Normal-incidence Ge quantum-dot photodetectors at 1.5 μm based on Si substrate

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(Received 7 August 2001; accepted for publication 11 December 2001)

Coherent Ge quantum dots embedded in Si spacing layers were grown on Si substrate by molecular-beam epitaxy in the Stranski–Krastanov mode. Photoluminescence measurement showed a Ge-dot-related peak at 1.46 μm. *p-i-n* photodiodes with the intrinsic layer containing Ge dots were fabricated, and current–voltage ($I-V$) measurement showed a low dark current density of 3×10^{-5} A/cm^2 at -1 V. A strong photoresponse at 1.3–1.52 μm originating from Ge dots was observed, and at normal incidence, an external quantum efficiency of 8% was achieved at -2.5 V. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1449525]

The advantage of their compatibility with the state-of-the-art very large scale integrated technology makes Si-based photodetectors a very important subject of investigation for application in long distance optical fiber communications, local area networks, as well as Si-based optoelectronic devices for optical interconnects in high-speed computers. Although highly efficient InP based InGaAs detectors for 1.3–1.55 μm can be bonded onto Si for achieving integration, the bonding technique requires sophisticated and costly procedures. It is therefore desirable to grow materials directly on Si substrate. Because of its narrower band gap compared to Si, the $Si_{1-x}Ge_x$ alloy system has been widely exploited for infrared detectors.[1–4] However, no efficient device for 1.3–1.55 μm was successfully obtained. The growth of strained layer superlattice (SLS) usually did not use relaxed buffer layers. Using such structures, both waveguide and surface-normal photodetectors have been demonstrated.[5–7] Due to the large lattice mismatch between Si and Ge, the critical thickness for a strained SiGe layer with high Ge mole fraction (larger than 50%) is limited to less than 10 nm.[8] The overall Ge content in SLS was also limited to low value, and the response wavelength could barely reach 1.3 μm.[5–7] The use of a graded buffer[9,10] helps to achieve pure Ge and high Ge mole fraction SiGe with a reduced defect density, but the dislocation density still remains problematic for device application. All these factors limit the application of SiGe alloy or SLS in the important optical fiber communication wavelength of 1.55 and 1.3 μm. Ge quantum dots[11–14] grown on Si are partially relaxed with low defect density, and the Si content in dots can be controlled to be low by appropriate growth conditions,[13] thus they offer an attractive method of fabricating detectors for tuning the wavelength to 1.55 μm.

In this letter, we present the results of our normal-incidence *p-i-n* photodetectors using coherent Ge quantum dots embedded in undoped Si layers. The photoresponse wavelength of Ge dots covered the wavelength range of 1.3–1.52 μm. Low leakage current and relatively high external quantum efficiency were obtained.

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The sample was grown using a solid-source molecular beam epitaxy (MBE) system. The substrate used was an n-doped (100) Si wafer with the resistivity of 14–22 Ω cm. The wafer was cleaned using the standard Shiraki method immediately before being introduced into the MBE chamber. The growth temperature was kept at 550 °C. A 100 nm undoped Si buffer layer was first grown, then a 300 nm n^+ Si layer was grown with a Sb doping concentration of $1-2\times10^{18}$ cm^{-3} followed by 50 nm undoped Si. Then ten periods of Ge dots were grown in the Stranski–Krastanov mode, and they were separated by 20 nm undoped Si spacer layers. The nominal growth thickness of each Ge layer was 1 nm. A 100 nm undoped Si space layer and a 100 nm p^+ Si contact layer with a boron doping concentration of 5×10^{18} cm^{-3} were then deposited. The growth rates were 0.1 and 0.02 nm/s for Si and Ge, respectively. The cross-sectional transmission electron microscope image showed that the Ge dots were approximately 10 nm in height and 100 nm in base diameter and that the dots were vertically correlated. No dislocation was detected in the image, indicating that the dislocation density is below the detection limit ($\sim$1 μm^{-2}).

