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High-performance, tensile-strained Ge *p-i-n* photodetectors on a Si platform

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We demonstrate a high-performance, tensile-strained Ge *p-i-n* photodetector on Si platform with an extended detection spectrum of 650–1605 nm and a 3 dB bandwidth of 8.5 GHz measured at $\lambda = 1040$ nm. The full bandwidth of the photodetector is achieved at a low reverse bias of 1 V, compatible with the low driving voltage requirements of Si ultralarge-scale integrated circuits. Due to the direct bandgap shrinkage induced by a 0.20% tensile strain in the Ge layer, the device covers the entire C band and a large part of the L band in telecommunications. The responsivities of the device at 850, 980, 1310, 1550, and 1605 nm are 0.55, 0.68, 0.87, 0.56, and 0.11 A/W, respectively, without antireflection coating. The internal quantum efficiency in the wavelength range of 650–1340 nm is over 90%. The entire device was fabricated using materials and processing that can be implemented in a standard Si complementary metal oxide semiconductor (CMOS) process flow. With high speed, a broad detection spectrum and compatibility with Si CMOS technology, this device is attractive for applications in both telecommunications and integrated optical interconnects. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2037200]

Si microphotonics has emerged as a promising technology to break through the interconnect bottlenecks in telecommunications and on-chip interconnects.[1] By substituting electrical cable with optical fiber, fiber-to-the-home (FTTH) technology can drastically improve the bit rate through the internet from 10 Mb/s to the order of 10 Gb/s.[2] Combined with dense wavelength division multiplexing technology (DWDM) in the C band (1528–1560 nm) and L band (1561–1620 nm),[3] the technology has the potential to achieve a bit rate of greater than 1 Tb/s. On the other hand, the RC delay and heat dissipation problems caused by metal interconnects on a Si chip have become increasingly severe as the feature size shrinks below 100 nm.[1] Integrated optical interconnection on Si has been considered as the ultimate solution. The wavelength used in this application will most likely be <1000 nm (e.g., 850 nm GaAs laser) due to the need for a cost-effective laser source. In both FTTH technology and integrated optical interconnects, high speed, high responsivity photodetectors compatible with Si complimentary metal oxide semiconductor (CMOS) processing are indispensable devices to convert the optical signals into electrical ones. The epitaxial Ge photodetector on Si has been demonstrated to be a promising candidate in previous reports.[4–8] In this letter we present a high-performance, tensile-strained Ge photodetector on Si platform fabricated using materials and processing that can be implemented in a standard Si CMOS process flow. The device shows a 3 dB bandwidth of 8.5 GHz at a low reverse bias of 1 V, and a high responsivity over a broad detection spectrum from 650 to 1605 nm, having promising applications in both telecommunications and integrated optical interconnects.

Smooth Ge epitaxial layers with a root-mean-square roughness of ~0.7 nm (determined by atomic force microscopy in a $10 \times 10\ \mu m^2$ area) were selectively grown directly on Si in windows opened through a SiO_2 layer. A ~60 nm Ge buffer layer[9,10] was grown at 335 °C followed by a high temperature growth at 700 °C to deposit 2.35 μm of Ge. The Ge layers were grown on boron doped *p*-type Si wafers. The Ge epitaxial film was then subjected to a 900 °C anneal to reduce the threading dislocation density from $8.0 \times 10^8/cm^2$ to $1.7 \times 10^7/cm^2$. Due to the thermal expansion mismatch between the Ge epitaxial layer and the Si substrate, 0.20% in-plane tensile strain was introduced into the Ge layer, reducing the direct bandgap of Ge from 0.801 to 0.773 eV and extending the effective photodetection range to 1605 nm.[11–14] An n^+ poly Si film on top of the intrinsic Ge layer forms the *n*-type side of the *p-i-n* diode, while the p^+ Si substrate naturally forms the *p*-type side of the device. Aluminum was used as the metal contact in this Ge/Si photodetector, and SiO_2 was used to insulate and passivate the devices. No antireflection coating was deposited on the devices. The entire device was fabricated using materials and processing that can be implemented in a standard CMOS process flow.

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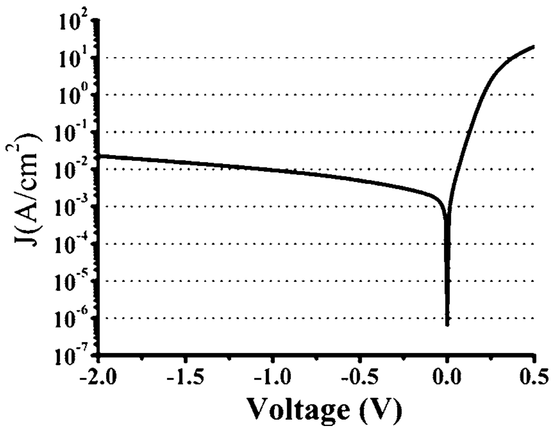

FIG. 1. *I-V* characteristics of a 100 μm diameter Ge *p-i-n* photodiode on Si.

