

and to get a flat surface (Fig. 27d). Due to its high resistance to polishing, the nitride acts as a stop-layer for the CMP process. After the polishing, the nitride layer and the oxide layer can be removed by H_3PO_4 and HF, respectively. This initial planarization step at the beginning is helpful for the subsequent polysilicon patterning and planarizations of the multilevel interconnection processes.

Gate-Engineering Technology

If we use n^+ -polysilicon for both PMOS and NMOS gates, the threshold voltage for PMOS ($V_{TP} \approx -0.5$ to -1.0 V) has to be adjusted by boron implantation. This makes the channel of the PMOS a buried type, shown in Fig. 28a. The buried-type PMOS suffers serious short-channel effects as the device size shrinks to $0.25\text{ }\mu\text{m}$ and less. The most noticeable phenomena for short-channel effects are the V_T roll-off, drain-induced barrier lowering (DIBL), and the large leakage current at the off state so that even with the gate voltage at zero, leakage current flows through source and drain. To alleviate this problem, one can change n^+ -polysilicon to p^+ -polysilicon for PMOS. Due to the work function difference (there is a 1.0 eV difference from n^+ - to p^+ -polysilicon), one can obtain a surface p -type channel device without the boron V_T adjustment implantation. Hence, as the technology shrinks to $0.25\text{ }\mu\text{m}$ and less, dual-gate structures are required, i.e., p^+ -polysilicon gate for PMOS, and n^+ -polysilicon for NMOS (Fig. 28b). A comparison of V_T for the surface channel and the buried channel is shown in Fig. 29. We note that the V_T of surface channel rolls off slowly in the deep-submicron regime compared with the buried-channel device. This makes the surface-channel device with the p^+ -polysilicon suitable for deep-submicron device operation.

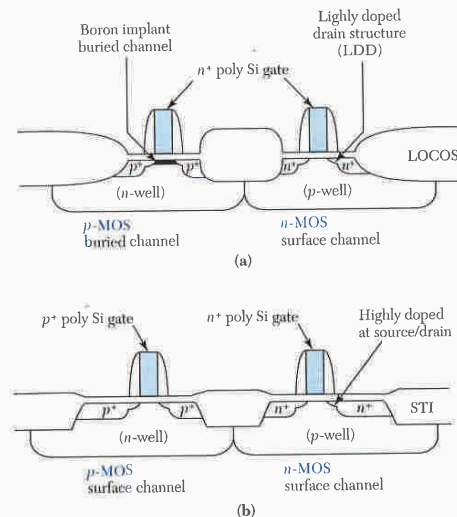


Fig. 28 (a) A conventional long-channel CMOS structure with a single-polysilicon gate (n^+). (b) Advanced CMOS structures with dual-polysilicon gates.

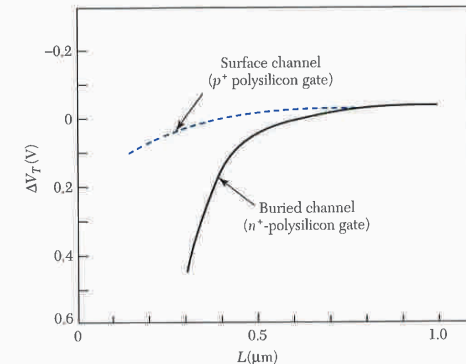


Fig. 29 The V_T roll-off for a buried type channel and for a surface type channel. The V_T drops very quickly as the channel length becomes less than $0.5\text{ }\mu\text{m}$.

To form the p^+ -polysilicon gate, ion implantation of BF_3^+ is commonly used. However, boron penetrates easily from the polysilicon through the oxide into the silicon substrate at high temperatures, resulting in a V_T shift. This penetration is enhanced in the presence of a F-atom. There are methods to reduce this effect: use of rapid thermal annealing to reduce the time at high temperatures and, consequently, the diffusion of boron; use of nitrided oxide to suppress the boron penetration, since boron can easily combine with nitrogen and becomes less mobile; and the making of a multilayer of polysilicon to trap the boron atoms at the interface of the two layers.

Figure 30 shows a microprocessor chip (Pentium 4) that has an area of about 200 mm^2 and contains 42 million components. This ULSI chip is fabricated using $0.18\text{ }\mu\text{m}$ CMOS technology with a six-level aluminum metallization.