Photoluminescence (PL) measurement was carried out at 4.5 K. The 514.5 nm line of an Ar^+ laser was used to excite the sample and a liquid nitrogen cooled Ge detector was used for detection. Figure 1 shows a PL peak related to Ge dots at 0.85 eV (1.46 μm) with a full width at half maximum (FWHM) of 60 meV. This peak extends to below 0.8 eV (1.55 μm), indicating the potential for photodetectors to work at this wavelength. Besides this peak, three other peaks at 1.094, 1.135, and 1.154 eV were also detected, and they were ascribed to transverse optical (TO) phonon assisted, transverse acoustic phonon assisted, and no-phonon transitions in Si, respectively.

p-i-n photodiodes were fabricated using standard lithography. Mesas were defined by dry etching with CF_4/O_2. The mesa size was 150×300 μm^2. A 220 nm SiO_2 passivation layer was deposited by plasma enhanced chemical vapor deposition and an Al/Ti metal layer was deposited for contact. Mirror-like morphology was kept throughout the pro-

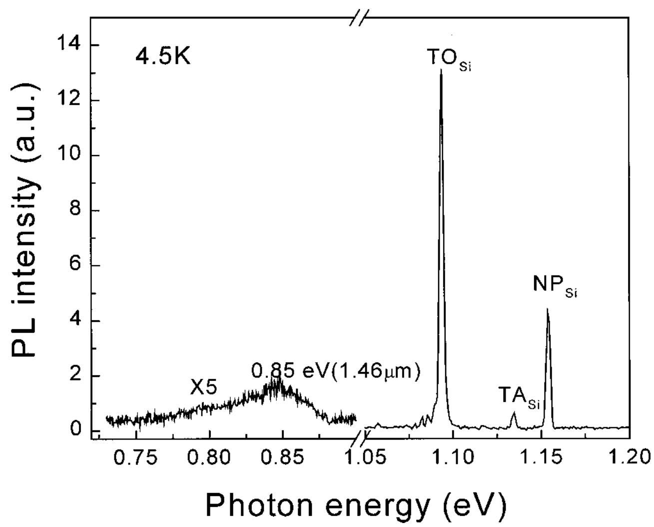

FIG. 1. PL spectrum of the Ge dot sample obtained at 4.5 K. It shows a Ge dot related peak at 0.85 eV (1.46 μm) with FWHM of 60 meV.

cessing. The wafer was diced and the chips were mounted in TO-5 packages.

Current–voltage ($I-V$) measurement was performed with HP41420A at both 300 and 77 K. Figure 2 shows the $I-V$ characteristics of a typical diode. The breakdown voltage was 6.5 V at 300 K and decreased to 4.5 V at 77 K. As shown in the inset, a low dark current of 3×10^{-5} A/cm^2 at -1 V was obtained at 300 K. This is 2 orders of magnitude lower than that reported by Huang *et al.*[5] (4×10^{-3} A/cm^2), and is similar to the results of Splett *et al.*[15] However, it is still much higher than the ideal dark current of pure silicon diodes. This may be due to additional generation processes in the Ge dots and the wetting layers, i.e., the emission of carriers from the potential wells formed by these regions and the silicon layers. The surface states can also contribute to the dark current.

Photocurrent measurement was performed in a normal-incidence configuration at both 300 and 77 K. A tungsten lamp was used as the light source. The light passed through a 34 cm monochrometer and was cast normally onto the diode and an 850 nm low-pass filter was placed in front of the device. The photocurrent was amplified by a complementary metal–oxide–semiconductor operational amplifier. Short circuit (no bias) photocurrent was directly measured with a Keithley digital multimeter. For biased photocurrent measurement, a lock-in amplifier was used.

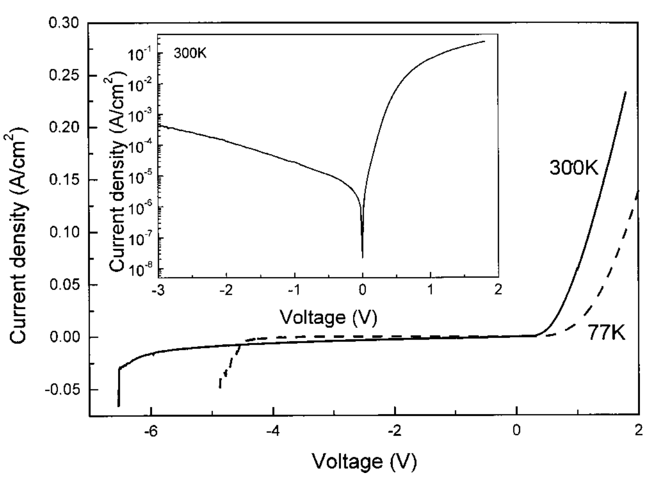

FIG. 2. $I-V$ characteristics of the Ge dot p-i-n diode at 77 and 300 K. The breakdown voltage at 300 K is 6.5 V. In the log scale plot in the inset, a dark current of 3×10^{-5} A/cm^2 at -1 V is shown.

