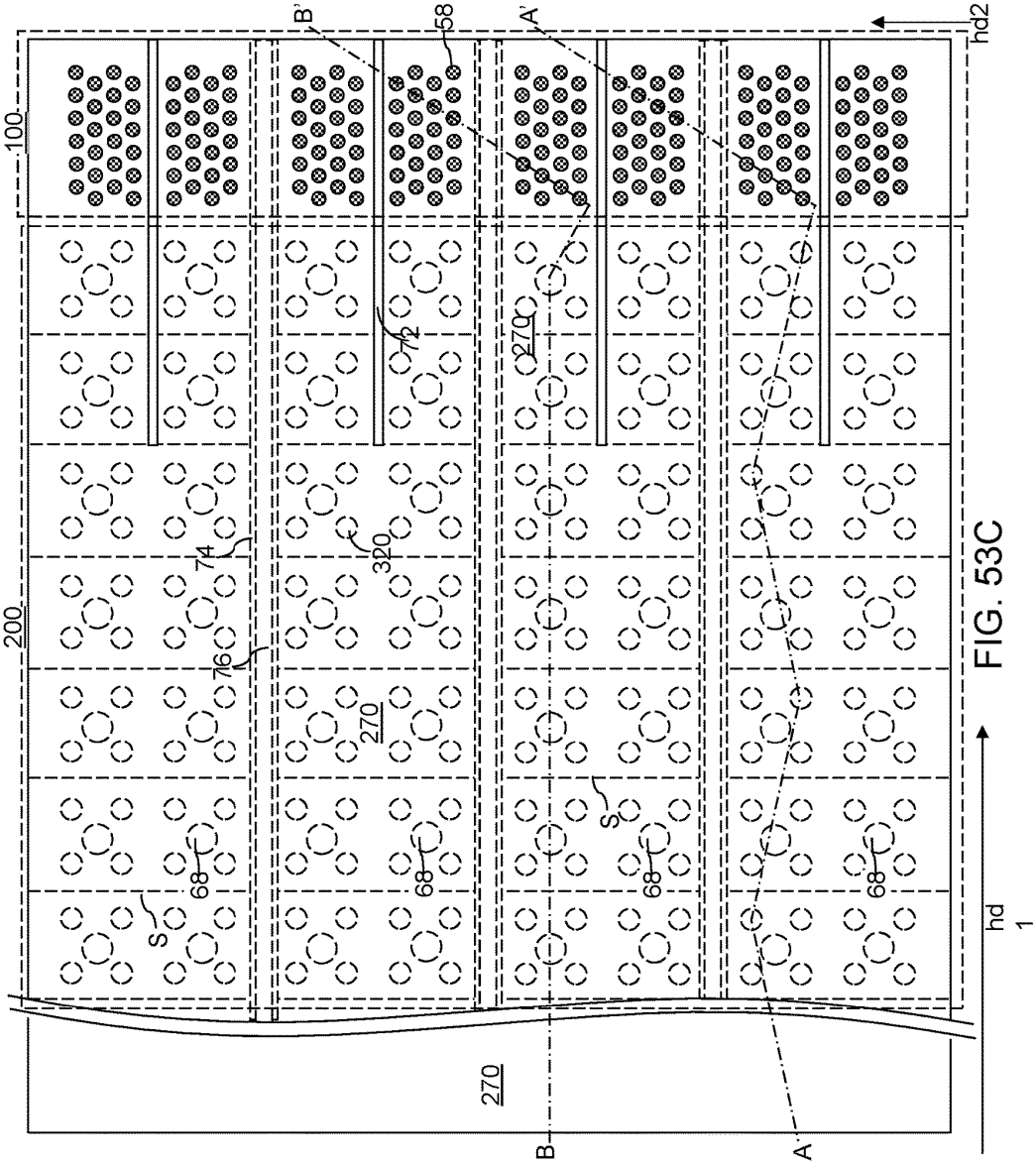
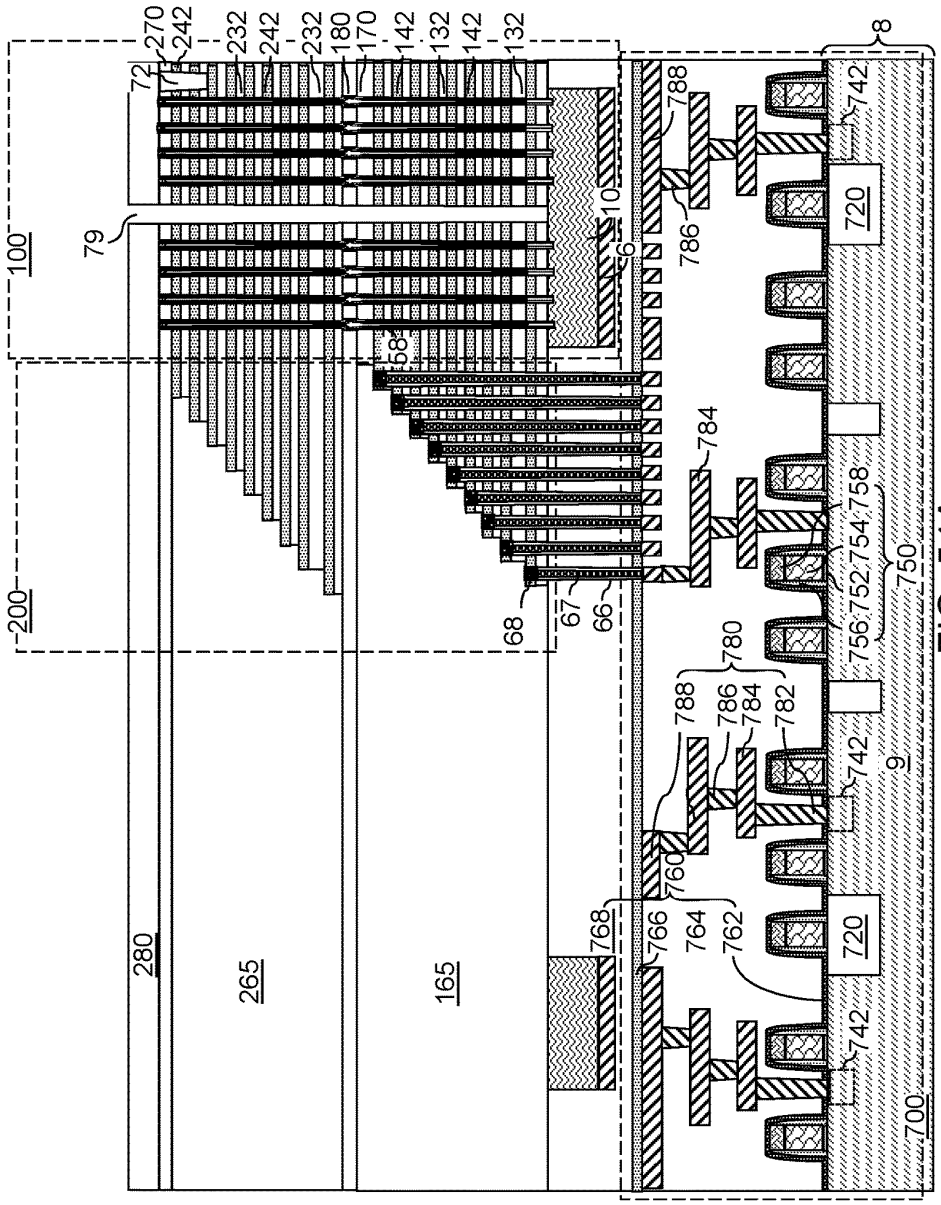


FIG. 53C


100
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758
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FIG. 54A

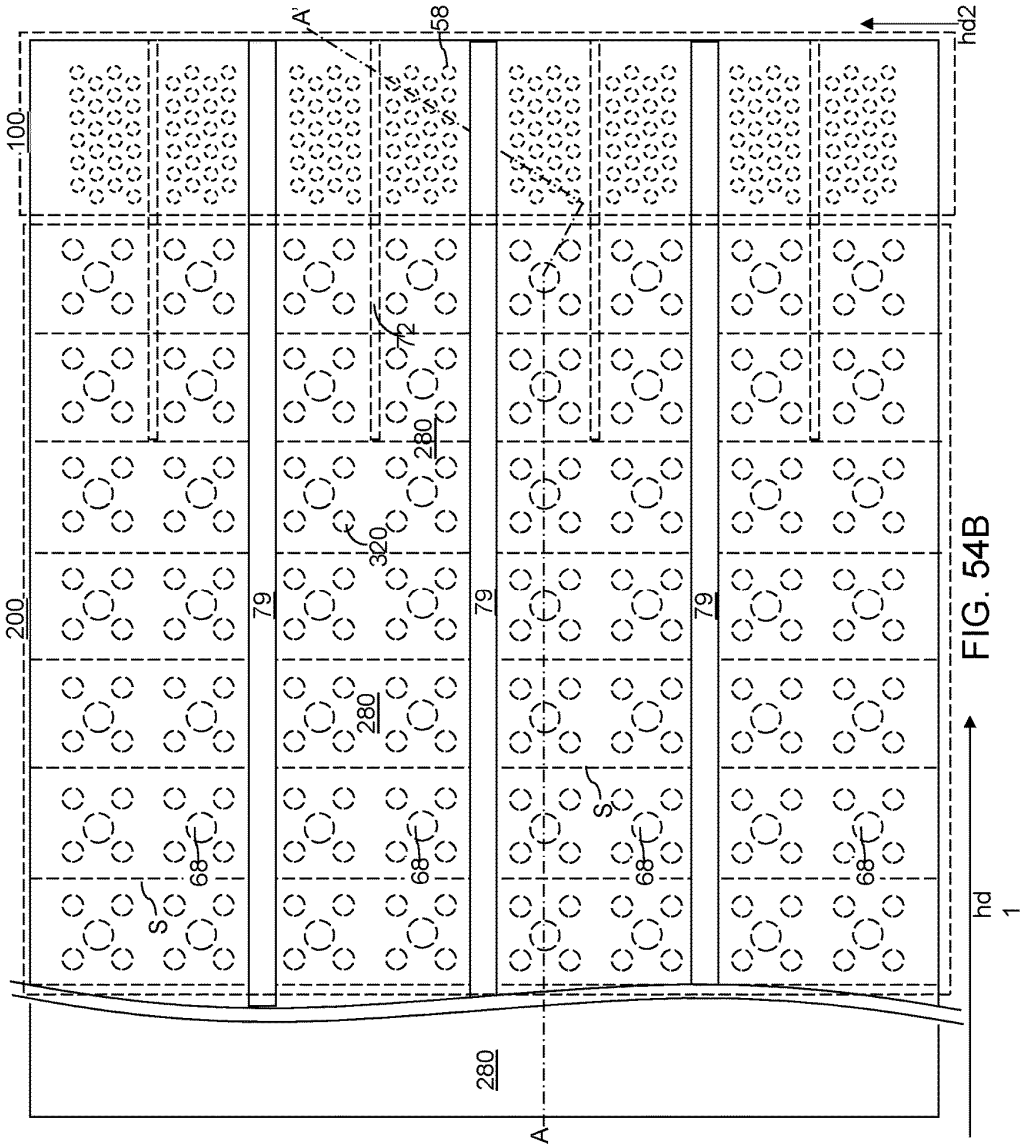
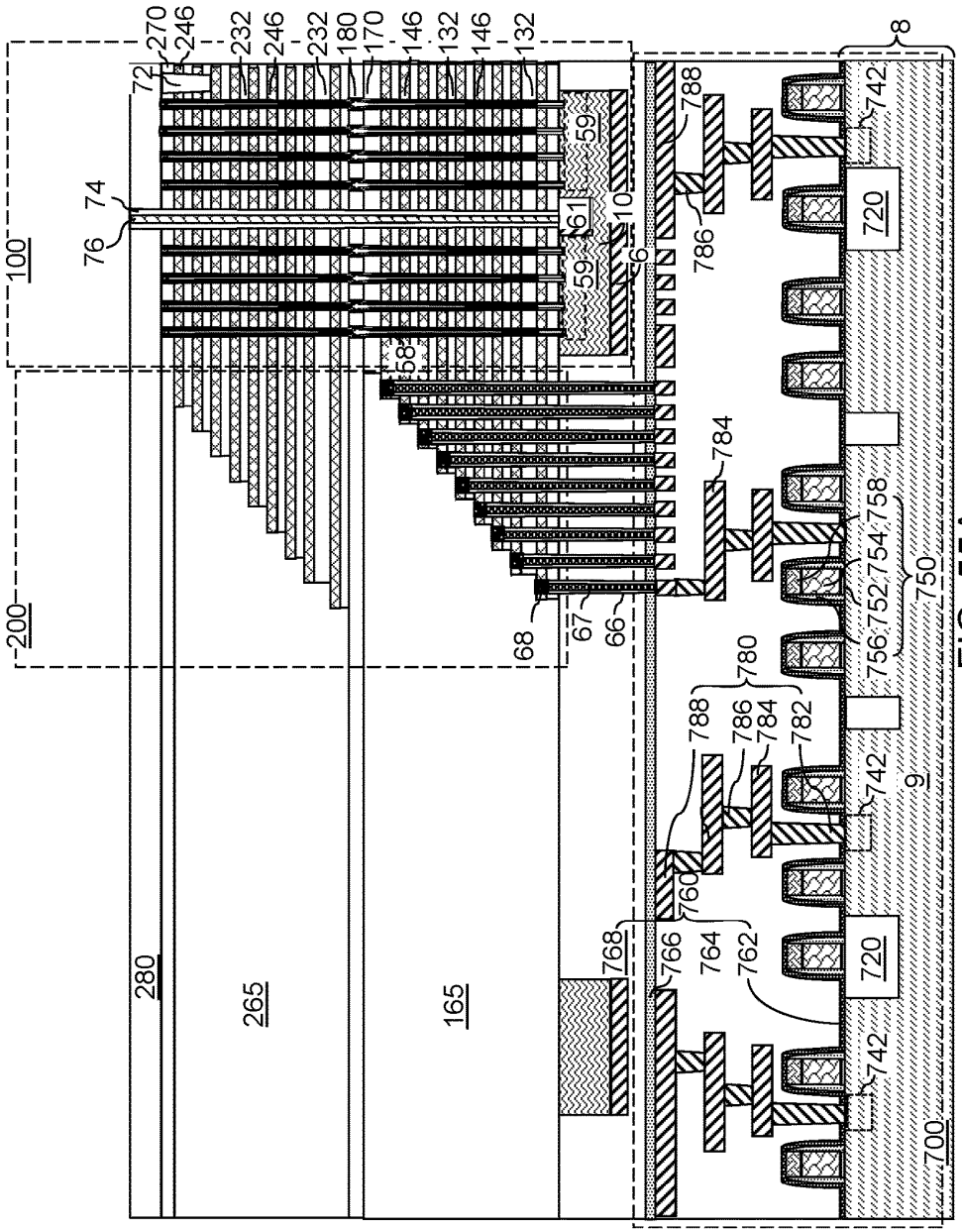


FIG. 54B


270
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232
246
232
180
170
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132
146
132
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100
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FIG. 55A

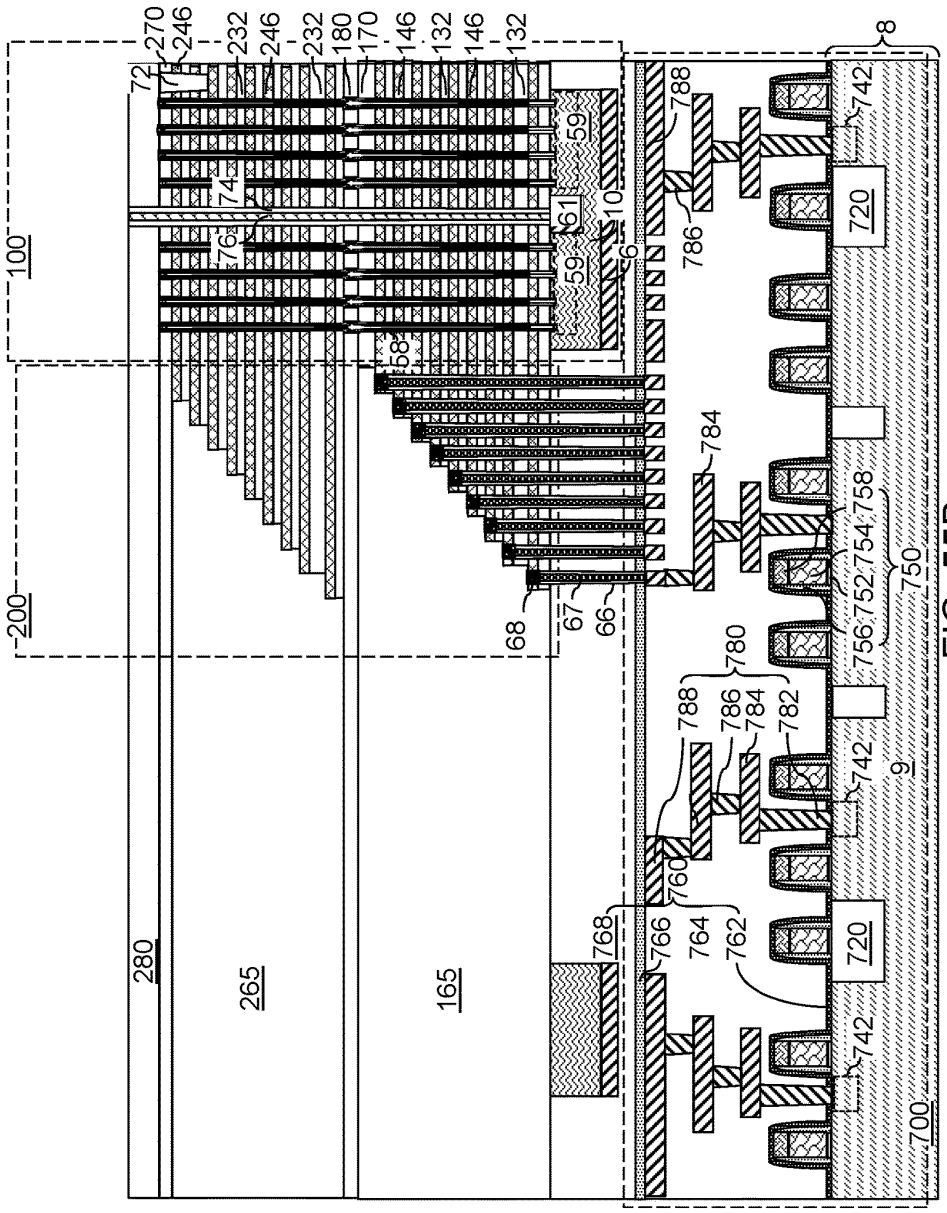
100
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FIG. 55B

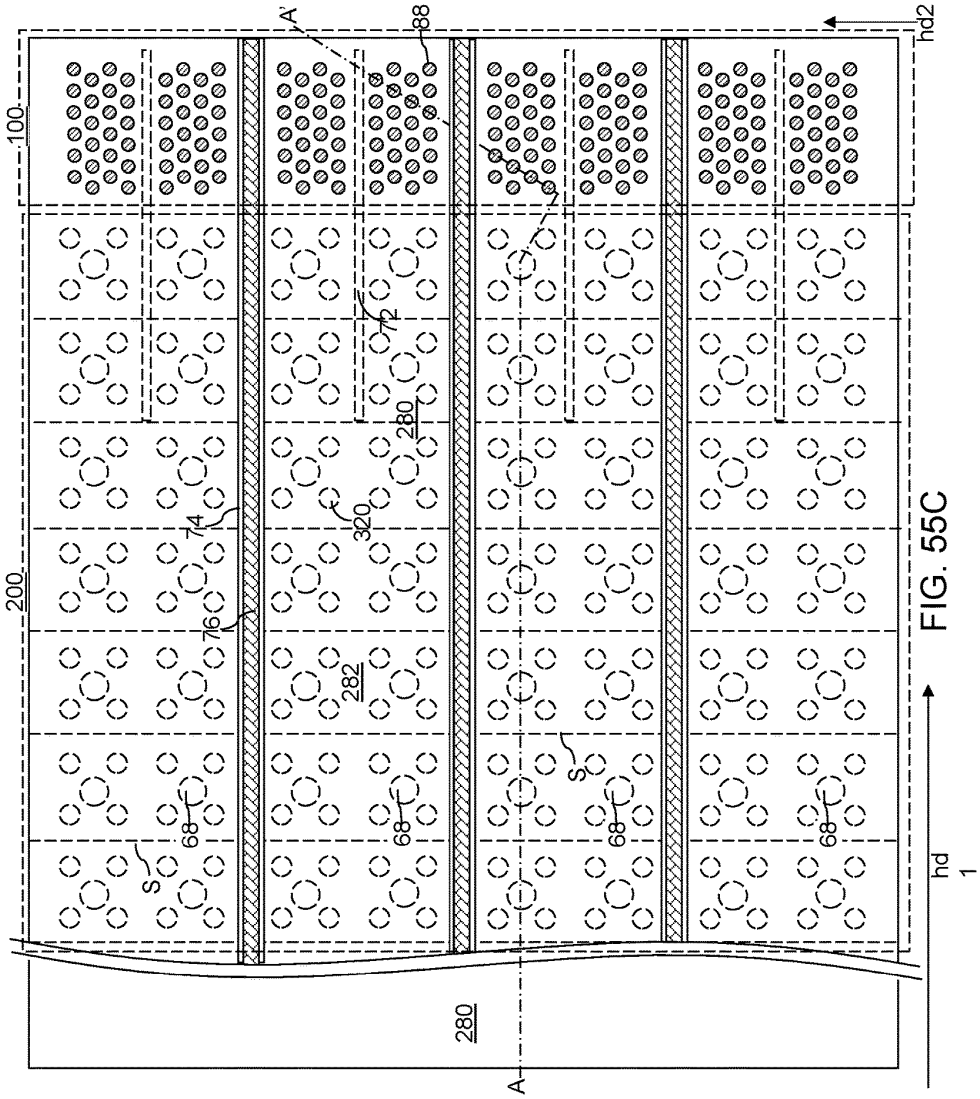
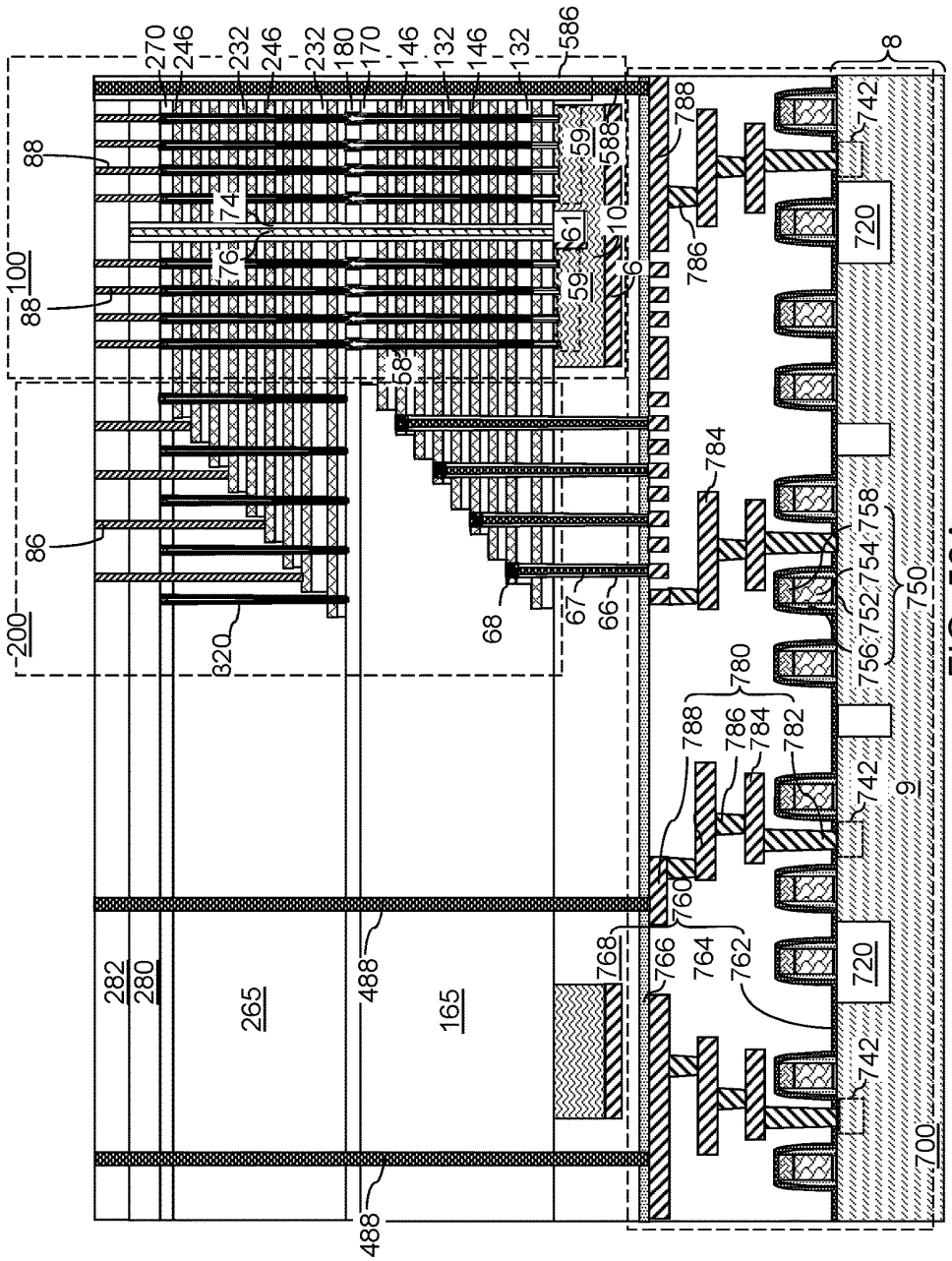


FIG. 55C


270
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232
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170
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132
146
132
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88
100
88
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165
488