14.3.4 BiCMOS Technology

BiCMOS is a technology that combines both CMOS and bipolar device structures in a single IC. The reason to combine these two different technologies is to create an IC chip that has the advantages of both CMOS and bipolar devices. As we know that CMOS exhibits advantages in power dissipation, noise margin, and packing density, whereas bipolar shows advantages in switching speed, current drive capability, and analog capability. As a result, for a given design rule, BiCMOS can have a higher speed than CMOS, better performance in analog circuits than CMOS, a lower power-dissipation than bipolar, and a higher component density than bipolar. Figure 31 shows the comparison of a BiCMOS and a CMOS logic gates. For a CMOS inverter, the current to drive (or to charging) the next loading, C_L , is the drain current I_{DS} . For a BiCMOS inverter, the current is $h_{fe}I_{DS}$, where h_{fe} is the current-gain of the bipolar transistor and I_{DS} is the base current of the bipolar transistor and is equal to the drain current of M_2 in the CMOS. Since h_{fe} is much larger than 1, the speed can be substantially enhanced.

BiCMOS has been widely used in many applications. In the early days, it was used in SRAM. At the present time, BiCMOS technology has been successfully developed for transceiver, amplifier, and oscillator applications in wireless-communication equipment.

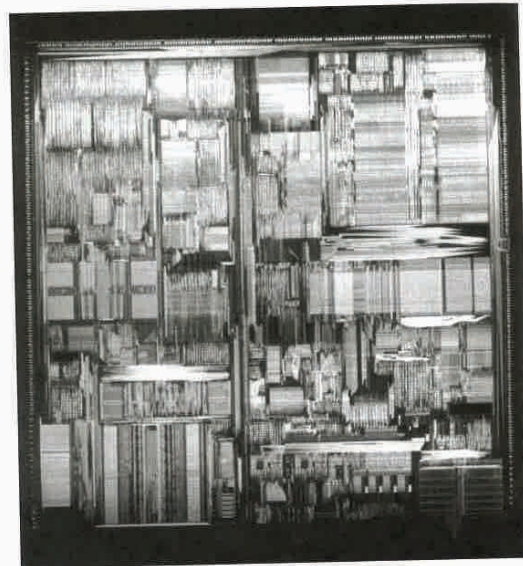


Fig. 30 Micrograph of a 32-bit microprocessor chip, Pentium 4. (Photography courtesy of Intel Corporation.)

Most of the BiCMOS processes are based on the CMOS process, with some modifications, such as adding masks for bipolar transistor fabrication. The following example is for a high-performance BiCMOS process based on the twin-well CMOS process, shown¹³ in Fig. 32.

The initial material is a p -type silicon substrate, and then an n^+ -buried layer is formed to reduce the collector's resistance. The buried p -layer is formed through ion implantation to increase the doping level to prevent punchthrough. A lightly doped n -epi layer is grown on the wafer and a twin-well process for the CMOS is performed. To achieve high performance of the bipolar transistor, four additional masks are needed. They are the

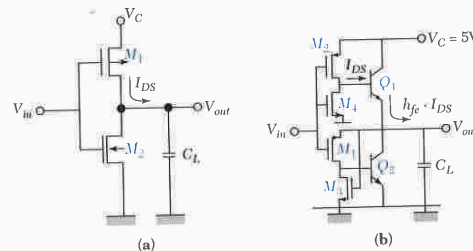


Fig. 31 (a) CMOS logic gate. (b) Bipolar CMOS (BiCMOS) logic gate.

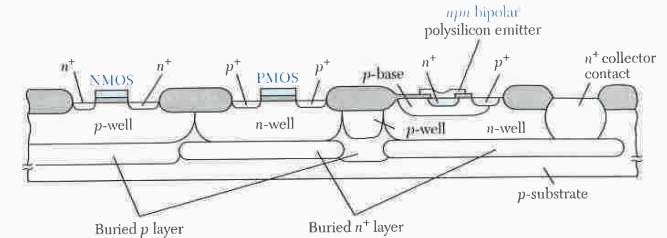


Fig. 32 Optimized BiCMOS device structure. Key features include self-aligned p and n^+ buried layers for improved packing density, separately optimized n - and p -well (twin-well CMOS) formed in an epitaxial layer with intrinsic background doping, and a polysilicon emitter for improved bipolar performance.¹³

