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Effect of uniaxial-strain on Ge p-i-n photodiodes integrated on Si

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We demonstrate the effect of uniaxial tensile and compressive strain in Ge p-i-n photodiode integrated on Si using four-point bending structures. Responsivity at 1550 nm is increased from 0.67 to 0.75 A/W by tensile strain in the ⟨110⟩ direction while for compressive strain it decreases from 0.67 to 0.477 A/W. These uniaxial tensile and compressive strains also effectively result in shifts of the absorption spectra toward longer and shorter wavelength as they reduce or increase the direct bandgap energy of the Ge layer, respectively. © *2009 American Institute of Physics*. [doi:10.1063/1.3254181]

Ge photodetectors fabricated on silicon substrate have recently gained widespread interest because Ge absorbs light in the 850 nm–1.55 μm wavelengths[1] and because they could be monolithically integrated with Si-based complementary metal-oxide-semiconductor (CMOS) technology. However, ideally such detectors should cover a wavelength range including both the C-band (1528–1561 nm) and the L-band (1561–1620 nm) for applications in dense wavelength division multiplexing (DWDM).[2] Lattice strain is one interesting approach to shift the optical absorption edge to longer wavelength through its control of semiconductor band structure.[3,4]

The growth of Ge films heteroepitaxially on Si introduces 0.2% biaxial tensile strain due to thermal expansion coefficient differences between Ge and Si. This has been utilized to extend the wavelength range.[5–8] Also, Ge p-i-n photodiodes on Si with 0.25% biaxial tensile strain using C54-TiSi$_2$ on the back side have been proposed for promising C+L band telecommunications.[9] In this case, it is well known[5,9] that the tensile strain reduces the direct bandgap (Eg) of the Ge layer, leading to a shift in the absorption edge toward lower energy compared to the bulk Eg of 0.80 eV, hence enhancing the absorption at longer wavelengths. In electrical devices, extensive research relating to uniaxial strain has been done to improve several electrical properties, such as mobility and drive current.[10,11]

In this letter, we demonstrate uniaxial tensile and compressive strain of Ge p-i-n photodiodes on Si using four-point bending structures. The resulting shift of the Ge direct bandgap is investigated through the photocurrent absorption spectrum shift in these photodiodes.

A 500-nm-thick SiO$_2$ film was thermally grown on a p-type (100) Si substrate at 1100 °C. The SiO$_2$ film was then patterned by etching in order to define desired locations for Ge growth. Ge epitaxial layers in the p-i-n structure were selectively grown by reduced-pressure chemical vapor deposition directly on Si in windows opened through the SiO$_2$ layer. The initial boron-doped Ge layer was grown at 400 °C at 8 Pa, yielding a 200-nm-thick film. This was followed by a 30 min annealing at 800 °C in an H$_2$ ambient. The growth temperature was then increased to 600 °C for the formation of a 1-μm-thick intrinsic Ge layer, and this was followed by an immediate 800 °C hydrogen annealing. Finally, a 60-nm-thick n$^+$ Ge layer was grown at 600 °C. To achieve low contact resistance, this layer was *in situ* heavily doped with phosphorus. There is no hydrogen annealing after this growth, thereby avoiding diffusion of the phosphorus into the 1.4-μm-thick intrinsic Ge layer at high temperature.

This selectively grown Ge showed 0.141% in-plane tensile strain as determined by a Raman spectrum measurement. This tensile strain arises from a difference in the thermal expansion coefficients between Ge and Si. During the cooling stage after Ge deposition, the decrease in lattice constant of Ge is suppressed by that of Si, resulting in residual tensile strain in the Ge layer.[7] This biaxial tensile strain reduces the direct bandgap of Ge from 0.801 to 0.781 eV, extending the effective photodetection wavelength. The p-i-n Ge photodiodes were fabricated into mesa diodes 300 μm diameter by etching the Ge layer to a depth of 1.4 μm by HBr/Cl$_2$ reactive ion etching. On top of this Ge film, a 100-nm-thick low temperature silicon oxide layer was deposited at 300 °C for surface passivation and anti-reflection coating. About 25 nm of Ti was used as metal contact, topped with ~45 nm of Au.

Figure 1 shows the I-V characteristics and responsivity spectra of selectively grown Ge p-i-n photodiodes on Si without any external uniaxial bending. These I-V characteristics show a high performance diode with low reverse current density (10 mA/cm^2 at -1 V) and 1×10^4 on-off ratio. This low dark current density indicates the high quality of the Ge epitaxial film. We measured a responsivity of ~0.67 A/W at 1550 nm for 1 V reverse bias in Fig. 1(b). This high responsivity could be attributed to the 0.141% biaxial tensile strain in the Ge film.

