Sixteen-element Ge-on-SOI PIN photo-detector arrays for parallel optical interconnects

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(Received 5 June 2013; revised manuscript received 13 August 2013; published online 24 January 2014)

We describe the structure and testing of one-dimensional array parallel-optics photo-detectors with 16 photodiodes of which each diode operates up to 8 Gb/s. The single element is vertical and top illuminated 30-μm-diameter silicon on insulator (Ge-on-SOI) PIN photodetector. High-quality Ge absorption layer is epitaxially grown on SOI substrate by the ultra-high vacuum chemical vapor deposition (UHV-CVD). The photodiode exhibits a good responsivity of 0.20 A/W at a wavelength of 1550 nm. The dark current is as low as 0.36 μA at a reverse bias of 1 V, and the corresponding current density is about 51 mA/cm^2. The detector with a diameter of 30 μm is measured at an incident light of 1.55 μm and 0.5 mW, and the 3-dB bandwidth is 7.39 GHz without bias and 13.9 GHz at a reverse bias of 3 V. The 16 devices show a good consistency.

Keywords: surface illuminate, line array, optical telecommunication, parallel optical interconnects

PACS: 85.60.Gz, 95.55.Aq, 85.30.De **DOI:** 10.1088/1674-1056/23/3/038507

1. Introduction

Silicon-based photonics devices have generated a growing interest for several years. The main applications are in optical interconnects to overcome the microelectronic circuit bottlenecks and optical telecommunications to fabricate low-cost, compact, and reliable devices.[1,2] Photodetector array is important component, especially when parallel optical links are considered. Commercial serial optical links are presently operating at wavelengths around 1550 nm for the lowest fiber losses or 1300 nm for low dispersion. However, at these wavelengths the absorption rate of silicon is diminishing. The efforts to create fully integrated high-speed photodiodes and opto-electronic interfaces for 1310-nm or 1550-nm communication on-chip, have been impeded. Fortunately, due to its high absorption coefficient at the wavelengths and the compatibility with silicon technology, qualified germanium is regarded as an ideal candidate for silicon compatible with the near-infrared light detection. To this extent, thin film germanium photodetectors fabricated on silicon substrates have recently gained widespread interest.[1] Much work on germanium-on-silicon p–i–n detectors has shown good responsivity at wavelengths up to 1550 nm. Integrated germanium-on-silicon p–i–n photodiode arrays are better for multi-channel high-speed serial interfaces. The technology and the components presented here are compatible with standard CMOS process, making them quite suitable for monolithic integration of receiver circuits.[3]

In this paper, with ultra-low temperature buffer layer and 40-s heat treatment at a temperature of 850 °C, high-quality Ge is epitaxially grown on Si using ultrahigh vacuum/chemical vapor deposition (UHV/CVD). We obtain very low density of threading dislocation (3×10^5 cm^{-2}) at the surface using the Secco etch method. We demonstrate that efficient 1×4 germanium-on-silicon p–i–n photodetector array with 0.8-μm Ge film has responsivity as high as 0.38 and 0.23 A/W at 1.31 and 1.55 μm, respectively. The dark current densities are 0.37 mA/cm^2 and 29.4 mA/cm^2 at 0 V and a reverse bias of 0.5 V. The dark current density is as low as ∼ 5 mA/cm^2, and the result is the best ever reported about Ge p–i–n photodetector.[4] The detector with a diameter of 30 μm, 3-dB bandwidth of 4.72 GHz at an incident wavelength of 1550 nm and a zero external bias is measured. At a reverse bias of 3 V, the bandwidth is 6.28 GHz. We have recently reported on the characteristic of a 23.3-GHz single Ge/Si p–i–n photodetector.[5] In this paper, we demonstrate a parallel system with sixteen-element photo-detector arrays made of 30-μm-diameter surface illumination Ge-on-SOI PIN photodetector. The center-to-center separation is 127 μm, which is the same as those of most commercial fiber arrays. Operating with 1 V bias, the array exhibits a uniform 3 dB bandwidth of 13.5 GHz and responsivity of 0.2 A/W at 1.55 μm. The structure design, hetero-structure growth, and fabrication procedure are described in Section 2. The device characteristics are described and discussed in Section 3. Finally, the results are summarized in Section 4.