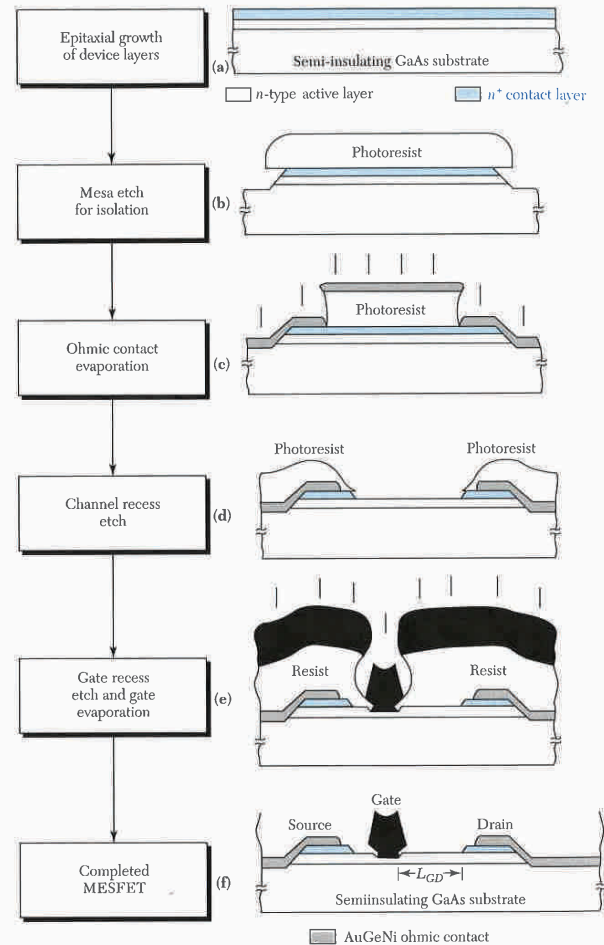
buried n^+ -mask, the collector deep- n^+ -mask, the base p -mask, and the poly-emitter mask. In other processing steps, the p^+ -region for base contact can be formed with the p^+ -implant in the source/drain implantation of the PMOS, and the n^+ -emitter can be formed with the source/drain implantation of the NMOS. The additional masks and longer processing time compared with a standard CMOS are the main drawbacks of BiCMOS. The additional cost should be justified by the enhanced performances of BiCMOS.

14.4 MESFET TECHNOLOGY

Recent advances in gallium arsenide processing techniques in conjunction with new fabrication and circuit approaches have made possible the development of "silicon-like" gallium arsenide IC technology. There are three inherent advantages of gallium arsenide compared with silicon: higher electron mobility, which results in lower series resistance for a given device geometry; higher drift velocity at a given electric field, which improves device speed; and the ability to be made semiinsulating, which can provide a lattice-matched dielectric-insulated substrate. However, gallium arsenide also has three disadvantages: a very short minority-carrier lifetime; lack of a stable, passivating native oxide; and crystal defects that are many orders of magnitude higher than in silicon. The short minority-carrier lifetime and the lack of high-quality insulating films have prevented the development of bipolar devices and delayed MOS technology using gallium arsenide. Thus, the emphasis of gallium arsenide IC technology is in the MESFET area, in which our main concerns are the majority carriers transport and the metal-semiconductor contact.

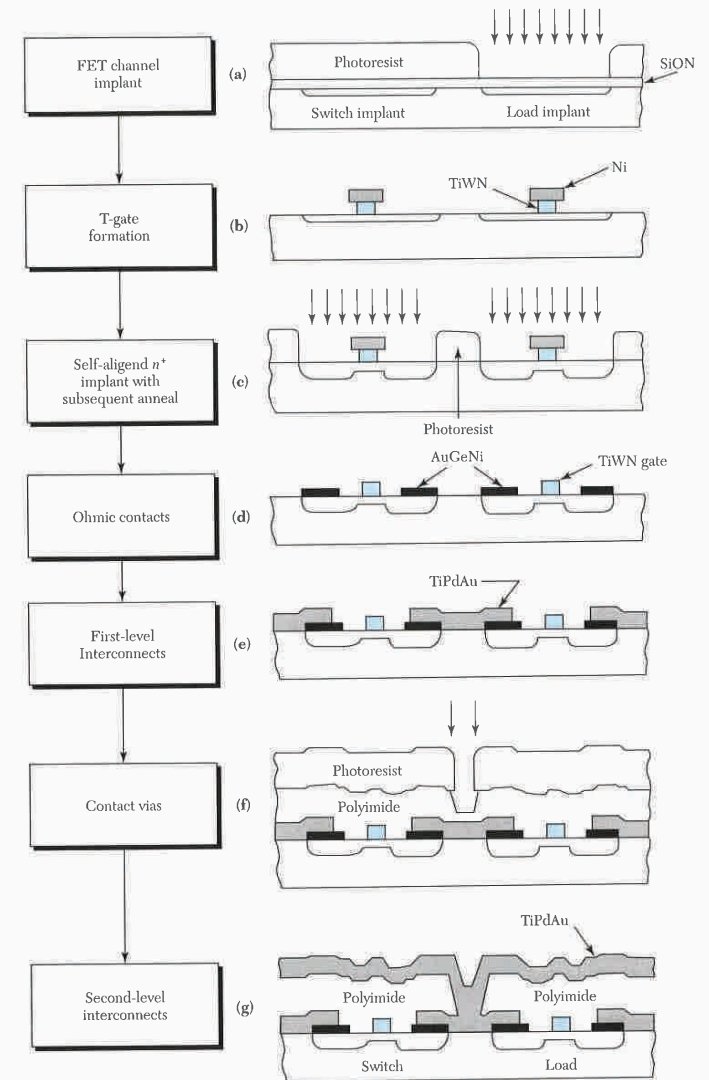
A typical fabrication sequence¹⁴ for a high-performance MESFET is shown in Fig. 33. A layer of GaAs is epitaxially grown on a semiinsulating GaAs substrate, followed by an n^+ -contact layer (Fig. 33a). A mesa etch step is performed for isolation (Fig. 33b), and a metal layer is evaporated for the source and drain ohmic contacts (Fig. 33c). A channel recess etch is followed by a gate recess etch and gate evaporation (Fig. 33d and e). After a liftoff process that removes the photoresist, shown in Fig. 33e, the MESFET is completed (Fig. 33f).