The *I-V* characteristics of the device were measured with a HP4145A semiconductor parameter analyzer. The DC responsivity was measured with a monochromatic light source in the wavelength range of 650–1650 nm on Ge photodiodes 100 μm in diameter. The light was directed at normal incidence on the top surface of the device. For high-speed characterization, a Tektronix 11801C digital oscilloscope with a SD-32 50 GHz sampling head was used to measure the temporal response of the photodetectors to a mode-locked Yb-fiber laser at 1040 nm.[15] The laser produces chirped pulses, which are compressible to 70 fs. For these measurements, the uncompressed pulses of ~1 ps duration were utilized. A 50 GHz ground-signal-ground (GSG) probe, a 50 GHz bias-T and 3.5 mm microwave cables were used in the measurement circuit.

Figure 1 shows the typical *I-V* characteristics of a Ge/Si photodiode 100 μm in diameter. The dark current density of 2.2×10^{-2} A/cm^2 at 2 V reverse bias is comparable to previous results of high quality Ge *p-i-n* diodes on Si.[4,5,8] The ideality factor under forward bias is 1.1, indicating little recombination in the depletion region and, therefore, good Ge material quality.

Figure 2 shows the DC responsivity spectrum of the device at 0 and 2 V reverse bias. Note that the effective detection range is extended from 1550 to 1605 nm compared with bulk Ge. This is due to the direct bandgap shrinkage from 0.801 to 0.773 eV induced by 0.20% tensile strain.[11–14] Therefore, the device is able to effectively cover the entire C band and a large part of the L band in telecommunications. The responsivities of the device at 850, 980, 1310, 1550, and 1605 nm are 0.55, 0.68, 0.87, 0.56, and 0.11 A/W, respectively, without antireflection coating on the surface. The internal quantum efficiency in the wavelength range of 650–1340 nm was determined to be over 90%. The high responsivity over a broad detection spectrum makes it not only applicable for telecommunication wavelengths (1310, 1528–1605 nm), but for integrated optical interconnect wavelength (<1000 nm) as well. The responsivity at 0 V bias is more than 98% of that at 2 V reverse bias over the whole spectrum, indicating excellent carrier collection. From the dopant depth profile measured by secondary ion mass spectroscopy (SIMS), we have calculated the built-in electric field in the intrinsic Ge layer to be ~2 kV/cm at 0 V bias, using a one dimensional finite-difference simulator (PC-1D). The drift velocity of electrons and holes in Ge at an electric field of 2 kV/cm are 5.1×10^6 cm/s and 3.0×10^6 cm/s,[16,17] respectively. Therefore, the drift transit time of electrons and holes in the intrinsic Ge layer are as short as 45 and 77 ps, respectively. The high speed measurement also shows that even with some carrier diffusion processes due to the incomplete depletion of the Ge layer at 0 V, the transit time is still

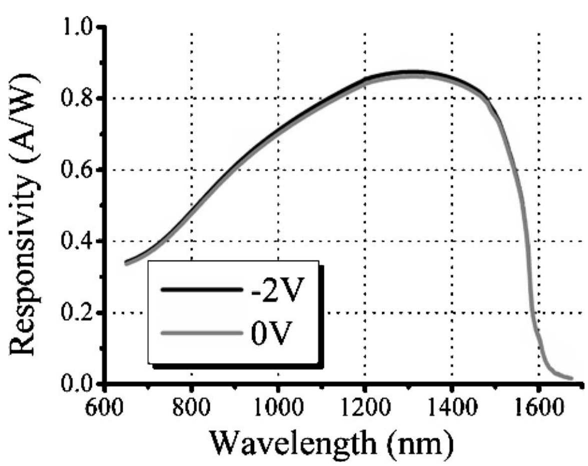

FIG. 2. DC responsivity at 0 and 2 V reverse bias in the wavelength range of 650–1650 nm without antireflection coating. With 0.20% tensile strain in the Ge layer, the effective detection limit of the device has been extended from 1550 to 1605 nm, covering the whole C band and a large part of the L band. The DC responsivity already saturates at 0 V bias, a very desirable feature for low voltage operation.