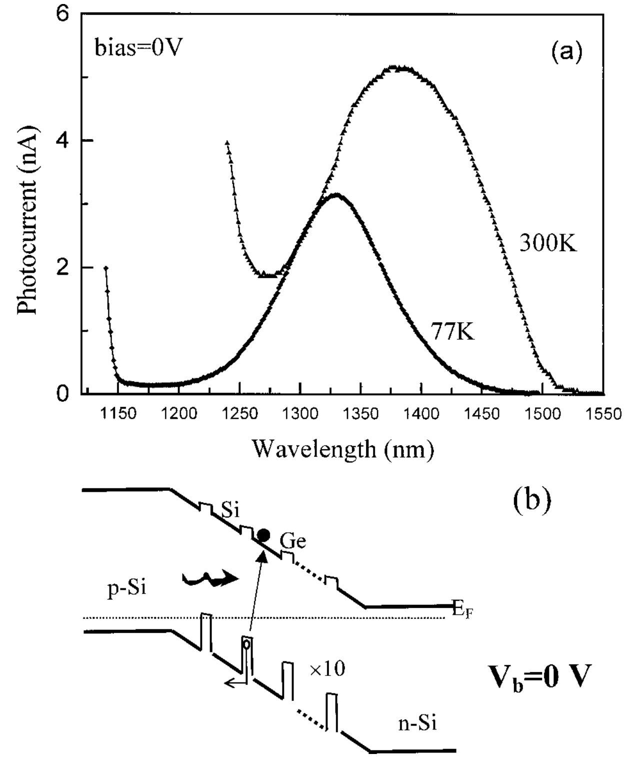

FIG. 3. (a) The short circuit photocurrent spectra of the Ge dot detector at 300 and 77 K. At 300 K, the response covers the range from 1.3 to 1.52 μm, with a peak at 1.4 μm. The peak shifts to 1.32 μm at 77 K. (b) Schematic band diagram of the structure without bias in the direction vertically across the dots.

Figure 3(a) shows the typical photocurrent spectra at 300 and 77 K. The device was operated in the photovoltaic mode. A Ge dot related response was clearly observed at both temperatures. At 300 K, this response ranges from 1.3 to 1.52 μm, with a maximum at 1.4 μm. The FWHM of the response is 95 meV. At 77 K, The peak shifts to 1.32 μm. The FWHM shrinks to 60 meV, and the photoresponse intensity clearly shows a decrease. A previous study indicated that the coherent Ge dots embedded in Si have a type-II band alignment.[16] We ascribe this peak to the interband transition between the holes in the Ge dots and electrons outside of the dots, i.e., in the neighboring Ge wetting layers and/or the Si barrier layers, as shown in Fig. 3(b). At 300 K, besides the Ge-dot related photoresponse, an abrupt increase of the photocurrent occurs at 1.25 μm and extends to the visible range (not shown completely in the plot). This wavelength is 100 nm longer than that for bulk silicon. Considering the microstructure of the material, the redshift could be due to the absorption effect of the Ge wetting layers as was discussed previously.[16] But on the other hand, the PL result shown in Fig. 1 does not have such a wetting-layer-related peak. At 77 K, the abrupt increase occurs at 1.15 μm (1.08 eV), which is also lower than the band gap of Si (1.17 eV). More effort is needed to clarify this phenomenon. The absorption of the intermixed Si/Ge interfacial region could also contribute to this redshift.