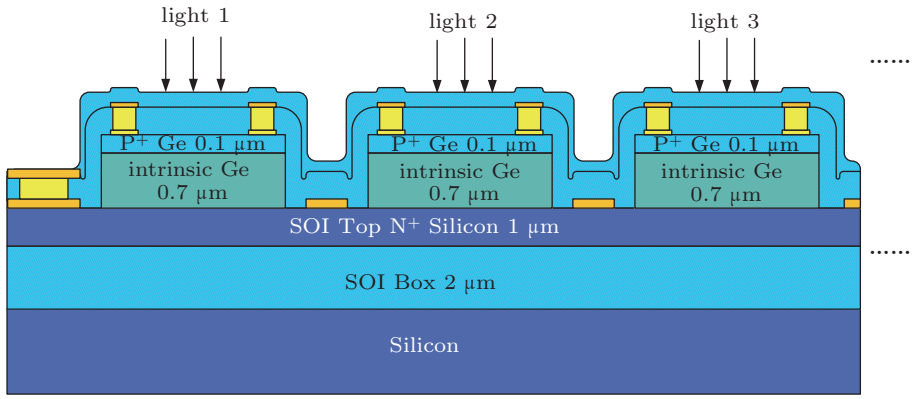
2. Material growth and device fabrication

A schematic cross-section view of the Ge-on-SOI line array photo-detectors is shown in Fig. 1(a). An SOI substrate with 2.0-μm-thick buried oxide and a 1.0-μm-thick highly phosphorus doped Si were chosen to reduce radio-frequency

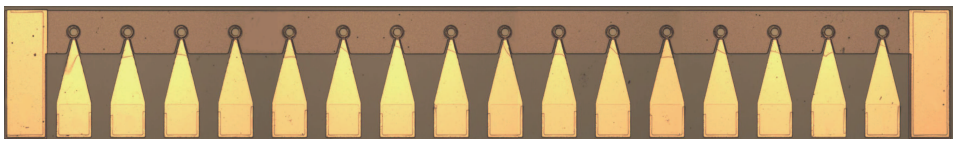
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losses. Germanium was deposited on the top n^+-Si (001) layer of the SOI wafers using germane (GeH_4) by cold wall ultra-high vacuum chemical vapor deposition (UHV-CVD). Before growing, the substrate was degassed at 300 °C in the pretreatment chamber and deoxidized in the growth chamber by heating up to 930 °C for 5 min.[6,7] In order to minimize the dislocation density of the heterogeneous region, the hetero-epitaxy of 50-nm-thick Ge on Si was initiated at 290 °C with a flow of 8 sccm of pure germane. After the low-temperature Ge buffer deposition, the substrate temperature was elevated to 600 °C and 0.8-μm-thick-Ge was deposited on the buffer layer. The wafer was implanted with BF^{2+} ions on the top of Ge film and went through a rapid-thermal-annealing (RTA) process at 650 °C for 15 s to activate the doping. The thickness of the germanium intrinsic layer was about 0.7 μm.



(a)



(b)

Fig. 1. (color online) (a) Schematic cross section of the linear detector array, and (b) top view of a linear photo-detector array consisting of 16×30-μm-diameter detectors.

