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Provisional Application for Patent Cover Sheet

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c)

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All Inventors Must Be Listed – Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Title of Invention	High Speed Silicon Avalanche Photodiode and Photodiodes Using Micro-Structured Absorption Enhancement Regions
Attorney Docket Number (if applicable)	SPW005-Prov

Correspondence Address

Direct all correspondence to (select one):

◉ The address corresponding to Customer Number	○ Firm or Individual Name
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- ○ Yes, the invention was made by an agency of the United States Government. The U.S. Government agency name is:
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Entity Status
Applicant asserts small entity status under 37 CFR 1.27 or applicant certifies micro entity status under 37 CFR 1.29

- (●) Applicant asserts small entity status under 37 CFR 1.27
- ( ) Applicant certifies micro entity status under 37 CFR 1.29. Applicant must attach form PTO/SB/15A or B or equivalent.
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Signature	/William L. Wang/			Date (YYYY-MM-DD)	2013-05-22
First Name	William	Last Name	Wang	Registration Number (If appropriate)	39871

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High Speed Silicon Avalanche Photodiode (APD) and photodiodes (PD) using micro-structured absorption enhancement regions

Shih-Yuan Wang, Shih-Ping Bob Wang 14 May 2013

Key points:

- Microstructures are used to enhance bulk absorption constant
- The enhance absorption constant allows the avalanche photodiode (APD)/photodiode (PD) to:
  - Extend the sensitivity of the APD/PD to wavelengths closer to the material bandgap (850, 980, 1300 and 1550 nm) for Si (bandgap 1.1 eV)
  - Operate at a high bandwidth >20 Gb/s
  - Increase quantum efficiency (QE)
- Use silicon which have the best APD properties rather than III-V material
  - Compatible with Si Photonics, CMOS processes
- 850 nm current datacom stardard for short distance < 1Km, 1300-1550 and 1600 nm are telecom standards for long distance, 1 to 1000 or more Km. Fiber to home will use 1300 and possibly 1550 nm at 10 Gb/s[1] (6.75 GHz) and later 20, 40 Gb/s.
- APD and PD are critical components; integration with CMOS highly desirable.

Silicon optical detectors are very robust due to the maturity of the material and processing techniques, the surfaces can be easily passivated to eliminate dangling bonds that can cause surface charges and carrier recombination, excellent carrier lifetimes due to low defects and high material purity, and for APD applications, the noise is very low due to the small ionization ratio between holes and electrons (k factor, silicon have the lowest k factor than any III-V material) and it is CMOS compatible.

Table 1: Silicon absorption constant vs wavelength

Wavelength nm	Absorption constant cm^{-1}
850	760
980	67
1000	63

Table 2: Percent absorbed in bulk Si vs length at wavelength of 850 nm

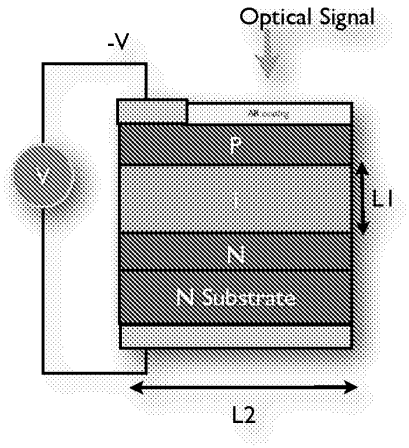
Percent absorbed at 850 nm	length um
7.3	1
14.1	2
90	30

[1] conversion from GHz to Gb/s depends on bit pattern RZ, NRZ but a conservative conversion is Gb/s *(0.675) = GHz Gb/s is digital and GHz is analog bandwidth.

Patent Owner, W&Wsens - Ex. 2035, p. 4

However, silicon photodetectors have been limited to wavelength ranges of 200 to 1000 nm due to its indirect bandgap of 1.1 eV. In particular, near the band gap wavelengths of 800-1000 nm, the frequency response of the silicon photodetector is limited to 1 GHz or less due to the weak absorption constant of Si at those wavelengths as can be seen in the **Table 1** on **Silicon absorption constant vs wavelength**[2]. The wavelengths 850 nm is of interest since this is the standard wavelength for short distance (few meters to a few kilometers) multimode fiber optical datacommunication.

Figure 1: Typical PIN structure photodiode



The amount of incident photons absorbed is approximately given by $\eta=1-e^{-\alpha x}$ where η (also the quantum efficiency (QE) if reflection off the surface of the PD is negligible, with antireflection (AR) coating, reflection can be less than 1-5 %) is the amount absorbed and "α" is α the absorption constant and "x" is the length length of the absorber (L1). **Table 2**, **Percent absorbed in bulk Si vs length at wavelength of 850 nm** shows that to absorb 90% of the incident photons a length (L1) of 30 um of silicon is necessary at a wavelength of 850 nm. Most high speed photodetectors, Fig. 1, typically have an absorption region of approximately 2 um in length. The reason for this is that transit time and RC time of the photodiode need to be considered to have a bandwidth of 20 GHz (30 Gb/s) or more and still have an external quantum efficiency of 80-90% or better. The typical PD operates at a reverse bias (negative voltage on the anode with respect to the cathode) of -4 to -25 volts to fully deplete the "i" region which is not intentionally doped with doping concentration of less than 10^{15}-10^{16} cm^{-3}. The p layer is about 1-2 um (micrometers) thick and can be mostly transparent to the incident optical signal with doping concentration greater than 10^{18} cm^{-3}. The N layer can be 1-10 um thick with doping concentration of 10^{17} to 10^{19} cm^{-3}. The layers are grown epitaxially on a N substrate.

Efficiency and bandwidth (transit and RC time): The electron drift velocity vs electric field and temperature in Si[3]; at a field strength of 6 .10^4 V/cm the electron drift velocity is 1.10^7 cm/s at a temperature of 300 K. The 3dB bandwidth of the photodetector is given by: f(3dB)=0.45/t(transit)[4] where t(transit) is the transit time for the carriers to

f(3dB transit) GHz	L1 um
45	1
22.5	2
1.5	30

Table 3: 3 dB bandwidth due to transit time with electron drift velocity of 1.10^7 cm/s

[2] http://www.cleanroom.byu.edu/OpticalCalc.phtml

[3] http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/electric.html

[4] http://www.rle.mit.edu/sclaser/6.973%20lecture%20notes/Lecture%2011c.pdf

cross the depleted high field region. As shown in Figure 1, **Typical PIN structure photodiode**, assuming negligible photocarriers generated in the P region of the PIN and mostly generated in the "i" region; the transit time is determined by the electron drift velocity and L1 (the high field "i" region, the PIN is reversed biased to -4 to -25 V; the "i" region is fully depleted in this case). The RC time of the PIN structure is determined by the capacitance; the ratio of the area of the PIN to L1.

From the Table 3, a 30 um thick absorption layer ('i") to achieve 90% absorption will give a transit time limited 3dB bandwidth of 1.5 GHz which is too low for current applications

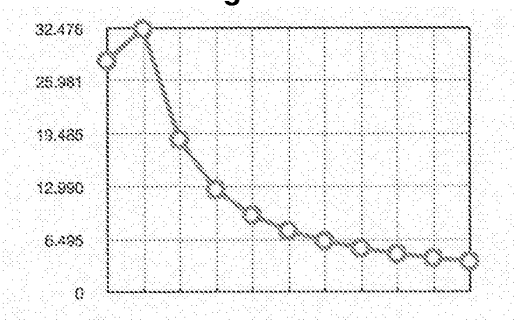
Table 4: RC 3dB bandwidth for a 25 um diameter PIN photodiode

f(3dB RC) GHz	L1 um
61.5	1
123	2
1846	30

Table 5:PD 25 um diameter at 850 nm wavelength; bandwidth and efficiency vs length

length um	f(3dB) GHz	η %
0.5	28.6	3.73
1	32.5	7.32
2	18.9	14.1
3	13	20.4
4	9.55	26.2
5	7.64	31.6
6	6.4	36.6
7	5.46	41.3
8	4.78	45.6
9	4.25	49.5
10	3.82	53.2

Figure 2: f(3dB) combined transit and RC; GHz vs length 0.5, 1,2,3,4,...um; PD diameter of 25 um; 850 nm wavelength



which is at 10 Gb/s (6.75 GHz) and 20 Gb/s (13.5 GHz) within the next few years. A L1 of 2 um or less is desirable for current high speed photodiodes in optical datacom applications, and low voltage (12 or less volts) as compare to 30 um i layer thickness requiring 180 V.