The dependence of the photoresponse spectrum on ap-

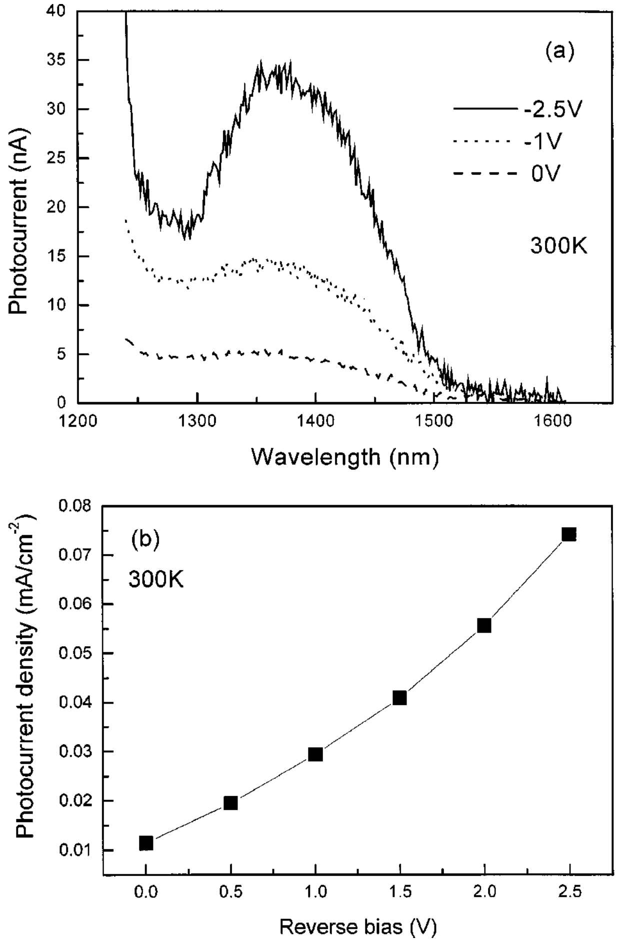

FIG. 4. (a) Dependence of the photoresponse spectrum on applied reverse bias at 300 K. The cutoff wavelength shifts are not so obvious. (b) Photocurrent density at different biases under a constant illumination power density of 0.8 mW/cm^{-2}. The wavelength was selected at 1.4 μm. The highest external efficiency is estimated to be 8% at 2.5 V.

plied reverse bias was investigated at 300 K. The results are shown in Fig. 4(a). As the bias increases, the shape of the response curve remains almost unchanged. The cutoff wavelength shift is not so obvious. This small quantum confined Stark effect is due to the low applied voltage on the devices. Our result is consistent with the result on SiGe quantum wells and superlattices reported by Kim *et al.*[17]

The dependence of photoresponse intensity with applied reverse voltage is shown in Fig. 4(b). The incident light wavelength is 1.4 μm and the excitation power density is 0.8 mW/cm^{-2}. The photocurrent increases with the increasing of the bias voltage in the experimental range. The increase of photocurrent is due to the detrapping of carriers confined by the potential barriers in the valence band of the Ge/Si heterostructure. The maximum external efficiency achieved is 8% at 2.5 V. If we assume that the Ge absorption coefficient is 5×10^3 cm^{-1} at 1.4 μm, the absorption of the nominal Ge thickness of 10 nm (for the ten layers) is estimated to be less than 0.5%. This indicates that there was a significant enhancement of the absorption. This enhancement can be explained by the trapping of the light by the dot structures. The dots serve as the diffusely scattering structures, and thus the absorption is increased.[18] This efficiency is comparable to that of the Si/Ge strained layer superlattice grown by MBE at 1.3 μm under waveguide coupling mode reported by Splett *et al.*[15] (12%). By further improving the device fabrication to reduce the dark current, high quantum efficiency of Ge quantum-dot photodetectors can be reached. Likewise, by incorporating a microcavity to the structure, the external efficiency can also be enhanced.[7]

In conclusion, we have developed Ge quantum-dot photodetectors fabricated on the Si substrate. The photoresponse wavelength ranged from 1.3 to 1.52 μm. An external efficiency of 8% at 1.4 μm was obtained. The active dot layer appeared to greatly enhance the absorption. The results indicate that Ge dot materials are potentially applicable for 1.3–1.55 μm fiber communications and optical interconnects for high-speed computers.

This work was supported in part by the U.S. Army Research Office and Semiconductor Research Corporation. The authors would like to thank S. Gaw and Professor Z. M. Jiang for constructive discussion.

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