FIG. 56A

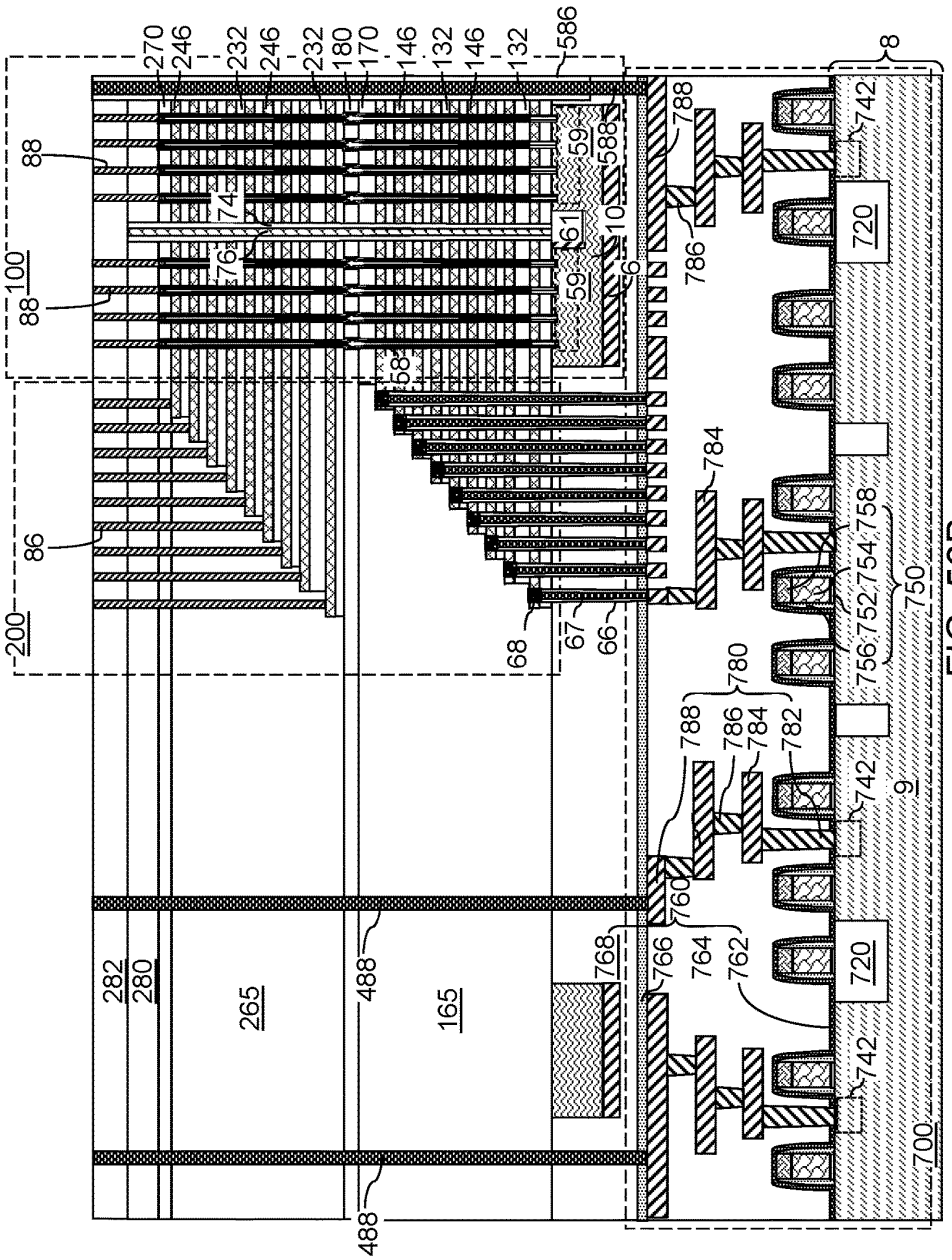
270
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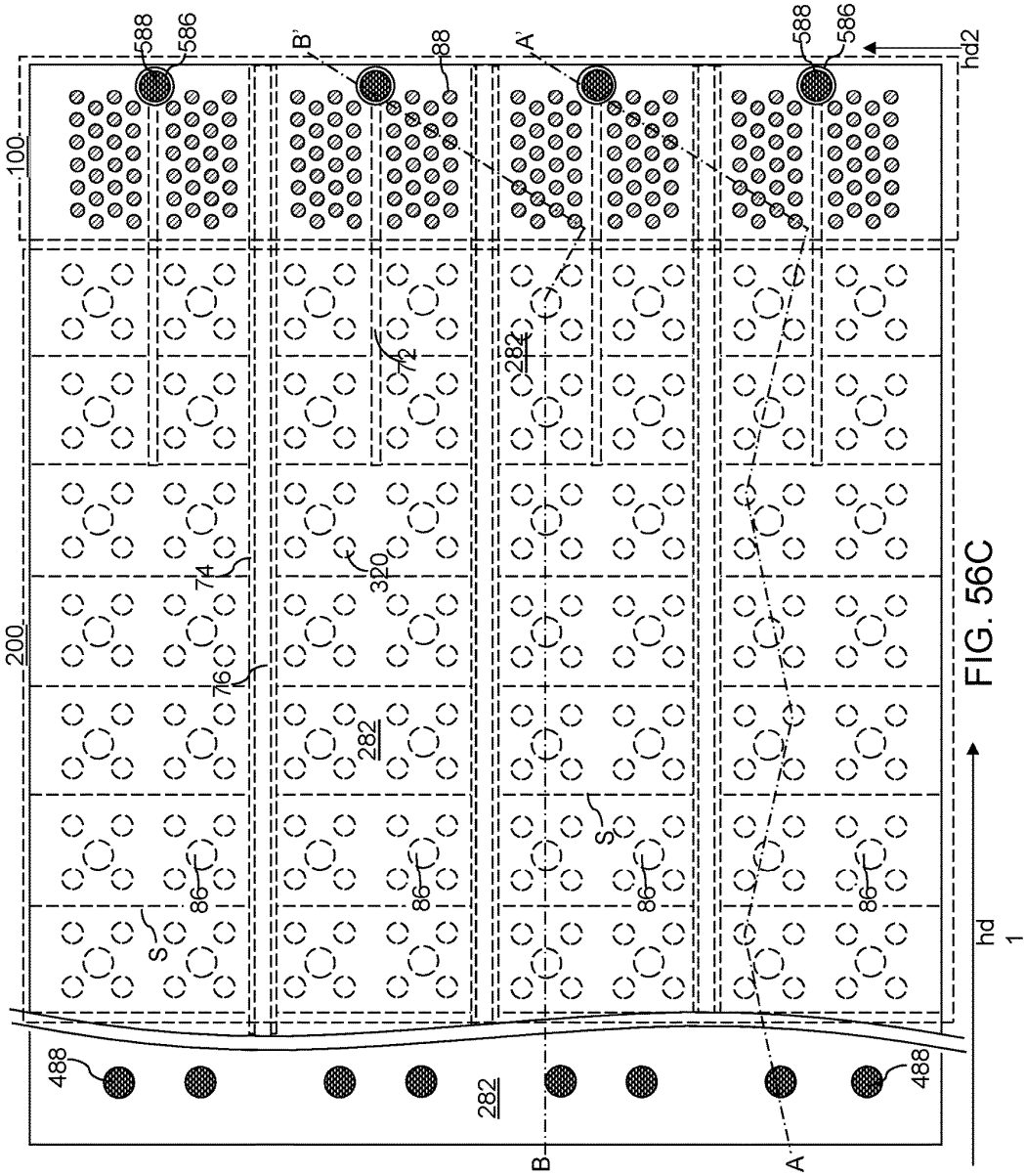
FIG. 56B


588
586
B'
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A'
588
586
hd2
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282
74
320
200
76
282
S
86
86
86
86
S
hd
1
488
282
B
A
488

FIG. 56C

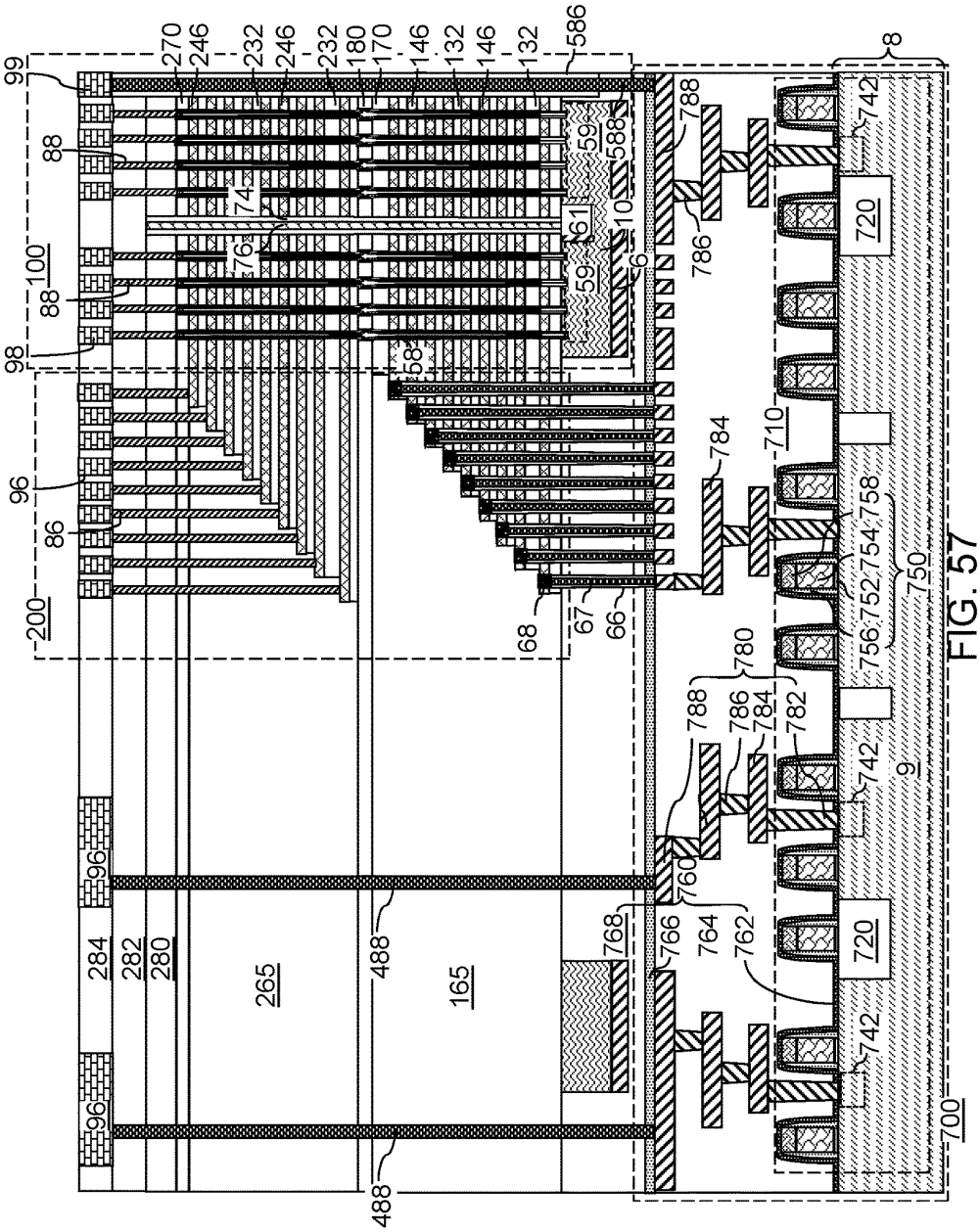
99
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FIG. 57

THREE-DIMENSIONAL MEMORY DEVICE INCLUDING CONTACT VIA STRUCTURES THAT EXTEND THROUGH WORD LINES AND METHOD OF MAKING THE SAME

FIELD

[0001] The present disclosure relates generally to the field of semiconductor devices and specifically to a three-dimensional memory device employing CMOS under array architecture with a hydrogen diffusion barrier layer, and methods of making the same.

BACKGROUND

[0002] Recently, ultra high density storage devices employing three-dimensional (3D) memory stack structures have been proposed. For example, a 3D NAND stacked memory device can be formed from an array of an alternating stack of insulating materials and spacer material layers that are formed as electrically conductive layer or replaced with electrically conductive layers. Memory openings are formed through the alternating stack, and are filled with memory stack structures, each of which includes a vertical stack of memory elements and a vertical semiconductor channel. A memory-level assembly including the alternating stack and the memory stack structures is formed over a substrate. The electrically conductive layers can function as word lines of a 3D NAND stacked memory device, and bit lines overlying an array of memory stack structures can be connected to drain-side ends of the vertical semiconductor channels.

SUMMARY

[0003] According to an aspect of the present disclosure, a three-dimensional memory device is provided, which comprises: semiconductor devices located on a semiconductor substrate; lower interconnect level dielectric layers located over the semiconductor devices and embedding lower interconnect structures that are electrically connected to respective semiconductor devices; an alternating stack of insulating layers and electrically conductive layers located over the lower interconnect level dielectric layers, wherein stepped surfaces of layers of the alternating stack are provided in a terrace region; memory stack structures vertically extending through the alternating stack, wherein each of the memory stack structures comprises a memory film and a vertical semiconductor channel laterally surrounded by the memory film; and contact via structures located in the terrace region, wherein each of the contact via structures laterally contacts a respective one of the electrically conductive layers, vertically extends through a respective opening in at least a bottommost electrically conductive layer of the alternating stack, and contacts a respective one of the lower interconnect structures that underlie the alternating stack.

[0004] According to another aspect of the present disclosure, a method of forming a three-dimensional memory device is provided, which comprises: forming semiconductor devices on a top surface of a semiconductor substrate; forming lower interconnect level dielectric layers embedding lower interconnect structures over the semiconductor devices, wherein the lower interconnect structures are electrically connected to a respective one of the semiconductor devices; forming an alternating stack of insulating layers and sacrificial material layers over the lower interconnect level dielectric layers; forming stepped surfaces on the alternating stack in a word line contact region by patterning the alternating stack; forming contact via structures in the word line contact region, wherein each of the contact via structures laterally contacts a respective one of the sacrificial material layers, vertically extends through a respective opening in at least a bottommost sacrificial material layer of the alternating stack, and contacts a respective one of the lower interconnect structures that underlie the alternating stack; forming memory stack structures through the alternating stack, wherein each of the memory stack structures comprises a memory film and a vertical semiconductor channel laterally surrounded by the memory film; and replacing the sacrificial materials with electrically conductive layers.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. **1** is a vertical cross-sectional view of a first exemplary structure after formation of semiconductor devices, lower level dielectric layers including a silicon nitride layer, lower metal interconnect structures, and a planar semiconductor material layer on a semiconductor substrate according to a first embodiment of the present disclosure.

[0006] FIG. **2** is a vertical cross-sectional view of the first exemplary structure after formation of a first-tier alternating stack of first insulting layers and first spacer material layers according to an embodiment of the present disclosure.

[0007] FIG. **3** is a vertical cross-sectional view of the first exemplary structure after patterning first-tier staircase regions on the first-tier alternating stack and forming a first-tier retro-stepped dielectric material portion according to an embodiment of the present disclosure.

[0008] FIG. **4**A is a vertical cross-sectional view of the first exemplary structure after formation of first-tier memory openings and first-tier support openings according to an embodiment of the present disclosure.

[0009] FIG. **4**B is a horizontal cross-sectional view of the first exemplary structure along the horizontal plane B-B' in FIG. **4**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **4**A.

[0010] FIG. **5** is a vertical cross-sectional view of the first exemplary structure after formation of sacrificial memory opening fill portions and sacrificial support opening fill portions according to an embodiment of the present disclosure.

[0011] FIG. **6** is a vertical cross-sectional view of the first exemplary structure after formation of a second-tier alternating stack of second insulating layers and second spacer material layers, a second-tier retro-stepped dielectric material portion, and a second insulating cap layer according to an embodiment of the present disclosure.

[0012] FIG. **7**A is a vertical cross-sectional view of the first exemplary structure after formation of inter-tier memory openings and inter-tier support openings according to an embodiment of the present disclosure.

[0013] FIG. **7**B is a horizontal cross-sectional view of the first exemplary structure along the horizontal plane B-B' in FIG. **7**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **7**A.

[0014] FIG. **8** is a vertical cross-sectional view of the first exemplary structure after formation of memory stack structures according to an embodiment of the present disclosure.

[0015] FIGS. **9**A-**9**H are sequential vertical cross-sectional views of an inter-tier memory opening during forma-

tion of a pillar channel portion, a memory stack structure, a dielectric core, and a drain region according to an embodiment of the present disclosure.

[0016] FIG. **10**A is a vertical cross-sectional view of the first exemplary structure after formation of first through-stack via cavities according to an embodiment of the present disclosure.

[0017] FIG. **10**B is a horizontal cross-sectional view of the first exemplary structure along the horizontal plane B-B' in FIG. **10**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **10**A.

[0018] FIG. **11**A is a vertical cross-sectional view of the first exemplary structure after formation of through-stack insulating material portion according to an embodiment of the present disclosure.

[0019] FIG. **11**B is a horizontal cross-sectional view of the first exemplary structure. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **11**A.

[0020] FIG. **12**A is a vertical cross-sectional view of the first exemplary structure after formation of backside contact trenches according to an embodiment of the present disclosure.

[0021] FIG. **12**B is a horizontal cross-sectional view of the first exemplary structure along the horizontal plane B-B' in FIG. **12**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **12**A.

[0022] FIG. **13**A is a vertical cross-sectional view of the first exemplary structure after replacement of sacrificial material layers with electrically conductive layers and formation of insulating spacers and backside contact via structures according to an embodiment of the present disclosure.

[0023] FIG. **13**B is a horizontal cross-sectional view of the first exemplary structure along the horizontal plane B-B' in FIG. **13**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **13**A.

[0024] FIG. **14** is a vertical cross-sectional view of the first exemplary structure after formation of drain contact via structures and word line contact via structures according to an embodiment of the present disclosure.

[0025] FIG. **15** is a vertical cross-sectional view of the first exemplary structure after formation of second through-track via cavities and through-dielectric via cavities according to an embodiment of the present disclosure.

[0026] FIG. **16**A is a vertical cross-sectional view of the first exemplary structure after formation of through-stack contact via structures and through-dielectric contact via structures according to an embodiment of the present disclosure.

[0027] FIG. **16**B is a horizontal cross-sectional view of the first exemplary structure along the horizontal plane B-B' in FIG. **16**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **16**A.

[0028] FIG. **17** is a vertical cross-sectional view of the first exemplary structure after formation of upper metal line structures according to an embodiment of the present disclosure.

[0029] FIG. **18**A is a vertical cross-sectional view of a first alternative configuration of the first exemplary structure after formation of first through-stack via cavities and first through-dielectric via cavities according to an embodiment of the present disclosure.

[0030] FIG. **18**B is a horizontal cross-sectional view of first alternative configuration of the first exemplary structure along the horizontal plane B-B' in FIG. **18**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **18**A.

[0031] FIG. **19**A is a vertical cross-sectional view of the first alternative configuration of the first exemplary structure after formation of through-stack contact via structures and through-dielectric contact via structures according to an embodiment of the present disclosure.

[0032] FIG. **19**B is a horizontal cross-sectional view of the first exemplary structure along the horizontal plane B-B' in FIG. **19**A. The zig-zag vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **19**A.

[0033] FIG. **20** is a vertical cross-sectional view of the first alternative configuration of the first exemplary structure after formation of upper metal line structures according to an embodiment of the present disclosure.

[0034] FIG. **21** is a vertical cross-sectional view of a second alternative configuration of the first exemplary structure according to an embodiment of the present disclosure.

[0035] FIG. **22** is a vertical cross-sectional view of a second exemplary structure after the processing steps of FIG. **2** with appropriate changes to the pattern of the optional planar conductive material layer and the planar semiconductor material layer according to an embodiment of the present disclosure.

[0036] FIG. **23**A is a vertical cross-sectional view of the second exemplary structure after formation of first-tier memory openings and first-tier contact openings according to an embodiment of the present disclosure.

[0037] FIG. **23**B is a top-down view of the second exemplary structure of FIG. **23**A.

[0038] FIG. **24**A is a vertical cross-sectional view of the second exemplary structure after formation of sacrificial memory opening fill portions and sacrificial contact opening fill portions according to an embodiment of the present disclosure.

[0039] FIG. **24**B is a top-down view of the second exemplary structure of FIG. **24**A.

[0040] FIG. **25**A is a vertical cross-sectional view of the second exemplary structure after formation of a second-tier alternating stack of second insulating layers and second spacer material layers, second-tier memory openings and second-tier contact openings according to an embodiment of the present disclosure.

[0041] FIG. **25**B is a top-down view of the second exemplary structure of FIG. **25**A.

[0042] FIG. **26** is a vertical cross-sectional view of the second exemplary structure after formation of inter-tier memory openings and inter-tier contact openings, and formation of sacrificial memory opening pillars and sacrificial contact opening pillars according to an embodiment of the present disclosure.

[0043] FIG. **27** is a vertical cross-sectional view of the second exemplary structure after removal of the sacrificial memory opening pillars from the inter-tier memory openings according to an embodiment of the present disclosure.

[0044] FIG. **28** is a vertical cross-sectional view of the second exemplary structure after formation of memory stack structures in the inter-tier memory openings according to an embodiment of the present disclosure.

[0045] FIG. **29** is a vertical cross-sectional view of the second exemplary structure after application and patterning of a trimmable mask layer and an anisotropic etch process

that removes a physically exposed portion of a second insulating cap layer according to an embodiment of the present disclosure.

[0046] FIG. **30** is a vertical cross-sectional view of the second exemplary structure during formation of stepped surfaces in a word line contact region by repetition of an anisotropic etch process and trimming of the trimmable mask layer according to an embodiment of the present disclosure.

[0047] FIG. **31** is a vertical cross-sectional view of the second exemplary structure after formation of stepped surfaces in a word line contact region by repetition of an anisotropic etch process and trimming of the trimmable mask layer according to an embodiment of the present disclosure.

[0048] FIG. **32** is a vertical cross-sectional view of the second exemplary structure after selective removal of remaining portions of the sacrificial contact opening pillars to form contact via cavities according to an embodiment of the present disclosure.

[0049] FIG. **33** is a vertical cross-sectional view of the second exemplary structure after formation of a continuous insulating liner layer, a continuous metallic nitride liner layer, and a continuous metal fill layer according to an embodiment of the present disclosure.

[0050] FIG. **34** is a vertical cross-sectional view of the second exemplary structure after recessing the continuous metallic nitride liner layer and a continuous metal fill layer to form metallic nitride liners and metal fill portions according to an embodiment of the present disclosure.

[0051] FIG. **35** is a vertical cross-sectional view of the second exemplary structure after formation of metallic pillar structures on each metal fill portion employing a selective metal deposition process according to an embodiment of the present disclosure.

[0052] FIG. **36**A is a vertical cross-sectional view of the second exemplary structure after formation of a retro-stepped dielectric material portion according to an embodiment of the present disclosure.

[0053] FIG. **36**B is a top-down view of the second exemplary structure of FIG. **36**A.

[0054] FIG. **37** is a vertical cross-sectional view of the second exemplary structure after formation of a first contact level dielectric layer and backside trenches and replacement of the sacrificial material layers with electrically conductive layers according to an embodiment of the present disclosure.

[0055] FIG. **38**A is a vertical cross-sectional view of the second exemplary structure after formation of a second contact level dielectric layer, through-stack insulating spacers, and through-stack contact via structures according to an embodiment of the present disclosure.

[0056] FIG. **38**B is a top-down view of the second exemplary structure of FIG. **38**A.

[0057] FIG. **39** is a vertical cross-sectional view of the second exemplary structure after formation of through-dielectric contact via structures, at least one upper interconnect level dielectric layer, and various upper interconnect level metal structures according to an embodiment of the present disclosure.

[0058] FIG. **40**A is a vertical cross-sectional view of a third exemplary structure after formation of a first alternating stack of first insulating layers and first sacrificial material layers and first-tier memory openings according to an embodiment of the present disclosure.

[0059] FIG. **40**B is a top-down view of the third exemplary structure of FIG. **40**A.

[0060] FIG. **41** is a vertical cross-sectional view of the third exemplary structure after formation of sacrificial memory opening fill portions in the first-tier memory openings according to an embodiment of the present disclosure.

[0061] FIG. **42**A is a vertical cross-sectional view of the third exemplary structure after formation of first-tier contact openings according to an embodiment of the present disclosure.

[0062] FIG. **42**B is a top-down view of the third exemplary structure of FIG. **42**A.

[0063] FIG. **43** is a vertical cross-sectional view of the third exemplary structure after formation of sacrificial contact opening pillars according to an embodiment of the present disclosure.

[0064] FIG. **44** is a vertical cross-sectional view of the third exemplary structure during formation of first stepped surfaces by repetition of an anisotropic etch process and trimming of the trimmable mask layer according to an embodiment of the present disclosure.

[0065] FIG. **45** is a vertical cross-sectional view of the third exemplary structure after formation of the first stepped surfaces according to an embodiment of the present disclosure.

[0066] FIG. **46** is a vertical cross-sectional view of the third exemplary structure after selective removal of remaining portions of the sacrificial contact opening pillars to form contact via cavities according to an embodiment of the present disclosure.

[0067] FIG. **47** is a vertical cross-sectional view of the third exemplary structure after formation of metallic nitride liners and metal fill portions according to an embodiment of the present disclosure.

[0068] FIG. **48** is a vertical cross-sectional view of the third exemplary structure after formation of metallic pillar structures on each metal fill portion employing a selective metal deposition process according to an embodiment of the present disclosure.

[0069] FIG. **49**A is a vertical cross-sectional view of the third exemplary structure after formation of a first retro-stepped dielectric material portion and an inter-tier dielectric layer, and extension of the sacrificial memory opening fill portions into the inter-tier dielectric layer according to an embodiment of the present disclosure.

[0070] FIG. **49**B is a top-down view of the third exemplary structure of FIG. **49**A.

[0071] FIG. **50**A is a vertical cross-sectional view of the third exemplary structure after formation of a second-tier alternating stack of second insulating layers and second spacer material layers, a second retro-stepped dielectric material portion, a second insulating cap layer, and drain-select-level shallow trench isolation structures according to an embodiment of the present disclosure.

[0072] FIG. **50**B is a top-down view of the third exemplary structure of FIG. **50**A.

[0073] FIG. **51**A is a vertical cross-sectional view of the third exemplary structure after formation of second-tier memory openings and support openings according to an embodiment of the present disclosure.

[0074] FIG. **51**B is another vertical cross-sectional view of the third exemplary structure of FIG. **51**A according to an embodiment of the present disclosure.

[0075] FIG. **51**C is a top-down view of the third exemplary structure of FIGS. **51**A and **51**B. Plane A-A' is the plane of the vertical cross-sectional view of FIG. **51**A, and plane B-B' is the plane of the vertical cross-sectional view of FIG. **51**B.

[0076] FIG. **52** is a vertical cross-sectional view of the third exemplary structure after formation of inter-tier memory opening by removal of the sacrificial memory opening fill portions according to an embodiment of the present disclosure.

[0077] FIG. **53**A is a vertical cross-sectional view of the third exemplary structure after formation of memory opening fill structures and support opening fill structures according to an embodiment of the present disclosure.

[0078] FIG. **53**B is another vertical cross-sectional view of the third exemplary structure of FIG. **53**A.

[0079] FIG. **53**C is a top-down view of the third exemplary structure of FIGS. **53**A and **53**B. Plane A-A' is the plane of the vertical cross-sectional view of FIG. **53**A, and plane B-B' is the plane of the vertical cross-sectional view of FIG. **53**B.

[0080] FIG. **54**A is a vertical cross-sectional view of the third exemplary structure after formation of a first contact level dielectric layer and backside trenches according to an embodiment of the present disclosure.

[0081] FIG. **54**B is a top-down view of the third exemplary structure of FIG. **54**A.

[0082] FIG. **55**A is a vertical cross-sectional view of the third exemplary structure after replacement of the sacrificial material layers with electrically conductive layers according to an embodiment of the present disclosure.

[0083] FIG. **55**B is another vertical cross-sectional view of the third exemplary structure of FIG. **55**A.

[0084] FIG. **55**C is a top-down view of the third exemplary structure of FIGS. **55**A and **55**B. Plane A-A' is the plane of the vertical cross-sectional view of FIG. **55**A, and plane B-B' is the plane of the vertical cross-sectional view of FIG. **55**B.

[0085] FIG. **56**A is a vertical cross-sectional view of the third exemplary structure after formation of a second contact level dielectric layer, through-stack insulating spacers, and through-stack contact via structures according to an embodiment of the present disclosure.

[0086] FIG. **56**B is another vertical cross-sectional view of the third exemplary structure of FIG. **56**A.

[0087] FIG. **56**C is a top-down view of the third exemplary structure of FIGS. **56**A and **56**B. Plane A-A' is the plane of the vertical cross-sectional view of FIG. **56**A, and plane B-B' is the plane of the vertical cross-sectional view of FIG. **56**B.

[0088] FIG. **57** is a vertical cross-sectional view of the third exemplary structure after formation of through-dielectric contact via structures, at least one upper interconnect level dielectric layer, and various upper interconnect level metal structures according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0089] As three-dimensional memory devices scale to smaller device dimensions, the device area for peripheral devices can take up a significant portion of the total chip area. CMOS under array architecture has been proposed to stack a three-dimensional array of memory devices over underlying peripheral devices on a substrate. However, electrical connections between the word lines and the underlying peripheral devices include a substantial number of interconnect via structures and interconnect line structures, which are typically located in a dedicated interconnect region, which decreases the overall device density.

[0090] The embodiments of the present disclosure provide contact via structures which extend through the stepped surfaces in a contact region to interconnect the underlying peripheral devices and the word lines in the stepped region. The embodiments of the present disclosure can be employed to form various semiconductor devices such as three-dimensional monolithic memory array devices comprising a plurality of NAND memory strings. The drawings are not drawn to scale. Multiple instances of an element may be duplicated where a single instance of the element is illustrated, unless absence of duplication of elements is expressly described or clearly indicated otherwise.

[0091] Ordinals such as "first," "second," and "third" are employed merely to identify similar elements, and different ordinals may be employed across the specification and the claims of the instant disclosure. As used herein, a first element located "on" a second element can be located on the exterior side of a surface of the second element or on the interior side of the second element. As used herein, a first element is located "directly on" a second element if there exist a physical contact between a surface of the first element and a surface of the second element. As used herein, an "in-process" structure or a "transient" structure refers to a structure that is subsequently modified.

[0092] As used herein, a "layer" refers to a material portion including a region having a thickness. A layer may extend over the entirety of an underlying or overlying structure, or may have an extent less than the extent of an underlying or overlying structure. Further, a layer may be a region of a homogeneous or inhomogeneous continuous structure that has a thickness less than the thickness of the continuous structure. For example, a layer may be located between any pair of horizontal planes between or at a top surface and a bottom surface of the continuous structure. A layer may extend horizontally, vertically, and/or along a tapered surface. A substrate may be a layer, may include one or more layers therein, and/or may have one or more layer thereupon, thereabove, and/or therebelow.

[0093] As used herein, a "memory level" or a "memory array level" refers to the level corresponding to a general region between a first horizontal plane (i.e., a plane parallel to the top surface of the substrate) including topmost surfaces of an array of memory elements and a second horizontal plane including bottommost surfaces of the array of memory elements. As used herein, a "through-stack" element refers to an element that vertically extends through a memory level.