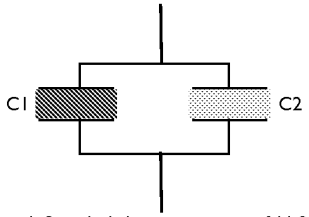
RC time is another time to consider in photodiodes (applies to both APD and PD). The 3 dB bandwidth due to RC time is given by f(RC)= 1/(2πRC); where C is the capacitance of the photodiode and R is the load resistance which is typically 50 ohms; occasionally it can be 25 ohms. Capacitance in the case of a typical PIN structure photodiode with the "i" region fully depleted by the reverse bias, is just a parallel plate capacitance given by εA/L1 where ε is the dielectric

Patent Owner, W&Wsens - Ex. 2035, p. 6

constant of the material (multiplied by vacuum permittivity of 8.854 10^{-14} farads/cm) which is 11.9 for Si[5], A is the area of the capacitor; $\pi(L2/2)^2$, and L1 is the depleted "i". From the **RC 3dB bandwidth table,** the f(RC) becomes larger as L1 increases since the capacitance is decreasing with increasing L1 and a fixed area where the diode diameter is L2=25 um; typical high speed APD/PD have diameters of 20-50 um (L2) depending on bandwidth; larger L2 is desirable for ease of coupling of optical signal to APD/PD. For low bandwidth, a large L2 (50-75 um) is chosen for ease of packaging which also reduce cost of assembly.

The overall frequency bandwidth of the photodiode is a sum of the square of the transit time and the RC time. This is given by the equation (in footnote 3); $f=1/(2\pi(RC)^2+(\tau/2.4)^2)^{1/2}$).
From the **Table 5** for the combined f(3dB) of the transit time and RC time and the quantum efficiency η (assuming negligible reflection losses) we see that for bulk silicon even at 10 um thick silicon absorbing region, the QE is only 53.2% and the bandwidth is 3.8 GHz (5.6 Gb/s), much too low (both QE and bandwidth) for datacom

Figure 5: Effective capacitance of microstructured PD/APD



C1 is filled with Si with dielectric constant of 11.9
C2 is filled with polyimide with dielectric constant of 3.4
The area of each capacitor is A/2; where A is the area of a 25 um diameter plate.
C(effective)=C1+C2

Figure 3: Conventional Si APD structure with > 100 um of absorption length, and 10 um of multiplication; operating at a reverse bias voltage of > 100V. Footnote 5.

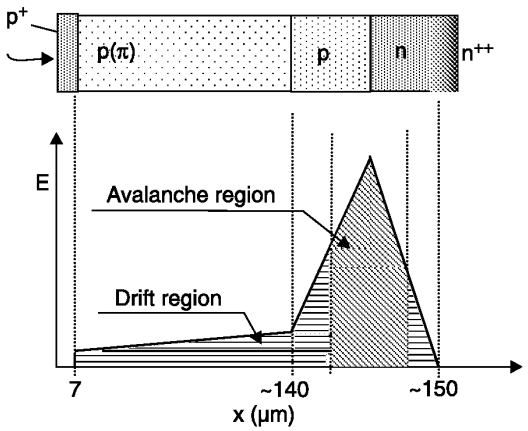


Fig. 6. Schematic profile of electric field for an RCA APD structure.

Figure 4: Garnett and Yang, Light trapping in Silicon nanowire solar cell

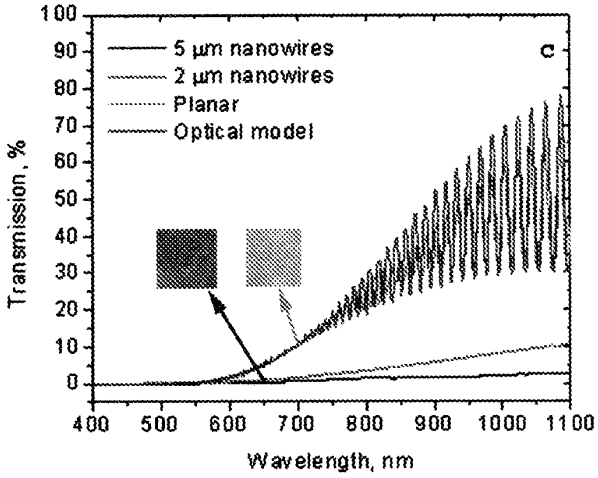


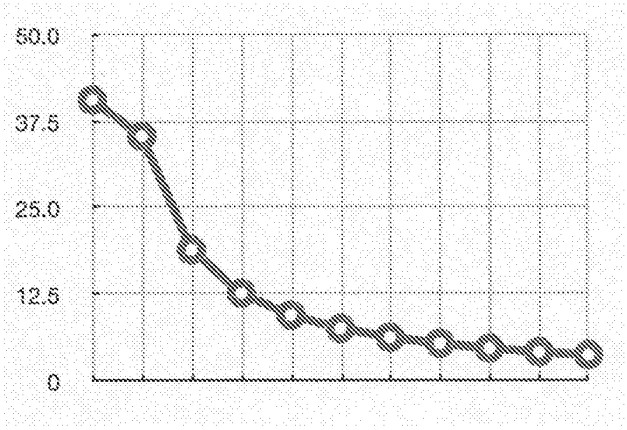
Table 6: Absorption constant α for bulk and nanowire Si at 850 nm

α(bulk)	α(nanowire)
760	55480

[5] http://www.virginiasemi.com/pdf/generalpropertiessi62002.pdf

applications.

Figure 6: f(3 dB) effective microstructured PD/ APD bandwidth GHz vs length 0.5, 1, 2, 3, ... um at 850 nm with 25 um diameter PD/ADP



Wang Invention:

To overcome the weak absorption of Si at 850 nm, we use a **microstructured array** that is etched (dry etch using reactive ion etch (RIE) or deep reactive ion etch (DRIE) process together with thermal oxidation for smooth side walls. Wet chemical etch may also be used entirely or partially to remove damages due to RIE/DRIE) into silicon that is grown by conventional methods epitaxially such as chemical vapor deposition (CVD) or metal organic chemical vapor deposition (MOCVD), atomic layer deposition (ALD),

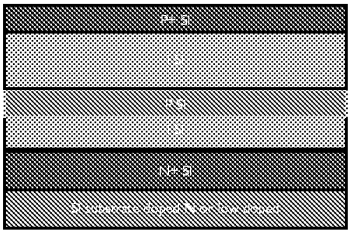
Table 7: Overall frequency response of Microstructured 25 um diameter PD/APD with effective capacitance and QE as a multiple of bulk absorption constant 760/cm at 850 nm wavelength

length um	f(3dB) GHz	η% 15X	η% 30X	η% 73X
0.5	40.7	43.5	68	93.8
1	35.5	68	89.7	99.6
2	19	89.7	98.9	100
3	12.7	96.7	99.9	100

molecular beam epitaxy (MBE). The microstructured array of silicon consists of pillars (or holes) of Si. A paper by *Garnett and Yang,* ***Light Trapping in Silicon Nanowire Solar Cells****, Nano Lett. 2010, 10, 1082–1087;* they experimentally demonstrated than an ordered array of silicon nanowires increased the optical path length of the incident optical radiation by 73 times greater than that of bulk silicon. Or in other words, the enhanced absorption constant of the ordered array of Si nanowires is 73X that of bulk silicon; as in **Table 6** bulk α is 760 and nanowire α is $5.548\ 10^4$ (with 73 times enhancement) which is higher than direct bandgap III-V material.