The n^+ -contact layer reduces the source and drain ohmic contact resistances. Note that the gate is offset toward the source to minimize the source resistance. The epitaxial layer is thick enough to minimize the effect of surface depletion on the source and drain resistance. The gate electrode has maximal cross-sectional area with a minimal foot

Fig. 33 Fabrication sequence of a GaAs MESFET.¹⁴

print, which provides low gate resistance and minimal gate length. In addition, the length L_{CD} is designed to be greater than the depletion width at gate-drain breakdown.

A representative fabrication sequence for a MESFET integrated circuit is shown in Fig. 34. In this process, n^+ -source and drain regions are self-aligned to the gate of each MESFET. A relatively light channel implant is used for the enhancement-mode switching

Fig. 34 Fabrication process for MESFET direct-coupled FET logic (DCFL) with active loads. Note that the n^+ -source and drain regions are self-aligned to the gate.¹⁵

device and a heavier implant is used for the depletion-mode load device. A gate recess is usually not used for such digital IC fabrication because the uniformity of each depth has been difficult to control, leading to an unacceptable variation of the threshold voltage. This process sequence can also be used for a monolithic microwave integrated circuit (MMIC). Note that the gallium arsenide MESFET processing technology is similar to the silicon-based MOSFET processing technology.

Gallium arsenide ICs with complexities up to the large-scale integration level (~10,000 components per chip) have been fabricated. Because of the higher drift velocity (~20% higher than silicon), gallium arsenide ICs will have a 20% higher speed than silicon ICs that use the same design rules. However, substantial improvements in crystal quality and processing technology are needed before gallium arsenide can seriously challenge the preeminent position of silicon in ULSI applications.

14.5 CHALLENGES FOR MICROELECTRONICS

Since the beginning of the integrated-circuit era in 1959, the minimum device dimension, also called the minimum feature length, has been reduced at an annual rate of about 13% (i.e., a reduction of 30% every 3 years). According to the prediction by the International Technology Roadmap for Semiconductors¹⁶, the minimum feature length will shrink from 130 nm (0.13 μm) in the year 2002 to 35 nm (0.035 μm) around 2014, as shown in Table 1. Also shown in Table 1 is the DRAM size. The DRAM has increased its memory cell capacity four times every 3 years and 64 Gbit DRAM is expected to be available in year 2011 using 50 nm design rules. The table also shows that the wafer size will increase to 450 mm (18 in. diameter) in 2014. In addition to the feature size reduction, challenges come from the device level, material level, and system level, discussed in the following subsections.

14.5.1 Challenges for Integration

Figure 35 shows the trends of power supply voltage V_{DD} , threshold voltage V_T , and gate oxide thickness d versus channel length for CMOS logic technology.¹⁷ From the figure, one can find that the gate oxide thickness will soon approach the tunneling-current limit of 2 nm. V_{DD} scaling will slow down because of nonscalable V_T (i.e., to a minimum V_T of about 0.3 V due to subthreshold leakage and circuit noise immunity). Some challenges of the 180 nm technology and beyond are shown¹⁸ in Fig. 36. The most stringent requirements are as follows.

TABLE 1 The Technology Generation¹⁶ from 1997 to 2014

Year of the first product shipment	1997	1999	2002	2005	2008	2011	2014
Feature size (nm)	250	180	130	100	70	50	35
DRAM ^a size (bit)	256M	1G	—	8G	—	64G	—
Wafer size (mm)	200	300	300	300	300	300	450
Gate oxide (nm)	3–4	1.9–2.5	1.3–1.7	0.9–1.1	<1.0	—	—
Junction depth (nm)	50–100	42–70	25–43	20–33	15–30	—	—

^aDRAM, dynamic random access memory.