[0094] As used herein, a "semiconducting material" refers to a material having electrical conductivity in the range from 1.0×10^{-6} S/cm to 1.0×10^{5} S/cm. As used herein, a "semiconductor material" refers to a material having electrical conductivity in the range from 1.0×10^{-6} S/cm to 1.0×10^{5} S/cm in the absence of electrical dopants therein, and is capable of producing a doped material having electrical conductivity in a range from 1.0 S/cm to 1.0×10^{5} S/cm upon suitable doping with an electrical dopant. As used herein, an "electrical dopant" refers to a p-type dopant that adds a hole to a valence band within a band structure, or an n-type dopant that adds an electron to a conduction band within a

band structure. As used herein, a "conductive material" refers to a material having electrical conductivity greater than 1.0×10^5 S/cm. As used herein, an "insulating material" or a "dielectric material" refers to a material having electrical conductivity less than 1.0×10^{-6} S/cm. As used herein, a "heavily doped semiconductor material" refers to a semiconductor material that is doped with electrical dopant at a sufficiently high atomic concentration to become a conductive material, i.e., to have electrical conductivity greater than 1.0×10^5 S/cm. A "doped semiconductor material" may be a heavily doped semiconductor material, or may be a semiconductor material that includes electrical dopants (i.e., p-type dopants and/or n-type dopants) at a concentration that provides electrical conductivity in the range from 1.0×10^{-6} S/cm to 1.0×10^5 S/cm. An "intrinsic semiconductor material" refers to a semiconductor material that is not doped with electrical dopants. Thus, a semiconductor material may be semiconducting or conductive, and may be an intrinsic semiconductor material or a doped semiconductor material. A doped semiconductor material can be semiconducting or conductive depending on the atomic concentration of electrical dopants therein. As used herein, a "metallic material" refers to a conductive material including at least one metallic element therein. All measurements for electrical conductivities are made at the standard condition.

[0095] A monolithic three-dimensional memory array is one in which multiple memory levels are formed above a single substrate, such as a semiconductor wafer, with no intervening substrates. The term "monolithic" means that layers of each level of the array are directly deposited on the layers of each underlying level of the array. In contrast, two dimensional arrays may be formed separately and then packaged together to form a non-monolithic memory device. For example, non-monolithic stacked memories have been constructed by forming memory levels on separate substrates and vertically stacking the memory levels, as described in U.S. Pat. No. 5,915,167 titled "Three-dimensional Structure Memory." The substrates may be thinned or removed from the memory levels before bonding, but as the memory levels are initially formed over separate substrates, such memories are not true monolithic three-dimensional memory arrays. The substrate may include integrated circuits fabricated thereon, such as driver circuits for a memory device

[0096] The various three-dimensional memory devices of the present disclosure include a monolithic three-dimensional NAND string memory device, and can be fabricated employing the various embodiments described herein. The monolithic three-dimensional NAND string is located in a monolithic, three-dimensional array of NAND strings located over the substrate. At least one memory cell in the first device level of the three-dimensional array of NAND strings is located over another memory cell in the second device level of the three-dimensional array of NAND strings.

[0097] Referring to FIG. **1**, a first exemplary structure according to an embodiment of the present disclosure is illustrated. The first exemplary structure includes a semiconductor substrate **8**, and semiconductor devices **710** formed thereupon. The semiconductor substrate **8** includes a substrate semiconductor layer **9** at least at an upper portion thereof. Shallow trench isolation structures **720** can be formed in an upper portion of the substrate semiconductor layer **9** to provide electrical isolation among the semiconductor devices. The semiconductor devices **710** can include, for example, field effect transistors including respective transistor active regions **742** (i.e., source regions and drain regions), channel regions **746** and gate structures **750**. The field effect transistors may be arranged in a CMOS configuration. Each gate structure **750** can include, for example, a gate dielectric **752**, a gate electrode **754**, a dielectric gate spacer **756** and a gate cap dielectric **758**. The semiconductor devices can include any semiconductor circuitry to support operation of a memory structure to be subsequently formed, which is typically referred to as a driver circuitry, which is also known as peripheral circuitry. As used herein, a peripheral circuitry refers to any, each, or all, of word line decoder circuitry, word line switching circuitry, bit line decoder circuitry, bit line sensing and/or switching circuitry, power supply/distribution circuitry, data buffer and/or latch, or any other semiconductor circuitry that can be implemented outside a memory array structure for a memory device. For example, the semiconductor devices can include word line switching devices for electrically biasing word lines of three-dimensional memory structures to be subsequently formed.

[0098] Dielectric material layers are formed over the semiconductor devices, which is herein referred to as lower level dielectric layers **760**. The lower level dielectric layers **760** constitute a dielectric layer stack in which each lower level dielectric layer **760** overlies or underlies other lower level dielectric layers **760**. The lower level dielectric layers **760** can include, for example, a dielectric liner **762** such as a silicon nitride liner that blocks diffusion of mobile ions and/or apply appropriate stress to underlying structures, at least one first dielectric material layer **764** that overlies the dielectric liner **762**, a silicon nitride layer (e.g., hydrogen diffusion barrier) **766** that overlies the dielectric material layer **764**, and at least one second dielectric layer **768**.

[0099] The dielectric layer stack including the lower level dielectric layers **760** functions as a matrix for lower metal interconnect structures **780** that provide electrical wiring among the various nodes of the semiconductor devices and landing pads for through-stack contact via structures to be subsequently formed. The lower metal interconnect structures **780** are embedded within the dielectric layer stack of the lower level dielectric layers **760**, and comprise a lower metal line structure located under and optionally contacting a bottom surface of the silicon nitride layer **766**.

[0100] For example, the lower metal interconnect structures **780** can be embedded within the at least one first dielectric material layer **764**. The at least one first dielectric material layer **764** may be a plurality of dielectric material layers in which various elements of the lower metal interconnect structures **780** are sequentially embedded. Each dielectric material layer among the at least one first dielectric material layer **764** may include any of doped silicate glass, undoped silicate glass, organosilicate glass, silicon nitride, silicon oxynitride, and dielectric metal oxides (such as aluminum oxide). In one embodiment, the at least one first dielectric material layer **764** can comprise, or consist essentially of, dielectric material layers having dielectric constants that do not exceed the dielectric constant of undoped silicate glass (silicon oxide) of 3.9.

[0101] The lower metal interconnect structures **780** can include various device contact via structures **782** (e.g., source and drain electrodes which contact the respective source and drain nodes of the device or gate electrode

contacts), intermediate lower metal line structures **784**, lower metal via structures **786**, and topmost lower metal line structures **788** that are configured to function as landing pads for through-stack contact via structures to be subsequently formed. In this case, the at least one first dielectric material layer **764** may be a plurality of dielectric material layers that are formed level by level while incorporating components of the lower metal interconnect structures **780** within each respective level. For example, single damascene processes may be employed to form the lower metal interconnect structures **780**, and each level of the lower metal via structures **786** may be embedded within a respective via level dielectric material layer and each level of the lower level metal line structures (**784**, **788**) may be embedded within a respective line level dielectric material layer. Alternatively, a dual damascene process may be employed to form integrated line and via structures, each of which includes a lower metal line structure and at least one lower metal via structure.

[0102] The topmost lower metal line structures **788** can be formed within a topmost dielectric material layer of the at least one first dielectric material layer **764** (which can be a plurality of dielectric material layers). Each of the lower metal interconnect structures **780** can include a metallic nitride liner **78**A and a metal fill portion **78**B. Each metallic nitride liner **78**A can include a conductive metallic nitride material such as TiN, TaN, and/or WN. Each metal fill portion **78**B can include an elemental metal (such as Cu, W, Al, Co, Ru) or an intermetallic alloy of at least two metals. Top surfaces of the topmost lower metal line structures **788** and the topmost surface of the at least one first dielectric material layer **764** may be planarized by a planarization process, such as chemical mechanical planarization. In this case, the top surfaces of the topmost lower metal line structures **788** and the topmost surface of the at least one first dielectric material layer **764** may be within a horizontal plane that is parallel to the top surface of the substrate **8**.

[0103] The silicon nitride layer **766** can be formed directly on the top surfaces of the topmost lower metal line structures **788** and the topmost surface of the at least one first dielectric material layer **764**. Alternatively, a portion of the first dielectric material layer **764** can be located on the top surfaces of the topmost lower metal line structures **788** below the silicon nitride layer **766**. In one embodiment, the silicon nitride layer **766** is a substantially stoichiometric silicon nitride layer which has a composition of Si_3N_4. A silicon nitride material formed by thermal decomposition of a silicon nitride precursor is preferred for the purpose of blocking hydrogen diffusion. In one embodiment, the silicon nitride layer **766** can be deposited by a low pressure chemical vapor deposition (LPCVD) employing dichlorosilane (SiH_2Cl_2) and ammonia (NH_3) as precursor gases. The temperature of the LPCVD process may be in a range from 750 degrees Celsius to 825 degrees Celsius, although lesser and greater deposition temperatures can also be employed. The sum of the partial pressures of dichlorosilane and ammonia may be in a range from 50 mTorr to 500 mTorr, although lesser and greater pressures can also be employed. The thickness of the silicon nitride layer **766** is selected such that the silicon nitride layer **766** functions as a sufficiently robust hydrogen diffusion barrier for subsequent thermal processes. For example, the thickness of the silicon nitride layer **766** can be in a range from 6 nm to 100 nm, although lesser and greater thicknesses may also be employed.

[0104] The at least one second dielectric material layer **768** may include a single dielectric material layer or a plurality of dielectric material layers. Each dielectric material layer among the at least one second dielectric material layer **768** may include any of doped silicate glass, undoped silicate glass, and organosilicate glass. In one embodiment, the at least one first second material layer **768** can comprise, or consist essentially of, dielectric material layers having dielectric constants that do not exceed the dielectric constant of undoped silicate glass (silicon oxide) of 3.9.

[0105] An optional layer of a metallic material and a layer of a semiconductor material can be deposited over, or within patterned recesses of, the at least one second dielectric material layer **768**, and is lithographically patterned to provide an optional planar conductive material layer **6** and a planar semiconductor material layer **10**. The optional planar conductive material layer **6**, if present, provides a high conductivity conduction path for electrical current that flows into, or out of, the planar semiconductor material layer **10**. The optional planar conductive material layer **6** includes a conductive material such as a metal or a heavily doped semiconductor material. The optional planar conductive material layer **6**, for example, may include a tungsten layer having a thickness in a range from 3 nm to 100 nm, although lesser and greater thicknesses can also be employed. A metal nitride layer (not shown) may be provided as a diffusion barrier layer on top of the planar conductive material layer **6**. Layer **6** may function as a special source line in the completed device. Alternatively, layer **6** may comprise an etch stop layer and may comprise any suitable conductive, semiconductor or insulating layer.

[0106] The planar semiconductor material layer **10** can include horizontal semiconductor channels and/or source regions for a three-dimensional array of memory devices to be subsequently formed. The optional planar conductive material layer **6** can include a metallic compound material such as a conductive metallic nitride (e.g., TiN) and/or a metal (e.g., W). The thickness of the optional planar conductive material layer **6** may be in a range from 5 nm to 100 nm, although lesser and greater thicknesses can also be employed. The planar semiconductor material layer **10** includes a polycrystalline semiconductor material such as polysilicon or a polycrystalline silicon-germanium alloy. The thickness of the planar semiconductor material layer **10** may be in a range from 30 nm to 300 nm, although lesser and greater thicknesses can also be employed.

[0107] The planar semiconductor material layer **10** includes a semiconductor material, which can include at least one elemental semiconductor material, at least one III-V compound semiconductor material, at least one II-VI compound semiconductor material, at least one organic semiconductor material, and/or other semiconductor materials known in the art. In one embodiment, the planar semiconductor material layer **10** can include a polycrystalline semiconductor material (such as polysilicon), or an amorphous semiconductor material (such as amorphous silicon) that is converted into a polycrystalline semiconductor material in a subsequent processing step (such as an anneal step). The planar semiconductor material layer **10** can be formed directly above a subset of the semiconductor devices on the semiconductor substrate **8** (e.g., silicon wafer). As used herein, a first element is located "directly above" a second element if the first element is located above a horizontal plane including a topmost surface of the second

element and an area of the first element and an area of the second element has an areal overlap in a plan view (i.e., along a vertical plane or direction perpendicular to the top surface of the substrate **9**). In one embodiment, the planar semiconductor material layer **10** or portions thereof can be doped with electrical dopants, which may be p-type dopants or n-type dopants. The conductivity type of the dopants in the planar semiconductor material layer **10** is herein referred to as a first conductivity type.

[0108] The optional planar conductive material layer **6** and the planar semiconductor material layer **10** may be patterned to provide openings in areas in which through-stack contact via structures and through-dielectric contact via structures are to be subsequently formed. In one embodiment, the openings in the optional planar conductive material layer **6** and the planar semiconductor material layer **10** can be formed within the area of a memory array region **100**, in which a three-dimensional memory array including memory stack structures is to be subsequently formed. Further, additional openings in the optional planar conductive material layer **6** and the planar semiconductor material layer **10** can be formed within the area of a word line contact region **200** in which contact via structures contacting word line electrically conductive layers are to be subsequently formed.

[0109] The region of the semiconductor devices **710** and the combination of the lower level dielectric layers **760** and the lower metal interconnect structures **780** is herein referred to an underlying peripheral device region **700**, which is located underneath a memory-level assembly to be subsequently formed and includes peripheral devices for the memory-level assembly. The lower metal interconnect structures **780** are embedded in the lower level dielectric layers **760**.

[0110] The lower metal interconnect structures **780** can be electrically shorted to active nodes (e.g., transistor active regions **742** or gate electrodes **750**) of the semiconductor devices **710** (e.g., CMOS devices), and are located at the level of the lower level dielectric layers **760**. Only a subset of the active nodes is illustrated in FIG. **1** for clarity. Through-stack contact via structures (not shown in FIG. **1**) can be subsequently formed directly on the lower metal interconnect structures **780** to provide electrical connection to memory devices to be subsequently formed. In one embodiment, the pattern of the lower metal interconnect structures **780** can be selected such that the topmost lower metal line structures **788** (which are a subset of the lower metal interconnect structures **780** located at the topmost portion of the lower metal interconnect structures **780**) can provide landing pad structures for the through-stack contact via structures to be subsequently formed.

[0111] Referring to FIG. **2**, an alternating stack of first material layers and second material layers is subsequently formed. Each first material layer can include a first material, and each second material layer can include a second material that is different from the first material. In case at least another alternating stack of material layers is subsequently formed over the alternating stack of the first material layers and the second material layers, the alternating stack is herein referred to as a first-tier alternating stack. The level of the first-tier alternating stack is herein referred to as a first-tier level, and the level of the alternating stack to be subsequently formed immediately above the first-tier level is herein referred to as a second-tier level, etc.

[0112] The first-tier alternating stack can include first insulting layers **132** as the first material layers, and first spacer material layers as the second material layers. In one embodiment, the first spacer material layers can be sacrificial material layers that are subsequently replaced with electrically conductive layers. In another embodiment, the first spacer material layers can be electrically conductive layers that are not subsequently replaced with other layers. While the present disclosure is described employing embodiments in which sacrificial material layers are replaced with electrically conductive layers, embodiments in which the spacer material layers are formed as electrically conductive layers (thereby obviating the need to perform replacement processes) are expressly contemplated herein.

[0113] In one embodiment, the first material layers and the second material layers can be first insulating layers **132** and first sacrificial material layers **142**, respectively. In one embodiment, each first insulating layer **132** can include a first insulating material, and each first sacrificial material layer **142** can include a first sacrificial material. An alternating plurality of first insulating layers **132** and first sacrificial material layers **142** is formed over the planar semiconductor material layer **10**. As used herein, a "sacrificial material" refers to a material that is removed during a subsequent processing step.

[0114] As used herein, an alternating stack of first elements and second elements refers to a structure in which instances of the first elements and instances of the second elements alternate. Each instance of the first elements that is not an end element of the alternating plurality is adjoined by two instances of the second elements on both sides, and each instance of the second elements that is not an end element of the alternating plurality is adjoined by two instances of the first elements on both ends. The first elements may have the same thickness thereamongst, or may have different thicknesses. The second elements may have the same thickness thereamongst, or may have different thicknesses. The alternating plurality of first material layers and second material layers may begin with an instance of the first material layers or with an instance of the second material layers, and may end with an instance of the first material layers or with an instance of the second material layers. In one embodiment, an instance of the first elements and an instance of the second elements may form a unit that is repeated with periodicity within the alternating plurality.

[0115] The first-tier alternating stack (**132**, **142**) can include first insulating layers **132** composed of the first material, and first sacrificial material layers **142** composed of the second material, which is different from the first material. The first material of the first insulating layers **132** can be at least one insulating material. Insulating materials that can be employed for the first insulating layers **132** include, but are not limited to silicon oxide (including doped or undoped silicate glass), silicon nitride, silicon oxynitride, organosilicate glass (OSG), spin-on dielectric materials, dielectric metal oxides that are commonly known as high dielectric constant (high-k) dielectric oxides (e.g., aluminum oxide, hafnium oxide, etc.) and silicates thereof, dielectric metal oxynitrides and silicates thereof, and organic insulating materials. In one embodiment, the first material of the first insulating layers **132** can be silicon oxide.

[0116] The second material of the first sacrificial material layers **142** is a sacrificial material that can be removed selective to the first material of the first insulating layers

132. As used herein, a removal of a first material is "selective to" a second material if the removal process removes the first material at a rate that is at least twice the rate of removal of the second material. The ratio of the rate of removal of the first material to the rate of removal of the second material is herein referred to as a "selectivity" of the removal process for the first material with respect to the second material.

[0117] The first sacrificial material layers **142** may comprise an insulating material, a semiconductor material, or a conductive material. The second material of the first sacrificial material layers **142** can be subsequently replaced with electrically conductive electrodes which can function, for example, as control gate electrodes of a vertical NAND device. In one embodiment, the first sacrificial material layers **142** can be material layers that comprise silicon nitride.

[0118] In one embodiment, the first insulating layers **132** can include silicon oxide, and sacrificial material layers can include silicon nitride sacrificial material layers. The first material of the first insulating layers **132** can be deposited, for example, by chemical vapor deposition (CVD). For example, if silicon oxide is employed for the first insulating layers **132**, tetraethylorthosilicate (TEOS) can be employed as the precursor material for the CVD process. The second material of the first sacrificial material layers **142** can be formed, for example, CVD or atomic layer deposition (ALD).

[0119] The thicknesses of the first insulating layers **132** and the first sacrificial material layers **142** can be in a range from 20 nm to 50 nm, although lesser and greater thicknesses can be employed for each first insulating layer **132** and for each first sacrificial material layer **142**. The number of repetitions of the pairs of a first insulating layer **132** and a first sacrificial material layer **142** can be in a range from 2 to 1,024, and typically from 8 to 256, although a greater number of repetitions can also be employed. In one embodiment, each first sacrificial material layer **142** in the first-tier alternating stack (**132**, **142**) can have a uniform thickness that is substantially invariant within each respective first sacrificial material layer **142**.

[0120] A first insulating cap layer **170** is subsequently formed over the stack (**132**, **142**). The first insulating cap layer **170** includes a dielectric material, which can be any dielectric material that can be employed for the first insulating layers **132**. In one embodiment, the first insulating cap layer **170** includes the same dielectric material as the first insulating layers **132**. The thickness of the insulating cap layer **170** can be in a range from 20 nm to 300 nm, although lesser and greater thicknesses can also be employed.

[0121] Referring to FIG. **3**, the first insulating cap layer **170** and the first-tier alternating stack (**132**, **142**) can be patterned to form first stepped surfaces in the word line contact region **200**. The word line contact region **200** can include a respective first stepped area in which the first stepped surfaces are formed, and a second stepped area in which additional stepped surfaces are to be subsequently formed in a second-tier structure (to be subsequently formed over a first-tier structure) and/or additional tier structures. The first stepped surfaces can be formed, for example, by forming a mask layer with an opening therein, etching a cavity within the levels of the first insulating cap layer **170**, and iteratively expanding the etched area and vertically recessing the cavity by etching each pair of a first insulating layer **132** and a first sacrificial material layer **142** located directly underneath the bottom surface of the etched cavity within the etched area. A dielectric material can be deposited to fill the first stepped cavity to form a first-tier retro-stepped dielectric material portion **165**. As used herein, a "retro-stepped" element refers to an element that has stepped surfaces and a horizontal cross-sectional area that increases monotonically as a function of a vertical distance from a top surface of a substrate on which the element is present. The first-tier alternating stack (**132**, **142**) and the first-tier retro-stepped dielectric material portion **165** collectively constitute a first-tier structure, which is an in-process structure that is subsequently modified.

[0122] Referring to FIGS. **4**A and **4**B, an inter-tier dielectric layer **180** may be optionally deposited over the first-tier structure (**132**, **142**, **165**, **170**). The inter-tier dielectric layer **180** includes a dielectric material such as silicon oxide. The thickness of the inter-tier dielectric layer **180** can be in a range from 30 nm to 300 nm, although lesser and greater thicknesses can also be employed. Locations of steps S in the first-tier alternating stack (**132**, **142**) are illustrated as dotted lines.

[0123] First-tier memory openings **149** and first-tier support openings **119** can be formed. The first-tier memory openings **149** and the first-tier support openings **119** extend through the first-tier alternating stack (**132**, **142**) at least to a top surface of the planar semiconductor material layer **10**. The first-tier memory openings **149** can be formed in the memory array region **100** at locations at which memory stack structures including vertical stacks of memory elements are to be subsequently formed. The first-tier support openings **119** can be formed in the word line contact region **200**. For example, a lithographic material stack (not shown) including at least a photoresist layer can be formed over the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**, if present), and can be lithographically patterned to form openings within the lithographic material stack. The pattern in the lithographic material stack can be transferred through the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**), and through the entirety of the first-tier alternating stack (**132**, **142**) by at least one anisotropic etch that employs the patterned lithographic material stack as an etch mask. Portions of the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**), and the first-tier alternating stack (**132**, **142**) underlying the openings in the patterned lithographic material stack are etched to form the first-tier memory openings **149** and the first-tier support openings **119**. In other words, the transfer of the pattern in the patterned lithographic material stack through the first insulating cap layer **170** and the first-tier alternating stack (**132**, **142**) forms the first-tier memory openings **149** and the first-tier support openings **119**.

[0124] In one embodiment, the chemistry of the anisotropic etch process employed to etch through the materials of the first-tier alternating stack (**132**, **142**) can alternate to optimize etching of the first and second materials in the first-tier alternating stack (**132**, **142**). The anisotropic etch can be, for example, a series of reactive ion etches or a single etch (e.g., $CF_4/O_2/Ar$ etch). The sidewalls of the first-tier memory openings **149** and the support openings **119** can be substantially vertical, or can be tapered. Subsequently, the patterned lithographic material stack can be subsequently removed, for example, by ashing.

[0125] Optionally, the portions of the first-tier memory openings **149** and the first-tier support openings **119** at the level of the inter-tier dielectric layer **180** can be laterally expanded by an isotropic etch. For example, if the inter-tier dielectric layer **180** comprises a dielectric material (such as borosilicate glass) having a greater etch rate than the first insulating layers **132** (that can include undoped silicate glass), an isotropic etch (such as a wet etch employing HF) can be employed to expand the lateral dimensions of the first-tier memory openings at the level of the inter-tier dielectric layer **180**. The portions of the first-tier memory openings **149** (and the first-tier support openings **119**) located at the level of the inter-tier dielectric layer **180** may be optionally widened to provide a larger landing pad for second-tier memory openings to be subsequently formed through a second-tier alternating stack (to be subsequently formed prior to formation of the second-tier memory openings).

[0126] Referring to FIG. **5**, sacrificial memory opening fill portions **148** can be formed in the first-tier memory openings **149**, and sacrificial support opening fill portions **118** can be formed in the first-tier support openings **119**. For example, a sacrificial fill material layer is deposited in the first-tier memory openings **149** and the first-tier support openings **119**. The sacrificial fill material layer includes a sacrificial material which can be subsequently removed selective to the materials of the first insulator layers **132** and the first sacrificial material layers **142**. In one embodiment, the sacrificial fill material layer can include germanium, a silicon-germanium alloy, carbon, borosilicate glass (which provides higher etch rate relative to undoped silicate glass), porous or non-porous organosilicate glass, organic polymer, or inorganic polymer. Optionally, a thin etch stop layer (such as a silicon oxide layer having a thickness in a range from 1 nm to 3 nm) may be employed prior to depositing the sacrificial fill material layer. If an etch stop layer is employed, semiconductor materials such as amorphous silicon may be employed as the sacrificial fill material. The sacrificial fill material layer may be formed by a non-conformal deposition or a conformal deposition method.

[0127] Portions of the deposited sacrificial material can be removed from above the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**, if present). For example, the sacrificial fill material layer can be recessed to a top surface of the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**) employing a planarization process. The planarization process can include a recess etch, chemical mechanical planarization (CMP), or a combination thereof. The top surface of the first insulating layer **170** (and optionally layer **180** if present) can be employed as an etch stop layer or a planarization stop layer. Each remaining portion of the sacrificial material in a first-tier memory opening **149** constitutes a sacrificial memory opening fill portion **148**. Each remaining portion of the sacrificial material in a first-tier support opening **119** constitutes a sacrificial support opening fill portion **118**. The top surfaces of the sacrificial memory opening fill portions **148** and the sacrificial support opening fill portions **118** can be coplanar with the top surface of the inter-tier dielectric layer **180** (or the first insulating cap layer **170** if the inter-tier dielectric layer **180** is not present). The sacrificial memory opening fill portion **148** and the sacrificial support opening fill portions **118** may, or may not, include cavities therein.

[0128] Referring to FIG. **6**, a second-tier structure can be formed over the first-tier structure (**132**, **142**, **170**, **148**, **118**). The second-tier structure can include an additional alternating stack of insulating layers and spacer material layers, which can be sacrificial material layers. For example, a second alternating stack (**232**, **242**) of material layers can be subsequently formed on the top surface of the first alternating stack (**132**, **142**). The second stack (**232**, **242**) includes an alternating plurality of third material layers and fourth material layers. Each third material layer can include a third material, and each fourth material layer can include a fourth material that is different from the third material. In one embodiment, the third material can be the same as the first material of the first insulating layer **132**, and the fourth material can be the same as the second material of the first sacrificial material layers **142**.

[0129] In one embodiment, the third material layers can be second insulating layers **232** and the fourth material layers can be second spacer material layers that provide vertical spacing between each vertically neighboring pair of the second insulating layers **232**. In one embodiment, the third material layers and the fourth material layers can be second insulating layers **232** and second sacrificial material layers **242**, respectively. The third material of the second insulating layers **232** may be at least one insulating material. The fourth material of the second sacrificial material layers **242** may be a sacrificial material that can be removed selective to the third material of the second insulating layers **232**. The second sacrificial material layers **242** may comprise an insulating material, a semiconductor material, or a conductive material. The fourth material of the second sacrificial material layers **242** can be subsequently replaced with electrically conductive electrodes which can function, for example, as control gate electrodes of a vertical NAND device.

[0130] In one embodiment, each second insulating layer **232** can include a second insulating material, and each second sacrificial material layer **242** can include a second sacrificial material. In this case, the second stack (**232**, **242**) can include an alternating plurality of second insulating layers **232** and second sacrificial material layers **242**. The third material of the second insulating layers **232** can be deposited, for example, by chemical vapor deposition (CVD). The fourth material of the second sacrificial material layers **242** can be formed, for example, CVD or atomic layer deposition (ALD).

[0131] The third material of the second insulating layers **232** can be at least one insulating material. Insulating materials that can be employed for the second insulating layers **232** can be any material that can be employed for the first insulating layers **132**. The fourth material of the second sacrificial material layers **242** is a sacrificial material that can be removed selective to the third material of the second insulating layers **232**. Sacrificial materials that can be employed for the second sacrificial material layers **242** can be any material that can be employed for the first sacrificial material layers **142**. In one embodiment, the second insulating material can be the same as the first insulating material, and the second sacrificial material can be the same as the first sacrificial material.

[0132] The thicknesses of the second insulating layers **232** and the second sacrificial material layers **242** can be in a range from 20 nm to 50 nm, although lesser and greater thicknesses can be employed for each second insulating

layer **232** and for each second sacrificial material layer **242**. The number of repetitions of the pairs of a second insulating layer **232** and a second sacrificial material layer **242** can be in a range from **2** to **1,024**, and typically from 8 to 256, although a greater number of repetitions can also be employed. In one embodiment, each second sacrificial material layer **242** in the second stack (**232**, **242**) can have a uniform thickness that is substantially invariant within each respective second sacrificial material layer **242**.