The nanowire array in Garnett el al's paper the diameter of the nanowire is approximately 390 nm using an array of beads of 530 nm diameter as an dry etch mask. Roughly 1/2 of the Si material is etched away; the effective capacitance for the nanowire array is less than that of the bulk. The effective capacitance can be estimated as two parallel capacitors, one with Si and another with polyimide (filler) whose dielectric constants are 11.9 and 3.4 respectively. The area of each capacitor will be 1/2

Figure 7: A Si epitaxial layer structure for high speed microstructured APD prior to fab

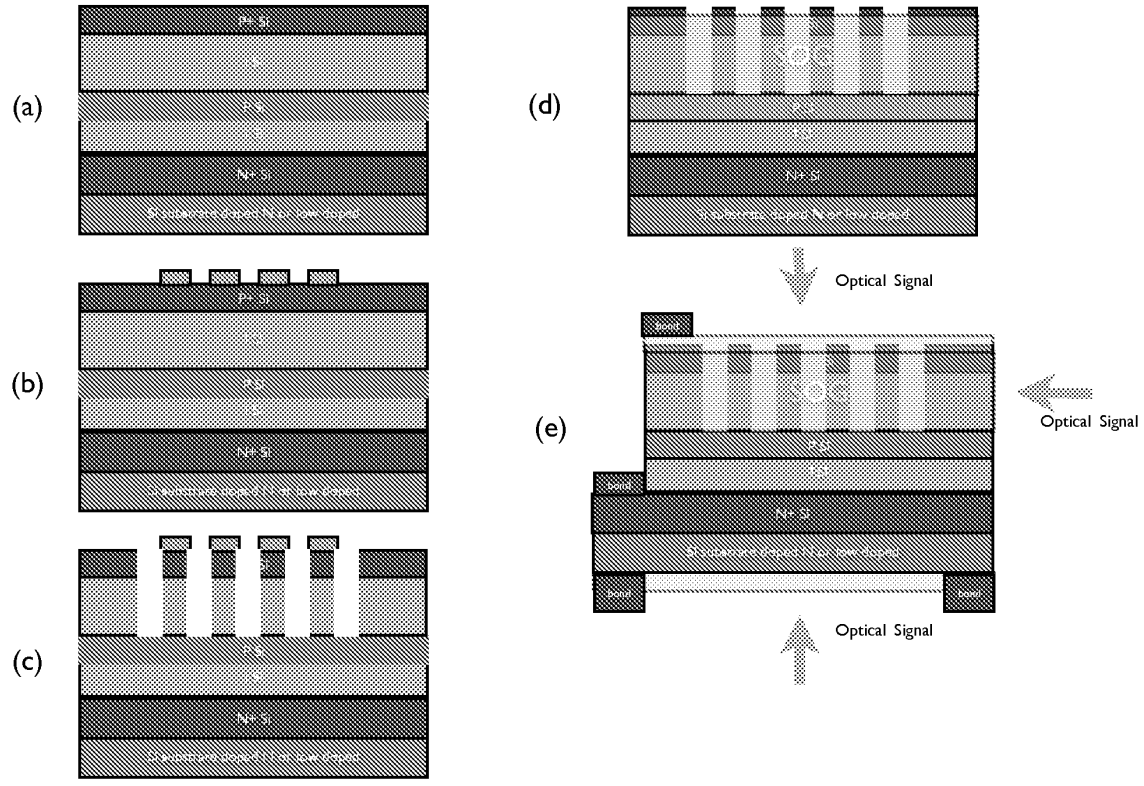


p+ 0.1 um >2.10^20 /cm3 p contact
p- or i 0.5 um <1. 10^16/cm3 absorption
p 0.1 um 2.10^17/cm3 charge
i 0.5 um < 1.10^16/cm3 multiplication
n+ 2-8 um > 5.10^18/cm3 n contact
n or undoped substrate

that of a 25 um diameter parallel plate.

With the effective capacitance lower, the overall 3dB bandwidth for a 25 um diameter device is significantly higher (see **Table 7** for the microstructured PD/APD bandwidth, QE vs length). **At a length of 2 um, the APD/PD can reach 28 Gb/s and have QE of 90% even with a 15X enhancement in the bulk absorption constant.** In addition with the absorption constant enhancement of 73X, the QE for a 0.5 um microstructure is 94% and a bandwith of **41 GHz or 61 Gb/s**. ***The combination of low capacitance due to the gaps between the microstructured pillars and the enhanced absorption allows the silicon photodiode and avalanche photodiode to operate at bandwidths greater than 10 GHz (14.8 Gb/s) with high quantum efficiencies (> 90%) at 850 nm wavelength.***

Figure 8: Basic processing steps in fabricating a microstructured APD



We will show later that the weak absorption in the bulk can be taken advantage of for photodetector (APD and PD) applications since this will allow light at 850 nm and longer

to pass through toward the microstructured silicon with minimal diffusion current which can cause the photodetector to have a degradation in frequency response. In addition, it should be noted that this invention is not limited to Si but can also be used in Ge on Si where microstructures are fabricated on the Ge to increase absorption which allows a shorter length of Ge to be used resulting in higher speed due to a combination of reduction in transit time and lower effective capacitance.

An example in **Figure 7** of the silicon epitaxial structure for a high speed high efficiency microstructured APD is shown. With minor modifications the n and p doping can be switched and the direction of illumination may also be affected. Starting with a N silicon substrate (or low doped or silicon on sapphire or a BOX (buffer oxide)/SOI (silicon on insulator) wafer depending on the application and packaging considerations), an N^+ layer (N ohmic contact layer) with doping concentration of greater than 10^{18} cm^{-3} (typically phosphorous) with layer thickness ranging from 2-8 micrometers (um) or 0.1 to 10 um depending on doping level, an non-intentionally doped layer "i" or a P^- (very low doping level P layer) with doping concentration less than 10^{16} cm^{-3} (this is the multiplication layer of the APD) with thickness ranging from 0.1 to 1.0 um depending on gain and bandwidth of the APD, a P charge layer of thickness 0.05-0.2 um and doping concentration of 2-5 10^{17} cm^{-3} is grown; an absorption layer P^- or "i" with doping less than 10^{16} cm^{-3} with thickness ranging from 0.1 to 5 um is grown; finally a P^+ contact layer is grown with doping greater than 5 $.10^{19}$ cm^{-3} with layer thickness ranging from 0.1 to 1.0 um. All layers are grown epitaxially using CVD or MOCVD reactors.

For best noise performance of the Si APD, photogenerated electrons should dominate in the multiplication process; i.e. holes diffuse/drift toward p (anode) and electrons diffuse/drift toward the n (cathode). The Si layers are grown epitaxially using chemical vapor deposition, plasma enhanced chemical vapor deposition, molecular beam epitaxy, atomic layer deposition (can be a combination of these methods to generate the optimal layer structure in doping and interface quality) on doped or undoped substrates. The total length for the electrons to transit is 1.1 um for the example shown in Fig. 7. For higher QE, the absorption region can be lengthened to one um for a total transit length of 1.6 um. Other layer thickness and doping concentrations can be adjusted to optimize device characteristics for different wavelength, integration with CMOS, application requirements, operating conditions such as bias voltage, gain, bandwidth and noise.

As shown in Figure 8: **Basic Processing Steps** drawings, (a) start with a high speed APD epi structure as in Figure 7; (b) a dry etch mask is deposited on the surface using photolithography, metal/dielectric deposition techniques and wet/dry etching; (c) reactive ion etching (RIE) or deep reactive ion etching (DRIE), wet etching using chemicals and oxidation of the Si are used to generate the microstructured pillars and using native silicon oxide for surface passivation by thermal oxidation (preferred), electrochemical anodization, plasma enhanced chemical vapor deposition. The thermal oxidation of the pillars can also be used to fine tune the diameter of the pillar since the oxide is created from the Si material. Thermal oxidation also smooth the surface favorable for electrical properties ; (d) a filler is used to fill the space between the Si pillars to support subsequent contact layers to be deposited. The filler can be spin on glass, polyimide,

Patent Owner, W&Wsens - Ex. 2035, p. 10

dielectric such as silicon nitride, silicon oxide, that can be deposited using plasma enhance chemical vapor deposition. Once the contacts are made in (e) the fillers can be left in place or removed by dissolving the filler with an etchant or solvent; removing the filler have the advantage of further reducing the capacitance of the device since air has a dielectric constant of 1. The reduction of the capacitance allow the device to operate at higher bandwidth due to reduction of the RC time (filler is removed not the passivation oxide on the microstructures); (e) anode and cathode ohmic contacts are made at this step. Depending on the direction of illumination, transparent conducting oxide (TCO) (such as indium tin oxide ITO) can be use. Consider the case of top illumination (surface opposite to the substrate), a dry etch (oxygen plasma for removing polyimide or other organic fillers) is used to expose the pillars if it is buried in the filler; then TCO can be used to contact the P^+ silicon pillars at the tip. Ohmic contact metallization are then applied to the cathode (N^+) layer either on the surface or bottom (depending on integration topology); metal bond pads are applied to both anode and cathode.

