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High Speed Selective-Area-Epitaxial Ge-on-SOI *PIN* Photo-detector Using Thin Low Temperature $Si_{0.8}Ge_{0.2}$ Buffer by Ultra-High-Vacuum Chemical Vapor Deposition

Loh Ter-Hoe, Wang Jian, Nguyen Hoai-Son, Murthy Ramana, Yu Ming-Bin, Loh Wei-Yip, Lo Guo-Qiang, Narayanan Balasubramanian, and Kwong Dim-Lee
Institute of Microelectronics, 11 Science Park Rd, Science Park-II, Singapore (117685).

Abstract
Ge/SiGe/SOI *PIN* photodiodes with 15~17GHz bandwidth at 1550nm, external quantum efficiency of 20%~27% at 850nm, and bulk dark current density of 1.5~2mA/cm^2, using low temperature $Si_{0.8}Ge_{0.2}$ buffer and without cyclic annealing were demonstrated.

1. Introduction

Ge-on-Si is an important material for optical communications because of its ability to absorb light at 850nm, 1.3~1.55μm, and of its ease of integration with mainstream Si CMOS. A vertical light incidence Ge/Si *PIN* photodetector monolithically integrated on Si or SOI substrate is cost effective solution for optical fiber and chip-to-chip communications. Currently, highest reported speed of vertical Ge/Si *PIN* is 39GHz [1], in which Ge/Si epitaxy is prepared by molecular beam epitaxy (MBE). However, MBE is not useful for mass production. So far, the ultra-high vacuum chemical vapor deposition (UHVCVD) prepared Ge/Si is by the two stage Ge growth method. Namely, 30~50nm of low temperature Ge (350~400°C) followed by ≥1μm of high temperature Ge (550~600°C) is grown on Si(100) substrate. Cyclic annealing is required to reduce the dislocation density of Ge to 10^6 cm^{-2} [2]. In this work, vertical incidence Ge/SiGe/Si *PIN* photodiode is fabricated by selective area growth (SAG) of Ge using ~14nm thick low temperature $Si_{0.8}Ge_{0.2}$ buffer prior to two stage Ge epitaxy on SOI substrate without cyclic annealing. The use of low temperature $Si_{0.8}Ge_{0.2}$ buffer eliminate the cyclic annealing step yet achieving dislocation density of ~10^6 cm^{-2} [3]. Furthermore, reduced area Ge epitaxy not only improves the epitaxy quality, it also simplifies process integration into mainstream CMOS process.

2. Experiment

The photo-detector structure is shown schematically in Fig.1. Photo-detectors with round mesas for diameters of ϕ: 10, 20 and 28μm, and square mesas of 7x7, 10x10, 15x15, 25x25μm^2 were fabricated on the same die. Fig.2 shows the Scanning Electron Micrograph images for both round and square mesa structures. An 8-inch *p*-type SOI wafer with resistivity of ~12Ωcm was deposited with 150nm of plasma-enhanced (PE) CVD SiO_2. The wafer is patterned with openings for SAG of Ge. The SiO_2 is first partially etched by RIE, followed by wet etch in dilute HF(1:25) solution to expose Si surface after resist removal. Wafer is cleaned in NH_4OH:H_2O_2 solution for 5min., HF(1:200) solution for 2min., rinsed, and dried in slow N_2 flow before loading into Anelva-UHVCVD reactor for SAG-Ge epi-growth. Details of the Ge growth can be found in [3]. *Ex-situ* Cl_2 has been utilized to clean the poly-Ge formed due to non-selectivity and also Ge mesa etching. SAG-Ge has a thickness of ~350nm. The mesa depth was 150nm~220nm. Top of the mesa was phosphorus implanted with at dose of 4x10^{15} cm^{-2} and energy of 30keV. The bottom of mesa was boron implanted at dose of 4x10^{15} cm^{-2} and energy of 15keV. The dopants were activated at 650°C for 10sec. Then, 500nm of PECVD SiO_2 was deposited. Contact vias were opened by RIE. Al deposition followed by Al-pad patterning, and Al-RIE were done to form the devices.

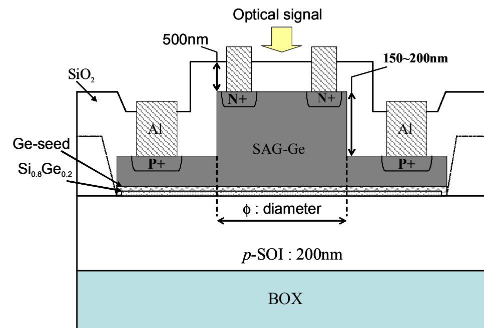

Figure 1 Schematic structural diagram of normal incidence Ge/SiGe/Si *PIN* photodiode.