[0133] Second stepped surfaces in the second stepped area can be formed in the word line contact region **200** employing a same set of processing steps as the processing steps employed to form the first stepped surfaces in the first stepped area with suitable adjustment to the pattern of at least one masking layer. A second-tier retro-stepped dielectric material portion **265** can be formed over the second stepped surfaces in the word line contact region **200**.

[0134] A second insulating cap layer **270** can be subsequently formed over the second alternating stack (**232**, **242**). The second insulating cap layer **270** includes a dielectric material that is different from the material of the second sacrificial material layers **242**. In one embodiment, the second insulating cap layer **270** can include silicon oxide. In one embodiment, the first and second sacrificial material layers (**142**, **242**) can comprise silicon nitride.

[0135] Generally speaking, at least one alternating stack of insulating layers (**132**, **232**) and spacer material layers (such as sacrificial material layers (**142**, **242**)) can be formed over the planar semiconductor material layer **10**, and at least one retro-stepped dielectric material portion (**165**, **265**) can be formed over the staircase regions on the at least one alternating stack (**132**, **142**, **232**, **242**).

[0136] Optionally, drain-select-level shallow trench isolation structures **72** can be formed through a subset of layers in an upper portion of the second-tier alternating stack (**232**, **242**). The second sacrificial material layers **242** that are cut by the select-drain-level shallow trench isolation structures **72** correspond to the levels in which drain-select-level electrically conductive layers are subsequently formed. The drain-select-level shallow trench isolation structures **72** include a dielectric material such as silicon oxide.

[0137] Referring to FIGS. **7**A and **7**B, second-tier memory openings **249** and second-tier support openings **219** extending through the second-tier structure (**232**, **242**, **270**, **265**) are formed in areas overlying the sacrificial memory opening fill portions **148**. A photoresist layer can be applied over the second-tier structure (**232**, **242**, **270**, **265**), and can be lithographically patterned to form a same pattern as the pattern of the sacrificial memory opening fill portions **148** and the sacrificial support opening fill portions **118**, i.e., the pattern of the first-tier memory openings **149** and the first-tier support openings **119**. Thus, the lithographic mask employed to pattern the first-tier memory openings **149** and the first-tier support openings **119** can be employed to pattern the second-tier memory openings **249** and the second-tier support openings **219**. An anisotropic etch can be performed to transfer the pattern of the lithographically patterned photoresist layer through the second-tier structure (**232**, **242**, **270**, **265**). In one embodiment, the chemistry of the anisotropic etch process employed to etch through the materials of the second-tier alternating stack (**232**, **242**) can alternate to optimize etching of the alternating material layers in the second-tier alternating stack (**232**, **242**). The anisotropic etch can be, for example, a series of reactive ion etches. The patterned lithographic material stack can be removed, for example, by ashing after the anisotropic etch process.

[0138] A top surface of an underlying sacrificial memory opening fill portion **148** can be physically exposed at the bottom of each second-tier memory opening **249**. A top surface of an underlying sacrificial support opening fill portion **118** can be physically exposed at the bottom of each second-tier support opening **219**. After the top surfaces of the sacrificial memory opening fill portions **148** and the sacrificial support opening fill portions **118** are physically exposed, an etch process can be performed, which removes the sacrificial material of the sacrificial memory opening fill portions **148** and the sacrificial support opening fill portions **118** selective to the materials of the second-tier alternating stack (**232**, **242**) and the first-tier alternating stack (**132**, **142**) (e.g., $C_4F_8/O_2/Ar$ etch).

[0139] Upon removal of the sacrificial memory opening fill portions **148**, each vertically adjoining pair of a second-tier memory opening **249** and a first-tier memory opening **149** forms a continuous cavity that extends through the first-tier alternating stack (**132**, **142**) and the second-tier alternating stack (**232**, **242**). Likewise, upon removal of the sacrificial support opening fill portions **118**, each vertically adjoining pair of a second-tier support opening **219** and a first-tier support opening **119** forms a continuous cavity that extends through the first-tier alternating stack (**132**, **142**) and the second-tier alternating stack (**232**, **242**). The continuous cavities are herein referred to as memory openings (or inter-tier memory openings) and support openings (or inter-tier support openings), respectively. A top surface of the planar semiconductor material layer **10** can be physically exposed at the bottom of each memory opening and at the bottom of each support openings. Locations of steps S in the first-tier alternating stack (**132**, **142**) and the second-tier alternating stack (**232**, **242**) are illustrated as dotted lines.

[0140] Referring to FIG. **8**, memory opening fill structures **58** are formed within each memory opening, and support pillar structures **20** are formed within each support opening. The memory opening fill structures **58** and the support pillar structures **20** can include a same set of components, and can be formed simultaneously.

[0141] FIGS. **9**A-**9**H provide sequential cross-sectional views of a memory opening **49** or a support opening (**119**, **219**) during formation of a memory opening fill structure **58** or a support pillar structure **20**. While a structural change in a memory opening **49** is illustrated in FIGS. **9**A-**9**H, it is understood that the same structural change occurs in each memory openings **49** and in each of the support openings (**119**, **219**) during the same set of processing steps.

[0142] Referring to FIG. **9**A, a memory opening **49** in the exemplary device structure of FIG. **14** is illustrated. The memory opening **49** extends through the first-tier structure and the second-tier structure. Likewise, each support opening (**119**, **219**) extends through the first-tier structure and the second-tier structure.

[0143] Referring to FIG. **9**B, an optional pedestal channel portion (e.g., an epitaxial pedestal) **11** can be formed at the bottom portion of each memory opening **49** and each support openings (**119**, **219**), for example, by a selective semiconductor deposition process. In one embodiment, the pedestal channel portion **11** can be doped with electrical dopants of the same conductivity type as the planar semiconductor material layer **10**. In one embodiment, at least one

source select gate electrode can be subsequently formed by replacing each sacrificial material layer **42** located below the horizontal plane including the top surfaces of the pedestal channel portions **11** with a respective conductive material layer. A cavity **49'** is present in the unfilled portion of the memory opening **49** (or of the support opening) above the pedestal channel portion **11**. In one embodiment, the pedestal channel portion **11** can comprise single crystalline silicon. In one embodiment, the pedestal channel portion **11** can have a doping of the same as the conductivity type of the planar semiconductor material layer **10**.

[0144] Referring to FIG. **9**C, a stack of layers including a blocking dielectric layer **52**, a charge storage layer **54**, a tunneling dielectric layer **56**, and an optional first semiconductor channel layer **601** can be sequentially deposited in the memory openings **49**.

[0145] The blocking dielectric layer **52** can include a single dielectric material layer or a stack of a plurality of dielectric material layers. In one embodiment, the blocking dielectric layer can include a dielectric metal oxide layer consisting essentially of a dielectric metal oxide. As used herein, a dielectric metal oxide refers to a dielectric material that includes at least one metallic element and at least oxygen. The dielectric metal oxide may consist essentially of the at least one metallic element and oxygen, or may consist essentially of the at least one metallic element, oxygen, and at least one non-metallic element such as nitrogen. In one embodiment, the blocking dielectric layer **52** can include a dielectric metal oxide having a dielectric constant greater than 7.9, i.e., having a dielectric constant greater than the dielectric constant of silicon nitride.

[0146] Non-limiting examples of dielectric metal oxides include aluminum oxide (Al_2O_3), hafnium oxide (HfO_2), lanthanum oxide (LaO_2), yttrium oxide (Y_2O_3), tantalum oxide (Ta_2O_5), silicates thereof, nitrogen-doped compounds thereof, alloys thereof, and stacks thereof. The dielectric metal oxide layer can be deposited, for example, by chemical vapor deposition (CVD), atomic layer deposition (ALD), pulsed laser deposition (PLD), liquid source misted chemical deposition, or a combination thereof. The thickness of the dielectric metal oxide layer can be in a range from 1 nm to 20 nm, although lesser and greater thicknesses can also be employed. The dielectric metal oxide layer can subsequently function as a dielectric material portion that blocks leakage of stored electrical charges to control gate electrodes. In one embodiment, the blocking dielectric layer **52** includes aluminum oxide. In one embodiment, the blocking dielectric layer **52** can include multiple dielectric metal oxide layers having different material compositions.

[0147] Alternatively or additionally, the blocking dielectric layer **52** can include a dielectric semiconductor compound such as silicon oxide, silicon oxynitride, silicon nitride, or a combination thereof. In one embodiment, the blocking dielectric layer **52** can include silicon oxide. In this case, the dielectric semiconductor compound of the blocking dielectric layer **52** can be formed by a conformal deposition method such as low pressure chemical vapor deposition, atomic layer deposition, or a combination thereof. The thickness of the dielectric semiconductor compound can be in a range from 1 nm to 20 nm, although lesser and greater thicknesses can also be employed. Alternatively, the blocking dielectric layer **52** can be omitted, and a backside blocking dielectric layer can be formed after formation of backside recesses on surfaces of memory films to be subsequently formed.

[0148] Subsequently, the charge storage layer **54** can be formed. In one embodiment, the charge storage layer **54** can be a continuous layer or patterned discrete portions of a charge trapping material including a dielectric charge trapping material, which can be, for example, silicon nitride. Alternatively, the charge storage layer **54** can include a continuous layer or patterned discrete portions of a conductive material such as doped polysilicon or a metallic material that is patterned into multiple electrically isolated portions (e.g., floating gates), for example, by being formed within lateral recesses into sacrificial material layers (**142**, **242**). In one embodiment, the charge storage layer **54** includes a silicon nitride layer. In one embodiment, the sacrificial material layers (**142**, **242**) and the insulating layers (**132**, **232**) can have vertically coincident sidewalls, and the charge storage layer **54** can be formed as a single continuous layer.

[0149] In another embodiment, the sacrificial material layers (**142**, **242**) can be laterally recessed with respect to the sidewalls of the insulating layers (**132**, **232**), and a combination of a deposition process and an anisotropic etch process can be employed to form the charge storage layer **54** as a plurality of memory material portions that are vertically spaced apart. While the present disclosure is described employing an embodiment in which the charge storage layer **54** is a single continuous layer, embodiments are expressly contemplated herein in which the charge storage layer **54** is replaced with a plurality of memory material portions (which can be charge trapping material portions or electrically isolated conductive material portions) that are vertically spaced apart.

[0150] The charge storage layer **54** can be formed as a single charge storage layer of homogeneous composition, or can include a stack of multiple charge storage layers. The multiple charge storage layers, if employed, can comprise a plurality of spaced-apart floating gate material layers that contain conductive materials (e.g., metal such as tungsten, molybdenum, tantalum, titanium, platinum, ruthenium, and alloys thereof, or a metal silicide such as tungsten silicide, molybdenum silicide, tantalum silicide, titanium silicide, nickel silicide, cobalt silicide, or a combination thereof) and/or semiconductor materials (e.g., polycrystalline or amorphous semiconductor material including at least one elemental semiconductor element or at least one compound semiconductor material). Alternatively or additionally, the charge storage layer **54** may comprise an insulating charge trapping material, such as one or more silicon nitride segments. Alternatively, the charge storage layer **54** may comprise conductive nanoparticles such as metal nanoparticles, which can be, for example, ruthenium nanoparticles. The charge storage layer **54** can be formed, for example, by chemical vapor deposition (CVD), atomic layer deposition (ALD), physical vapor deposition (PVD), or any suitable deposition technique for storing electrical charges therein. The thickness of the charge storage layer **54** can be in a range from 2 nm to 20 nm, although lesser and greater thicknesses can also be employed.

[0151] The tunneling dielectric layer **56** includes a dielectric material through which charge tunneling can be performed under suitable electrical bias conditions. The charge tunneling may be performed through hot-carrier injection or by Fowler-Nordheim tunneling induced charge transfer

depending on the mode of operation of the monolithic three-dimensional NAND string memory device to be formed. The tunneling dielectric layer **56** can include silicon oxide, silicon nitride, silicon oxynitride, dielectric metal oxides (such as aluminum oxide and hafnium oxide), dielectric metal oxynitride, dielectric metal silicates, alloys thereof, and/or combinations thereof. In one embodiment, the tunneling dielectric layer **56** can include a stack of a first silicon oxide layer, a silicon oxynitride layer, and a second silicon oxide layer, which is commonly known as an ONO stack. In one embodiment, the tunneling dielectric layer **56** can include a silicon oxide layer that is substantially free of carbon or a silicon oxynitride layer that is substantially free of carbon. The thickness of the tunneling dielectric layer **56** can be in a range from 2 nm to 20 nm, although lesser and greater thicknesses can also be employed.

[0152] The optional first semiconductor channel layer **601** includes a semiconductor material such as at least one elemental semiconductor material, at least one III-V compound semiconductor material, at least one II-VI compound semiconductor material, at least one organic semiconductor material, or other semiconductor materials known in the art. In one embodiment, the first semiconductor channel layer **601** includes amorphous silicon or polysilicon. The first semiconductor channel layer **601** can be formed by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD). The thickness of the first semiconductor channel layer **601** can be in a range from 2 nm to 10 nm, although lesser and greater thicknesses can also be employed. A cavity **49'** is formed in the volume of each memory opening **49** that is not filled with the deposited material layers (**52**, **54**, **56**, **601**).

[0153] Referring to FIG. **9**D, the optional first semiconductor channel layer **601**, the tunneling dielectric layer **56**, the charge storage layer **54**, the blocking dielectric layer **52** are sequentially anisotropically etched employing at least one anisotropic etch process. The portions of the first semiconductor channel layer **601**, the tunneling dielectric layer **56**, the charge storage layer **54**, and the blocking dielectric layer **52** located above the top surface of the second insulating cap layer **270** can be removed by the at least one anisotropic etch process. Further, the horizontal portions of the first semiconductor channel layer **601**, the tunneling dielectric layer **56**, the charge storage layer **54**, and the blocking dielectric layer **52** at a bottom of each cavity **49'** can be removed to form openings in remaining portions thereof. Each of the first semiconductor channel layer **601**, the tunneling dielectric layer **56**, the charge storage layer **54**, and the blocking dielectric layer **52** can be etched by a respective anisotropic etch process employing a respective etch chemistry, which may, or may not, be the same for the various material layers.

[0154] Each remaining portion of the first semiconductor channel layer **601** can have a tubular configuration. The charge storage layer **54** can comprise a charge trapping material or a floating gate material. In one embodiment, each charge storage layer **54** can include a vertical stack of charge storage regions that store electrical charges upon programming. In one embodiment, the charge storage layer **54** can be a charge storage layer in which each portion adjacent to the sacrificial material layers (**142**, **242**) constitutes a charge storage region.

[0155] A surface of the pedestal channel portion **11** (or a surface of the planar semiconductor material layer **10** in case the pedestal channel portions **11** are not employed) can be physically exposed underneath the opening through the first semiconductor channel layer **601**, the tunneling dielectric layer **56**, the charge storage layer **54**, and the blocking dielectric layer **52**. Optionally, the physically exposed semiconductor surface at the bottom of each cavity **49'** can be vertically recessed so that the recessed semiconductor surface underneath the cavity **49'** is vertically offset from the topmost surface of the pedestal channel portion **11** (or of the semiconductor material layer **10** in case pedestal channel portions **11** are not employed) by a recess distance. A tunneling dielectric layer **56** is located over the charge storage layer **54**. A set of a blocking dielectric layer **52**, a charge storage layer **54**, and a tunneling dielectric layer **56** in a memory opening **49** constitutes a memory film **50**, which includes a plurality of charge storage regions (as embodied as the charge storage layer **54**) that are insulated from surrounding materials by the blocking dielectric layer **52** and the tunneling dielectric layer **56**. In one embodiment, the first semiconductor channel layer **601**, the tunneling dielectric layer **56**, the charge storage layer **54**, and the blocking dielectric layer **52** can have vertically coincident sidewalls.

[0156] Referring to FIG. **9**E, a second semiconductor channel layer **602** can be deposited directly on the semiconductor surface of the pedestal channel portion **11** or the semiconductor material layer **10** if the pedestal channel portion **11** is omitted, and directly on the first semiconductor channel layer **601**. The second semiconductor channel layer **602** includes a semiconductor material such as at least one elemental semiconductor material, at least one III-V compound semiconductor material, at least one II-VI compound semiconductor material, at least one organic semiconductor material, or other semiconductor materials known in the art. In one embodiment, the second semiconductor channel layer **602** includes amorphous silicon or polysilicon. The second semiconductor channel layer **602** can be formed by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD). The thickness of the second semiconductor channel layer **602** can be in a range from 2 nm to 10 nm, although lesser and greater thicknesses can also be employed. The second semiconductor channel layer **602** may partially fill the cavity **49'** in each memory opening, or may fully fill the cavity in each memory opening.

[0157] The materials of the first semiconductor channel layer **601** and the second semiconductor channel layer **602** are collectively referred to as a semiconductor channel material. In other words, the semiconductor channel material is a set of all semiconductor material in the first semiconductor channel layer **601** and the second semiconductor channel layer **602**.

[0158] Referring to FIG. **9**F, in case the cavity **49'** in each memory opening is not completely filled by the second semiconductor channel layer **602**, a dielectric core layer **62**L can be deposited in the cavity **49'** to fill any remaining portion of the cavity **49'** within each memory opening. The dielectric core layer **62**L includes a dielectric material such as silicon oxide or organosilicate glass. The dielectric core layer **62**L can be deposited by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD), or by a self-planarizing deposition process such as spin coating.

[0159] Referring to FIG. **9**G, the horizontal portion of the dielectric core layer **62**L can be removed, for example, by a

recess etch from above the top surface of the second insulating cap layer **270**. Each remaining portion of the dielectric core layer **62**L constitutes a dielectric core **62**. Further, the horizontal portion of the second semiconductor channel layer **602** located above the top surface of the second insulating cap layer **270** can be removed by a planarization process, which can employ a recess etch or chemical mechanical planarization (CMP). Each remaining portion of the second semiconductor channel layer **602** can be located entirety within a memory opening **49** or entirely within a support opening (**119**, **219**).

[0160] Each adjoining pair of a first semiconductor channel layer **601** and a second semiconductor channel layer **602** can collectively form a vertical semiconductor channel **60** through which electrical current can flow when a vertical NAND device including the vertical semiconductor channel **60** is turned on. A tunneling dielectric layer **56** is surrounded by a charge storage layer **54**, and laterally surrounds a portion of the vertical semiconductor channel **60**. Each adjoining set of a blocking dielectric layer **52**, a charge storage layer **54**, and a tunneling dielectric layer **56** collectively constitute a memory film **50**, which can store electrical charges with a macroscopic retention time. In some embodiments, a blocking dielectric layer **52** may not be present in the memory film **50** at this step, and a blocking dielectric layer may be subsequently formed after formation of backside recesses. As used herein, a macroscopic retention time refers to a retention time suitable for operation of a memory device as a permanent memory device such as a retention time in excess of 24 hours.

[0161] Referring to FIG. **9**H, the top surface of each dielectric core **62** can be further recessed within each memory opening, for example, by a recess etch to a depth that is located between the top surface of the second insulating cap layer **270** and the bottom surface of the second insulating cap layer **270**. Drain regions **63** can be formed by depositing a doped semiconductor material within each recessed region above the dielectric cores **62**. The drain regions **63** can have a doping of a second conductivity type that is the opposite of the first conductivity type. For example, if the first conductivity type is p-type, the second conductivity type is n-type, and vice versa. The dopant concentration in the drain regions **63** can be in a range from $5.0\times10^{19}/cm^3$ to $2.0\times10^{21}/cm^3$, although lesser and greater dopant concentrations can also be employed. The doped semiconductor material can be, for example, doped polysilicon. Excess portions of the deposited semiconductor material can be removed from above the top surface of the second insulating cap layer **270**, for example, by chemical mechanical planarization (CMP) or a recess etch to form the drain regions **63**.

[0162] Each combination of a memory film **50** and a vertical semiconductor channel **60** (which is a vertical semiconductor channel) within a memory opening **49** constitutes a memory stack structure **55**. The memory stack structure **55** is a combination of a semiconductor channel, a tunneling dielectric layer, a plurality of memory elements as embodied as portions of the charge storage layer **54**, and an optional blocking dielectric layer **52**. Each combination of a pedestal channel portion **11** (if present), a memory stack structure **55**, a dielectric core **62**, and a drain region **63** within a memory opening **49** constitutes a memory opening fill structure **58**. Each combination of a pedestal channel portion **11** (if present), a memory film **50**, a vertical semiconductor channel **60**, a dielectric core **62**, and a drain region **63** within each support opening (**119**, **219**) fills the respective support openings (**119**, **219**), and constitutes a support pillar structure **20**.

[0163] The first-tier structure (**132**, **142**, **170**, **165**), the second-tier structure (**232**, **242**, **270**, **265**), the inter-tier dielectric layer **180**, the memory opening fill structures **58**, and the support pillar structures **20** collectively constitute a memory-level assembly. The memory-level assembly is formed over the planar semiconductor material layer **10** such that the planar semiconductor material layer **10** includes horizontal semiconductor channels electrically connected to vertical semiconductor channels **60** within the memory stack structures **55**.

[0164] Referring to FIGS. **10**A and **10**B, a first contact level dielectric layer **280** can be formed over the memory-level assembly. The first contact level dielectric layer **280** is formed at a contact level through which various contact via structures are subsequently formed to the drain regions **63** and the various electrically conductive layers that replaces the sacrificial material layers (**142**, **242**) in subsequent processing steps.

[0165] Referring to FIGS. **13**A and **13**B, first through-stack via cavities **585** can be formed with the memory array region **100**, for example, by applying and patterning of a photoresist layer to form openings therein, and by anisotropically etching the portions of the first contact level dielectric layer **280**, the alternating stacks (**132**, **146**, **232**, **246**), and the at least one second dielectric material layer **768** that underlie the openings in the photoresist layer. In one embodiment, each of the first through-stack via cavities **585** can be formed within a respective three-dimensional memory array so that each first through-stack via cavities **585** is laterally surrounded by memory opening fill structures **58**. In one embodiment, one or more of the first through-stack via cavities **585** can be formed through the drain-select-level shallow trench isolation structures **72**, as shown in FIG. **10**B. However, other locations may also be selected. In one embodiment, the first-through-stack via cavities **585** can be formed within areas of openings in the planar semiconductor material layer **10** and the optional planar conductive material layer **6**. The bottom surface of each first through-stack via cavity **585** can be formed at, or above, the silicon nitride layer **766**. In one embodiment, the silicon nitride layer **766** can be employed as an etch stop layer during the anisotropic etch process that forms the first through-stack via cavities. In this case, the bottom surface of each first through-stack via cavity **585** can be formed at the silicon nitride layer **766**, and the silicon nitride layer **766** can be physically exposed at the bottom of each first through-stack via cavity **585**. In an alternative embodiment described below with respect to FIG. **21**, the bottom surface of each first through-stack via cavity **585** can be located above the silicon nitride layer **766** and the silicon nitride layer **766** is not exposed in the cavity **585**. Sidewalls of all layers within the alternating stacks (**132**, **146**, **232**, **246**) can be physically exposed inside each first through-stack via cavity **585**. The photoresist layer can be subsequently removed, for example, by ashing.

[0166] Referring to FIG. **11**, a dielectric material is deposited in the first through-stack via cavities **585**. The dielectric material can include a silicon-oxide based material such as undoped silicate glass, doped silicate glass, or a flowable oxide material. The dielectric material can be deposited by

a conformal deposition method such as chemical vapor deposition or spin coating. A void may be formed within an unfilled portion of each first through-stack via cavity **585**. Excess portion of the deposited dielectric material may be removed from above a horizontal plane including the top surface of the first contact level dielectric layer **280**, for example, by chemical mechanical planarization or a recess etch. Each remaining dielectric material portion filling a respective one of the first through-stack via cavity **585** constitutes a through-stack insulating material portion **584**. The through-stack insulating material portions **584** contact sidewalls of the alternating stacks (**132**, **146**, **232**, **246**), and may contact the silicon nitride layer **766**.

[0167] Referring to FIGS. **12**A and **12**B, backside contact trenches **79** are subsequently formed through the first contact level dielectric layer **280** and the memory-level assembly. For example, a photoresist layer can be applied and lithographically patterned over the first contact level dielectric layer **280** to form elongated openings that extend along a first horizontal direction hd**1**. An anisotropic etch is performed to transfer the pattern in the patterned photoresist layer through the first contact level dielectric layer **280** and the memory-level assembly to a top surface of the planar semiconductor material layer **10**. The photoresist layer can be subsequently removed, for example, by ashing.

[0168] The backside contact trenches **79** extend along the first horizontal direction hd**1**, and thus, are elongated along the first horizontal direction hd**1**. The backside contact trenches **79** can be laterally spaced among one another along a second horizontal direction hd**2**, which can be perpendicular to the first horizontal direction hd**1**. The backside contact trenches **79** can extend through the memory array region (e.g., a memory plane) **100** and the word line contact region **200**. The fist subset of the backside contact trenches **79** laterally divides the memory-level assembly (e.g., into memory blocks).

[0169] Referring to FIGS. **13**A and **13**B, an etchant that selectively etches the materials of the first and second sacrificial material layers (**142**, **242**) with respect to the materials of the first and second insulating layers (**132**, **232**), the first and second insulating cap layers (**170**, **270**), and the material of the outermost layer of the memory films **50** can be introduced into the backside contact trenches **79**, for example, employing an isotropic etch process. First backside recesses are formed in volumes from which the first sacrificial material layers **142** are removed. Second backside recesses are formed in volumes from which the second sacrificial material layers **242** are removed. In one embodiment, the first and second sacrificial material layers (**142**, **242**) can include silicon nitride, and the materials of the first and second insulating layers (**132**, **232**), can be silicon oxide. In another embodiment, the first and second sacrificial material layers (**142**, **242**) can include a semiconductor material such as germanium or a silicon-germanium alloy, and the materials of the first and second insulating layers (**132**, **232**) can be selected from silicon oxide and silicon nitride.

[0170] The isotropic etch process can be a wet etch process employing a wet etch solution, or can be a gas phase (dry) etch process in which the etchant is introduced in a vapor phase into the backside contact trench **79**. For example, if the first and second sacrificial material layers (**142**, **242**) include silicon nitride, the etch process can be a wet etch process in which the first exemplary structure is immersed within a wet etch tank including phosphoric acid, which etches silicon nitride selective to silicon oxide, silicon, and various other materials employed in the art. In case the sacrificial material layers (**142**, **242**) comprise a semiconductor material, a wet etch process (which may employ a wet etchant such as a KOH solution) or a dry etch process (which may include gas phase HC**1**) may be employed.

[0171] Each of the first and second backside recesses can be a laterally extending cavity having a lateral dimension that is greater than the vertical extent of the cavity. In other words, the lateral dimension of each of the first and second backside recesses can be greater than the height of the respective backside recess. A plurality of first backside recesses can be formed in the volumes from which the material of the first sacrificial material layers **142** is removed. A plurality of second backside recesses can be formed in the volumes from which the material of the second sacrificial material layers **242** is removed. Each of the first and second backside recesses can extend substantially parallel to the top surface of the substrate **9**. A backside recess can be vertically bounded by a top surface of an underlying insulating layer (**132** or **232**) and a bottom surface of an overlying insulating layer (**132** or **232**). In one embodiment, each of the first and second backside recesses can have a uniform height throughout.

[0172] In one embodiment, a sidewall surface of each pedestal channel portion **11** can be physically exposed at each bottommost first backside recess after removal of the first and second sacrificial material layers (**142**, **242**). Further, a top surface of the planar semiconductor material layer **10** can be physically exposed at the bottom of each backside contact trench **79**. An annular dielectric spacer (not shown) can be formed around each pedestal channel portion **11** by oxidation of a physically exposed peripheral portion of the pedestal channel portions **11**. Further, a semiconductor oxide potion (not shown) can be formed from each physically exposed surface portion of the planar semiconductor material layer **10** concurrently with formation of the annular dielectric spacers.

[0173] A backside blocking dielectric layer (not shown) can be optionally deposited in the backside recesses and the backside contact trenches **79** and over the first contact level dielectric layer **280**. The backside blocking dielectric layer can be deposited on the physically exposed portions of the outer surfaces of the memory stack structures **55**. The backside blocking dielectric layer includes a dielectric material such as a dielectric metal oxide, silicon oxide, or a combination thereof. If employed, the backside blocking dielectric layer can be formed by a conformal deposition process such as atomic layer deposition or chemical vapor deposition. The thickness of the backside blocking dielectric layer can be in a range from 1 nm to 60 nm, although lesser and greater thicknesses can also be employed.

[0174] At least one conductive material can be deposited in the plurality of backside recesses, on the sidewalls of the backside contact trench **79**, and over the first contact level dielectric layer **280**. The at least one conductive material can include at least one metallic material, i.e., an electrically conductive material that includes at least one metallic element.