For optical signal coming from the substrate side (bottom), the wafer need to be thinned (if by etching it can include a

Figure 9: A high bandwidth III-V photodiode where the P InP layer is transparent to the incident optical signal. Photocarriers are generated only in the high field i layer

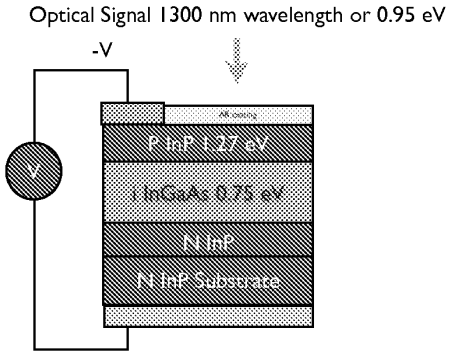


Figure 10: Substrate side illuminated APD fabricated on a SOI wafer.

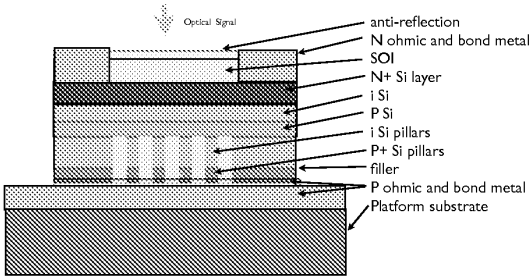


Table 8: QE (η) for bulk and microstructured pillars at 980 and 1000 nm wavelength

length um	980 nm bulk α = 67 η%	1000 nm bulk α=63 η%	980 nm 73X η%	1000 nm 73X η%
0.5	0.3	0.3	21.7	20.5
1	0.7	0.6	38.7	36.9
2	1.3	1.3	62.4	60.1
3	2.0	1.9	76.9	74.8
4	2.6	2.5	85.9	84.1

buried silicon dioxide layer such as silicon on insulator, SOI, or BOX, such that the oxide layer can act as an etch stop layer.) The wafer can be thinned first by chemical mechanical polishing and to 100 um or less followed by a via etch to the oxide layer such that the optical signal only need to traverse a few micrometer of Si bulk material. Anti-reflection is applied to the Si or SiOx surface to minimize reflection loss (to less than 5% reflection); ohmic metallization is applied to the N^+ layer (and annealed; ohmic contact may need annealing at high temperatures using rapid thermal anneal machines) followed by bond metal. On the microstructured pillar, ohmic metallization is applied to the P^+ tips, followed by bond metal. **The advantage of the optical signal entering from the substrate surface is that the light will bounce twice within the pillar structures, thus increasing the quantum efficiency. Or the pillars can be made shorter to improve the transit time.**

Figure 11: Top view of possible arrangements of the microstructured pillars in a APD/ PD for an edge entry optical signal to minimize reflection

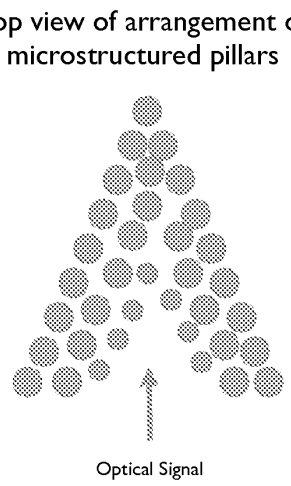
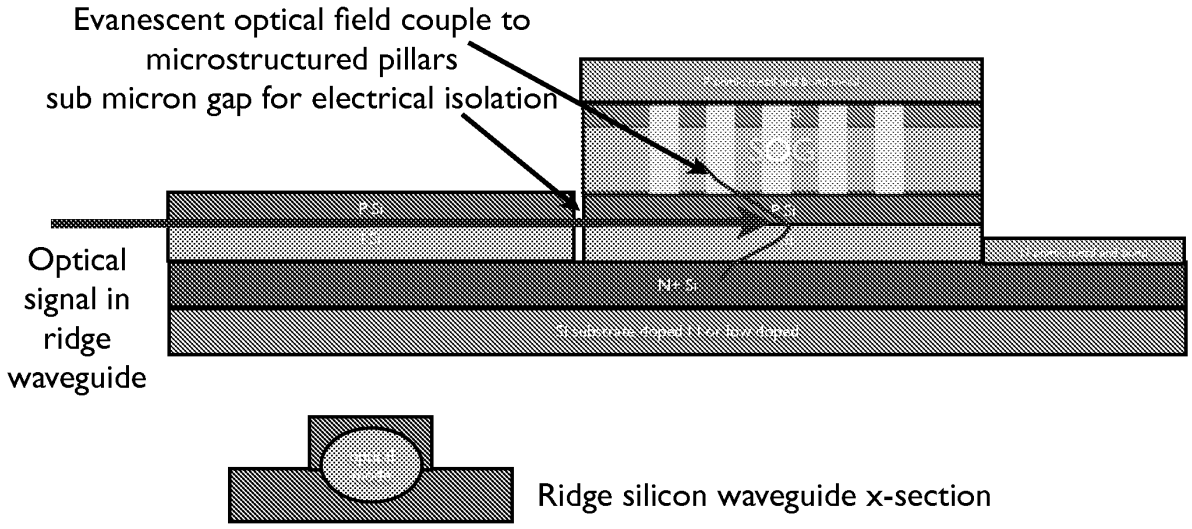
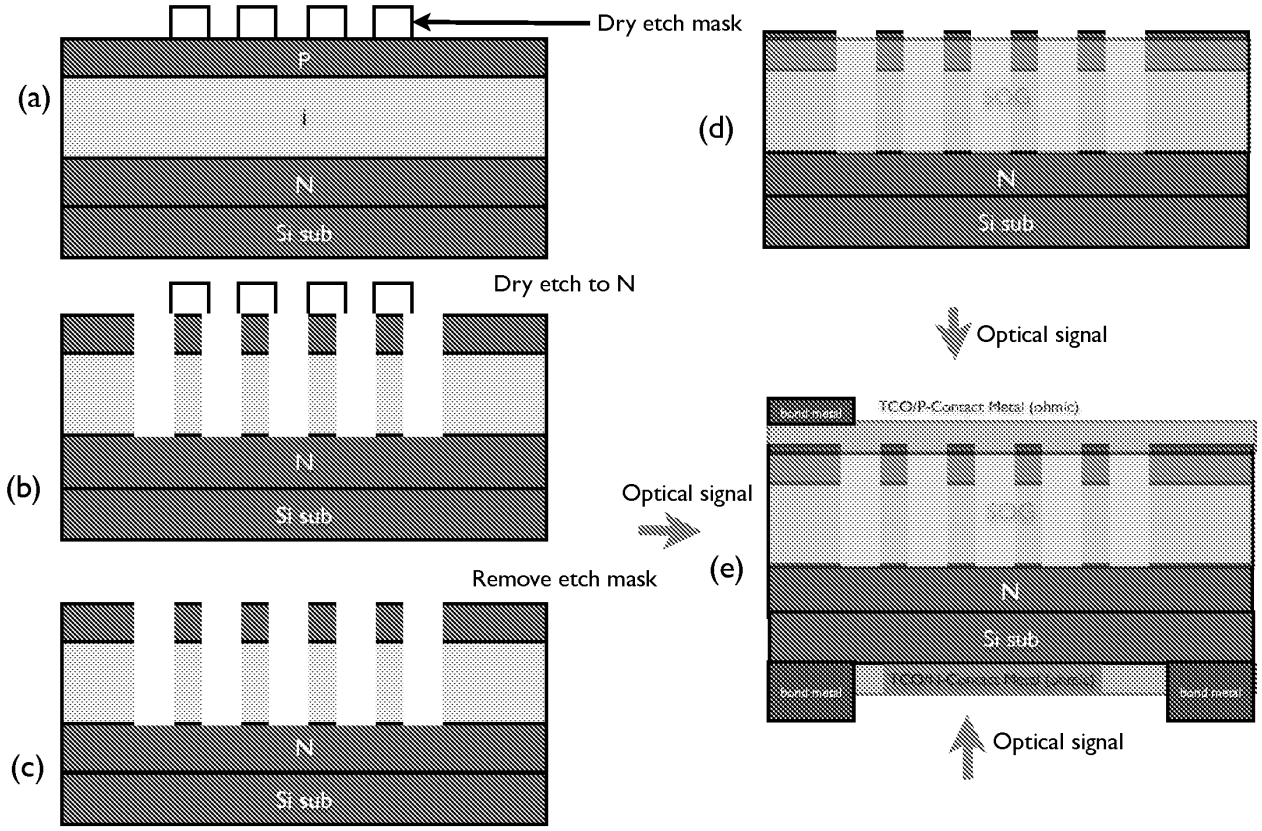


Figure 12: Guided optical wave evanescent coupled to microstrustured pillars



Optical signal can also enter from the edge as shown in the drawings, either in a guided mode or in free space. In the edge application, TCO need not be used, solid anode

Figure 13: An example of a microstructured pillar photodiode PD



ohmic contacts and wafer thinning is not necessary, with cathode ohmic contact to complete the structure. In edge approach, the pillars may be arranged such that its density is not uniform to optimize the capture of the optical radiation. It can be arranged in a V pattern for example to reduce optical reflection as shown in **Figure 11**.