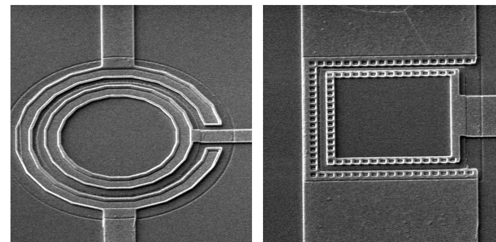

Figure 2 Scanning electron micrograph of both round-mesa and square-mesa Ge/SiGe/Si *PIN* photodiodes.

3. Results and discussion

(3.1) Dark currents

Figure 3 (a) shows the dark currents against voltage for all the round and square mesa photodiodes. The dark current density for these devices is ~21mA/cm^2 for round-mesa and ~27mA/cm^2 for square-mesa at 1V reverse bias for largest area devices. Figure 3(b) shows the plot of dark current against mesa-area for both types of photodiodes. The straight line

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through these data does not pass through the origin. This shows that surface leakage is present. At 1V reverse bias, for round-mesa diodes, the bulk current-density (J_{bulk}) and surface leakage density ($J_{surface}$) are 1.5mA/cm^2 and 14 µA/cm, respectively. For square-mesa diodes, the J_{bulk} and J_{surf} are 2mA/cm^2 and 19.5µA/cm, respectively. The higher surface leakage in square mesa is most likely due to corner effects. The high surface leakage can be mitigated in future using amorphous-Si surface passivation [4].

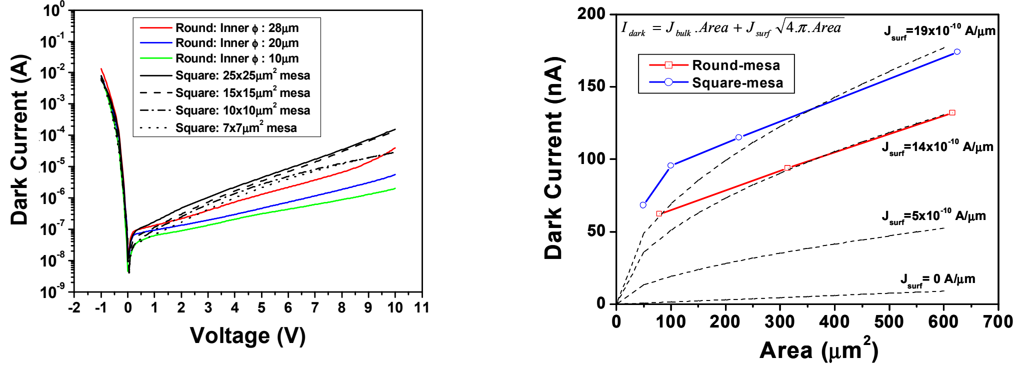

Figure 3 (a) Dark current against voltage curves of both the round and square shaped mesa Ge/SiGe/SOI-*PIN* photo-detectors. (b) Dark current against mesa area of both round and square photodiodes. The red and blue curves are actual dark current data. The dashed curves are computed I(dark) vs area according to the equation in the inset.

(3.2) External quantum efficiency

Fiber-pigtailed laser diode with multimode fiber probe has been used for quantum efficiency measurements. Figure 4 shows the photo-I-V characteristics of both the 28µm-diameter round mesa and 25x25µm^2 square-mesa photodiodes, at λ=850nm and 1300nm. The external quantum efficiency (ext.QE) of the round-mesa for 850nm was 18%~27% depending on the optical power injection and the bias voltage, as shown in Fig.5(a). The square-mesa diode exhibited ext.QE from 14% to about 27% as reverse bias voltage increases to 5V depending on the optical power injected at 850nm.

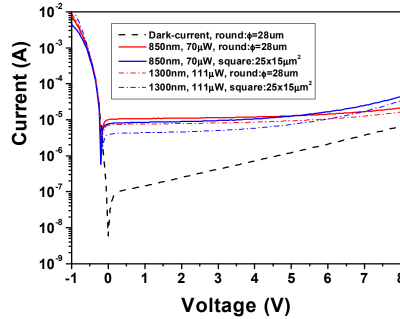

Figure 4 I-V characteristics of photocurrent for round (ϕ=28µm) and 25x25µm^2-square mesa Ge/SiGe/Si photodiodes for 850nm and 1300nm optical wavelengths.