[0175] A plurality of first electrically conductive layers **146** can be formed in the plurality of first backside recesses, a plurality of second electrically conductive layers **246** can be formed in the plurality of second backside recesses, and

a continuous metallic material layer (not shown) can be formed on the sidewalls of each backside contact trench **79** and over the first contact level dielectric layer **280**. Thus, the first and second sacrificial material layers (**142**, **242**) can be replaced with the first and second conductive material layers (**146**, **246**), respectively.

[0176] Specifically, each first sacrificial material layer **142** can be replaced with an optional portion of the backside blocking dielectric layer and a first electrically conductive layer **146**, and each second sacrificial material layer **242** can be replaced with an optional portion of the backside blocking dielectric layer and a second electrically conductive layer **246**. A backside cavity is present in the portion of each backside contact trench **79** that is not filled with the continuous metallic material layer.

[0177] The metallic material can be deposited by a conformal deposition method, which can be, for example, chemical vapor deposition (CVD), atomic layer deposition (ALD), electroless plating, electroplating, or a combination thereof. The metallic material can be an elemental metal, an intermetallic alloy of at least two elemental metals, a conductive nitride of at least one elemental metal, a conductive metal oxide, a conductive doped semiconductor material, a conductive metal-semiconductor alloy such as a metal silicide, alloys thereof, and combinations or stacks thereof. Non-limiting exemplary metallic materials that can be deposited in the backside recesses include tungsten, tungsten nitride, titanium, titanium nitride, tantalum, tantalum nitride, cobalt, and ruthenium. In one embodiment, the metallic material can comprise a metal such as tungsten and/or metal nitride. In one embodiment, the metallic material for filling the backside recesses can be a combination of titanium nitride layer and a tungsten fill material. In one embodiment, the metallic material can be deposited by chemical vapor deposition or atomic layer deposition.

[0178] Residual conductive material can be removed from inside the backside contact trenches **79**. Specifically, the deposited metallic material of the continuous metallic material layer can be etched back from the sidewalls of each backside contact trench **79** and from above the first contact level dielectric layer **280**, for example, by an anisotropic or isotropic etch. Each remaining portion of the deposited metallic material in the first backside recesses constitutes a first electrically conductive layer **146**. Each remaining portion of the deposited metallic material in the second backside recesses constitutes a second electrically conductive layer **246**. Each electrically conductive layer (**146**, **246**) can be a conductive line structure.

[0179] A subset of the second electrically conductive layers **246** located at the levels of the drain-select-level shallow trench isolation structures **72** constitutes drain select gate electrodes. A subset of the first electrically conductive layers **146** located at each level of the annular dielectric spacers (not shown) constitutes source select gate electrodes. A subset of the electrically conductive layer (**146**, **246**) located between the drain select gate electrodes and the source select gate electrodes can function as combinations of a control gate and a word line located at the same level. The control gate electrodes within each electrically conductive layer (**146**, **246**) are the control gate electrodes for a vertical memory device including the memory stack structure **55**.

[0180] Each of the memory stack structures **55** comprises a vertical stack of memory elements located at each level of the electrically conductive layers (**146**, **246**). A subset of the electrically conductive layers (**146**, **246**) can comprise word lines for the memory elements. The semiconductor devices in the underlying peripheral device region **700** can comprise word line switch devices configured to control a bias voltage to respective word lines. The memory-level assembly is located over the substrate semiconductor layer **9**. The memory-level assembly includes at least one alternating stack (**132**, **146**, **232**, **246**) and memory stack structures **55** vertically extending through the at least one alternating stack (**132**, **146**, **232**, **246**). Each of the at least one an alternating stack (**132**, **146**, **232**, **246**) includes alternating layers of respective insulating layers (**132** or **232**) and respective electrically conductive layers (**146** or **246**). The at least one alternating stack (**132**, **146**, **232**, **246**) comprises staircase regions that include terraces in which each underlying electrically conductive layer (**146**, **246**) extends farther along the first horizontal direction hd**1** than any overlying electrically conductive layer (**146**, **246**) in the memory-level assembly.

[0181] Dopants of a second conductivity type, which is the opposite of the first conductivity type of the planar semiconductor material layer **10**, can be implanted into a surface portion of the planar semiconductor material layer **10** to form a source region **61** underneath the bottom surface of each backside contact trench **79**. An insulating spacer **74** including a dielectric material can be formed at the periphery of each backside contact trench **79**, for example, by deposition of a conformal insulating material (such as silicon oxide) and a subsequent anisotropic etch. The first contact level dielectric layer **280** may be thinned due to a collateral etch during the anisotropic etch that removes the vertical portions of horizontal portions of the deposited conformal insulating material.

[0182] A conformal insulating material layer can be deposited in the backside contact trenches **79**, and can be anisotropically etched to form insulating spacers **74**. The insulating spacers **74** include an insulating material such as silicon oxide, silicon nitride, and/or a dielectric metal oxide. A cavity laterally extending along the first horizontal direction hd**1** is present within each insulating spacer **74**.

[0183] A backside contact via structure can be formed in the remaining volume of each backside contact trench **79**, for example, by deposition of at least one conductive material and removal of excess portions of the deposited at least one conductive material from above a horizontal plane including the top surface of the first contact level dielectric layer **280** by a planarization process such as chemical mechanical planarization or a recess etch. The backside contact via structures are electrically insulated in all lateral directions, and is laterally elongated along the first horizontal direction hd**1**. As such, the backside contact via structures are herein referred to as laterally-elongated contact via structures **76**. As used herein, a structure is "laterally elongated" if the maximum lateral dimension of the structure along a first horizontal direction is greater than the maximum lateral dimension of the structure along a second horizontal direction that is perpendicular to the first horizontal direction at least by a factor of 5.

[0184] Optionally, each laterally-elongated contact via structure **76** may include multiple backside contact via portions such as a lower backside contact via portion and an upper backside contact via portion. In an illustrative example, the lower backside contact via portion can include a doped semiconductor material (such as doped polysilicon),

and can be formed by depositing the doped semiconductor material layer to fill the backside contact trenches **79** and removing the deposited doped semiconductor material from upper portions of the backside contact trenches **79**. The upper backside contact via portion can include at least one metallic material (such as a combination of a TiN liner and a W fill material), and can be formed by depositing the at least one metallic material above the lower backside contact via portions, and removing an excess portion of the at least one metallic material from above the horizontal plane including the top surface of the first contact level dielectric layer **280**. The first contact level dielectric layer **280** can be thinned and removed during a latter part of the planarization process, which may employ chemical mechanical planarization (CMP), a recess etch, or a combination thereof. Each laterally-elongated contact via structure **76** can be formed through the memory-level assembly and on a respective source region **61**. The top surface of each laterally-elongated contact via structure **76** can located above a horizontal plane including the top surfaces of the memory stack structures **55**.

[0185] Referring to FIGS. **14**A and **14**B, a second contact level dielectric layer **282** can be optionally formed over the first contact level dielectric layer **280**. The second contact level dielectric layer **282** includes a dielectric material such as silicon oxide or silicon nitride. The thickness of the second contact level dielectric layer **282** can be in a range from 30 nm to 300 nm, although lesser and greater thicknesses can also be employed.

[0186] Drain contact via structures **88** contacting the drain regions **63** can extend through the contact level dielectric layers (**280**, **282**) and the second insulating cap layer **270** in the memory array region **100**. A source connection via structure **91** can extend through the contact level dielectric layers (**280**, **282**) to provide electrical connection to the laterally-elongated contact via structures **76**.

[0187] Various contact via structures can be formed through the contact level dielectric layers (**280**, **282**) and the retro-stepped dielectric material portions (**165**, **265**). For example, word line contact via structures **86** can be formed in the word line contact region **200**. A subset of the word line contact via structures **86** contacting the second electrically conductive layers **246** extends through the second-tier retro-stepped dielectric material portion **265** in the word line contact region **200**, and does not extend through the first-tier retro-stepped dielectric material portion **165**. Another subset of the word line contact via structures **86** contacting the first electrically conductive layers **146** extends through the second-tier retro-stepped dielectric material portion **265** and through the first-tier retro-stepped dielectric material portion **165** in the word line contact region **200**.

[0188] Referring to FIG. **15**, a photoresist layer is applied over the second contact level dielectric layer **282**, and is lithographically patterned to form openings that overlie the through-stack insulating material portions **584** in the memory array region **100**, and additional memory openings in which layers of the alternating stacks (**132**, **146**, **232**, **246**) are absent, i.e., in a peripheral region **400** located outside the memory array region **100** and the word line contact region **200**. For example, the peripheral region may surround memory array region **100** and/or the word line contact region **200** and/or may be located on one or more sides of the memory array region **100** and/or the word line contact region **200**. In one embodiment, the areas of the openings in the memory array region **100** may be entirely within the areas of the through-stack insulating material portions **584**. In one embodiment, the areas of the openings outside the areas of the memory array region **100** and the word line contact region **200** (e.g., the areas of the openings in the peripheral region **400**) may be within areas of openings in the planar semiconductor material layer **10** and the optional planar conductive material layer **6**.

[0189] Via cavities (**487**, **587**) are formed by an anisotropic etch process that transfers the pattern of the openings in the photoresist layer to the top surfaces of the topmost lower metal line structures **788**. Specifically, second through-stack via cavities **587** are formed through the through-stack insulating material portions **584** such that a remaining portion of each through-stack insulating material portion **584** after formation of the second through-stack via cavities **587** constitutes a through-stack insulating spacer **586**. In one embodiment, the second through-stack via cavities **587** can be formed employing an anisotropic etch process that includes a first etch step that etches the dielectric material of the through-stack insulating material portions **584** selective to silicon nitride, and a second etch step that etches a physically exposed portion of the silicon nitride layer **766**. The first etch step employs the silicon nitride layer **766** as an etch stop layer. Thus, the via cavities **587** are etched through the insulating material (e.g., silicon oxide) of the through-stack insulating material portions **584**, rather than through the electrically conductive layers (e.g., tungsten and/or titanium nitride layers) (**146**, **246**). Etching silicon oxide of portions **584** is easier than etching refractory metal and/or refractory metal nitride layers (**146**, **246**). Furthermore, etching the opening **585** through the alternating stack of insulating layers (**132**, **232**) such as silicon oxide, and sacrificial material layers (**142**, **242**) such as silicon nitride before forming the electrically conductive layers (**146**, **246**) easier than etching the opening through the electrically conductive layers (**146**, **246**). Thus, by forming and filling the openings **585** with an insulating material (e.g., with portions **584**) before replacing the sacrificial material layers with the electrically conductive layers makes it easier to subsequently form the second through-stack via cavities **587** through the insulating material after replacing the sacrificial material layers with the electrically conductive layers, instead of etching the cavities **587** through the electrically conductive layers.

[0190] Each through-stack insulating spacer **586** can have a substantially cylindrical shape. Depending on the lithographic alignment of the pattern of the openings in the photoresist layer and the through-stack insulating material portions **584**, the second through-stack via cavities **587** may, or may not, have a lateral offset from the geometrical center of a respective one of the through-stack insulating material portion **584**. Thus, the through-stack insulating spacers **586** may, or may not, have a uniform thickness around the vertical axis passing through the geometrical center thereof as a function of an azimuthal angle. In other words, the through-stack insulating spacers **586** may have the same thickness irrespective of the azimuthal angle in the case of perfect lithographic alignment, or may have an azimuthally-varying thickness that is measured between the inner sidewall and the outer sidewall of a respective through-stack insulating spacer **586**. The second through-stack via cavities **587** are formed through the silicon nitride layer **766**. A top surface of a lower metal line structure (such as a topmost

lower metal liner structure **788**) can be physically exposed at the bottom of each second through-stack via cavity **587**.

[0191] Further, through-dielectric via cavities **487** can be formed in the peripheral region through the contact level dielectric layers (**280**, **282**), the retro-stepped dielectric material portions (**165**, **265**), the at least one second dielectric material layer **768**, and the silicon nitride layer **766** to a top surface of a respective one of the topmost lower metal liner structures **788**. The through-dielectric via cavities **487** can be formed concurrently with formation of the second through-stack via cavities **587** employing a same photolithography and anisotropic etch processes. In one embodiment, the through-dielectric via cavities **487** can pass through openings in the planar semiconductor material layer **10** and the optional planar conductive material layer **6**. The photoresist layer can be removed, for example, by ashing.

[0192] Referring to FIGS. **16**A and **16**B, at least one conductive material can be simultaneously deposited in the second through-stack via cavities **587** and the through-dielectric via cavities **487**. The at least one conductive material can include, for example, a metallic nitride liner (such as a TiN liner) and a metal fill material (such as W, Cu, Al, Ru, or Co). Excess portions of the at least one conductive material can be removed from outside the second through-stack via cavities **587** and the through-dielectric via cavities **487**. For example, excess portions of the at least one conductive material can be removed from above the top surface of the second contact level dielectric layer **282** by a planarization process such as chemical mechanical planarization and/or a recess etch. Each remaining portion of the at least one conductive material in the second through-stack via cavities **587** constitutes a through-stack contact via structure **588** that contacts a top surface of a respective one of the topmost lower metal line structure **788**. Each remaining portion of the at least one conductive material in the through-dielectric via cavities **487** that contacts a top surface of a respective one of the topmost lower metal line structure **788** constitutes a through-dielectric contact via structure **488**. Each through-stack contact via structure **588** can be formed within a respective second through-stack via cavity **587** and inside a respective through-stack insulating spacer **586**. Thus, through-stack contact via structures **588** are formed through the alternating stacks (**132**, **146**, **232**, **246**), the at least one second dielectric material layer **768**, and the silicon nitride layer **766**, and directly on a top surface of a lower metal line structure (such as a topmost lower metal line structure **788**). In this embodiment, each through-stack contact via structure **588** extends through the second contact level dielectric layer **282** and the silicon nitride layer (i.e., the hydrogen barrier layer) **766**, while the respective through-stack insulating spacer **586** does not extend through the second contact level dielectric layer **282** and the silicon nitride layer (i.e., the hydrogen barrier layer) **766**.

[0193] Referring to FIG. **17**, at least one upper interconnect level dielectric layer **284** can be formed over the contact level dielectric layers (**280**, **282**). Various upper interconnect level metal structures can be formed in the at least one upper interconnect level dielectric layer **284**. For example, the various upper interconnect level metal structures can include line level metal interconnect structures (**96**, **98**, **99**). The line level metal interconnect structures (**96**, **98**, **99**) can include first upper metal line structures **99** that contact a top surfaces of a respective one of the through-stack contact via structures **588**, second upper metal line structures **96** that contact a top surface of a respective one of the through-dielectric contact via structures **488**, and bit lines **98** that contact a respective one of the drain contact via structures **88** and extend along the second horizontal direction (e.g., bit line direction) hd**2** and perpendicular to the first horizontal direction (e.g., word line direction) hd**1**. In one embodiment, a subset of the first upper metal line structures **99** may be employed to provide electrical connections through the source connection via structures **91** described above to the laterally-elongated contact via structures **76** and to the source regions **61**. In one embodiment, a subset of the second upper metal line structures **96** may contact, or are electrically coupled to, a respective pair of a word line contact via structure **86** and a through-dielectric contact via structure **488**.

[0194] At least a subset of the upper metal interconnect structures (which include the line level metal interconnect structures (**96**, **98**, **99**)) is formed over the three-dimensional memory array. The upper metal interconnect structures comprise an upper metal line structure (such as a first upper metal line structure **99**) that is formed directly on a through-stack contact via structure **588**. A set of conductive structures including the through-stack contact via structure **588** and a lower metal line structure (such as a topmost lower metal line structure **788**) provides an electrically conductive path between the at least one semiconductor device **710** on the substrate semiconductor layer and the upper metal line structure. A through-dielectric contact via structure **488** can be provided through the retro-stepped dielectric material portions (**165**, **265**), the at least one second dielectric material layer **768**, and the silicon nitride layer **766** and directly on a top surface of another lower metal line structure (e.g., another topmost lower metal line structure **788**) of the lower metal interconnect structures **780**.

[0195] Referring to FIGS. **18**A and **18**B, a first alternative configuration of the first exemplary structure can be derived from the first exemplary structure of FIGS. **14**A and **14**B by forming first through-dielectric via cavities **485** concurrently with formation of the first through-stack via cavities **585**. In this embodiment, the first through-stack via cavities **585** are formed through the electrically conductive layers (**146**, **246**) in the alternating stack (**132**, **232**, **146**, **246**) after the sacrificial material layers are replaced with the electrically conductive layers.

[0196] The first through-dielectric via cavities **485** and the first through-stack via cavities **585** can be concurrently formed by a same anisotropic etch process, similar to the step shown in FIG. **15**. Optionally, the silicon nitride layer **766** may be employed as an etch stop layer for the anisotropic etch process.

[0197] Referring to FIGS. **19**A and **19**B, the processing steps of FIG. **11** can be performed to fill each of the first through-stack via cavities **585** and the first through-dielectric via cavities **485** with insulating material. Through-stack insulating material portions **584** are formed in the first through-stack via cavities **585**, and through-dielectric insulating material portions are formed in the first through-dielectric via cavities **485**.

[0198] The processing steps of FIG. **15** can be performed to form second through-stack via cavities **587** through the through-stack insulating material portions **584**, and to form second through-dielectric via cavities **487**. A through-stack insulating spacer **586** is formed around each second through-

stack via cavity **587**, and a through-dielectric insulating spacer **486** is formed around each second through-dielectric via cavity.

[0199] The processing steps of FIGS. **16**A and **16**B can be performed to form a through-stack contact via structure **588** within each second through-stack via cavity **587**, and to form a through-dielectric contact via structure **488** within each second through-dielectric via cavity.

[0200] Referring to FIG. **20**, the processing steps of FIG. **17** can be performed to form at least one upper interconnect level dielectric layer **284** and various upper interconnect level metal structures.

[0201] FIG. **21** illustrates a second alternative configuration of the first exemplary structure in which the anisotropic etch process that forms the first through-stack via cavities do not employ the silicon nitride layer **766** as an etch stop layer. In this case, the through-stack insulating spacers **586** may not physically contact the silicon nitride layer **766**.

[0202] The first exemplary structures and alternative embodiments of the present disclosure include a semiconductor structure. The semiconductor structure includes a semiconductor device **710**, a hydrogen diffusion barrier layer **766**, a lower metal line structure **788** located below the hydrogen diffusion barrier layer **766**, an alternating stack of insulating layers (**132**, **232**) and electrically conductive layers (**146**, **246**), memory stack structures **55** vertically extending through the alternating stack in a memory array region **100**, a through-stack contact via structure **588** extending through the alternating stack and through the hydrogen diffusion barrier layer **766** in the memory array region **100** and contacting the lower metal line structure **788**, and a through-stack insulating spacer laterally **586** surrounding the through-stack contact via structure **588** and extending through the alternating stack but not extending through the hydrogen diffusion barrier layer **766**. In one embodiment, the hydrogen diffusion barrier layer **766** can be a silicon nitride layer.

[0203] In another embodiment, the semiconductor structure can include: at least one semiconductor device **710**; a dielectric layer stack **760** of at least one first dielectric material layer **764**, a silicon nitride layer comprising a hydrogen diffusion barrier **766**, and at least one second dielectric material layer **768** overlying the at least one semiconductor device **710**; lower metal interconnect structures **780** embedded within the dielectric layer stack **760**, the lower metal interconnect structures **780** comprising a lower metal line structure **788** located below a bottom surface of the silicon nitride layer **766**; a three-dimensional memory array overlying the dielectric layer stack **760** and including an alternating stack of insulating layers (**132**, **232**) and electrically conductive layers (**146**, **246**); and memory stack structures **55** vertically extending through the alternating stack (**132**, **232**, **146**, **246**) in a memory array region. A through-stack contact via structure **588** extends through the alternating stack (**132**, **232**, **146**, **246**) in the memory array region, through the at least one second dielectric material layer **768**, and through the silicon nitride layer **766**, and contacting the lower metal line structure **788**. A through-stack insulating spacer **586** laterally surrounds the through-stack contact via structure **588** and extends through the alternating stack (**132**, **232**, **146**, **246**) and through the at least one second dielectric material layer **768**, but not extending through the silicon nitride layer **566**.

[0204] Upper metal interconnect structures including an upper metal line structure (**96**, **98**, **99**) are located over the three-dimensional memory array. The through-stack contact via structure **588** contacts a top surface of the lower metal line structure **788** and a bottom surface of the upper metal line structure **99**. A set of conductive structures (**782**, **784**, **786**, **788**, **588**) including the through-stack contact via structure **588** and the lower metal line structure **788** provides an electrically conductive path between the at least one semiconductor device **710** and the upper metal line structure **99**.

[0205] In one embodiment, the at least one semiconductor device **710** comprises a CMOS driver circuit device located on a top surface of a substrate semiconductor layer **9** of a substrate **8**, or on a top surface of the substrate **8** if layer **9** is omitted; In one embodiment, an inner sidewall of the through-stack insulating spacer **586** contacts a sidewall of the through-stack contact via structure **588**, and an outer sidewall of the through-stack insulating spacer **586** contacts sidewalls of each layer within the alternating stack (**132**, **232**, **146**, **246**).

[0206] In one embodiment, the semiconductor structure further comprises a planar semiconductor material layer **10** located between the at least one second dielectric material layer **768** and the alternating stack (**132**, **232**, **146**, **246**), wherein the through-stack insulating spacer **586** vertically extends through an opening in the planar semiconductor material layer **10** and through at least an upper portion of the at least one second dielectric material layer **768**. In one embodiment, each of the memory stack structures **55** includes a memory film **50** and a vertical semiconductor channel **60** that extend through the alternating stack (**132**, **232**, **146**, **246**), and the planar semiconductor material layer **10** includes a horizontal semiconductor channel **59** that is electrically connected to the vertical semiconductor channels **60** of the memory stack structures **55**. In one embodiment, the through-stack insulating spacer **586** is laterally spaced from a sidewall of the opening of the planar semiconductor material layer **10** by a portion of the at least one second dielectric material layer **768**.

[0207] In one embodiment, the through-stack insulating spacer **586** directly contacts the silicon nitride layer **766**, and the through-stack contact via structure **588** is laterally spaced from the at least one second dielectric material layer **768** by the through-stack insulating spacer **586**. In one embodiment, the through-stack insulating spacer **586** does not directly contact the silicon nitride layer **766**, and the through-stack contact via structure **588** directly contacts the at least one second dielectric material layer **768** as illustrated in FIG. **21**.

[0208] In one embodiment, the semiconductor structure further comprises: a terrace region including stepped surfaces of layers of the alternating stack (**132**, **232**, **146**, **246**); a retro-stepped dielectric material portion (**165** or **265**) overlying the stepped surfaces and located at levels of the alternating stack (**132**, **232**, **146**, **246**) and above the at least one second dielectric material layer **768**; and a through-dielectric contact via structure **488** vertically extending through the retro-stepped dielectric material portion (**165** or **265**), the at least one second dielectric material layer **768**, and the silicon nitride layer **766** and contacting a top surface of another lower metal line structure **788** of the lower metal interconnect structures **780**. In one embodiment, the through-stack contact via structure **488** is laterally spaced

from each layer within the alternating stack (**132**, **232**, **146**, **246**) by a through-stack insulating spacer **486** (as illustrated in FIG. **20**). Alternatively, the through-dielectric contact via structure **488** directly contacts the retro-stepped dielectric material portion (**165** or **265**) and the at least one second dielectric material layer **768** (as illustrated in FIGS. **17** and **21**).

[0209] In one embodiment, the memory stack structures **55** can comprise memory elements of a vertical NAND device. The electrically conductive layers (**146**, **246**) can comprise, or can be electrically connected to, a respective word line of the vertical NAND device. The substrate **8** can comprises a silicon substrate. The vertical NAND device can comprise an array of monolithic three-dimensional NAND strings over the silicon substrate. At least one memory cell in a first device level of the array of monolithic three-dimensional NAND strings is located over another memory cell in a second device level of the array of monolithic three-dimensional NAND strings. The silicon substrate can contain an integrated circuit comprising the word line driver circuit and a bit line driver circuit for monolithic three-dimensional NAND memory device. The array of monolithic three-dimensional NAND strings can comprise a plurality of semiconductor channels, wherein at least one end portion (such as a vertical semiconductor channel **60**) of each of the plurality of semiconductor channels (**59**, **11**, **60**) extends substantially perpendicular to a top surface of the semiconductor substrate **8**, a plurality of charge storage elements (as embodied as portions of the memory material layer **54** located at each word line level), each charge storage element located adjacent to a respective one of the plurality of semiconductor channels (**59**, **11**, **60**), and a plurality of control gate electrodes (as embodied as a subset of the electrically conductive layers (**146**, **246**) having a strip shape extending substantially parallel to the top surface of the substrate **8** (e.g., along the first horizontal direction hd**1**), the plurality of control gate electrodes comprise at least a first control gate electrode located in the first device level and a second control gate electrode located in the second device level.

[0210] Various electrical dopants in the source region **61** and the drain regions **63** are activated by an activation anneal, which is typically conducted at a temperature greater than 950 degrees Celsius. Hydrogen diffusion from the various materials at the level of the three-dimensional memory device (such as from the alternating stack (**132**, **142**) and/or from a TEOS oxide in the retro-stepped dielectric material portions (**165**, **265**)) to the semiconductor devices **710** may adversely impact the performance of the semiconductor devices. The silicon nitride layer **766** blocks diffusion of hydrogen to reduce or prevent degradation of performance of the various semiconductor devices **710** on the substrate **8** during high temperature anneal processes, thereby providing superior performance for the three-dimensional memory device. In one embodiment, the silicon nitride layer **766** is continuous and not etched until after the source and drain regions are annealed and the sacrificial material layers are replaced with electrically conductive layers. This continuity improves its hydrogen blocking properties during the high temperature annealing and replacement steps during which hydrogen diffusion may be generated. Furthermore, in one embodiment, the second through-stack via cavities **587** can be formed through insulating and sacrificial layers (**132**, **232**, **142**, **242**) rather than through electrically conductive layers (**146**, **246**) to make the etching of the cavities easier. The cavities **587** are then filled with insulating spacers **586** to prevent short circuiting the electrically conductive layers (**146**, **246**) of the stack before forming the through-stack contact via structure **588** over the spacers **586**. Both sets of cavities **487** and **587** may be filled with the electrically conductive material (e.g., tungsten) of respective structures **488** and **588** during the same deposition step, which reduces process cost and complexity by eliminating a separate conductive material deposition step for structures **588**.

[0211] Referring to FIG. **22**, a second exemplary structure according to a second embodiment of the present disclosure can be derived from the first exemplary structure after the processing steps of FIG. **2**. Appropriate changes to the pattern of the optional planar conductive material layer **6** and the planar semiconductor material layer **10** may be made. In one embodiment, the optional planar conductive material layer **6** and the planar semiconductor material layer **10** can be removed from the word line contact region **200**. Thus, the at least one second dielectric material layer **768** extends into the word line contact region **200**. The pattern of the topmost lower metal liner structures **788** can be modified so that the topmost lower metal liner structures **788** extend into the word line contact region **200**, and are located in areas in which word line contact via structures are to be subsequently formed.

[0212] Referring to FIG. **23**A and **23**B, first-tier memory openings **149** and first-tier contact openings **115** can be formed. The first-tier memory openings **149** can be formed in the memory array region **100** at locations at which memory stack structures including vertical stacks of memory elements are to be subsequently formed. The first-tier memory openings **149** extend through the first-tier alternating stack (**132**, **142**) at least to a top surface of the planar semiconductor material layer **10**. The first-tier contact openings **115** can be formed in the word line contact region **200**. The first-tier contact openings **115** extend through the first-tier alternating stack (**132**, **142**), and the at least one second dielectric material layer **768**, and the silicon nitride layer **766**, and to a top surface of a respective one of the topmost lower metal liner structures **788**.

[0213] For example, a lithographic material stack (not shown) including at least a photoresist layer can be formed over the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**, if present), and can be lithographically patterned to form openings within the lithographic material stack. The pattern in the lithographic material stack can be transferred through the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**), and through the entirety of the first-tier alternating stack (**132**, **142**) by at least one anisotropic etch that employs the patterned lithographic material stack as an etch mask. Portions of the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**), the first-tier alternating stack (**132**, **142**), the at least one second dielectric material layer **768**, and the silicon nitride layer **766** underlying the openings in the patterned lithographic material stack can be etched in a same anisotropic etch process to form the first-tier memory openings **149** and the first-tier contact openings **115**. In other words, the transfer of the pattern in the patterned lithographic material stack through the first insulating cap layer **170** and the first-tier alternating stack

(**132**, **142**) forms the first-tier memory openings **149** and the first-tier contact openings **115**.