Steps that are not shown etching to define the diameter of the APD, mesa etching. thermal oxidation passivation of exposed surfaces, guard rings, thinning of the wafer, anti-reflection coatings, annealing of ohmic contacts, via holes for removal of filler, to name a few.

Figure 14: Guard ring in a typical Si APD, footnote 5

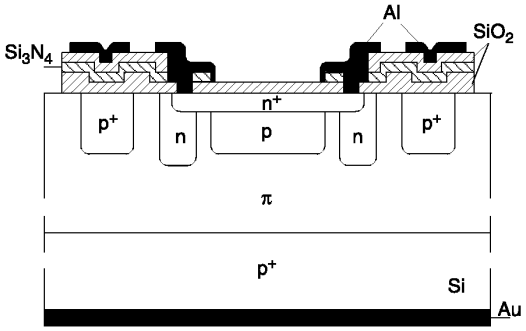


Fig. 8. Cross-section of an ITE APD structure.

Taking advantage of low absorption constant of bulk Si:

Figure 15: APD with microstructured pillars/holes and guard ring

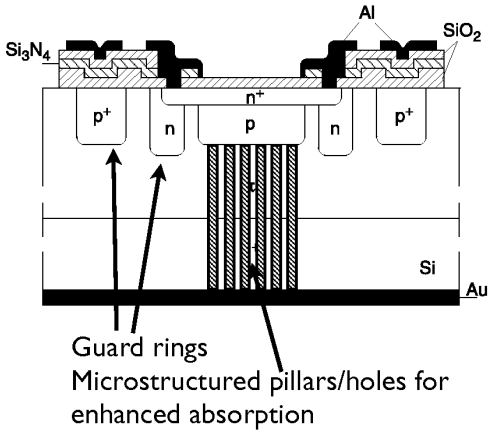
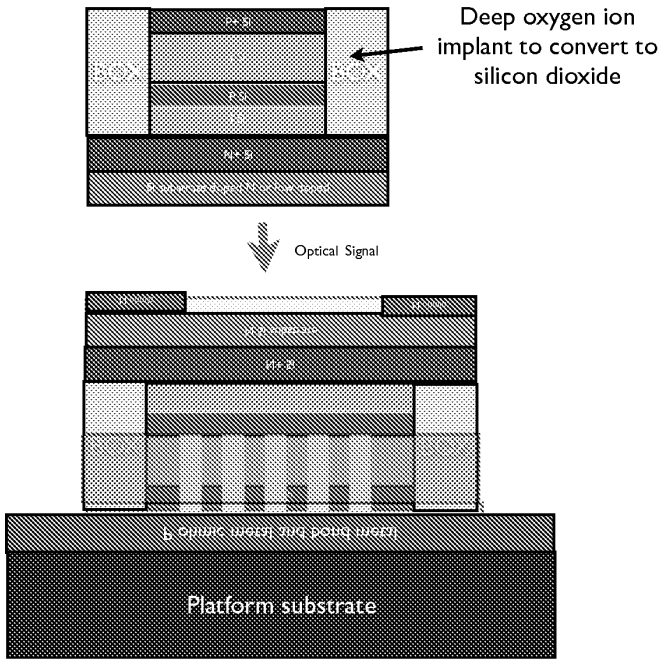
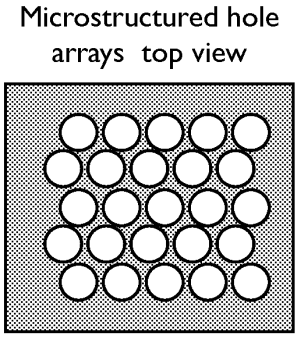


Figure 16: Deep oxygen ion implant to convert Si to SiO_2 for isolation and reduction of capacitance using oxygen ions are in SOI or BOX standard process in Si



High speed photodiodes made with III-V material (**Fig. 9**) often are constructed such than the photocarriers are generated predominantly in the i layer of a PiN structure to minimize the photogenerated carriers to the low field region that can cause degradation to the frequency response of the device. This can be done easily in III-V material since there are many ternary and quaternary material such as InGaAsP, InGaAs, InAs, that are lattice matched to InP and the bandgap of these alloys can be changed by changing the composition. In Figure 9, optical signal at 1300 nm wavelength impinge on InP which has a bandgap of 1.27 eV and therefore will have no band to band absorption due to the 1300 nm optical signal, whereas InGaAs lattice matched to InP has a bandgap of 0.75 eV and will generate e-h (electron-hole) pairs due to the 1300 nm optical signal.

Figure 17: Microstructured hole array



However it is not easy for silicon since there are no materials that is lattice matched to silicon and have a lower bandgap. Germanium can be grown on silicon but with the addition of a buffer layer to accommodate for the lattice mismatch. (SiGe is another possible candidate, with bandgap between silicon and germanium)

Since bulk absorption constant in silicon is low at radiation near the bandgap of silicon, we can take advantage of this and use bulk silicon as a l**ow absorption window** at wavelengths near the silicon bandgap. The wafer can be thinned to the insulator of an SOI or BOX structure and the 850 nm optical signal will only traverse 1-2 um of bulk silicon losing approximately 10% or less of the incident radiation. The rest of the

radiation continue to the microstructured pillar silicon where the enhanced absorption is stronger possibly due to resonance effects. The shape of the pillar can be circular, oval, rectangle, chevron, hexagon, double-circle, crescent, star, or any shape to optimize the enhanced absorption and collection efficiency. The pillar diameter range from 50-2000 nm (smallest dimension can be 50 and largest dimension 2000 nm approximately) and can be spaced uniformly or non-uniformly, periodic or aperiodic, chirped, or a pattern to optimize APD/PD performance and applications. The spacing of the pillars can be 20-5000 nm (adjacent edge to adjacent edge of neighboring elements) and can vary

Table 9: Ge on Si bulk and microstructure absorption enhancement

length um	QE% 850 nm 4.53E4/ cm	1300 nm 8198/cm QE %	1550 nm 459/cm QE %	850 nm 30X QE %	1300 nm 30X QE %	1550 nm 30X QE %	1550 nm 70X QE%
0.5	89.62	33.63	2.27	100	100	49.84	79.91
1	98.92	55.95	4.49	100	100	74.84	95.96
2	99.99	80.59	8.77	100	100	93.67	99.84
3	100	91.45	12.86	100	100	98.41	100
4	100	96.23	16.77	100	100	99.60	100

Table 10: Ge on Si microstructure 3 dB bandwidth for a 25 um diameter APD/PD

Length um	f(3dB) microstructure 25 um diameter device GHz
0.5	32
1	27
2	14
3	9.6
4	7.2

from neighboring element to neighboring element to l**ocally adjust optical field coupling efficiency and locally adjust the enhanced absorption constant**. The microstructured pillars can be 100 to 10000 nm in length and can vary in length, each or groups of elements (pillars or holes) can have its own characteristic length for **optimal coupling efficiency of the radiation field and to locally adjust the enhanced absorption constant** that is optimized for bandwidth and efficiency for a particular

Figure 18: A Ge on Si APD structure; footnote 7

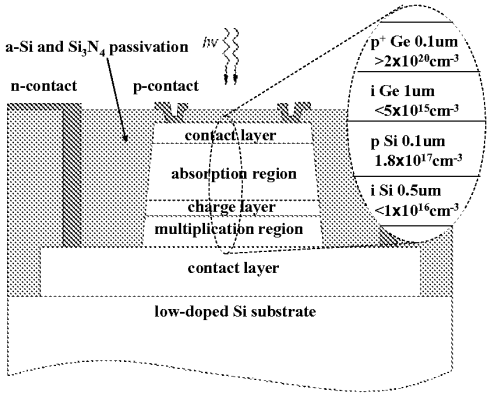


Fig. 1 Schematic cross-section of a GeSi SACM APD. The GeSi PIN PD used for primary photoresponsivity calibration has the same device cross section except for the p-type Si charge layer.