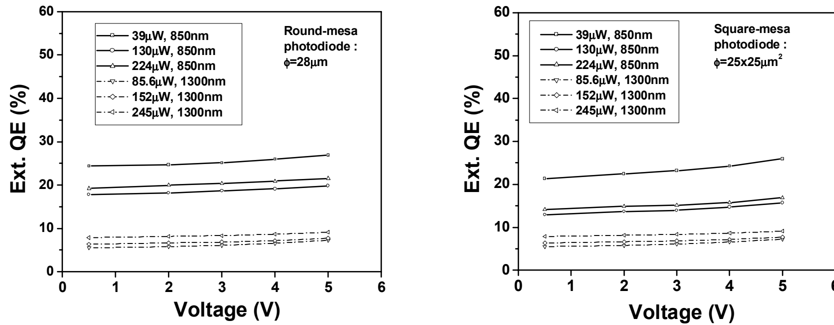

Figure 5 External quantum efficiencies of (a) round-mesa (ϕ=28µm) (b) Square (25x25µm^2) photodiodes, measured at 850nm and 1300nm wavelength for various optical powers.

For 1300nm, the ext.QE is reduced to 4%~8% due to lower optical absorption coefficient. The low ext.QE is accounted by the optical mode size mismatched between that of the multimode fiber probe and the photodiode aperture and 500nm of SiO_2 on Ge is not optimized for anti-reflection of optical power at the respective wavelengths. In spite of this, ext. QE of ~27% for 850nm is comparable to [5] for about the same Ge thickness.

(3.3) Photodetector bandwidth

Impulse response measurements were done on the various sized photodiodes using 1550nm pulsed fiber laser which has a optical pulse width of 80fs. The laser was directed onto the device via a lensed fiber probe. Figure 6(a) shows the impulse response of a 15x15μm^2 square-mesa photodiode reversed bias at 1V. The photo-current pulse is picked up by microwave probe and registered on a 40GHz sampling scope. A 26GHz bandwidth bias-tee was used in the temporal measurement set up. As shown in Fig.6 (a), the pulse-width at the foot of the pulse is about 0.5×10^{-10} sec. The frequency bandwidth of the diode should be in the order of ~$1/(0.5\times10^{-10}$sec)=20GHz. Indeed, the FFT of the temporal response in Fig.6(b), shows that the 3dB bandwidth is about 15~17GHz at 1V reversed bias. We believe that the FFT-3dB bandwidth should be slightly higher. Present recorded bandwidth is limited by the bias-tee in the measurement set-up.

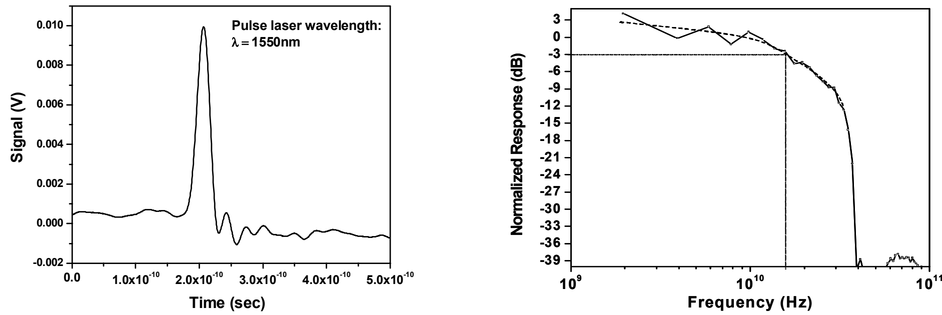

Figure 6 (a) Temporal impulse response of 15x15μm^2 square-mesa photodiode at λ=1550nm, at reversed bias of 1V. (b) The fast Fourier transform of the temporal response of Fig.6(a).

4. Conclusion

A 15~17GHz bandwidth at 1550nm vertical incidence Ge/SiGe/Si *PIN* photo-detector using SAG of Ge with low temperature thin $Si_{0.8}Ge_{0.2}$ buffer without cyclic annealing has been demonstrated. The low bulk dark current density of 1.5~2mA/cm^2 testifies to the good Ge quality. This paves the way for monolithic integration to mainstream CMOS process.

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