[0214] In one embodiment, the chemistry of the anisotropic etch process employed to etch through the materials of the first-tier alternating stack (**132**, **142**) can alternate to optimize etching of the first and second materials in the first-tier alternating stack (**132**, **142**). The anisotropic etch can be, for example, a series of reactive ion etches or a single etch (e.g., $CF_4/O_2/Ar$ etch). The sidewalls of the first-tier memory openings **149** and the first-tier contact openings **115** can be substantially vertical, or can be tapered. The planar semiconductor material layer **10** and the topmost lower metal liner structures **788** can be employed as etch stop structures. Subsequently, the patterned lithographic material stack can be subsequently removed, for example, by ashing. The locations of the steps to be subsequently formed as shown by dashed lines "S".

[0215] Optionally, the portions of the first-tier memory openings **149** and the first-tier contact openings **115** at the level of the inter-tier dielectric layer **180** can be laterally expanded by an isotropic etch. For example, if the inter-tier dielectric layer **180** comprises a dielectric material (such as borosilicate glass) having a greater etch rate than the first insulating layers **132** (that can include undoped silicate glass), an isotropic etch (such as a wet etch employing HF) can be employed to expand the lateral dimensions of the first-tier memory openings at the level of the inter-tier dielectric layer **180**. The portions of the first-tier memory openings **149** (and the first-tier contact openings **115**) located at the level of the inter-tier dielectric layer **180** may be optionally widened to provide a larger landing pad for second-tier memory openings to be subsequently formed through a second-tier alternating stack (to be subsequently formed prior to formation of the second-tier memory openings).

[0216] Referring to FIGS. **24**A and **24**B, sacrificial memory opening fill portions **148** can be formed in the first-tier memory openings **149**, and sacrificial contact opening fill portions **127** can be formed in the first-tier contact openings **115**. For example, a sacrificial fill material layer is deposited in the first-tier memory openings **149** and the first-tier contact openings **115**. The sacrificial fill material layer includes a sacrificial material which can be subsequently removed selective to the materials of the first insulator layers **132** and the first sacrificial material layers **142**. In one embodiment, the sacrificial fill material layer can include germanium, a silicon-germanium alloy, carbon, borosilicate glass (which provides higher etch rate relative to undoped silicate glass), porous or non-porous organosilicate glass, organic polymer, or inorganic polymer.

[0217] Optionally, a thin etch stop layer (such as a silicon oxide layer having a thickness in a range from 1 nm to 3 nm) may be employed prior to depositing the sacrificial fill material layer. If an etch stop layer is employed, semiconductor materials such as amorphous silicon may be employed as the sacrificial fill material. The sacrificial fill material layer may be formed by a non-conformal deposition or a conformal deposition method.

[0218] Portions of the deposited sacrificial material can be removed from above the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**, if present). For example, the sacrificial fill material layer can be recessed to a top surface of the first insulating cap layer **170** (and the optional inter-tier dielectric layer **180**) employing a planarization process. The planarization process can include a recess etch, chemical mechanical planarization (CMP), or a combination thereof. The top surface of the first insulating layer **170** (and optionally layer **180** if present) can be employed as an etch stop layer or a planarization stop layer. Each remaining portion of the sacrificial material in a first-tier memory opening **149** constitutes a sacrificial memory opening fill portion **148**. Each remaining portion of the sacrificial material in a first-tier contact opening **115** constitutes a sacrificial contact opening fill portion **127**. The top surfaces of the sacrificial memory opening fill portions **148** and the sacrificial contact opening fill portions **127** can be coplanar with the top surface of the inter-tier dielectric layer **180** (or the first insulating cap layer **170** if the inter-tier dielectric layer **180** is not present). The sacrificial memory opening fill portion **148** and the sacrificial contact opening fill portions **127** may, or may not, include cavities therein.

[0219] Referring to FIGS. **25**A and **25**B, a second-tier structure can be formed over the first-tier structure (**132**, **142**, **170**, **148**, **117**). The second-tier structure can include an additional alternating stack of insulating layers and spacer material layers, which can be sacrificial material layers. For example, a second alternating stack (**232**, **242**) of material layers can be subsequently formed on the top surface of the first alternating stack (**132**, **142**). The second stack (**232**, **242**) includes an alternating plurality of third material layers and fourth material layers. Each third material layer can include a third material, and each fourth material layer can include a fourth material that is different from the third material. In one embodiment, the third material can be the same as the first material of the first insulating layer **132**, and the fourth material can be the same as the second material of the first sacrificial material layers **142**.

[0220] In one embodiment, the third material layers can be second insulating layers **232** and the fourth material layers can be second spacer material layers that provide vertical spacing between each vertically neighboring pair of the second insulating layers **232**. In one embodiment, the third material layers and the fourth material layers can be second insulating layers **232** and second sacrificial material layers **242**, respectively. The third material of the second insulating layers **232** may be at least one insulating material. The fourth material of the second sacrificial material layers **242** may be a sacrificial material that can be removed selective to the third material of the second insulating layers **232**. The second sacrificial material layers **242** may comprise an insulating material, a semiconductor material, or a conductive material. The fourth material of the second sacrificial material layers **242** can be subsequently replaced with electrically conductive electrodes which can function, for example, as control gate electrodes of a vertical NAND device.

[0221] In one embodiment, each second insulating layer **232** can include a second insulating material, and each second sacrificial material layer **242** can include a second sacrificial material. In this case, the second stack (**232**, **242**) can include an alternating plurality of second insulating layers **232** and second sacrificial material layers **242**. The third material of the second insulating layers **232** can be deposited, for example, by chemical vapor deposition (CVD). The fourth material of the second sacrificial material layers **242** can be formed, for example, CVD or atomic layer deposition (ALD).

[0222] The third material of the second insulating layers **232** can be at least one insulating material. Insulating materials that can be employed for the second insulating layers **232** can be any material that can be employed for the first insulating layers **132**. The fourth material of the second sacrificial material layers **242** is a sacrificial material that can be removed selective to the third material of the second insulating layers **232**. Sacrificial materials that can be employed for the second sacrificial material layers **242** can be any material that can be employed for the first sacrificial material layers **142**. In one embodiment, the second insulating material can be the same as the first insulating material, and the second sacrificial material can be the same as the first sacrificial material.

[0223] The thicknesses of the second insulating layers **232** and the second sacrificial material layers **242** can be in a range from 20 nm to 50 nm, although lesser and greater thicknesses can be employed for each second insulating layer **232** and for each second sacrificial material layer **242**. The number of repetitions of the pairs of a second insulating layer **232** and a second sacrificial material layer **242** can be in a range from 2 to 1,024, and typically from 8 to 256, although a greater number of repetitions can also be employed. In one embodiment, each second sacrificial material layer **242** in the second stack (**232**, **242**) can have a uniform thickness that is substantially invariant within each respective second sacrificial material layer **242**.

[0224] Optionally, drain-select-level shallow trench isolation structures **72** can be formed through a subset of layers in an upper portion of the second-tier alternating stack (**232**, **242**). The second sacrificial material layers **242** that are cut by the select-drain-level shallow trench isolation structures **72** correspond to the levels in which drain-select-level electrically conductive layers are subsequently formed. The drain-select-level shallow trench isolation structures **72** include a dielectric material such as silicon oxide.

[0225] Second-tier memory openings **249** and second-tier contact openings **215** can be formed. The second-tier memory openings **249** can be formed in the areas of the sacrificial memory opening fill portions **148**. The second-tier memory openings **249** extend through the second-tier alternating stack (**232**, **242**) to a top surface of a respective one of the sacrificial memory opening fill portions **148**. The second-tier contact openings **215** can be formed in the areas of the sacrificial contact opening fill portions **127**. The second-tier contact openings **215** extend through the second-tier alternating stack (**232**, **242**) to a top surface of a respective one of the sacrificial contact opening fill portions **127**.

[0226] For example, a lithographic material stack (not shown) including at least a photoresist layer can be formed over the second insulating cap layer **270**, and can be lithographically patterned to form openings within the lithographic material stack. The lithographic mask stack can be patterned with the same lithographic mask that is employed to pattern the first-tier memory openings **149** and the first-tier contact openings **115**. The pattern in the lithographic material stack can be transferred through the second insulating cap layer **270**, and through the entirety of the second-tier alternating stack (**232**, **242**) by at least one anisotropic etch that employs the patterned lithographic material stack as an etch mask. Portions of the second insulating cap layer **270** and the second-tier alternating stack (**132**, **142**) underlying the openings in the patterned lithographic material stack can be etched in a same anisotropic etch process to form the second-tier memory openings **249** and the second-tier contact openings **215**. In other words, the transfer of the pattern in the patterned lithographic material stack through the second insulating cap layer **270** and the second-tier alternating stack (**232**, **242**) forms the second-tier memory openings **249** and the second-tier contact openings **215**.

[0227] In one embodiment, the chemistry of the anisotropic etch process employed to etch through the materials of the second-tier alternating stack (**232**, **242**) can alternate to optimize etching of the second and second materials in the second-tier alternating stack (**232**, **242**). The sidewalls of the second-tier memory openings **249** and the second-tier contact openings **215** can be substantially vertical, or can be tapered. Subsequently, the patterned lithographic material stack can be subsequently removed, for example, by ashing.

[0228] Referring to FIG. **26**, the sacrificial materials of the sacrificial memory opening fill portions **148** and the sacrificial contact opening fill portions **127** can be removed selective to the materials of the second alternating stack (**232**, **242**), the first alternating stack (**132**, **142**), the first and second insulating cap layers (**170**, **270**), the inter-tier dielectric layer **180** (if present), the semiconductor material layer **10**, and the topmost lower metal line structures **788**. If an etch stop layer is present, the etch stop layer can be removed by an isotropic etch process such as a wet etch process. A memory opening is provided by each continuous volume including a volume of a second-tier memory opening **249** and a volume of a first-tier memory opening **149** from which a sacrificial memory opening fill portion **148** is removed. A contact opening is provided by each continuous volume including a volume of a second-tier contact opening **215** and a volume of a first-tier contact opening **115** from which a sacrificial contact opening fill portion **127** is removed.

[0229] Another sacrificial material is deposited in the memory openings and in the contact openings by a conformal deposition process. The deposited sacrificial material can include germanium, a silicon-germanium alloy, carbon, borosilicate glass (which provides higher etch rate relative to undoped silicate glass), porous or non-porous organosilicate glass, organic polymer, or inorganic polymer. Optionally, a thin etch stop layer (such as a silicon oxide layer having a thickness in a range from 1 nm to 3 nm) may be employed prior to depositing the sacrificial fill material. If an etch stop layer is employed, semiconductor materials such as amorphous silicon may be employed as the sacrificial fill material. The sacrificial fill material layer may be formed by a non-conformal deposition or a conformal deposition method. Excess portions of the sacrificial fill material can be removed from above the horizontal plane including the top surface of the second insulating cap layer **270** by a planarization process. The planarization process can include a recess etch process or a chemical mechanical planarization process. Each remaining portion of the deposited sacrificial material in the memory openings constitutes a sacrificial memory opening pillar **158**. Each remaining portion of the deposited sacrificial material in the contact openings constitutes a sacrificial contact opening pillar **120**. The sacrificial memory opening pillars **158** and the sacrificial contact opening pillars **120** include the same sacrificial fill material.

[0230] In an alternative embodiment, the sacrificial memory opening pillars **158** and the sacrificial contact opening pillars **120** can be formed by filling the volumes of the second-tier memory openings **249** and the second-tier

contact opening **215** without removing the sacrificial memory opening fill portions **148** or the sacrificial contact opening fill portions **127**. In this case, each sacrificial memory opening pillar **158** can include a sacrificial memory opening fill portion **148** and an overlying portion of a newly deposited sacrificial fill material that fills a respective second-tier memory opening **249**. Each sacrificial contact opening pillar **120** can include a sacrificial contact opening fill portion **127** and an overlying portion of the newly deposited sacrificial fill material that fills a respective second-tier contact opening **215**. Excess portions of the deposited sacrificial material can be removed from above the horizontal plane including the top surface of the second insulating cap layer **270**.

[0231] Referring to FIG. **27**, an etch mask layer **137** can be applied over the second exemplary structure, and can be patterned to cover the word line contact region **200** without covering the memory array region **100**. The etch mask layer **137** can be a patterned photoresist layer or a patterned hard mask layer. The sacrificial memory opening pillars **158** can be removed selective to the materials of the second alternating stack (**232**, **242**), the first alternating stack (**132**, **142**), the first and second insulating cap layers (**170**, **270**), the inter-tier dielectric layer **180** (if present), and the semiconductor material layer **10**. For example, if the sacrificial memory opening pillars **158** include borosilicate glass, a wet etch employing hydrofluoric acid or a vapor phase clean using HF vapor can be employed to remove the sacrificial memory opening pillars **158**.

[0232] An inter-tier memory opening **49** can be formed in each volume from which the sacrificial memory opening pillars **158** are removed. Each inter-tier memory opening **49** includes a continuous volume that includes the volume of a first-tier memory opening **149** and the volume of a second-tier memory opening **249**. The etch mask layer **137** is subsequently removed.

[0233] Referring to FIG. **28**, memory opening fill structures **58** are formed in each of the inter-tier memory openings **49**. For example, the processing steps of FIGS. **9**A-**9**H can be performed to form the memory opening fill structures **58**, each of which includes a respective memory stack structure **55**. Each memory stack structure vertically extends through the first alternating stack (**132**, **142**) and the second alternating stack (**232**, **242**). Each memory stack structure **55** comprises a memory film **50** and a vertical semiconductor channel **60** laterally surrounded by the memory film **50**.

[0234] Subsequently, stepped surfaces are formed in the word line contact region **200**. The stepped surfaces can be formed, for example, by forming a trimmable mask layer **117** that covers the memory array region **100** and a predominant portion of the word line contact region **200** that excludes a distal peripheral region of the word line contact region **200**, etching unmasked areas of the word line contact region **200** to vertically recess a layer or a pair of layers in the unmasked areas, and iteratively trimming the trimmable mask layer **117** and vertically recessing unmasked areas of the word line contact region **200** by a pair of layers that includes a sacrificial material layer (**242**, **142**) and an insulating layer (**232**, **132**).

[0235] Referring to FIG. **29**, the second exemplary structure is illustrated during formation of the stepped surfaces. Specifically, the trimmable mask layer **117** is applied and patterned to cover the memory array region **100** and the predominant portion of the word line contact region **200** that excludes the distal peripheral region of the word line contact region **200**. An anisotropic etch process is performed to etch a physically exposed portion of the second insulating cap layer **270**.

[0236] Referring to FIG. **30**, a set of processing steps can be repeated multiple times to shift existing stepped surfaces downward and to form additional stepped surfaces. During the set of processing steps, upper portions of the sacrificial contact opening pillars **120** can be removed at approximately the same etch rate as the unmasked portions of the alternating stack (**132**, **142**, **232**, **242**) so that the sacrificial contact opening pillars **120** do not protrude above the stepped surfaces.

[0237] Each set of processing steps includes a first step of removing an uppermost pair of layers that includes one of the insulating layers (**232**, **132**) and one of the sacrificial material layers (**242**, **142**) within each area that is not covered by the trimmable mask layer **117**, and removing each portion of the sacrificial contact opening pillars **120** from above a physically exposed horizontal surface within each area that is not covered by the trimmable material layer **117**. In one embodiment, the insulating layers (**232**, **132**) can include, and/or can consist essentially of, undoped silicate glass, the sacrificial material layers (**242**, **142**) can include, and/or can consist essentially of, silicon nitride, and the sacrificial contact opening pillars **120** can include, and/or can consist essentially of, borosilicate glass or a porous organosilicate glass. The first step can be effected by an anisotropic etch process. The etch chemistry of the anisotropic etch process can be selected to remove the materials of the insulating layers (**232**, **132**), the sacrificial material layers (**242**, **142**), and the sacrificial contact opening pillars **120** at approximately the same removal rate.

[0238] Each set of processing steps include a second step of trimming the trimmable mask layer **117** to provide an additional area that is not covered by the trimmable mask layer **117**. Each additional area can include the area of a sacrificial contact opening pillar **120** that is more proximal to the memory array region **100** than previously exposed sacrificial contact opening pillars **120**. Thus, each second step can physically expose an additional sacrificial contact opening pillar **120** among each row of sacrificial contact opening pillars **120** that are arranged along the first horizontal direction hd**1**.

[0239] Referring to FIG. **31**, the set of processing steps is repeated until the at least one second dielectric material layer **768** is physically exposed and the stepped surfaces continuously extend from the bottommost layer of the alternating stacks (**132**, **142**, **232**, **242**) to the topmost layer of the alternating stacks (**132**, **142**, **232**, **242**). Generally, an anisotropic etch process and trimming of the trimmable mask layer **117** can be repeated to pattern the alternating stacks (**132**, **142**, **232**, **242**), thereby forming the stepped surfaces in the word line contact region **200**. The stepped surfaces can include stepped terraces that laterally extend along the second horizontal direction hd**2**. Upper portions of the sacrificial contact opening pillars **120** can be removed concurrently with formation of the stepped surfaces.

[0240] Mismatch between the etch rate of the material of the sacrificial contact opening pillars **120** and the materials of the alternating stacks (**132**, **142**, **232**, **242**) may cause remaining portions of the sacrificial contact opening pillars **120** to protrude above the stepped surfaces of the alternating stacks (**132**, **142**, **232**, **242**) or to be recessed below the

stepped surfaces of the alternating stacks (**132**, **142**, **232**, **242**). Such protrusions or recesses are acceptable because the sacrificial contact opening pillars **120** are subsequently removed selective to the alternating stacks (**132**, **142**, **232**, **242**). The trimmable mask layer **117** can be subsequently removed, for example, by ashing or by dissolving in a solvent.

[0241] Referring to FIG. **32**, remaining portions of the sacrificial contact opening pillars **120** can be removed selective to the materials of the alternating stacks (**132**, **142**, **232**, **242**), the at least one second dielectric material layer **768**, the first and second insulating cap layers (**170**, **270**), the inter-tier dielectric layer **180** (if present), and the semiconductor material layer **10**. For example, if the sacrificial contact opening pillars **120** include borosilicate glass, a wet etch employing hydrofluoric acid or a vapor phase clean using HF vapor can be employed to remove the remaining portions of the sacrificial contact opening pillars **120**. Contact via cavities **119** can be formed in each volume from which the sacrificial contact opening pillars **120** are removed. A top surface of a respective one of the topmost lower metal line structures **788** can be physically exposed at the bottom of each contact via cavity **119**. The bottom surfaces of the contact via cavities **119** can be within a same horizontal plane such as the horizontal plane including the top surfaces of the topmost lower metal line structures **788**. Each of the contact via cavities **119** has a top periphery that is adjoined to a respective horizontal surface of the stepped surfaces.

[0242] Subsequently, a continuous insulating liner layer is formed by a conformal deposition process. The continuous insulating liner layer includes an insulating material that is different from the material of the sacrificial material layers (**142**, **242**). In one embodiment, the continuous insulating liner layer can include a dielectric metal oxide (such as aluminum oxide) or silicon oxide. The continuous insulating liner layer can be deposited within each contact via cavity **119** and over the stepped surfaces of the alternating stacks (**132**, **142**, **232**, **242**). The thickness of the continuous insulating liner layer may be in a range from 2 nm to 40 nm, such as from 4 nm to 20 nm, although lesser and greater thicknesses can also be employed. The continuous insulating liner layer continuously covers the exposed underlying area prior to the subsequent etching step.

[0243] An anisotropic etch process is performed on the continuous insulating liner layer to remove horizontal portions of the continuous insulating liner layer. Each remaining vertical portion of the continuous insulating liner layer within the contact via cavities **119** constitutes an insulating tubular liner **66**, having the configuration shown in FIG. **33**. Each insulating tubular liner **66** has a general configuration of a tube, and extends from a bottom surface of a respective contact via cavity **119** to a topmost region of the contact via cavity **119**. A top surface of a respective one of the topmost lower metal line structures **788** is physically exposed within a bottom region of each insulating tubular liner **66**.

[0244] At least one continuous conductive material layer **67**L is deposited in unfilled volumes of the contact via cavities **119** and over the stepped surfaces of the alternating stacks (**132**, **142**, **232**, **242**). The at least one continuous conductive material layer **67**L can include a stack of multiple conductive layers. For example, the at least one continuous conductive material layer **67**L can include a continuous metallic nitride liner layer **67**A and a continuous metal fill layer **67**B. The continuous metallic nitride liner layer **67**A can be deposited on physically exposed top surfaces of the lower interconnect structures **780** and on inner sidewalls of the insulating tubular liners **66**. The continuous metallic nitride liner **67**A can include a conductive metallic nitride material such as TiN, TaN, and/or WN, and can have a thickness in a range from 2 nm to 40 nm, such as from 4 nm to 20 nm, although lesser and greater thicknesses can also be employed. The continuous metal fill layer **67**B can be deposited on the continuous metallic nitride liner layer **67**A. The continuous metal fill layer **67**B includes a metal such as tungsten, copper, aluminum, ruthenium, cobalt, molybdenum, or any other metal that can be employed for metal interconnect structures. The continuous metal fill layer **67**B can fill remaining volumes of the contact via cavities **119**.

[0245] Referring to FIG. **34**, the continuous metal fill layer **67**B and the continuous metallic nitride liner layer **67**A can be anisotropically etched outside the volumes of the contact via cavities **119**. In one embodiment, top surfaces of remaining portions of the continuous metal fill layer **67**B and the continuous metallic nitride liner layer **67**A can be vertically recessed below the bottom surface of sacrificial material layers (**142**, **242**) including physically exposed horizontal surfaces as components of the stepped surfaces. Each remaining portion of the continuous metallic nitride liner layer **67**A constitutes a metallic nitride liner **67**A'. Each remaining portion of the continuous metal fill layer **67**B constitutes a metal fill portion **67**B'. Metallic nitride liners **67**A' are located within a respective one of the contact via cavities **119**, and metal fill portions **67**B' are located within a respective one of the metallic nitride liners **67**A'. Each contiguous set of a metallic nitride liner **67**A' and a metal fill portion **67**B' constitutes a laterally-insulated via structure **67**.

[0246] Physically exposed portions of the insulating tubular liners **66** that protrude above the top surfaces of the laterally-insulated via structure **67** can be removed by an etch process, which can be an isotropic etch process. Sidewalls of the sacrificial material layers (**142**, **242**) including physically exposed top surfaces as horizontal surfaces of the stepped surfaces are physically exposed around each contact via cavity **119** (which is partly filled with an insulating tubular liner **66** and a respective laterally-insulated via structure **67**). In one embodiment, the upper periphery of the outer sidewall of each insulating tubular liner **66** can be on a sidewall of an insulating layer (**132**, **232**) that contact a bottom surface of a sacrificial material layer (**142**, **242**) having a physically exposed top surface, or on a sidewall of the inter-tier dielectric layer **180** (or on a sidewall of the first insulating cap layer **170**) that contact a bottom surface of a sacrificial material layer (**142**, **242**) having a physically exposed top surface. A sidewall of a on respective sacrificial material layer (**142**, **242**) is physically exposed within each of the contact via cavities **119** after formation of the laterally-insulated via structures **67**, i.e., after formation of the metallic nitride liners **67**A' and the metal fill portions **67**B'.

[0247] Referring to FIG. **35**, a metallic pillar structure **68** is formed on top of each adjoining pair of a metallic nitride liner **67**A' and a metal fill portion **67**B', i.e., on top of each laterally-insulated via structure **67**. The metallic pillar structures **68** are formed in unfilled volumes of each of the contact via cavities **119** and directly on the sidewalls of the sacrificial material layers (**142**, **242**) that are present around

the contact via cavities **119**. Specifically, each of the metallic pillar structures **68** is formed in a respective unfilled volume of each respective one of the contact via cavities **119** and directly on the sidewall of the respective one of the sacrificial material layers (**142**, **242**) that is present around the respective contact via cavities **119**. The metallic pillar structures **68** include a metal such as tungsten, copper, aluminum, ruthenium, cobalt, molybdenum, or a combination thereof. The material of the metallic pillar structures **68** may be the same as, or may be different from, the material of the metal fill portions **67**B'.

[0248] In one embodiment, the metallic pillar structures **68** may be formed by a selective metal deposition process that grows a metallic material from surfaces of the metallic nitride liners **67**A' and the metal fill portions **67**B' and does not grow the metallic material from surfaces of the insulating layers (**132**, **232**) and the sacrificial material layers (**142**, **242**). The duration of the selective metal deposition process can be selected such that the metallic pillar structures **68** has a top surface that is substantially coplanar with the horizontal surfaces in the stepped surfaces, i.e., with the physically exposed top surfaces of the sacrificial material layers (**142**, **242**) in the stepped surfaces. In one embodiment, top surfaces of the metallic pillar structures **68** protrude above the physically exposed surfaces of the sacrificial material layers (**142**, **242**) within the stepped surfaces. In another embodiment, top surfaces of the metallic pillar structures **68** are recessed below the physically exposed surfaces of the sacrificial material layers (**142**, **242**) within the stepped surfaces. In yet another embodiment, top surfaces of the metallic pillar structures **68** are coplanar with the physically exposed surfaces of the sacrificial material layers (**142**, **242**) within the stepped surfaces.

[0249] Each contiguous set of a laterally-insulated via structure **67** and a metallic pillar structure **68** constitutes a word line contact via structure (**67**, **68**), which is a contact via structure that provides electrical connection to one of word lines to be subsequently formed by replacement of the sacrificial material layers (**142**, **242**) with electrically conductive layers.

[0250] Thus, remaining portions of the sacrificial contact opening pillars **120** provided at the processing steps of FIG. **31** are replaced with the word line contact via structures (**67**, **68**). Each of the contact via structures (**67**, **68**) can be formed on a sidewall of a respective one of the insulating tubular liners **66**. Specifically, the laterally-insulated via structure **67** portion of each of the contact via structures (**67**, **68**) can be formed on a sidewall of a respective one of the insulating tubular liners **66**. The word line contact via structures (**67**, **68**) are formed in the word line contact region **200**. Each word line contact via structure (**67**, **68**) laterally contacts a respective one of the sacrificial material layers (**142**, **242**), vertically extends through a respective opening in at least a bottommost sacrificial material layer of the alternating stacks (**132**, **142**, **232**, **242**), and contacts a respective one of the lower interconnect structures **780** that underlie the alternating stacks (**132**, **142**, **232**, **242**). Specifically, the metallic pillar structure **68** portion of each word line contact via structure (**67**, **68**) laterally contacts the respective one of the sacrificial material layers (**142**, **242**).

[0251] Referring to FIGS. **36**A and **36**B, a dielectric material can be deposited in the stepped cavity overlying the stepped surfaces. The dielectric material can be subsequently planarized employing the top surface of the second insulating cap layer **270** as a stopping surface. The remaining portion of the deposited dielectric material forms a retro-stepped dielectric material portion **365**. The retro-stepped dielectric material portion **365** includes a dielectric material that is different from the material of the sacrificial material layers (**142**, **242**). For example, the retro-stepped dielectric material portion **365** can include undoped silicate glass or doped silicate glass. The top surface of the retro-stepped dielectric material portion **365** can be coplanar with the top surface of the second insulating cap layer **270**. The bottom surfaces of the retro-stepped dielectric material portion **365** contacts the stepped surfaces of the alternating stacks (**132**, **142**, **232**, **242**) and top surfaces of the word line contact via structures (**67**, **68**).

[0252] Referring to FIG. **37**, the processing steps of FIGS. **10**A and **10**B can be performed to form a first contact level dielectric layer **280** and backside trenches **79**. Subsequently, a first subset of the processing steps of FIGS. **11**A and **11**B can be performed to replace the sacrificial material layers (**142**, **242**) with electrically conductive layers (**246**, **246**). The word line contact via structures (**67**, **68**) provide structural support in the word line contact region **200** and the memory opening fill structures **58** provide structural support in the memory array region **100** while backside recesses are present between vertically neighboring pairs of insulating layers (**132**, **232**) during replacement of the sacrificial material layers (**142**, **242**) with the electrically conductive layers (**246**, **246**). Each electrically conductive layer (**146**, **246**) contacts a respective one of the word line contact via structures (**67**, **68**). In other words, each electrically conductive layer (**146**, **246**) contacts the metallic pillar structure **68** portion of the respective one of the word line contact via structures (**67**, **68**).

[0253] Referring to FIGS. **38**A and **38**B, a second subset of the processing steps of FIGS. **11**A and **11**B can be performed to form source regions **61**, insulating spacers **74**, and backside contact via structures **76** (which may be laterally-elongated contact via structures). Subsequently, a second contact level dielectric layer **282** can be formed over the second contact level dielectric layer **280**.