wavelength near the silicon bandgap for example 850, 880, 980, 1000 nm. **It should be noted that in this invention, the non uniformity of each or groups of elements allow for spatial adjustment of the enhanced absorption coefficient and to spatially adjust the optical field coupling between the incoming optical signal and the optical detector which can be thought of as an array of optical antennas.** The substrate becomes less absorbing as the wavelength approaches 1100 nm (1.1 eV Si indirect bandgap). **From Table 8, the substrate illuminated structure works particularly well for wavelengths at 980 and 1000 nm. The silicon substrate is basically transparent and the absorption by the mictostructure pillars of > 80% with a 2 um length (double pass with illumination normal to substrate surface) for both APD and PD operation at > 28 Gb/s bandwidth, Table 7.**

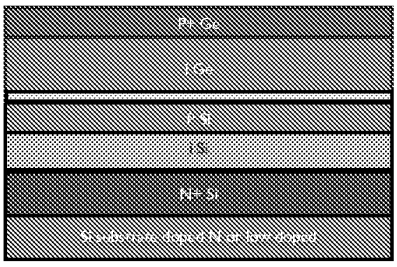
The microstructured pillars can be arranged in a pattern (**Figure 11**) for edge entry of the optical signal to minimize reflection. The pillars can be of different diameters and shape limited only by lithographic technology; photolithographic, electron beam lithography, nanoimprint lithography to name a few.

In addition, the optical signal can be guided in a waveguide such as in silicon photonics where the waveguides are made of silicon, **Figure 12**. In this case, the APD/PD can be a part of the waveguide and the optical signal can evanescently couple to the microstructured pillars as shown in the drawing on the right. An APD/PD structure with waveguide coupling can have very short microstructured pillars (less than 1 um) and be distributed along a length of the waveguide to partially or completely absorb the optical signal. The partial absorption of the optical signal allows the APD/PD to behave as a signal integrity monitoring photo detector or to allow part of the optical signal split off as electrical signal (optical to electrical tap). An optical waveguide then can have multiple APD/PD combinations to split off the signal.

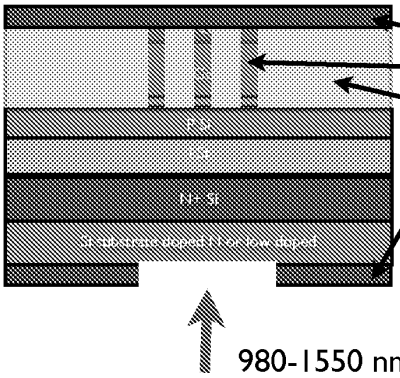
For completeness, a microstructured pillar photodiode is shown in **Figure 13**. The photodiode (PD) is similar to an APD but without the multiplication region. High speed silicon photodiodes at the infrared wavelengths don't exist for the same reasons; the absorption length in bulk silicon at infrared wavelength is too long due to small absorption constant. However with microstructured pillars, these silicon photodiodes can be made with dimensions to have high bandwidth and good quantum efficiencies. Doping concentration are the same as for an APD P^+ and N^+ layers with same thickness

Patent Owner, W&Wsens - Ex. 2035, p. 16

Figure 19: Heteroepitaxy; Ge on Si where Ge epitaxial film is patterned into microstructured pillars/holes for enhanced absorption for APD/PD applications



p+ 0.1 um >2.10^20 /cm3 p contact
p- or i 0.5 um <1. 10^16/cm3 absorption
low temp Ge buffer layer p- ~ 0.02 um
p 0.1 um 2.10^17/cm3 charge
i 0.5 um < 1.10^16/cm3 multiplication
n+ 2-8 um > 5.10^18/cm3 n contact
n or undoped substrate



p ohmic contact and bond metallization
dry etched microstructured pillars or holes
filler, polyimide/spin on glass/silicon nitride to passivate Ge surfaces
n ohmic contact and bond metallization
980-1550 nm

ranges and substrate. The "i" or P- layer are also same ranges as the APD doping and thickness.

The photodiode is reversed biased from -2 to -25 V and the APD are reversed biased from -10 to -45 V. Guard rings are often used in APD to prevent premature edge break down or excessive leakage current which can contribute to the noise of the APD amplifier. A typical guard ring for a conventional Si APD[6] is shown. Guard rings can also be floating or connected to a biasing circuit, Figure 14. Figure 15 shows the microstructured pillar/holes superimposed on a Si APD (footnote 6) with guard rings.

Figure 20: Transmission line Ge on Si PD footnote 8

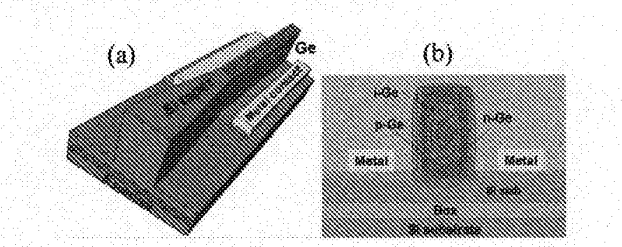
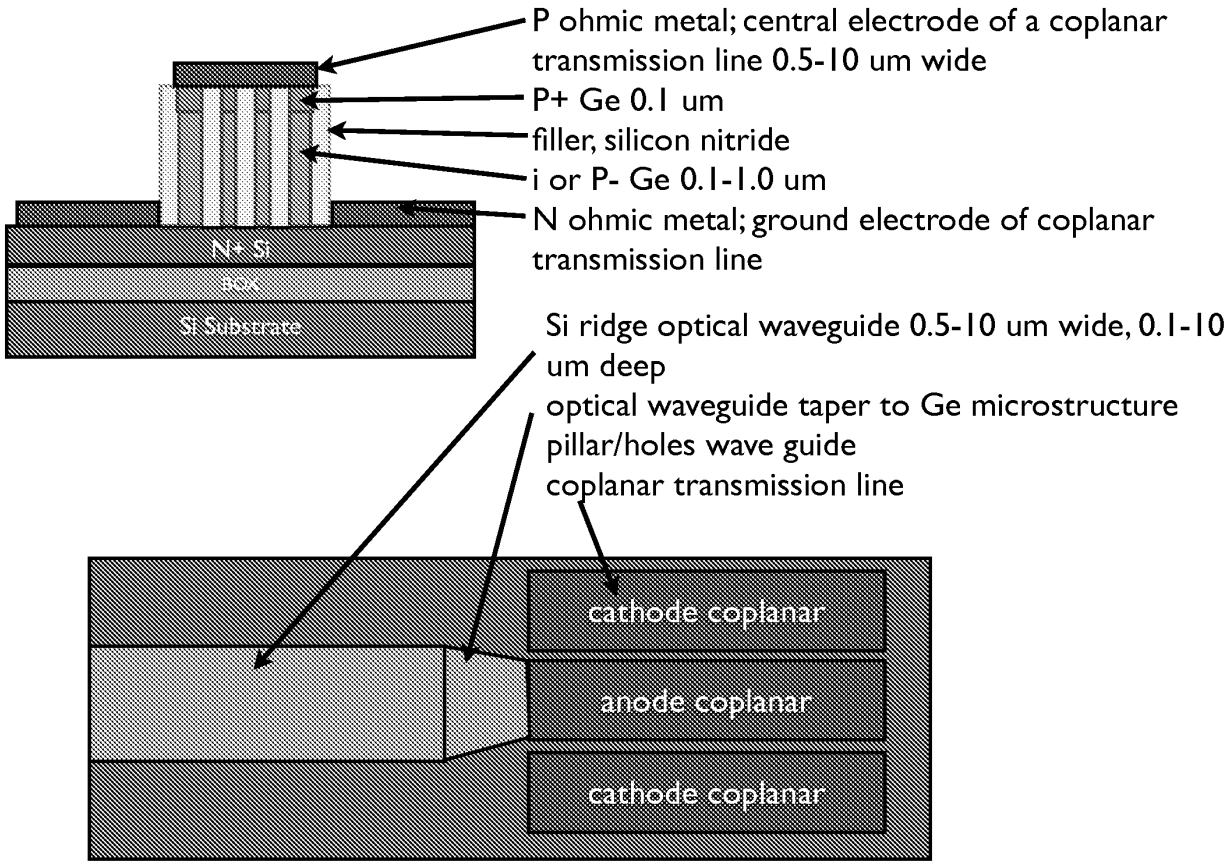


FIG. 1. (Color online) (a) Schematic view of Ge photodetector integrated with SOI waveguide. (b) Cross-section view of the Ge p-i-n region.