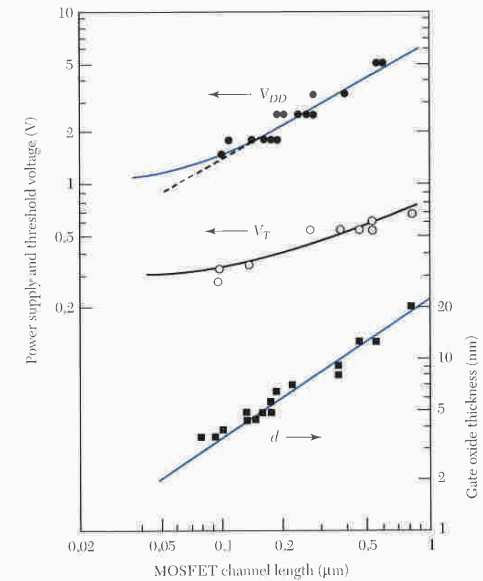


Fig. 35 Trends of power supply voltage V_{DD} , threshold voltage V_T , and gate oxide thickness d versus channel length for CMOS logic technologies. Points are collected from data published over recent years.¹⁷

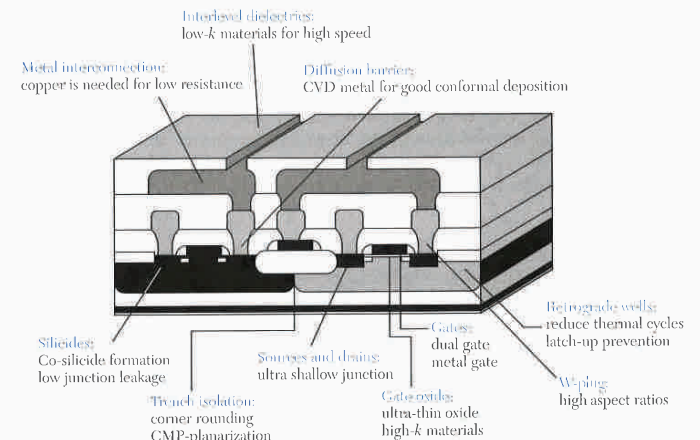


Fig. 36 Challenges for 180 nm and smaller MOSFET.¹⁸

Ultrashallow Junction Formation

As mentioned in Chapter 6, the short-channel effect happens as the channel length is reduced. This problem becomes critical as the device dimension is scaled down to 100 nm. To achieve an ultrashallow junction with low sheet resistance, low-energy (less than 1 keV) implantation technology with high dosage must be employed to reduce the short-channel effect. Table 1 shows the required junction depth versus the technology generation. The requirements of the junction for 100 nm are depths around 20–33 nm with a doping concentration of $1 \times 10^{20}/\text{cm}^3$.

Ultrathin Oxide

As the gate length shrinks below 130 nm, the oxide equivalent thickness of gate dielectric must be reduced around 2 nm to maintain the performance. However, if only SiO_2 (with a dielectric constant of 3.9) is used, the leakage through the gate becomes very high because of direct tunneling. For this reason, thicker high- k dielectric materials that have lower leakage current are suggested to replace oxide. Candidates for the short term are silicon nitride (with a dielectric constant of 7), Ta_2O_5 (25), and TiO_2 (60–100).

Silicide Formation

Silicide-related technology has become an integral part of submicron devices for reducing the parasitic resistance to improve device and circuit performance. The conventional Ti-silicide process has been widely used in 350–250 nm technology. However, the sheet resistance of a TiSi_2 line increases with decreasing line width, which limits the use of TiSi_2 in 100 nm CMOS applications and beyond. CoSi_2 or NiSi processes will replace TiSi_2 in the technology beyond 100 nm.

New Materials for Interconnection

To achieve high-speed operation, the RC time delay of the interconnection must be reduced. In Fig. 14 of Chapter 11 we have shown the delay as a function of feature size.¹⁹ It is obvious that the gate delay decreases as the channel length decreases, meanwhile the delay resulting from interconnect increases significantly as the size decreases. This causes the total delay time to increase as the dimension of the device size scales down to 250 nm. Consequently, both high-conductivity metals, such as Cu, and low-dielectric-constant (low- k) insulators, such as organic (polyimide) or inorganic (F-doped oxide) materials offer major performance gains. Cu exhibits superior performance because of its high conductivity ($1.7 \mu\Omega\text{-cm}$ compared with $2.7 \mu\Omega\text{-cm}$ of Al) and is 10–100 times more resistant to electromigration. The delay using the Cu and low- k material shows a significant decrease compared with that of the conventional Al and oxide. Hence, Cu with the low- k material is essential in multilevel interconnection for future deep-submicron technology.