[0254] The processing steps of FIGS. **12**A and **12**B can be performed, with modification, to form the drain contact via structures **88** without forming the word line contact via structures **86** of the first embodiment. Omission of formation of the word line contact via structures **86** can be effected by modifying the pattern in the etch mask for forming cavities for the drain contact via structures **88** such that the etch mask does not include any openings in the word line contact region **200**. In the second exemplary structure, the word line contact via structures (**67**, **68**) as formed at the processing steps of FIG. **35** provide vertical electrical connection to the peripheral devices on the substrate semiconductor layer **9**, and therefore, formation of additional contact via structures on the electrically conductive layers (**146**, **246**) is not necessary.

[0255] Subsequently, the processing steps of FIGS. **13**A and **13**B, FIG. **14**, FIG. **15**, and FIGS. **16**A and **16**B can optionally be performed to form through-stack insulating spacers **586**, through-stack contact via structures **588**, and through-dielectric contact via structures **488**. The through-stack contact via structures **588** and through-dielectric contact via structures **488** can be employed to provide electrical connections to bit lines to be subsequently formed and to provide power and ground connections to the three-dimen-

sional memory device formed on the semiconductor material layer **10**. The word line contact via structures (**67**, **68**) can be employed to provide electrical connections between the peripheral devices on the substrate semiconductor layer **9** and the electrically conductive layers (**146**, **246**), which include the word lines for the three-dimensional memory device.

[0256] Referring to FIG. **39**, the processing steps of FIG. **17** can be performed to form at least one upper interconnect level dielectric layer **284** over the contact level dielectric layers (**280**, **282**). The at least one upper interconnect level dielectric layer **284** can include multiple upper interconnect level dielectric layers. Various upper interconnect structures, such as upper interconnect level metal structures, can be formed in the at least one upper interconnect level dielectric layer **284**. For example, the various upper interconnect level metal structures can include line level metal interconnect structures (**96**, **98**, **99**). The line level metal interconnect structures (**96**, **98**, **99**) can include first upper metal line structures **99** that contact a top surfaces of a respective one of the through-stack contact via structures **588**, second upper metal line structures **96** that contact a top surface of a respective one of the through-dielectric contact via structures **488**, and bit lines **98** that contact a respective one of the drain contact via structures **88** and extend along the second horizontal direction (e.g., bit line direction) hd**2** and perpendicular to the first horizontal direction (e.g., word line direction) hd**1**.

[0257] At least a subset of the upper metal interconnect structures (which include the line level metal interconnect structures (**96**, **98**, **99**)) is formed over the three-dimensional memory array. The upper metal interconnect structures comprise an upper metal line structure (such as a first upper metal line structure **99**) that is formed directly on a through-stack contact via structure **588**. A set of conductive structures including the through-stack contact via structure **588** and a lower metal line structure (such as a topmost lower metal line structure **788**) provides an electrically conductive path between the at least one semiconductor device **710** on the substrate semiconductor layer and the upper metal line structure. A through-dielectric contact via structure **488** can be provided through the retro-stepped dielectric material portion **365**, the at least one second dielectric material layer **768**, and the silicon nitride layer **766** and directly on a top surface of another lower metal line structure (e.g., another topmost lower metal line structure **788**) of the lower metal interconnect structures **780**.

[0258] The through-dielectric contact via structures **488** can be formed on a respective one of the lower interconnect structures **780** within an area outside of the alternating stacks (**132**, **146**, **232**, **246**). In one embodiment, the entire region of the retro-stepped dielectric material portion **365** within the area of the stepped surfaces, i.e., the entire volume of the portion of the retro-stepped dielectric material portion **365** that has an areal overlap with the area of the stepped surfaces in a see-through top-down view, can be free of any conductive via structure after formation of the upper interconnect structures. Optionally, the stepped word line contact region **200** can also be free of support pillar structures **20**. In one embodiment, the upper interconnect structures comprise bit lines **98** that are electrically shorted via a respective drain region **63** to an upper end of a respective one of the vertical semiconductor channels **60** and to a respective one of the through-dielectric contact via structures **488**, and the semiconductor devices on the substrate semiconductor layer **9** can include bit line drivers for driving the bit lines **98**.

[0259] Referring to FIGS. **40**A and **40**B, a third exemplary structure according to a third embodiment of the present disclosure can be derived from the first exemplary structure after the processing steps of FIG. **2**. Appropriate changes to the pattern of the optional planar conductive material layer **6** and the planar semiconductor material layer **10** may be made. In one embodiment, the optional planar conductive material layer **6** and the planar semiconductor material layer **10** can be removed from the word line contact region **200**. Thus, the at least one second dielectric material layer **768** extends into the word line contact region **200**. The pattern of the topmost lower metal liner structures **788** can be modified so that the topmost lower metal liner structures **788** extend into the word line contact region **200**, and are located in areas in which word line contact via structures are to be subsequently formed.

[0260] First-tier memory openings **149** can be formed in the memory array region **100** at locations at which memory stack structures including vertical stacks of memory elements are to be subsequently formed. The first-tier memory openings **149** extend through the first-tier alternating stack (**132**, **142**) at least to a top surface of the planar semiconductor material layer **10**. For example, a lithographic material stack (not shown) including at least a photoresist layer can be formed over the first insulating cap layer **170**, and can be lithographically patterned to form openings within the lithographic material stack. The openings in the lithographic material stack are located within the memory array region **100**, and can be arranged as rows extending along the first horizontal direction hd**1**. The pattern in the lithographic material stack can be transferred through the first insulating cap layer **170**, and through the entirety of the first-tier alternating stack (**132**, **142**) by at least one anisotropic etch that employs the patterned lithographic material stack as an etch mask. Portions of the first insulating cap layer **170** and the first-tier alternating stack (**132**, **142**) underlying the openings in the patterned lithographic material stack can be etched to form the first-tier memory openings **149**. In other words, the transfer of the pattern in the patterned lithographic material stack through the first insulating cap layer **170** and the first-tier alternating stack (**132**, **142**) forms the first-tier memory openings **149**.

[0261] In one embodiment, the chemistry of the anisotropic etch process employed to etch through the materials of the first-tier alternating stack (**132**, **142**) can alternate to optimize etching of the first and second materials in the first-tier alternating stack (**132**, **142**). The anisotropic etch can be, for example, a series of reactive ion etches or a single etch (e.g., $CF_4/O_2/Ar$ etch). The sidewalls of the first-tier memory openings **149** can be substantially vertical, or can be tapered. The planar semiconductor material layer **10** can be employed as etch stop structures. Subsequently, the patterned lithographic material stack can be subsequently removed, for example, by ashing.

[0262] Referring to FIG. **41**, sacrificial memory opening fill portions **148** can be formed in the first-tier memory openings **149**. For example, a sacrificial fill material layer is deposited in the first-tier memory openings **149**. The sacrificial fill material layer includes a sacrificial material which can be subsequently removed selective to the materials of the first insulator layers **132** and the first sacrificial material

layers **142**. In one embodiment, the sacrificial fill material layer can include germanium, a silicon-germanium alloy, carbon, borosilicate glass (which provides higher etch rate relative to undoped silicate glass), porous or non-porous organosilicate glass, organic polymer, or inorganic polymer. Optionally, a thin etch stop layer (such as a silicon oxide layer having a thickness in a range from 1 nm to 3 nm) may be employed prior to depositing the sacrificial fill material layer. If an etch stop layer is employed, semiconductor materials such as amorphous silicon may be employed as the sacrificial fill material. The sacrificial fill material layer may be formed by a non-conformal deposition or a conformal deposition method.

[0263] Portions of the deposited sacrificial material can be removed from above the first insulating cap layer **170**. For example, the sacrificial fill material layer can be recessed to a top surface of the first insulating cap layer **170** employing a planarization process. The planarization process can include a recess etch, chemical mechanical planarization (CMP), or a combination thereof. The top surface of the first insulating layer **170** can be employed as an etch stop layer or a planarization stop layer. Each remaining portion of the sacrificial material in a first-tier memory opening **149** constitutes a sacrificial memory opening fill portion **148**. The top surfaces of the sacrificial memory opening fill portions **148** can be coplanar with the top surface of the first insulating cap layer **170**. The sacrificial memory opening fill portion **148** may, or may not, include cavities therein.

[0264] Referring to FIGS. **42**A and **42**B, first-tier contact openings **109** can be formed in the word line contact region **200**. The first-tier contact openings **109** extend through the first-tier alternating stack (**132**, **142**), and the at least one second dielectric material layer **768**, and the silicon nitride layer **766**, and to a top surface of a respective one of the topmost lower metal liner structures **788**. For example, a lithographic material stack (not shown) including at least a photoresist layer can be formed over the first insulating cap layer **170**, and can be lithographically patterned to form openings within the lithographic material stack. The openings in the lithographic material stack are located within the word line contact region **200**, and can be arranged as rows extending along the first horizontal direction hd**1**. The pattern in the lithographic material stack can be transferred through the first insulating cap layer **170**, and through the entirety of the first-tier alternating stack (**132**, **142**) by at least one anisotropic etch that employs the patterned lithographic material stack as an etch mask. Portions of the first insulating cap layer **170**, the first-tier alternating stack (**132**, **142**), the at least one second dielectric material layer **768**, and the silicon nitride layer **766** underlying the openings in the patterned lithographic material stack can be etched to form the first-tier contact openings **109**. In other words, the transfer of the pattern in the patterned lithographic material stack through the first insulating cap layer **170** and the first-tier alternating stack (**132**, **142**) forms the first-tier contact openings **109**.

[0265] In one embodiment, the chemistry of the anisotropic etch process employed to etch through the materials of the first-tier alternating stack (**132**, **142**) can alternate to optimize etching of the first and second materials in the first-tier alternating stack (**132**, **142**). The anisotropic etch can be, for example, a series of reactive ion etches or a single etch (e.g., $CF_4/O_2/Ar$ etch). The sidewalls of the first-tier contact openings **109** can be substantially vertical, or can be tapered. The topmost lower metal liner structures **788** can be employed as etch stop structures. Subsequently, the patterned lithographic material stack can be subsequently removed, for example, by ashing.

[0266] Referring to FIG. **43**, sacrificial contact opening pillars **120** can be formed in the first-tier contact openings **109**. For example, a sacrificial fill material layer is deposited in the first-tier contact openings **109**. The sacrificial fill material layer includes a sacrificial material which can be subsequently removed selective to the materials of the first insulator layers **132** and the first sacrificial material layers **142**. The sacrificial fill material of the sacrificial contact opening pillars **120** is different from the sacrificial material of the sacrificial memory opening fill portions **148**. For example, the sacrificial fill material of the sacrificial contact opening pillars **120** can be selected from germanium, a silicon-germanium alloy, carbon, borosilicate glass (which provides higher etch rate relative to undoped silicate glass), porous or non-porous organosilicate glass, organic polymer, or inorganic polymer, provided that the sacrificial fill material of the sacrificial contact opening pillars **120** is different from the sacrificial material of the sacrificial memory opening fill portions **148**. Optionally, a thin etch stop layer (such as a silicon oxide layer having a thickness in a range from 1 nm to 3 nm) may be employed prior to depositing the sacrificial fill material to form the sacrificial contact opening pillar **120**. If an etch stop layer is employed, semiconductor materials such as amorphous silicon may be employed as the sacrificial fill material. The sacrificial fill material layer may be formed by a non-conformal deposition or a conformal deposition method.

[0267] In an illustrative example, the sacrificial memory opening fill portions **148** can include a combination of an etch stop layer such as a thin silicon oxide layer and a first sacrificial fill material such as germanium, a silicon-germanium alloy, or carbon. In this case, the sacrificial contact opening pillars **120** can include a second sacrificial fill material selected from borosilicate glass (which provides higher etch rate relative to undoped silicate glass), porous or non-porous organosilicate glass, organic polymer, and inorganic polymer. Portions of the second sacrificial material can be removed from above the first insulating cap layer **170** employing a planarization process. The planarization process can include a recess etch, chemical mechanical planarization (CMP), or a combination thereof. The top surface of the first insulating layer **170** can be employed as an etch stop layer or a planarization stop layer. Each remaining portion of the second sacrificial material in a first-tier contact opening **109** constitutes a sacrificial contact opening pillar **120**. The top surfaces of the sacrificial memory opening fill portions **148** and the sacrificial contact opening pillars **120** can be coplanar with the top surface of the first insulating cap layer **170**. The sacrificial contact opening pillars **120** may, or may not, include cavities therein.

[0268] Referring to FIG. **44**, stepped surfaces are formed in the word line contact region **200**. The stepped surfaces can be formed, for example, by forming a trimmable mask layer **117** that covers the memory array region **100** and a predominant portion of the word line contact region **200** that excludes a distal peripheral region of the word line contact region **200**, etching unmasked areas of the word line contact region **200** to vertically recess a layer or a pair of layers in the unmasked areas, and iteratively trimming the trimmable mask layer **117** and vertically recessing unmasked areas of

the word line contact region **200** by a pair of layers that includes a first sacrificial material layer **142** and a first insulating layer **132**.

[0269] Specifically, the trimmable mask layer **117** is applied and patterned to cover the memory array region **100** and the predominant portion of the word line contact region **200** that excludes the distal peripheral region of the word line contact region **200**. An anisotropic etch process is performed to etch a physically exposed portion of the second insulating cap layer **170**. A set of processing steps can be repeated multiple times to shift existing stepped surfaces downward and to form additional stepped surfaces. During the set of processing steps, upper portions of the sacrificial contact opening pillars **120** can be removed at approximately the same etch rate as the unmasked portions of the first alternating stack (**132**, **142**) so that the sacrificial contact opening pillars **120** do not protrude above the stepped surfaces.

[0270] Each set of processing steps includes a first step of removing an uppermost pair of layers that includes one of the first insulating layers **132** and one of the first sacrificial material layers **142** within each area that is not covered by the trimmable mask layer **117**, and removing each portion of the sacrificial contact opening pillars **120** from above a physically exposed horizontal surface within each area that is not covered by the trimmable material layer **117**. In one embodiment, the first insulating layers **132** can include, and/or can consist essentially of, undoped silicate glass, the first sacrificial material layers **142** can include, and/or can consist essentially of, silicon nitride, and the sacrificial contact opening pillars **120** can include, and/or can consist essentially of, borosilicate glass or a porous organosilicate glass. The first step can be effected by an anisotropic etch process. The etch chemistry of the anisotropic etch process can be selected to remove the materials of the first insulating layers **132**, the first sacrificial material layers **242**, and the sacrificial contact opening pillars **120** at approximately the same removal rate.

[0271] Each set of processing steps include a second step of trimming the trimmable mask layer **117** to provide an additional area that is not covered by the trimmable mask layer **117**. Each additional area can include the area of a sacrificial contact opening pillar **120** that is more proximal to the memory array region **100** than previously exposed sacrificial contact opening pillars **120**. Thus, each second step can physically expose an additional sacrificial contact opening pillar **120** among each row of sacrificial contact opening pillars **120** that are arranged along the first horizontal direction hd**1**.

[0272] Referring to FIG. **45**, the set of processing steps is repeated until the at least one second dielectric material layer **768** is physically exposed and the stepped surfaces continuously extend from the bottommost layer of the first alternating stack (**132**, **142**) to the topmost layer of the first alternating stack (**132**, **142**). Generally, an anisotropic etch process and trimming of the trimmable mask layer **117** can be repeated to pattern the first alternating stack (**132**, **142**), thereby forming the stepped surfaces in the word line contact region **200**. The stepped surfaces can include stepped terraces that laterally extend along the second horizontal direction hd**2**. Upper portions of the sacrificial contact opening pillars **120** can be removed concurrently with formation of the stepped surfaces.

[0273] Mismatch between the etch rate of the material of the sacrificial contact opening pillars **120** and the materials of the first alternating stack (**132**, **142**) may cause remaining portions of the sacrificial contact opening pillars **120** to protrude above the stepped surfaces of the first alternating stack (**132**, **142**) or to be recessed below the stepped surfaces of the first alternating stack (**132**, **142**). Such protrusions or recesses are acceptable because the sacrificial contact opening pillars **120** are subsequently removed selective to the first alternating stack (**132**, **142**). The trimmable mask layer **117** can be subsequently removed, for example, by ashing or by dissolving in a solvent.

[0274] Referring to FIG. **46**, remaining portions of the sacrificial contact opening pillars **120** can be removed selective to the materials of the first alternating stack (**132**, **142**), the at least one second dielectric material layer **768**, the first and second insulating cap layers (**170**, **270**), and the semiconductor material layer **10**. For example, if the sacrificial contact opening pillars **120** include borosilicate glass, a wet etch employing hydrofluoric acid or a vapor phase clean using HF can be employed to remove the remaining portions of the sacrificial contact opening pillars **120**. Contact via cavities **119** can be formed in each volume from which the sacrificial contact opening pillars **120** are removed. A top surface of a respective one of the topmost lower metal line structures **788** can be physically exposed at the bottom of each contact via cavity **119**. The bottom surfaces of the contact via cavities **119** can be within a same horizontal plane such as the horizontal plane including the top surfaces of the topmost lower metal line structures **788**. Each of the contact via cavities **119** has a top periphery that is adjoined to a respective horizontal surface of the stepped surfaces.

[0275] Referring to FIG. **47**, the processing steps of FIGS. **33** and **34** can be performed to form insulating tubular liners **66** and laterally-insulated via structures **67**. Specifically, a continuous insulating liner layer is formed by a conformation deposition process. An anisotropic etch process is performed on the continuous insulating liner layer to remove horizontal portions of the continuous insulating liner layer. Each remaining vertical portion of the continuous insulating liner layer within the contact via cavities **119** constitutes an insulating tubular liner **66**. Each insulating tubular liner **66** has a general configuration of a tube, and extends from a bottom surface of a respective contact via cavity **119** to a topmost region of the contact via cavity **119**. A top surface of a respective one of the topmost lower metal line structures **788** is physically exposed within a bottom region of each insulating tubular liner **66**. The insulating tubular liners **66** can have the same composition and the same thickness as in the second embodiment.

[0276] At least one continuous conductive material layer is deposited in unfilled volumes of the contact via cavities **119** and over the stepped surfaces of the first alternating stack (**132**, **142**). The at least one continuous conductive material layer can include a stack of multiple conductive layers. For example, the at least one continuous conductive material layer can include a continuous metallic nitride liner layer and a continuous metal fill layer as in the second embodiment. The continuous metallic nitride liner layer can be deposited on physically exposed top surfaces of the lower interconnect structures **780** and on inner sidewalls of the insulating tubular liners **66**. The continuous metallic nitride liner can include a conductive metallic nitride material such

as TiN, TaN, and/or WN, and can have a thickness in a range from 2 nm to 40 nm, such as from 4 nm to 20 nm, although lesser and greater thicknesses can also be employed. The continuous metal fill layer can be deposited on the continuous metallic nitride liner layer. The continuous metal fill layer includes a metal such as tungsten, copper, aluminum, ruthenium, cobalt, molybdenum, or any other metal that can be employed for metal interconnect structures. The continuous metal fill layer can fill remaining volumes of the contact via cavities **119**.

[0277] The continuous metal fill layer and the continuous metallic nitride liner layer can be anisotropically etched outside the volumes of the contact via cavities **119**. In one embodiment, top surfaces of remaining portions of the continuous metal fill layer and the continuous metallic nitride liner layer can be vertically recessed below the bottom surface of first sacrificial material layers **142** including physically exposed horizontal surfaces as components of the stepped surfaces. Each remaining portion of the continuous metallic nitride liner layer constitutes a metallic nitride liner **67**A'. Each remaining portion of the continuous metal fill layer constitutes a metal fill portion **67**B'. Metallic nitride liners **67**A' are located within a respective one of the contact via cavities **119**, and metal fill portions **67**B' are located within a respective one of the metallic nitride liners **67**A'. Each contiguous set of a metallic nitride liner **67**A' and a metal fill portion **67**B' constitutes a laterally-insulated via structure **67**.

[0278] Physically exposed portions of the insulating tubular liners **66** that protrude above the top surfaces of the laterally-insulated via structure **67** can be removed by an etch process, which can be an isotropic etch process. Sidewalls of the first sacrificial material layers **142** including physically exposed top surfaces as horizontal surfaces of the stepped surfaces are physically exposed around each contact via cavity **119** (which is partly filled with an insulating tubular liner **66** and a respective laterally-insulated via structure **67**). In one embodiment, the upper periphery of the outer sidewall of each insulating tubular liner **66** can be on a sidewall of a first insulating layer **132** that contact a bottom surface of a first sacrificial material layer having a physically exposed top surface, or on a sidewall of the first insulating cap layer **170** that contact a bottom surface of a first sacrificial material layer **142** having a physically exposed top surface. A sidewall of a first sacrificial material layer **142** is physically exposed within each of the contact via cavities **119** after formation of the laterally-insulated via structures **67**, i.e., after formation of the metallic nitride liners **67**A' and the metal fill portions **67**B'.

[0279] Referring to FIG. **48**, a metallic pillar structure **68** is formed on top of each adjoining pair of a metallic nitride liner **67**A' and a metal fill portion **67**B', i.e., on top of each laterally-insulated via structure **67**. The metallic pillar structures **68** are formed in unfilled volumes of each of the contact via cavities **119** and directly on the sidewalls of the first sacrificial material layers **142** that are present around the contact via cavities **119**. The metallic pillar structures **68** includes a metal such as tungsten, copper, aluminum, ruthenium, cobalt, molybdenum, or a combination thereof. The material of the metallic pillar structures **68** may be the same as, or may be different from, the material of the metal fill portions **67**B'.

[0280] In one embodiment, the metallic pillar structures **68** may be formed by a selective metal deposition process that grows a metallic material from surfaces of the metallic nitride liners **67**A' and the metal fill portions **67**B' and does not grow the metallic material from surfaces of the first insulating layers **132** and the first sacrificial material layers **142**. The duration of the selective metal deposition process can be selected such that the metallic pillar structures **68** has a top surface that is substantially coplanar with the horizontal surfaces in the stepped surfaces, i.e., with the physically exposed top surfaces of the first sacrificial material layers **142** in the stepped surfaces. In one embodiment, top surfaces of the metallic pillar structures **68** protrude above the physically exposed surfaces of the first sacrificial material layers **142** within the stepped surfaces. In another embodiment, top surfaces of the metallic pillar structures **68** are recessed below the physically exposed surfaces of the first sacrificial material layers **142** within the stepped surfaces. In yet another embodiment, top surfaces of the metallic pillar structures **68** are coplanar with the physically exposed surfaces of the first sacrificial material layers **142** within the stepped surfaces.

[0281] Each contiguous set of a laterally-insulated via structure **67** and a metallic pillar structure **68** constitutes a word line contact via structure (**67**, **68**), which is a contact via structure that provides electrical connection to one of word lines to be subsequently formed by replacement of the first sacrificial material layers **142** with electrically conductive layers. Thus, remaining portions of the sacrificial contact opening pillars **120** provided at the processing steps of FIG. **45** are replaced with the word line contact via structures (**67**, **68**). Each of the contact via structures (**67**, **68**) can be formed on a sidewall of a respective one of the insulating tubular liners **66**. The word line contact via structures (**67**, **68**) are formed in the word line contact region **200**. Each word line contact via structure (**67**, **68**) laterally contacts a respective one of the first sacrificial material layers **142**, vertically extends through a respective opening in at least a bottommost sacrificial material layer of the first alternating stack (**132**, **142**), and contacts a respective one of the lower interconnect structures **780** that underlie the first alternating stack (**132**, **142**).

[0282] Referring to FIGS. **49**A and **49**B, a dielectric material can be deposited to fill the stepped cavity overlying the stepped surfaces of the first alternating stack (**132**, **142**) to form a first-tier retro-stepped dielectric material portion **165**. Specifically, the dielectric material can be deposited in the stepped cavity overlying the stepped surfaces of the first alternating stack (**132**, **142**). The dielectric material can be subsequently planarized employing the top surface of the first insulating cap layer **170** as a stopping surface. The remaining portion of the deposited dielectric material forms a first retro-stepped dielectric material portion **165**. The first retro-stepped dielectric material portion **165** includes a dielectric material that is different from the material of the first sacrificial material layers **142**. For example, the first retro-stepped dielectric material portion **165** can include undoped silicate glass or doped silicate glass. The top surface of the first retro-stepped dielectric material portion **165** can be coplanar with the top surface of the first insulating cap layer **170**. The bottom surfaces of the first retro-stepped dielectric material portion **165** contacts the stepped surfaces of the first alternating stack (**132**, **142**) and top surfaces of the word line contact via structures (**67**, **68**).

[0283] An inter-tier dielectric layer **180** may be optionally deposited over the first-tier structure (**132**, **142**, **165**, **170**,

148, **67**, **68**). The inter-tier dielectric layer **180** includes a dielectric material such as silicon oxide. The thickness of the inter-tier dielectric layer **180** can be in a range from 30 nm to 300 nm, although lesser and greater thicknesses can also be employed. Locations of steps S in the first-tier alternating stack (**132**, **142**) are illustrated as dotted lines.

[0284] In one embodiment, openings can be formed through the inter-tier dielectric layer **180** in areas that overlap with the sacrificial memory opening fill portions **148**. An etch mask having the same pattern as the sacrificial memory opening fill portions **148** (which have the same pattern as the first-tier memory openings **149**) can be employed, and an anisotropic etch can be performed to transfer the pattern in the etch mask through the inter-tier dielectric layer **180**. The same sacrificial material layer as the sacrificial material layer of the sacrificial memory opening fill portions **148** can be deposited in the openings in the inter-level dielectric layer **180**. Upon incorporation of the additional sacrificial material in the inter-level dielectric layer **180**, the sacrificial memory opening fill portions **148** can extend through the first alternating stack (**132**, **142**) and the inter-level dielectric layer **180**. In one embodiment, each of the sacrificial memory opening fill portions **148** can have a greater lateral dimension at the level of the inter-tier dielectric layer **180** than at the levels of the first alternating stack (**132**, **142**). In this case, the wider regions of the sacrificial memory opening fill portions **148** at the level of the inter-tier dielectric layer **180** can function as landing pads during subsequent formation of second-tier memory openings.

[0285] Referring to FIGS. **50**A and **50**B, the processing steps of FIG. **6** can be performed to form a second-tier structure over the first-tier structure (**132**, **142**, **170**, **165**, **148**, **67**, **68**). The second-tier structure can include an additional alternating stack of insulating layers and spacer material layers, which can be sacrificial material layers in the same manner as in the first and second embodiments. For example, a second alternating stack (**232**, **242**) of second insulating layers **232** and second sacrificial material layers **242** can be formed.

[0286] Second stepped surfaces in the second stepped area can be formed in the word line contact region **200** in the same manner as in the first embodiment. A second-tier retro-stepped dielectric material portion **265** can be formed over the second stepped surfaces in the word line contact region **200**. A second insulating cap layer **270** can be subsequently formed over the second alternating stack (**232**, **242**). The second insulating cap layer **270** includes a dielectric material that is different from the material of the second sacrificial material layers **242**. In one embodiment, the second insulating cap layer **270** can include silicon oxide. In one embodiment, the first and second sacrificial material layers (**142**, **242**) can comprise silicon nitride.

[0287] Optionally, drain-select-level shallow trench isolation structures **72** can be formed through a subset of layers in an upper portion of the second-tier alternating stack (**232**, **242**). The second sacrificial material layers **242** that are cut by the select-drain-level shallow trench isolation structures **72** correspond to the levels in which drain-select-level electrically conductive layers are subsequently formed. The drain-select-level shallow trench isolation structures **72** include a dielectric material such as silicon oxide.

[0288] Referring to FIGS. **51**A-**51**C, second-tier memory openings **249** and second-tier support openings **219** are formed. The second-tier memory openings **249** extend through the second-tier structure (**232**, **242**, **270**, **265**) in areas overlying the sacrificial memory opening fill portions **148**. A photoresist layer can be applied over the second-tier structure (**232**, **242**, **270**, **265**), and can be lithographically patterned to form a pattern that includes the pattern of the sacrificial memory opening fill portions **148** and a pattern for subsequently forming support structures in the word line contact region **200**. An anisotropic etch can be performed to transfer the pattern of the lithographically patterned photoresist layer through the second-tier structure (**232**, **242**, **270**, **265**). In one embodiment, the chemistry of the anisotropic etch process employed to etch through the materials of the second-tier alternating stack (**232**, **242**) can alternate to optimize etching of the alternating material layers in the second-tier alternating stack (**232**, **242**). The anisotropic etch can be, for example, a series of reactive ion etches. The patterned lithographic material stack can be removed, for example, by ashing after the anisotropic etch process.