The photo-detector array was realized as 1×16 circular mesa diodes each with a diameter of 30 μm. The device process started with the formation of the p-mesa by dry etching in an inductively coupled plasma (ICP) etcher. In the first mesa process, the detectors were patterned. The etching depth has to be controlled to achieve a maximum remaining thickness of the n^+ Si layer, which was essential for a small series resistance. Then, the second mesa etching step down into the buried oxide layer of SOI was preformed by moving completely the n^+ Si layer. An anisotropic etched profile and a smooth and residue-free surface of the Ge mesa were realized by an optimized etch process.[8] This double mesa layout significantly reduces the parasitic capacitance. The n^+ and p^+ contacts were formed with a 50-nm titanium adhesion layer and a 350-nm-thick aluminum layer. A 500-nm-thick SiO_2 passivation was deposited by plasma enhanced chemical vapor deposition (PECVD) at 300 °C to insulate the mesa sidewall from the signal contact. Oxide window for the pad contacts was opened by subsequent CF inductively couple plasma (ICP) etching and wet etching of the last 50 nm for reduced irradiation damage. After the pad contacts were deposited by e-beam evaporation and patterned by liftoff, a passivation/antireflection layer was coated to reduce the incidence light loss. The micrograph of a photo-detector array is shown in Fig. 1(b).

3. Electronic and optical characterization

3.1. *I–V* characteristics

Figure 2 shows the measured photocurrent and dark currents in a voltage range from −1 V to 0 V for all the devices in the array. The *I–V* characteristics of the devices are measured with Agilent B1500A semiconductor parameter analyzer. The dark current of the 30-μm-diameter device is as low as 0.36 μA at a reverse bias of 1 V, and the corresponding current density is about 51 mA/cm^2. Contributions to the dark current can come from the sidewall and bulk, so both of them need to be dealt with to obtain the lowest possible value. The passivation and implantation location are used to reduce the former component, and the growth and annealing conditions are used for latter component. However, the oxide

silicon, mono-crystalline silicon, and mono-crystalline germanium have different temperature coefficients, so appropriate temperature and time should be chosen carefully.

The theoretical value of DC responsivity is 0.305 A/W[5] by using an optical absorption coefficient of 4×10^3 cm^{-1},[9] an absorption thickness of 0.7 μm, an input optical wavelength of 1.55 μm, a surface reflectivity of 0 and an internal quantum efficiency of 1. The experimental value is obtained with a monochromatic light source at a wavelength of 1550 nm on the optical interconnects wave between chips. The incident light is normal to the top surface of the device through a plane fiber probe with a core diameter of 9 μm. A fixed wavelength laser and a tunable wavelength laser are used as a light source. As shown in Fig. 2, the optical current is measured under an incident optical power of 0.5 mW, and the optical responsivity is about 0.2 A/W lower than the theoretical value, and mainly limited by the surface reflectivity. Using an erbium-doped fiber amplifier (EDFA) at an available optical power level up to 80 mW, no compression of the DC photocurrent is observed.

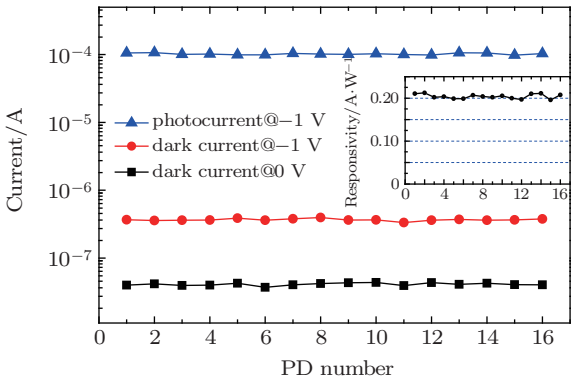


Fig. 2. (color online) Plots of current versus photo-detector number of the linear photo-receiver at different biases and the responsivities of the 16 photo-detectors for the same array with diameter of 30 μm, optical power of 0.5 mW, and $\lambda = 1.55$ μm.