Power Limitations

The power required merely to charge and discharge circuit nodes in an IC is proportional to the number of gates and the frequency at which they are switched (clock frequency). The power can be expressed as $P \approx 1/2 CV^2 nf$, when C is the capacitance per device, V is the applied voltage, n is the number of devices per chip, and f is the clock frequency. The temperature rise caused by this power dissipation in an IC package is limited by the thermal conductivity of the package material, unless auxiliary liquid or gas cooling is used. The maximum allowable temperature rise is limited by the bandgap of the semiconductor ($\sim 100^\circ\text{C}$ for Si with a bandgap of 1.1 eV). For such a temperature rise, the maximum power dissipation of a typical high-performance package is about 10

W. As a result, we must limit either the maximum clock rate or the number of gates on a chip. As an example, in an IC containing 100 nm MOS devices with $C = 5 \times 10^{-2}$ fF, running at a 20 GHz clock rate, the maximum number of gates we can have is about 10^7 if we assume a 10% duty cycle. This is a design constraint fixed by basic material parameters.

SOI Integration

Mentioned in Section 14.2.2 was the isolation of the SOI wafer. Recently SOI technology has received more attention. The advantages of the SOI integration become significant as the minimum feature length approaches 100 nm. From the process point of view, SOI does not need the complex well structure and isolation processes. In addition, shallow junctions are directly obtained through the SOI film thickness. There is no risk of nonuniform interdiffusion of silicon and Al in the contact regions because of oxide isolation at the bottom of the junction. Hence, the contact barrier is not necessary. From the device point of view, the modern bulk silicon device needs high doping at the drain and substrate to eliminate short-channel effects and punch-through. This high doping results in high capacitance when the junction is reversed bias. On the other hand, in SOI, the maximum capacitance between the junction and substrate is the capacitance of the buried insulator whose dielectric constant is three times smaller than that of silicon (3.9 versus 11.9). Based on the ring oscillator performance, the 130 nm SOI CMOS technology can achieve 25% faster speed or require 50% less power compared to a similar bulk technology.²⁰ SRAM, DRAM, CPU, and rf CMOS have all been successfully fabricated using SOI technology. Therefore SOI is a key candidate for the future system-on-a-chip technology, considered in the following section.

EXAMPLE 5

For an equivalent oxide thickness of 1.5 nm, what will be the physical thickness when high- k materials nitride ($\epsilon/\epsilon_0 = 7$), Ta_2O_5 (25), or TiO_2 (80) are used?

SOLUTION For nitride,

$$\left(\frac{\epsilon_{ox}}{1.5}\right) = \left(\frac{\epsilon_{nitride}}{d_{nitride}}\right),$$

$$d_{nitride} = 1.5 \left(\frac{7}{3.9}\right) = 2.69 \text{ nm}.$$

Using the same calculation, we obtain 9.62 nm for Ta_2O_5 and 10.77 nm for TiO_2 .

14.5.2 System-On-A-Chip

The increased component density and improved fabrication technology have helped the realization of the system-on-a-chip (SOC), that is, an IC chip that contains a complete electronic system. The designers can build all the circuitry needed for a complete electronic system, such as a camera, radio, television, or personal computer (PC), on a single chip. Figure 37 shows the SOC application in the PC's mother-board. Components (11 chips in this case) once found on boards are becoming virtual components on the chip at the right.²¹

There are two obstacles in the realization of the SOC. The first is the huge complexity of the design. Since the component board is presently designed by different companies and different design tools, it is difficult to integrate them into one chip. The other

A/MS = analog/mixed signal
 ASIC = application-specific IC
 CPU = central processing unit
 PLD = programmable logic device

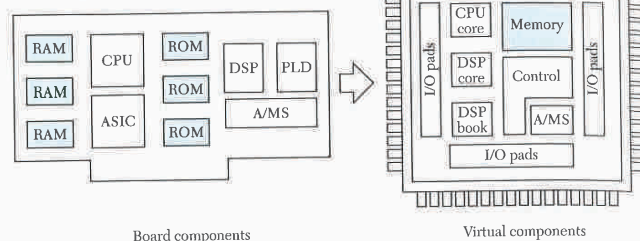


Fig. 37 System-on-a-chip of a conventional personal computer mother-board.²¹

is the difficulty of fabrication. In general, the fabricating processes of the DRAM are significantly different from those of logic IC (e.g., CPU). Speed is the first priority for the logic, whereas leakage of the stored charge is the priority for memory. Therefore, multilevel interconnection using five to six levels of metals is essential for logic IC to improve the speed. However, DRAM needs only two to three levels. In addition, to increase the speed, a silicide process must be used to reduce the series resistance, and ultrathin gate oxide is needed to increase the drive current. These requirements are not critical for the memory.