[6] WÊGRZECKA et al, Design and properties of silicon avalanche photodiodes,OPTO-ELECTRONICS REVIEW 12(1), 95–104 (2004)

Figure 21: An edge coupled optical waveguide with microwave coplanar transmission line Ge on Si PD with microstructured pillar/hole arrays for enhanced absorption



A deep oxygen ion implantation can be performed after the growth of all the epitaxial layers, to convert some of the supporting silicon into insulators and in particular to SiO_2 SiOx. This is to reduce capacitance and any surface leakage current. Since the overall length of the new invention microstructured pillar APD/PD is much shorter than conventional silicon APD/PD by almost two orders of magnitute; 2- 3 um compared to 100-200 um, ion implantation of the entire depth of the device is possible such as BOX or SOI process, **Figure 16**.

Microstructured hole arrays (Figure 17) will also work as light traps in silicon and have similar properties as microstructured pillars[7]. Instead of etching microstructured pillar arrays as above, microstructured hole arrays are etched using RIE and similar processing for the pillars, including thermal oxidation for surface passivation, deep ion implantation for electrical isolation, confinement of optical fields and reduction of capacitance are also employed. In the case of the hole arrays, it is possible that the filler need not extend the entire length of the hole, if the surface tension of the filler is high,

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[7] Lin et al, Optical absorption enhancement in silicon nanowire and nanohole arrays for photovoltaic applications, Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion, edited by Loucas Tsakalakos, Proc. of SPIE Vol. 7772, 77721G · © 2010 SPIE

only partial filling of the holes with filler will be possible and provide support for subsequent layers of TCO, metal, oxide, silicide, alloys to name a few that are necessary to complete the device structure.

The microstructured holes can have diameters of 50-2000 nm and can be a square, hexagon, oval, rectangle, chevron, double-hole, with the smallest dimension at 50 nm to the largest dimension of 2000 nm. The spacing between holes (adjacent neighboring element edges) can be regular or irregular or a pattern at 20-5000 nm. The depth (or length) of the hole can be 100 to 10000 nm and can be uniform depth or non-uniform depth. As in the case of the pillars, spatially varying from element to element or groups of elements (element is a hole or a pillar) can have different dimensions to adjust spatially the enhanced absorption constant and the optical field coupling of the signal field to the detector field which can be thought of as an optical antenna array. Dimensions are chosen for optimal absorption, quantum efficiency, bandwidth and radiation collection efficiency for a particular wavelength and application.

Also in this invention, within a single APD/PD the microstructure can have both pillars AND holes coexist, can be concentric (pillar within a hole or hole within a pillar or multiple concentric hole/pillar, not necessarily circular but any shape such as a square hole and a round pillar for example) and any mixture thereof.

This invention can also be applied to heteroepitaxial material such as Ge on Si. Ge (bandgap 0.66 eV at 300K) with a much small bandgap than Si, can be used for detecting optical signals at 850 and 1300 nm and 1550 nm.

From **Table 9**, bulk Ge can easily detect 850 and 1300 nm but not so well at 1550 nm.

Using this invention of using microstructured pillars/holes arrays for enhancing the absorption constant; 1550 nm wavelength optical signal can be detected (with an enhancement of the bulk absorption constant by 30X-70X) very well. The microstructured pillar array (approximately 1/2 Ge and 1/2 polyimide filler) have a 3dB bandwidth of 32 GHz (47 Gb/s) for a 0.5 um length Ge pillar and 27 GHz (40 Gb/s) for a 1 um Ge pillar (**Table 10**) with quantum efficiencies of 96 and 99.8 % respectively (double pass) with an enhancement of the bulk absorption constant by 70X **Table 9**.

Efforts by other researchers have grown Ge thin film epitaxially on Si[8] where an APD was fabricated for 1310 nm wavelength operation for a 30 um diameter device Figure 18. The QE of the device with a 1 um Ge absorption length is only 56% whereas with **this invention of using microstructured pillars/holes; QE of 100% can be achieved at 1300 nm wavelength and 94% at 1550 nm wavelength with 30X enhancement (Table 9).**

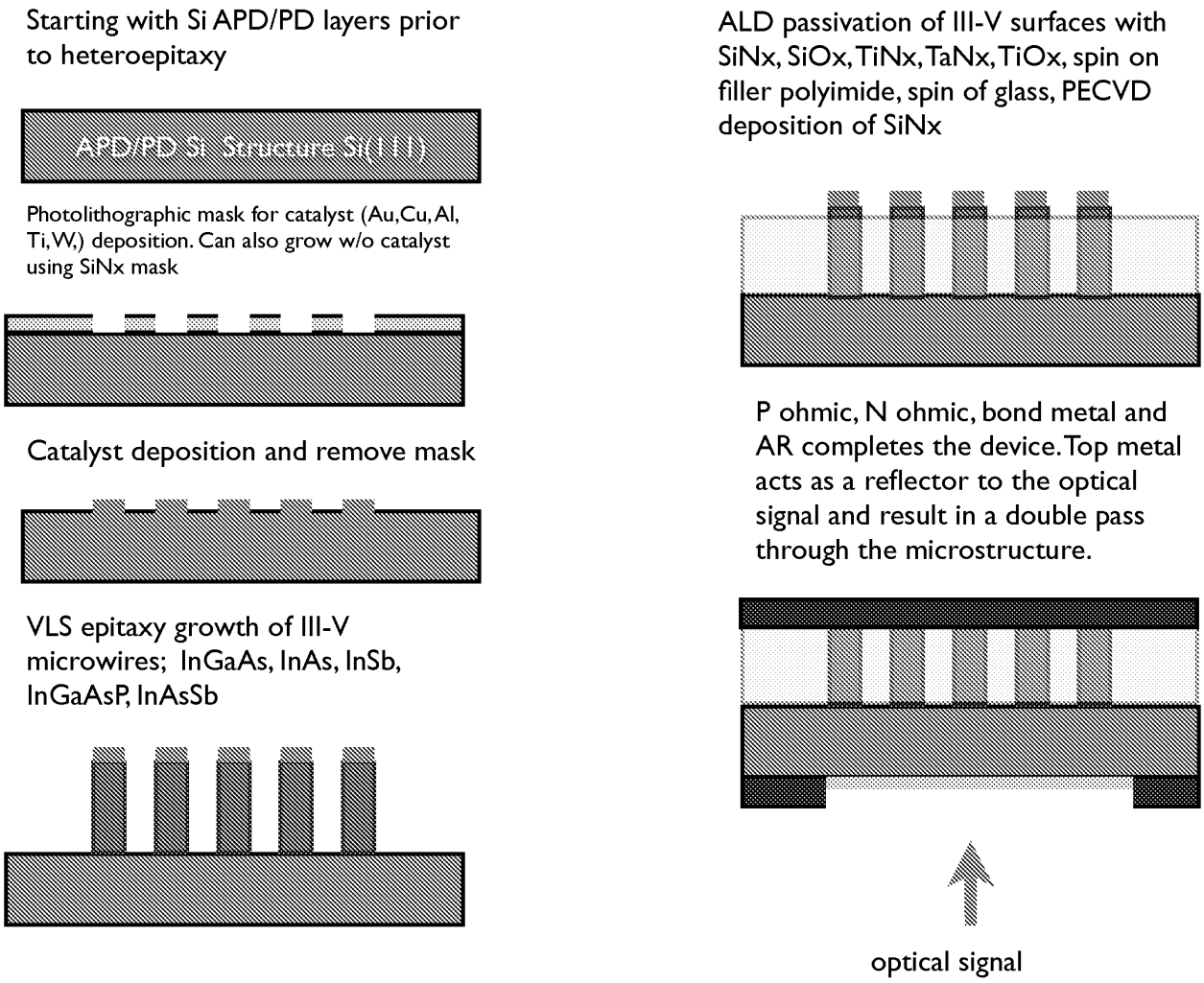
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[8] Kang et al, Epitaxially-grown Ge/Si avalanche photodiodes for 1.3μm light detection, 23 June 2008 / Vol. 16, No. 13 / OPTICS EXPRESS 9365

Patent Owner, W&Wsens - Ex. 2035, p. 19

Kang et al (footnote 7) with a 30 um diameter APD was only able to reach 10 GHz (14.8 Gb/s) bandwidth at 1310 nm. **With our invention of using microstructured pillars/**

Figure 22: Basic processing steps for heteroepitaxy growth of III-V microwires on Si with or without catalyst using VLS or SAG or a combination of the epitaxial methods. In the case of SAG (selective area gowth) the catalyst step is replaced with a SiNx layer of 50 nm, followed by a photolithographic step to define the position of the growth area (open via pattern) and then dry etched. For vertically oriented microwires, silicon wafers with (111) orientation are used.



holes, bandwidths of 32 GHz (47 Gb/s) can be reached for both 1300 AND 1550 nm.wavelength. This is very significant since future bandwidth requirements call for 20

and 40 Gb/s for applications in datacom for datacenters, fiber to home, local area networks (LAN) and metro area networks (MAN) and long distance telecom. The 1300 and 1550 nm are used in silicon photonics where optical circuits are made in silicon and silicon has low optical loss at these wavelengths. 1300 and 1550 nm wavelengths are also used in single mode optical fiber for high bandwidth optical communication applications for distances greater than 1-10 kilometers. Some short distance applications uses multi-mode optical fiber with multimode lasers at wavelengths of 780-1550 nm for distances less than 1-10 Km, often for distances of 100's of meters or less at bandwidths of 10 GHz or greater; 20, 40, 80 Gb/s are projected in future applications.