3.2. Bandwidth

The optoelectronic frequency response is measured on wafer with a network analyzer in a frequency range from 0.8 GHz to 30 GHz. The high-speed radio-frequency (RF) signal from the network analyzer is applied to an external modulator fed by a continuous wave laser. Optical signal at 1550 nm with an average power of 0.5 mW is modulated and was coupled to the photo-detector under vertical incidence using a lensed optical fiber in order to increase the signal/noise ratio. A high-speed RF probe is used to collect photo-generated carriers that are measured by light-wave component analyzer. To correct the measured frequency response for the limited bandwidth of the modulator, the modulator frequency response is determined using a 40-GHz reference photodiode with a known frequency response. The frequency response of the bias-tee, RF cable, and probe are factored out from the result. The normalized frequency responses of each of the 30-μm-diameter detectors in the array are shown in Fig. 3 at different bias voltages. The device shows a 13.9-GHz 3-dB bandwidth at bias voltage of −3.0 V. Moreover, the bandwidths of other devices in the array are all between 13.4 GHz and 14.2 GHz. Therefore, the detectors in the array have excellent uniformity in the frequency characteristics.

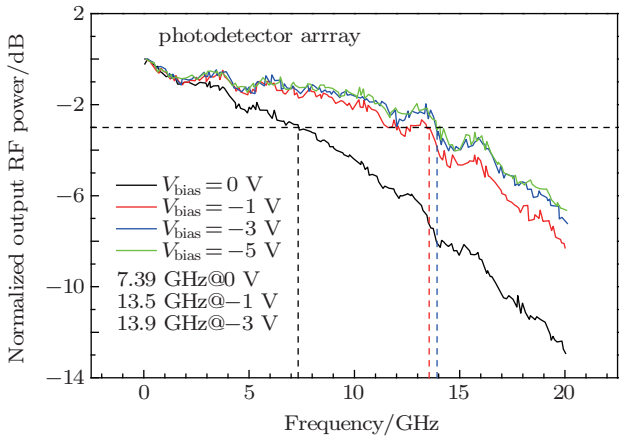


Fig. 3. (color online) Normalized frequency responses at 1550 nm of detector with a diameter of 30 μm.

Further investigation reveals that the speed of a vertical p–i–n detector is limited by the (slow) diffusion of carriers from outside the depletion layer, the carrier transport through the depletion layer, and the load time of the depletion capacity. For the high frequency response, we only need to consider the transit time and the load time RC delay when diffusion can be neglected.[10] Under the assumption of a saturation velocity $v_{sat} = 6\times10^6$ cm/s in Ge intrinsic layer, the calculated carrier transit frequency f_T is 36 GHz. With an intrinsic Ge thickness of 0.7 μm (total Ge thickness is 0.8 μm), the calculated depletion capacitance is 0.113 pF. Taking 50-Ω cable impedance into account, it sets the RC constant limited speed to be 28 GHz. The predicted electrical bandwidth is 22 GHz. In a more accurate assessment, the parasitic capacitance and pad capacitance are added to the intrinsic capacitance, giving reduced RC bandwidths, especially for a small device. In the current photodiode layout, the parasitic capacitance depends linearly on the overlap area between the signal contact and the p mesa. High series resistances further reduce the bandwidth and lead to disagreement between the experimental results and the theoretical values. Large contact resistance due to the Fermi level pinning effect at the interface between metal and Ge strongly restricts series resistances of Ge photodetectors and reduces the 3 dB bandwidth. Therefore, an Al/TaN stack electrode will be used to improve the frequency characteristic of the device.[11]

4. Conclusion

A 1×16 Ge/Si PIN photo-detector is grown on an SOI substrate for low radio-frequency losses using the ultrahigh vacuum chemical vapor deposition. The photo-detector is of 30 μm diameter and double mesa vertical structure. The 16 photodiodes have a similar dark current and an optical responsivity. The 30-μm-diameter device demonstrates a 13.5-GHz 3-dB bandwidth with bias voltage of −1.0 V. Thus, this one-dimensional array of photo-detectors can operate at 216 GHz for optical data link applications in digital processing of information and parallel optical interconnects between chips in optoelectronic integrated circuits.

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