To achieve the SOC goal, an embedded DRAM technology is introduced, i.e., to merge logic and DRAM into a single chip with compatible processes. Figure 38 shows the schematic cross section of the embedded DRAM, including the DRAM cells and the logic CMOS devices.²² Some processing steps are modified as a compromise. The trench-type capaci-

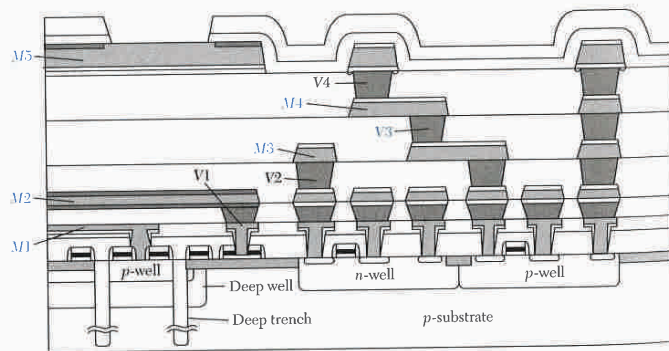


Fig. 38 Schematic cross section of the embedded DRAM including DRAM cells and logic MOSFETs. There is no height difference in the trench capacitor cell because of the DRAM cell structure. M1 to M5 are metal interconnections, and V1 to V4 are via holes.²²

tor, instead of the stacked type, is used so that there is no height difference in the DRAM cell structure. In addition, multiple gate oxide thicknesses exist on the same wafer to accommodate multiple supply voltages and/or combine memory and logic circuits on one chip.

SUMMARY

In this chapter we considered processing technologies for passive components, active devices, and IC. Three major IC technologies based on the bipolar transistor, the MOSFET, and the MESFET were discussed in detail. It appears that the MOSFET will be the dominant technology at least until 2014 because of its superior performance compared with the bipolar transistor. For 100 nm CMOS technology, a good candidate is the combination of an SOI-substrate with interconnections using Cu and low- k materials.

Because the rapid reduction in feature length, the technology will soon reach its practical limit as the channel length is reduced to about 20 nm. What will be the device beyond the CMOS is the question being asked by research scientists. Major candidates include many innovative devices based on quantum mechanical effects. This is because when the lateral dimension is reduced to below 100 nm, depending on the materials and the temperature of operation, electronic structures will exhibit nonclassical behaviors. The operation of such devices will be on the scale of single-electron transport. This approach has been demonstrated by the single-electron memory cell. The realization of such systems with trillions of components will be a major challenge beyond CMOS.²³

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PROBLEMS (* DENOTES DIFFICULT PROBLEMS)

FOR SECTION 14.1 PASSIVE COMPONENTS

1. For a sheet resistance of 1 $\text{k}\Omega/\square$, find the maximum resistance that can be fabricated on a $2.5 \times 2.5\text{-mm}$ chip using 2 μm lines with a 4 μm pitch (i.e., distance between the centers of the parallel lines).
2. Design a mask set for a 5 pF MOS capacitor. The oxide thickness is 30 nm. Assume that the minimum window size is $2 \times 10 \mu\text{m}$ and the maximum registration errors are 2 μm .
3. Draw a complete step-by-step set of masks for the spiral inductor with three turns on a substrate.
4. Design a 10 nH square spiral inductor in which the total length of the interconnect is 350 μm ; the spacing between turns is 2 μm .

FOR SECTION 14.2 BIPOLAR TECHNOLOGY

5. Draw the circuit diagram and device cross section of a clamped transistor.
6. Identify the purpose of the following steps in self-aligned double-polysilicon bipolar structure: (a) undoped polysilicon in trench in Fig. 13a, (b) the poly 1 in Fig. 13b, and (c) the poly 2 in Fig. 13d.

FOR SECTION 14.3 MOSFET TECHNOLOGY

- *7. In NMOS processing, the starting material is a p -type $10 \Omega\text{-cm}$ $\langle 100 \rangle$ -oriented silicon wafer. The source and drain are formed by arsenic implantation of 10^{16} ions/ cm^2 at 30 keV through a gate oxide of 25 nm. (a) Estimate the threshold voltage change of the device. (b) Draw the doping profile along a coordinate perpendicular to the surface and passing through the channel region or the source region.
8. (a) Why is $\langle 100 \rangle$ -orientation preferred in NMOS fabrication? (b) What are the disadvantages if too thin a field oxide is used in NMOS devices? (c) What problems occur if a polysilicon gate is used for gate lengths less than 3 μm ? Can another material be substituted for polysilicon? (d) How is a self-aligned gate obtained and what are its advantages? (e) What purpose does P-glass serve?
- *9. For a floating-gate nonvolatile memory, the lower insulator has a dielectric constant of 4 and is 10 nm thick. The insulator above the floating gate has a dielectric constant of 10 and is 100 nm thick. If the current density J in the lower insulators is given by $J = \sigma \mathcal{E}$,

where $\sigma = 10^{-7} \text{ S/cm}$, and the current in the other insulator is negligibly small, find the threshold voltage shift of the device caused by a voltage of 10 V applied to the control gate for (a) 0.25 μs , and (b) a sufficiently long time that J in the lower insulator becomes negligibly small.