[0289] A top surface of an underlying sacrificial memory opening fill portion **148** can be physically exposed at the bottom of each second-tier memory opening **249**. Each second-tier support opening **219** can extend to the inter-tier dielectric layer **180** or the first retro-stepped dielectric material portion **165** (in case the inter-tier dielectric layer **180** is not employed).

[0290] Referring to FIG. **52**, after the top surfaces of the sacrificial memory opening fill portions **148** are physically exposed, an etch process can be performed, which removes the sacrificial material of the sacrificial memory opening fill portions **148** selective to the materials of the second-tier alternating stack (**232**, **242**) and the first-tier alternating stack (**132**, **142**) (e.g., C_4F_8 /O_2 /Ar etch). Upon removal of the sacrificial memory opening fill portions **148**, each vertically adjoining pair of a second-tier memory opening **249** and a first-tier memory opening **149** forms a continuous cavity that extends through the first-tier alternating stack (**132**, **142**) and the second-tier alternating stack (**232**, **242**). Each continuous cavity is herein referred to as an inter-tier memory opening **49**. A top surface of the planar semiconductor material layer **10** can be physically exposed at the bottom of each inter-tier memory opening **49**.

[0291] Referring to FIGS. **53**A-**53**C, memory opening fill structures **58** are formed in each of the inter-tier memory openings **49**. For example, the processing steps of FIGS. **9**A-**9**H can be performed to form the memory opening fill structures **58** in the inter-tier memory openings **49**. Each memory opening fill structure **58** includes a respective memory stack structure **55**. Each memory stack structure vertically extends through the first alternating stack (**132**, **142**) and the second alternating stack (**232**, **242**). Each memory stack structure **55** comprises a memory film **50** and a vertical semiconductor channel **60** laterally surrounded by the memory film **50**.

[0292] Support pillar structures **320** are formed within each second-tier support opening **219** collaterally during the processing steps that form the memory opening fill structures **58** in the inter-tier memory openings **49**. As such, each material portion of a support pillar structure **320** can have the same composition as a corresponding material portion in a memory opening fill structures **58**. For example, each support pillar structure **320** can have a layer stack that has the same set of material layers as a memory film **50** within a memory opening fill structure **58**, at least one semicon-

ductor material layer having the same composition and thickness as a vertical semiconductor channel **60** within a memory opening fill structure **58**, a dielectric core having the same composition as a dielectric core **62** within a memory opening fill structure **58**, and a dummy drain region having a same composition as a drain region **63** within a memory opening fill structure **58**. In this embodiment, the support pillar structures **320** are present in the second tier, but can be omitted in the first tier. The locations of insulating spacers **74** and backside contact via structures **76** to be formed in subsequent steps are shown in dashed lines in FIG. **53**C.

[0293] Referring to FIGS. **54**A and **54**B, the processing steps of FIGS. **10**A and **10**B can be performed to form a first contact level dielectric layer **280** and backside trenches **79**.

[0294] Referring to FIGS. **55**A-**55**C, a first subset of the processing steps of FIGS. **11**A and **11**B can be performed to replace the sacrificial material layers (**142**, **242**) with electrically conductive layers (**246**, **246**). The word line contact via structures (**67**, **68**) provide structural support in the first tier of the word line contact region **200**, the support pillar structures **320** provide structural support in the second tier of the word line contact region **200**, and the memory opening fill structures **58** provide structural support in the memory array region **100** while backside recesses are present between vertically neighboring pairs of insulating layers (**132**, **232**) during replacement of the sacrificial material layers (**142**, **242**) with the electrically conductive layers (**246**, **246**). Replacement of the second sacrificial material layers **242** with the second electrically conducive layers **246** occurs concurrently with replacement of the first sacrificial material layers **142** with the first electrically conductive layers **146**. Each first electrically conductive layer **146** contacts a respective one of the word line contact via structures (**67**, **68**).

[0295] Subsequently, source regions **61** can be formed in the same manner as in the first embodiment. Upper portions of the semiconductor material layer **10** located between the source regions **61** and the pedestal channel portions **11** constitute horizontal semiconductor channels **59**.

[0296] A second subset of the processing steps of FIGS. **11**A and **11**B can be performed to form insulating spacers **74** and backside contact via structures **76** (which may be laterally-elongated contact via structures).

[0297] Referring to FIGS. **56**A-**56**C, a second contact level dielectric layer **282** over the second contact level dielectric layer **280**. The processing steps of FIGS. **12**A and **12**B can be performed, with modification, to form the drain contact via structures **88** and the word line contact via structures **86**. In this case, the word line contact via structures **86** extend only through the first and second contact level dielectric layers (**280**, **282**), the second insulating cap layer **270**, and the second retro-stepped dielectric material portion **265** and contacts a top surface of a respective one of the second electrically conductive layers **246**. The word line contact via structures **86** do not extend into the fist-tier structure (**132**, **146**, **170**, **165**, **67**, **68**), or extend below the horizontal plane including the bottommost layer within the second alternating stack (**232**, **246**).

[0298] The word line contact via structures (**67**, **68**) formed at the processing steps of FIG. **48** are herein referred to as first word line contact via structures (**67**, **68**), and the word line contact via structures **86** formed at the processing steps of FIGS. **56**A-**56**C are herein referred to as second word line contact via structures **86**. In the third exemplary structure, the first word line contact via structures (**67**, **68**) provide vertical electrical connection between the first electrically conductive layers **146** and the peripheral devices on the substrate semiconductor layer **9**, and the second word line contact via structures **86** provide vertical electrical connection between the second electrically conductive layers **246** and the peripheral devices on the substrate semiconductor layer **9**. The areas of the first word line contact via structures (**67**, **68**) and the areas of the second word line contact via structures **86** can overlap, and thus, the total area for the word line contact region **200** can be reduced compared to the configuration of the first exemplary structure.

[0299] Subsequently, the processing steps of FIGS. **13**A and **13**B, FIG. **14**, FIG. **15**, and FIGS. **16**A and **16**B can optionally be performed to form through-stack insulating spacers **586**, through-stack contact via structures **588**, and through-dielectric contact via structures **488**. The through-stack contact via structures **588** and through-dielectric contact via structures **488** can be employed to provide electrical connections to bit lines to be subsequently formed and to provide power and ground connections to the three-dimensional memory device formed on the semiconductor material layer **10**.

[0300] Referring to FIG. **57**, the processing steps of FIG. **17** can be performed to form at least one upper interconnect level dielectric layer **284** over the contact level dielectric layers (**280**, **282**). The at least one upper interconnect level dielectric layer **284** can include multiple upper interconnect level dielectric layers. Various upper interconnect structures, such as upper interconnect level metal structures, can be formed in the at least one upper interconnect level dielectric layer **284**. For example, the various upper interconnect level metal structures can include line level metal interconnect structures (**96**, **98**, **99**). The line level metal interconnect structures (**96**, **98**, **99**) can include first upper metal line structures **99** that contact a top surfaces of a respective one of the through-stack contact via structures **588**, second upper metal line structures **96** that contact a top surface of a respective one of the through-dielectric contact via structures **488**, and bit lines **98** that contact a respective one of the drain contact via structures **88** and extend along the second horizontal direction (e.g., bit line direction) hd**2** and perpendicular to the first horizontal direction (e.g., word line direction) hd**1**. In one embodiment, a subset of the first upper metal line structures **99** may be employed to provide electrical connections through the source connection via structures **91** described above to the laterally-elongated contact via structures **76** and to the source regions **61**. In one embodiment, a subset of the second upper metal line structures **96** may contact, or are electrically coupled to, a respective pair of a word line contact via structure **86** and a through-dielectric contact via structure **488**.

[0301] At least a subset of the upper metal interconnect structures (which include the line level metal interconnect structures (**96**, **98**, **99**)) is formed over the three-dimensional memory array. The upper metal interconnect structures comprise an upper metal line structure (such as a first upper metal line structure **99**) that is formed directly on a through-stack contact via structure **588**. A set of conductive structures including the through-stack contact via structure **588** and a lower metal line structure (such as a topmost lower metal line structure **788**) provides an electrically conductive path between the at least one semiconductor device **710** on

the substrate semiconductor layer and the upper metal line structure. A through-dielectric contact via structure **488** can be provided through the retro-stepped dielectric material portions (**165**, **265**), the at least one second dielectric material layer **768**, and the silicon nitride layer **766** and directly on a top surface of another lower metal line structure (e.g., another topmost lower metal line structure **788**) of the lower metal interconnect structures **780**. The through-dielectric contact via structures **488** can be formed on a respective one of the lower interconnect structures **780** within an area outside of the alternating stacks (**132**, **146**, **232**, **246**).

[0302] While a multi-tier structure containing at least two tiers of alternating stacks (**132**, **146**) and (**232**, **246**) is described above, the present disclosure is not limited to a multi-tier structure. In an alternative embodiment, a single tier structure containing only one alternating stack (**132**, **146**) can be formed. In this alternative embodiment, the upper alternating stack (**232**, **246**) can be omitted.

[0303] Furthermore, the first-tier memory openings **149** and first-tier contact openings **115** can be formed during the same etching step in a single tier structure, as shown in FIGS. **23**A and **23**B. In another alternative embodiment, the first-tier memory openings **149** and contact openings **115** can be formed in separate etching steps in a single tier structure. In this alternative embodiment, the first-tier memory openings **149** are formed in the alternating stack (**132**, **142**) first, and are then filled with memory opening fill structures **58** which contain memory stack structures **55**. After formation of the memory opening fill structures **58**, the contact openings **115** are formed in the alternating stack (**132**, **142**) and are then filled with the sacrificial contact opening fill portions **127**, as shown in FIGS. **24**A and **24**B. The terrace region is then formed in the alternating stack (**132**, **142**) using the method illustrated in FIGS. **29-31**. The sacrificial contact opening fill portions **127** are then removed from the contact openings **115** to form support openings **119**, as shown in FIG. **32**. The method then proceeds according to the steps illustrated in FIGS. **33-39**, as described above.

[0304] Referring to all drawings of the present disclosure and according to various embodiments of the present disclosure, a three-dimensional memory device is provided. The three-dimensional memory device includes: semiconductor devices **710** located on a semiconductor substrate **9**; lower interconnect level dielectric layers **760** located over the semiconductor devices **710** and embedding lower interconnect structures **780** that are electrically connected to the respective semiconductor devices **710**; an alternating stack {(**132**, **146**) and/or (**232**, **246**)} of insulating layers (**132**, **232**) and electrically conductive layers (**146**, **246**) located over the lower interconnect level dielectric layers **760**, wherein stepped surfaces of layers of the alternating stack {(**132**, **146**) and/or (**232**, **246**)} are provided in a terrace region; memory stack structures **55** vertically extending through the alternating stack {(**132**, **146**) and/or (**232**, **246**)}, wherein each of the memory stack structures **55** comprises a memory film **50** and a vertical semiconductor channel **60** laterally surrounded by the memory film **50**; and contact via structures (**67**, **68**) located in the terrace region, wherein each of the contact via structures (**67**, **68**) laterally contacts a respective one of the electrically conductive layers (**146**, **246**), vertically extends through a respective opening in at least a bottommost electrically conductive layer **146** of the alternating stack {(**132**, **146**) and/or (**232**, **246**)}, and contacts a respective one of the lower interconnect structures **780** that underlie the alternating stack {(**132**, **146**) and/or (**232**, **246**)}.

[0305] In one embodiment, a top surface of each of the contact via structures (**67**, **68**) is substantially coplanar with (i.e., within 2 nm of a top surface of) a horizontal stepped surface of the respective one of the electrically conductive layers (**146**, **246**). In one embodiment, each of the contact via structures (**67**, **68**) vertically extends through openings in each layer of the alternating stack {(**132**, **146**) and/or (**232**, **246**)} that underlies the respective one of the electrically conductive layers (**146**, **246**). In one embodiment, each of the contact via structures (**67**, **68**) is electrically isolated from each layer of the alternating stack {(**132**, **146**) and/or (**232**, **246**)} that underlies the respective one of the electrically conductive layers (**146**, **246**) by an insulating tubular liner **66**.

[0306] In one embodiment, each of the contact via structures (**67**, **68**) comprises: a metallic nitride liner **67**A' contacting the respective one of the lower interconnect structures **780**; a metal fill portion **67**B' located within the metallic nitride liner **67**A' and contacting the respective one of the lower interconnect structures **780**; and a metallic pillar structure **68** contacting a generally cylindrical sidewall of the respective one of the electrically conductive layers (**146**, **246**). As used herein, a "generally cylindrical sidewall" refers to a sidewall having a general configuration of a cylindrical surface, which may have a circular cylindrical surface, an elliptical cylindrical surface, or any other generally concave and vertical surface.

[0307] In one embodiment, the metallic pillar structure **68** contacts a top surface of the metal fill portion **67**B' and an annular top surface of the metallic liner layer **67**A'. In one embodiment, the metallic pillar structure **68** has a greater lateral extent than the metal fill portion **67**B', and an outer periphery of an interface between a bottom surface of the metallic pillar structure **68** and the metallic nitride liner **67**A' is located entirely on a sidewall of a respective one of the insulating layers (**132**, **232**) that contacts a bottom surface of the respective one of the electrically conductive layers (**146**, **246**).

[0308] In one embodiment, the stepped surfaces continuously extend from a bottommost layer within the alternating stack {(**132**, **146**) and (**232**, **246**)} to a topmost layer within the alternating stack {(**132**, **146**) and (**232**, **246**)}, and each electrically conductive layer (**146**, **246**) within the alternating stack {(**132**, **146**) and/or (**232**, **246**)} contacts a respective one of the contact via structures (**67**, **68**).

[0309] In one embodiment, a retro-stepped dielectric material portion **365** is located over the stepped surfaces in the terrace region, and an entire region of the retro-stepped dielectric material portion **365** within an area of the stepped surfaces is free of any conductive via structure, i.e., does not include any conductive via structure.

[0310] In one embodiment, the stepped surfaces are surfaces of a first subset (**132**, **146**) of layers in the alternating stack {(**132**, **146**) and (**232**, **246**)} that includes a bottommost layer within the alternating stack {(**132**, **146**) and (**232**, **246**)}. A second subset (**232**, **246**) of layers of the alternating stack {(**132**, **146**) and (**232**, **246**)} that overlies the first subset of layers include additional stepped surfaces that overhangs the stepped surfaces. Each electrically conductive layer **146** within the first subset (**132**, **146**) of layers contacts a respective one of the contact via structures (**67**, **68**), i.e., a

respective one of the first word line contact via structures (**67**, **68**), and each electrically conductive layer **246** within the second subset (**232**, **246**) of layers includes a respective top surface that contacts a bottom surface of a respective one of additional contact via structures **86**, i.e., a respective one of second word line contact via structures **86**. The first word line contact via structures (**67**, **68**) have bottom surfaces located within a first horizontal plane, and the second word line contact via structures **68** includes top surfaces located with a second horizontal plane. A retro-stepped dielectric material portion **265** is located over the additional stepped surfaces, and each of the additional contact via structures **86** vertically extends through the retro-stepped dielectric material portion **265**.

[0311] In one embodiment, the three-dimensional memory device further comprises upper interconnect level dielectric layers **284** located over the alternating stack {(**132**, **146**) and/or (**232**, **246**)} and embedding upper interconnect structures (**96**, **98**) that are electrically connected via a respective drain region **63** to an upper end of a respective one of the vertical semiconductor channels **60**, and through-dielectric contact via structures **488** vertically extending between a respective one of the upper interconnect structures (**96**., **98**) and a respective one of the lower interconnect structures **780** within an area outside of the alternating stack {(**132**, **146**), (**232**, **246**)}. The upper interconnect structures (**96**, **98**) comprises bit lines **98** that are electrically connected via a respective drain region **63** to an upper end of a respective one of the vertical semiconductor channels **60**. The semiconductor devices **710** comprise word line and/or bit line drivers.

[0312] In one embodiment, the three-dimensional memory device comprises a monolithic three-dimensional NAND memory device, the electrically conductive layers (**146**, **246**) comprise, or are electrically connected to, a respective word line of the monolithic three-dimensional NAND memory device, bottom ends of the memory stack structures **58** contact a planar semiconductor material layer **10**, and the monolithic three-dimensional NAND memory device comprises an array of monolithic three-dimensional NAND strings over the planar semiconductor material layer **10**.

[0313] At least one memory cell in a first device level of the array of monolithic three-dimensional NAND strings is located over another memory cell in a second device level of the array of monolithic three-dimensional NAND strings. The at least one semiconductor device **710** comprises an integrated circuit comprising a driver circuit for monolithic three-dimensional NAND memory device located thereon. The electrically conductive layers (**146**, **246**) comprise a plurality of control gate electrodes having a strip shape extending substantially parallel to the top surface of the substrate **9**.

[0314] The plurality of control gate electrodes comprises at least a first control gate electrode located in the first device level and a second control gate electrode located in the second device level. The array of monolithic three-dimensional NAND strings comprises a plurality of semiconductor channels (**59**, **11**, **60**), wherein at least one end portion **60** of each of the plurality of semiconductor channels (**59**, **11**, **60**) extends substantially perpendicular to a top surface of the semiconductor substrate, and a plurality of charge storage elements (as embodied as portions of the charge storage layers **54** located at levels of the electrically conductive layers (**146**, **246**)), each charge storage element located adjacent to a respective one of the plurality of semiconductor channels (**59**, **11**, **60**).

[0315] Although the foregoing refers to particular embodiments, it will be understood that the disclosure is not so limited. It will occur to those of ordinary skill in the art that various modifications may be made to the disclosed embodiments and that such modifications are intended to be within the scope of the disclosure. Compatibility is presumed among all embodiments that are not alternatives of one another. The word "comprise" or "include" contemplates all embodiments in which the word "consist essentially of" or the word "consists of" replaces the word "comprise" or "include," unless explicitly stated otherwise. Where an embodiment employing a particular structure and/or configuration is illustrated in the present disclosure, it is understood that the present disclosure may be practiced with any other compatible structures and/or configurations that are functionally equivalent provided that such substitutions are not explicitly forbidden or otherwise known to be impossible to one of ordinary skill in the art. All of the publications, patent applications and patents cited herein are incorporated herein by reference in their entirety.

What is claimed is:

1. A three-dimensional memory device, comprising:

semiconductor devices located on a top surface of a semiconductor substrate;

lower interconnect level dielectric layers located over the semiconductor devices and embedding lower interconnect structures that are electrically connected to a respective one of the semiconductor devices;

an alternating stack of insulating layers and electrically conductive layers located over the lower interconnect level dielectric layers, wherein stepped surfaces of layers of the alternating stack are provided in a terrace region;

memory stack structures vertically extending through the alternating stack, wherein each of the memory stack structures comprises a memory film and a vertical semiconductor channel laterally surrounded by the memory film; and

contact via structures located in the terrace region, wherein each of the contact via structures laterally contacts a respective one of the electrically conductive layers, vertically extends through a respective opening in at least a bottommost electrically conductive layer of the alternating stack, and contacts a respective one of the lower interconnect structures that underlie the alternating stack.

2. The three-dimensional memory device of claim **1**, wherein a top surface of each of the contact via structures is substantially coplanar with a horizontal stepped surface of the respective one of the electrically conductive layers.

3. The three-dimensional memory device of claim **1**, wherein:

each of the contact via structures vertically extends through openings in each layer of the alternating stack that underlies the respective one of the electrically conductive layers; and

each of the contact via structures is electrically isolated from each layer of the alternating stack that underlies the respective one of the electrically conductive layers by an insulating tubular liner.

4. The three-dimensional memory device of claim **1**, wherein each of the contact via structures comprises:

a metallic nitride liner contacting the respective one of the lower interconnect structures;

a metal fill portion located within the metallic nitride liner; and

a metallic pillar structure contacting a generally cylindrical sidewall of the respective one of the electrically conductive layers.

5. The three-dimensional memory device of claim **4**, wherein the metallic pillar structure contacts a top surface of the metal fill portion and an annular top surface of the metallic liner layer.

6. The three-dimensional memory device of claim **4**, wherein:

the metallic pillar structure has a greater lateral extent than the metal fill portion; and

an outer periphery of an interface between a bottom surface of the metallic pillar structure and the metallic nitride liner is located entirely on a sidewall of a respective one of the insulating layers that contacts a bottom surface of the respective one of the electrically conductive layers.

7. The three-dimensional memory device of claim **1**, wherein:

the stepped surfaces continuously extend from a bottommost layer within the alternating stack to a topmost layer within the alternating stack;

each electrically conductive layer within the alternating stack contacts a respective one of the contact via structures;

a retro-stepped dielectric material portion is located over the stepped surfaces in the terrace region; and

an entire region of the retro-stepped dielectric material portion within an area of the stepped surfaces is free of any conductive via structure.

8. The three-dimensional memory device of claim **1**, wherein:

the stepped surfaces are surfaces of a first subset of layers in the alternating stack that includes a bottommost layer within the alternating stack;

a second subset of layers of the alternating stack that overlies the first subset of layers include additional stepped surfaces that overhangs the stepped surfaces;

each electrically conductive layer within the first subset of layers contacts a respective one of the contact via structures; and

each electrically conductive layer within the second subset of layers includes a respective top surface that contacts a bottom surface of a respective one of additional contact via structures;

9. The three-dimensional memory device of claim **1**, wherein:

a retro-stepped dielectric material portion is located over the additional stepped surfaces; and

each of the additional contact via structures vertically extends through the retro-stepped dielectric material portion.

10. The three-dimensional memory device of claim **1**, further comprising:

upper interconnect level dielectric layers located over the alternating stack and embedding upper interconnect structures that are electrically connected via a respective drain region to an upper end of a respective one of the vertical semiconductor channels; and

through-dielectric contact via structures vertically extending between a respective one of the upper interconnect structures and a respective one of the lower interconnect structures within an area outside of the alternating stack,

wherein the upper interconnect structures comprise bit lines that are electrically connected via a respective drain region to an upper end of a respective one of the vertical semiconductor channels; and

wherein the semiconductor devices comprise at least one of word line drivers or bit line drivers.

11. The three-dimensional memory device of claim **1**, wherein:

the three-dimensional memory device comprises a monolithic three-dimensional NAND memory device;

the electrically conductive layers comprise, or are electrically connected to, a respective word line of the monolithic three-dimensional NAND memory device;

bottom ends of the memory stack structures contact a planar semiconductor material layer;

the monolithic three-dimensional NAND memory device comprises an array of monolithic three-dimensional NAND strings over the planar semiconductor material layer;

at least one memory cell in a first device level of the array of monolithic three-dimensional NAND strings is located over another memory cell in a second device level of the array of monolithic three-dimensional NAND strings;

the at least one semiconductor device comprises an integrated circuit comprising a driver circuit for monolithic three-dimensional NAND memory device located thereon;

the electrically conductive layers comprise a plurality of control gate electrodes having a strip shape extending substantially parallel to the top surface of the semiconductor substrate;

the plurality of control gate electrodes comprises at least a first control gate electrode located in the first device level and a second control gate electrode located in the second device level; and

the array of monolithic three-dimensional NAND strings comprises:

a plurality of semiconductor channels, wherein at least one end portion of each of the plurality of semiconductor channels extends substantially perpendicular to a top surface of the semiconductor substrate, and

a plurality of charge storage elements, each charge storage element located adjacent to a respective one of the plurality of semiconductor channels.

12. A method of forming a three-dimensional memory device, comprising:

forming semiconductor devices on a semiconductor substrate;

forming lower interconnect level dielectric layers embedding lower interconnect structures over the semiconductor devices, wherein the lower interconnect structures are electrically connected to the respective semiconductor devices;

forming an alternating stack of insulating layers and sacrificial material layers over the lower interconnect level dielectric layers;

forming stepped surfaces on the alternating stack in a word line contact region by patterning the alternating stack;

forming contact via structures in the word line contact region, wherein each of the contact via structures laterally contacts a respective one of the sacrificial material layers, vertically extends through a respective opening in at least a bottommost sacrificial material layer of the alternating stack, and contacts a respective one of the lower interconnect structures that underlie the alternating stack;

forming memory stack structures through the alternating stack, wherein each of the memory stack structures comprises a memory film and a vertical semiconductor channel laterally surrounded by the memory film; and

replacing the sacrificial materials with electrically conductive layers.

13. The method of claim **12**, further comprising:

forming sacrificial contact opening pillars in the word line contact region prior to forming the stepped surfaces;

removing upper portions of the sacrificial contact opening pillars concurrently with formation of the stepped surfaces; and

replacing remaining portions of the sacrificial contact opening pillars with the contact via structures.

14. The method of claim **13**, further comprising:

applying a trimmable mask layer over the alternating stack; and

repeating a set of processing steps multiple times to form the stepped surfaces and to remove the upper portions of the sacrificial contact opening pillars, wherein:

the step of processing steps comprises a first step of removing an uppermost pair of layers that includes one of the insulating layers and one of the sacrificial material layers within each area that is not covered by the trimmable mask layer, and removing each portion of the sacrificial contact opening pillars from above a physically exposed horizontal surface within each area that is not covered by the trimmable material layer, and a second step of trimming the trimmable mask layer to provide an additional area that is not covered by the trimmable mask layer.

15. The method of claim **13**, wherein:

the step of forming the contact via structures occurs before or after the step of forming the memory stack structures;

the insulating layers comprise undoped silicate glass;

the sacrificial material layers comprise silicon nitride; and

the sacrificial contact opening pillars comprise borosilicate glass or a porous organosilicate glass.

16. The method of claim **13**, further comprising:

removing remaining portions of the sacrificial contact opening pillars selective to materials of the insulating layers and the sacrificial material layers after formation of the stepped surfaces to form contact via cavities;

forming a continuous insulating liner layer within each of the contact via cavities and over the stepped surfaces of the alternating stack;

forming insulating tubular liners within each of the contact via cavities by anisotropically etching the continuous insulating liner layer, wherein the contact via structures are formed on a sidewall of a respective one of the insulating tubular liners;

depositing a continuous metallic nitride liner layer on top surfaces of the lower interconnect structures and on inner sidewalls of the insulating tubular liners;

depositing a continuous metal fill layer on the continuous metallic nitride liner layer;

anisotropically etching the continuous metal fill layer and the continuous metallic nitride liner layer, wherein remaining portions of the continuous metallic nitride liner layer constitute metallic nitride liners located within a respective one of the contact via cavities, and remaining portions of the continuous metal fill layer constitute metal fill portions located within a respective one of the metallic nitride liners; and

forming a metallic pillar structure on top of each adjoining pair of a metallic nitride liner and a metal fill portion.

17. The method of claim **16**, wherein:

each of the contact via cavities has a top periphery that is adjoined to a respective horizontal surface of the stepped surfaces;

a sidewall of a sacrificial material layer is physically exposed within each of the contact via cavities after formation of the metallic nitride liners and the metal fill portions;

the method further comprises forming metallic pillar structures in unfilled volumes of each of the contact via cavities and directly on the sidewalls of the sacrificial material layers around the contact via cavities; and

the metallic pillar structures are formed by a selective metal deposition process that grows a metallic material from surfaces of the metallic nitride liners and the metal fill portions and does not grow the metallic material from surfaces of the insulating layers and the sacrificial material layers.

18. The method of claim **13**, wherein:

the stepped surfaces continuously extend from a bottommost layer within the alternating stack to a topmost layer within the alternating stack;

the method further comprises forming a retro-stepped dielectric material portion over the stepped surfaces in the word line contact region;

each electrically conductive layer within the alternating stack contacts a respective one of the contact via structures;

the method further comprises forming upper interconnect structures over the memory stack structures after formation of the electrically conductive layers; and

an entire region of the retro-stepped dielectric material portion within an area of the stepped surfaces is free of any conductive via structure after formation of the upper interconnect structures.

19. The method of claim **13**, further comprising:

forming a retro-stepped dielectric material portion over the stepped surfaces in the word line contact region after formation of the contact via structures;

forming an additional alternating stack of additional insulating layers and additional sacrificial material layers over the retro-stepped dielectric material portion;

patterning the additional alternating stack to form additional stepped surfaces, wherein the memory stack structures are formed through the additional alternating stack and the alternating stack;

replacing the additional sacrificial material layers with additional electrically conductive layers concurrently

with replacement of the sacrificial material layers with the electrically conductive layers; and

forming additional contact via structures on top surfaces of the additional electrically conductive layers.

20. The method of claim **13**, further comprising:

forming through-dielectric contact via structures on a respective one of the lower interconnect structures within an area outside of the alternating stack; and

forming upper interconnect level dielectric layers embedding upper interconnect structures over the alternating stack, wherein:

the upper interconnect structures comprise bit lines that are electrically shorted to an upper end of a respective one of the vertical semiconductor channels and to a respective one of the through-dielectric contact via structures; and

the semiconductor devices comprise bit line drivers.

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