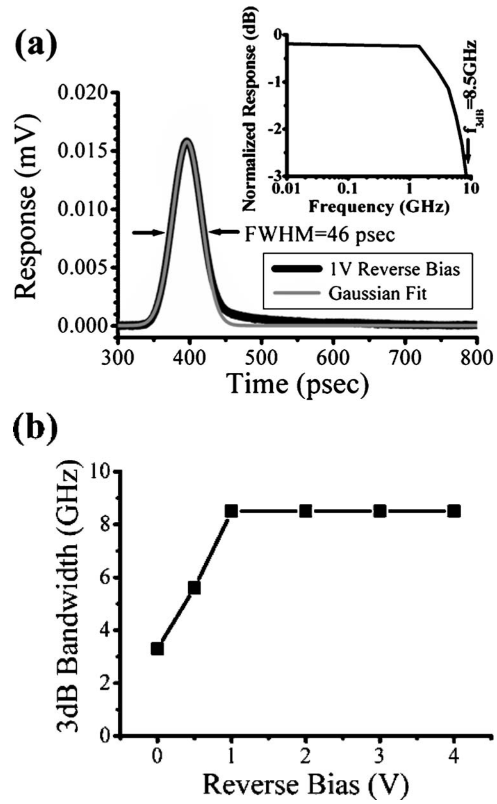

FIG. 3. (a) Temporal response of a 10×70 μm Ge/Si photodetecter at a reverse bias of 1 V to ~1 ps-long pulses generated by a mode-locked Yb-fiber laser at 1040 nm (black line). The gray line shows the Gaussian fit to the pulse. The full width at half maximum (FWHM) is 46 ps. The inset of the figure shows the Fourier transform of the pulse, which gives a 3 dB bandwidth of 8.5 GHz. (b) The 3 dB bandwidth of the device as a function of reverse bias. The full bandwidth is achieved at a low reverse bias of 1 V, which is very compatible with the low driving voltage requirements ($\leqslant$1.5 V) of Si ULSI.

as short as ~150 ps. On the other hand, the minority carrier life time is ~1 ns for the Ge film with a $1.7\times10^7/\mathrm{cm}^2$ dislocation density,[4] an order of magnitude longer than the carrier transit time. Therefore, all carriers generated by the excitation of photons are collected before they recombine even at 0 V bias, due to the high quality intrinsic Ge epitaxial layer and appropriate device design. The high collection efficiency explains why full responsivity is achieved at 0 V bias. The ability of the device to operate at such low reverse bias is compatible with the requirement of a low driving voltage of $\leqslant 1.5$ V in Si ultralarge-scale integrated circuits (ULSI).[18]

Figure 3(a) shows the temporal response of a 10×70 μm photodiode at a reverse bias of 1 V to the 1 ps-long pulses generated by the 1040 nm mode-locked fiber laser. Because the laser pulses are much shorter than the response time of the photodetector, the effect of laser pulse width on the measurement result is negligible. The resolution of the measurement is 0.2 ps. The shape of the temporal response of the photodetector is mostly Gaussian, with a small tail due to the carrier diffusion process. The full width at half maximum (FWHM) of the response pulse is 46 ps. To obtain the frequency response, a Fourier transform of the pulse was performed without deconvolving the contribution of the measurement circuit, and the result is shown in the inset of Fig. 3(a). We obtained a 3 dB bandwidth of 8.5 GHz, indicating that the device is suitable for a bit rate of 15 Gb/s. Theoretically, the 3 dB bandwidth is determined by the carrier transit time and RC delay of the device. The transit time limited bandwidth is given by[19]

$$f_{\mathrm{transit}}=\frac{0.44v_{\mathrm{sat}}}{W}, \tag{1}$$

where v_{sat} is the saturation drift velocity in Ge, and W is the thickness of the intrinsic Ge film. With $v_{\mathrm{sat}}=6.0\times10^6$ cm/s[16,17] and $W=2.35$ μm in our case, one calculates $f_{\mathrm{transit}}=11.2$ GHz. The RC limited bandwith is given by

$$f_{RC}=\frac{1}{2\pi RC}. \tag{2}$$

With a load resistance $R=50$ Ω and the capacitance of the device $C=0.18$ pF, f_{RC} is determined to be 17.7 GHz. The 3 dB frequency of the device can be estimated by

$$f_{3\ \mathrm{dB}}=\sqrt{\frac{1}{1/f_{\mathrm{transit}}^2+1/f_{RC}^2}}, \tag{3}$$

and it is determined to be 9.5 GHz, using the results of Eqs. (1) and (2). The calculated result is very close to the measured 3 dB bandwidth of 8.5 GHz. Figure 3(b) shows the bandwidth of the device as a function of the reverse bias. The full bandwidth is achieved at a low reverse bias of 1 V, which is very desirable for low voltage operation in Si ULSI. The bandwidth of the device is mainly limited by the transit time, which can be improved by reducing the film thickness. This is especially applicable for integrated optical interconnects, where an 850 nm GaAs laser source is likely to be used. For $\lambda=850$ nm, 90% internal quantum efficiency can be achieved with just 0.75 μm intrinsic Ge layer, giving a transit time limited bandwidth of 35 GHz. Also, in the current device about 80% of the capacitance is due to the 50×50 $\mu\mathrm{m}^2$ Al pads on SiO_2. In integrated photodetectors these large pads are no longer necessary, so the RC limited bandwidth can also be greatly improved.

In conclusion, we have demonstrated an 8.5 GHz tensile-strained Ge photodetector on Si with a broad detection spectrum from 650 to 1605 nm. The entire device was fabricated using materials and processing that can be implemented in a standard Si CMOS process flow, and it has promising applications in both telecommunications and integrated optical interconnects.

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