10. Draw a complete step-by-step set of masks for CMOS inverter shown in Fig. 23. Pay particular attention to the cross section shown in Fig. 23c for your scale.
- *11. A 0.5 μm digital CMOS technology has 5 μm wide transistors. The minimum wire width is 1 μm and the metallization layer consists of 1 μm thick aluminum. Assume that μ_n is $400 \text{ cm}^2/\text{V}\cdot\text{s}$, d is 10-nm, V_{DD} is 3.3 V, and the threshold voltage is 0.6 V. Finally, assume that the maximum voltage drop that can be tolerated is 0.1 V when a 1 μm^2 cross section aluminum wire is carrying the maximum current that can be supplied by the NMOS transistor. How long a wire can be allowed? Use a simple square-law, long-channel model to predict the MOS current drive (resistivity of aluminum is $2.7 \times 10^{-8} \Omega\text{-cm}$).
12. Plot the cross-sectional views of a twin-tub CMOS structure of the following stages of processing: (a) n -tub implant, (b) p -tub implant, (c) twin-tub drive-in, (d) nonselective p^+ -source/drain implant, (e) selective n^+ -source/drain implant using photoresist as mask, and (f) P-glass deposition.
13. Why do we use a p^+ -polysilicon gate for PMOS?
14. What is the boron penetration problem in p^+ -polysilicon PMOS? How would you eliminate it?
15. To obtain a good interfacial property, a buffered layer is usually deposited between the high- k material and substrate. Calculate the effective oxide thickness if the stacked gate dielectric structure is (a) a buffered nitride of 0.5 nm and (b) a Ta_2O_5 of 10 nm.
16. Describe the disadvantages of LOCOS technology and the advantages of shallow-trench isolation technology.

FOR SECTION 14.4 MESFET TECHNOLOGY

17. What is the purpose for the polyimide used in Fig. 34f?
18. What is the reason that it is difficult to make bipolar transistor and MOSFET in GaAs?

FOR SECTION 14.5 CHALLENGES FOR MICROELECTRONICS

19. (a) Calculate the RC time constant of a aluminum runner 0.5 μm thick formed on a thermally grown SiO_2 0.5 μm thick. The length and width of the runner are 1 cm and 1 μm , respectively. The resistivity of the runner is $10^{-5} \Omega\text{-cm}$. (b) What will be the RC time constant for a polysilicon runner ($R_{\square} = 30 \Omega/\square$) of identical dimension?
20. Why do we need multiple oxide thicknesses for a system-on-a-chip (SOC)?
21. Normally we need a buffered layer placed between a high- k Ta_2O_5 and the silicon substrate. Calculate the effective oxide thickness (EOT) when the stacked gate dielectric is Ta_2O_5 ($k = 25$) with a thickness of 75 Å on a buffered nitride layer ($k = 7$ and a thickness of 10 Å). Also calculate EOT for a buffered oxide layer ($k = 3.9$, and a thickness of 5 Å).

Appendix A

List of Symbols

Symbol	Description	Unit
a	Lattice constant	Å
$\mathcal{B}$	Magnetic induction	Wb/m ²
c	Speed of light in vacuum	cm/s
C	Capacitance	F
$\mathcal{D}$	Electric displacement	C/cm ²
D	Diffusion coefficient	cm ² /s
E	Energy	eV
E_C	Bottom of conduction band	eV
E_F	Fermi energy level	eV
E_g	Energy bandgap	eV
E_V	Top of valence band	eV
$\mathcal{E}$	Electric field	V/cm
$\mathcal{E}_c$	Critical field	V/cm
$\mathcal{E}_m$	Maximum field	V/cm
f	Frequency	Hz(cps)
$F(E)$	Fermi-Dirac distribution function	
h	Planck constant	J·s
$h\nu$	Photon energy	eV
I	Current	A
I_C	Collector current	A
J	Current density	A/cm ²
J_{th}	Threshold current density	A/cm ²
k	Boltzmann constant	J/K
kT	Thermal energy	eV
L	Length	cm or μm
m_0	Electron rest mass	kg
m_n	Electron effective mass	kg
m_p	Hole effective mass	kg
$\bar{n}$	Refractive index	
n	Density of free electrons	cm ⁻³
n_i	Intrinsic carrier concentration	cm ⁻³

(continued)