As shown in **Figure 19** of a possible heteroepitaxial APD structure of Ge on Si (as opposed to earlier discussions of homoepitaxial APD/PD structure where only silicon is used with different doping concentrations and N and P dopings). Applying similar processing methods as in the homoepitaxial Si APD to fabricate microstructured pillar/ hole arrays to enhance the absorption constant of bulk Si, can also be applied to enhancing the bulk absorption constant of Ge by as much as 73X resulting in APD and PD with bandwidths in excess of 32 GHz (47 Gb/s) in devices with an active diameter of 25 um or less. This is a significant improvement over existing Ge on Si APD with illumination normal to the surface of the substrates (prior art Figure 18).

In Figure 19, all the epitaxial layers are similar to that of the all Si microstructured APD (Figure 7) up to the absorption layer where it is replace with Ge "i" or P^- layer followed by a Ge P^+ ohmic contact layer. In particular the layers starting with a Si substrate the is N doped or undoped or low doped depending on the application; a N^+ layer of 1-10 um thick with doping greater than 10^{18} cm^{-3} which is the N ohmic contact layer (cathode); followed by an "i" or P^- layer of thickness range 0.1 to 4 um with doping concentration of less than 10^{16} cm^{-3} which is the multiplication layer; followed by a P charge layer of thickness range 0.02-0.2 um with doping concentration of greater than 10^{17} cm^{-3}; followed by a low temperature Ge buffer layer P^-, of thickness 0.01-0.05 um, this layer is to take the lattice mismatch stress, a transition layer from Si lattice to Ge lattice; followed by P^- Ge absorption layer of thickness range 0.1 - 5 um with a doping concentration less than 10^{16} cm^{-3}; followed by P^+ Ge ohmic contact layer with thickness from 0.1 to 2 um with doping concentrations of greater than 10^{19} cm^{-3}. The epitaxial layers are all grown by CVD, MOCVD, ALD or MBE or combination of the different growth techniques. Layer thicknesses and doping concentrations are chosen for optimal device performance and the point of entry of the optical signal. For example for substrate side illuminated, the P ohmic contact layer can be thicker since most of the light may be absorbed before reaching the P contact layer. For double pass , this layer will still need to be thin to minimize diffusion current.

In addition, guided structures with direct or evanescent coupling to the microstructured pillar/hole array can achieve even high bandwidth as even shorter length of microstructured pillar/hole can be used for reduced transit times. In guided mode structures, RC time is not a lump element but rather distributed into an impedance such

as coplanar or microstrip transmission line structures with impedances designed for 50 ohms transmission line for example[9]. In the transmission line Ge on Si PD, Feng el al (footnote 8) Figure 20, used a 0.65 um thick Ge and 10 um long to achieve > 90% absorption at 1500 nm (bulk absorption is 4000/cm at 1500 nm, and 459 at 1550 nm), the device will need to be 50 um long to achieve 90% quantum efficiency at 1550 nm.

Using this invention, a traveling wave PD/APD optical signal at 1550 nm wavelength can be attained with a length of 1 um and a bandwidth in excess of 65 GHz (96 Gb/s) Figure 21.

The transmission line structure can easily be adapted for Si APD/PD microstructured pillar/hole array and for Ge on Si APD/PD microstructured pillar/hole arrays and other material systems including III-V material family.

III-V on Si

III-V material such as InP, InGaAs, InGaAsP, InAs, InSb, GaSb, InGaSb on Si, Ge on Si, can be epitaxially grown in a sub micrometer selective area growth (SAG) or vapor liquid solid[10][11] (VLS) heteroepitaxy using metal organic vapor epitaxy with or without catalyst which can consists of Au, Cu, Al, Ti, W, Fe, Cr to name a few. Also for vertical oriented microwires grown on silicon, wafers with surface orientation (111) are selected. It is not necessary that the microwires have to be normal to the surface, it can be off normal and even have a mixture of orientations.
In VLS growth, the silicon wafer that has the layer structure for APD or PD just prior to heteroepitaxial growth are photolithographically (or e-beam or nanoimprint lithography) patterned with aperture ranging from 10-2000 nm, and spaced between 10-5000 nm (adjacent edges), followed by Au deposition (e-beam, or thermal evaporation) with thickness of 0.1-10 nm, followed by a lift-off. VLS epitaxial growth in a MOCVD reactor. For SAG growth[12], a 50 nm SiN_x is PECVD (or sputtered or ALD) deposited on a (111) oriented Si wafer with the necessary APD or PD epitaxial layers grown on it ready for heteroepitaxial growth. Using lithography (photo, e-beam or nanoimprint) apertures are defined with dimensions ranging from 10-2000 nm and spaced between 10-5000 nm followed by dry etching (RIE) to open a via to the silicon surface. The wafer is then ready for SAG of Ge, III-V microwires in a MOCVD reactor.

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[9] Feng et al, High-speed Ge photodetector monolithically integrated with large cross-section silicon-on-insulator waveguide, APPLIED PHYSICS LETTERS 95, 261105 (2009)

[10] Sarkar et al, Heteroepitaxial growth dynamics of InP nanowires on silicon, Journal of Nanophotonics, Vol. 2, 021775 (12 February 2008)

[11] Roest, et al, Position-controlled epitaxial III–V nanowires on silicon, Nanotechnology 17 (2006) S271–S275

[12] Chu et al, Wurtzite InP nanowire arrays grown by selective area MOCVD, Phys. Status Solidi C 7, No. 10, 2494 – 2497 (2010)

Patent Owner, W&Wsens - Ex. 2035, p. 22

Detailed steps such as surface treatments, surface preparations, annealing, plasma etching, are not mentioned for simplicity. These steps can be found in the literature.

Patent Owner, W&Wsens - Ex. 2035, p. 23

Electronic Patent Application Fee Transmittal

Application Number:	
Filing Date:	
Title of Invention:	High Speed Silicon Avalanche Photodiode and Photodiodes Using Micro-Structured Absorption Enhancement Regions
First Named Inventor/Applicant Name:	Shih-Yuan WANG
Filer:	William Li-Tien Wang
Attorney Docket Number:	SPW005-Prov

Filed as Small Entity

Provisional Filing Fees

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Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Miscellaneous:				
		Total in USD ($)		**130**

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Customer Number:	85395
Filer:	William Li-Tien Wang
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Warnings:					
Information:					
2	Specification	SPW005-PROV_Specification_22May2013.pdf	3020309 5760a45a9c9c0630ab8ca7a42dcb192da7ea1e22	no	20
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If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

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APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY.DOCKET.NO	TOT CLAIMS	IND CLAIMS
61/826,446	05/22/2013		130	SPW005-Prov		

CONFIRMATION NO. 8129

85395
William L. Wang
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Los Altos, CA 94022

FILING RECEIPT



Date Mailed: 06/19/2013

Receipt is acknowledged of this provisional patent application. It will not be examined for patentability and will become abandoned not later than twelve months after its filing date. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

Inventor(s)

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If Required, Foreign Filing License Granted: 06/17/2013

The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 61/826,446**

Projected Publication Date: None, application is not eligible for pre-grant publication

Non-Publication Request: No

Early Publication Request: No
**** SMALL ENTITY ****
Title

High Speed Silicon Avalanche Photodiode and Photodiodes Using Micro-Structured Absorption Enhancement Regions

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications: No

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