To impose external uniaxial tensile strain in the Ge photodiodes, a four-point bending structures as shown in Fig. 2(a) were used. The amount of the stress (σ_c) on the film can be extracted by

$$\sigma_c = \frac{-3dz \cdot E \cdot t}{a(3L-4a)},$$

where dz is the displacement of the wafer, E is the Young's modulus, and t is the wafer thickness (0.5 mm). a is the distance between the two adjacent inner and outer points, and L is the distance between two outer points. By increasing

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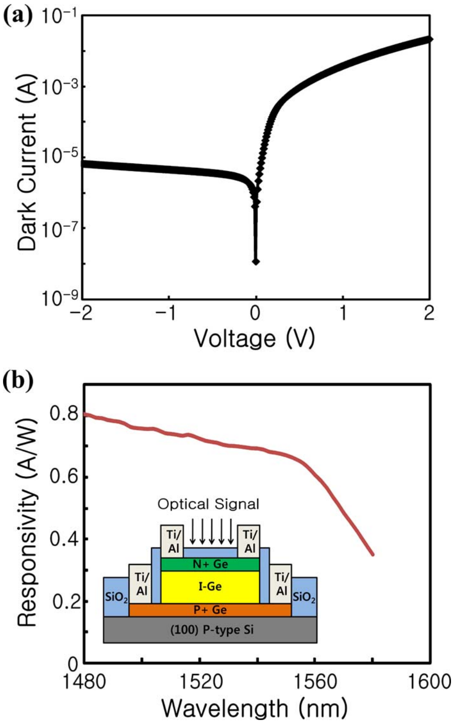

FIG. 1. (Color online) (a) Dark current vs reverse bias for circular shape mesa Ge/Si p-i-n photodiodes. (b) Photodiode responsivity at 1 V reverse bias vs wavelength.

the displacement of the wafer, we can increase the uniaxial stress that is applied to the sample.

The wafer was loaded in the $\langle 110 \rangle$ direction on the four-point bending apparatus. The maximum values of tensile stress was limited to 113 MPa, corresponding to a 0.082% tensile strain in the Ge layer by the wafer breakage due to the high stress. The optical absorption spectra were measured while the wafer was under uniaxial tensile stress, as shown in Fig. 3(a). The uniaxial tensile stress effectively shifts the absorption spectra toward higher wavelength from the absorption edge. At the same time, the responsivity at 1550 nm increases from 0.67 to 0.75 A/W with 0.082% tensile strain (113 MPa).

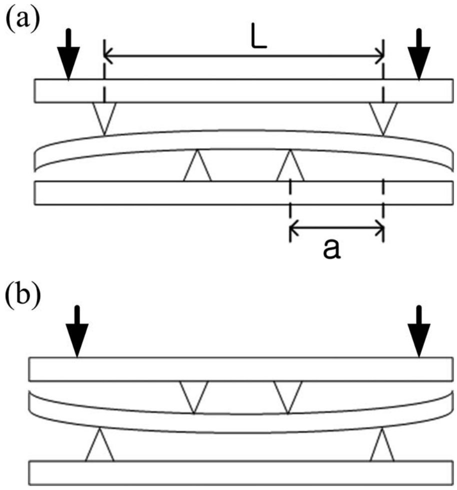

FIG. 2. Schematic diagrams of four-point bending structures for (a) uniaxial tensile strain and (b) uniaxial compressive strain.

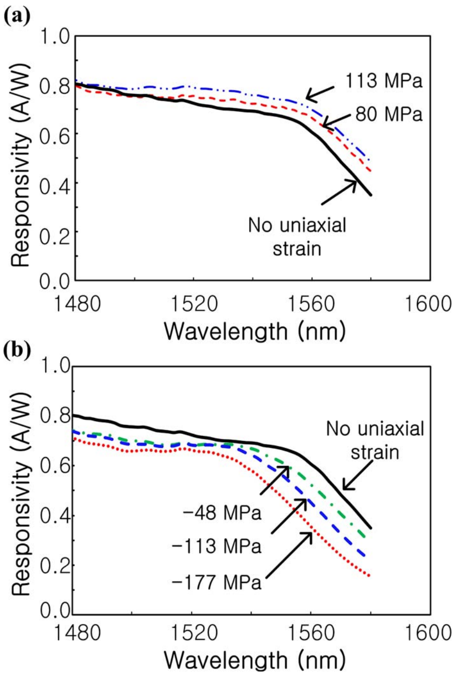

FIG. 3. (Color online) Photodiode responsivity at 1 V reverse bias vs wavelength under (a) uniaxial tensile and (b) compressive stress in the $\langle 110 \rangle$ direction.

A similar four-point bending structure, as shown in Fig. 2(b) can impose compressive stress to the sample. The maximum applied compressive stress in our measurement is 177 MPa, corresponding to a 0.129% compressive strain in the Ge layer. As shown in Fig. 3(b), the absorption edge shifts linearly under compressive stress. And the responsivity at 1550 nm decreases to 0.477A/W under 0.129% uniaxial compressive strain.

In order to examine the strain effect, the change in the Ge direct bandgap energy was calculated[10,11] in Fig. 4. In Fig. 4, 0.14% residual biaxial tensile strain is considered, in addition to various different uniaxial strain effects. Due to the residual biaxial tensile strain, bandgap shrinks for electron-light hole (e-lh) interband transition as well as for electron-heavy hole (e-hh) transition even without any uniaxial strain. These calculated values correspond fairly well to the absorption edges of the experimental data. The observed photon energy shift from the absorption edge is related to e-hh interband transition. In the uniaxial tensile strain case in $\langle 110 \rangle$ direction, the strain reduces the direct bandgap of Ge layer, leading to the shift in the absorption edge toward the lower energy regime. Also, the compressive strain increases the direct bandgap of Ge, resulting in the

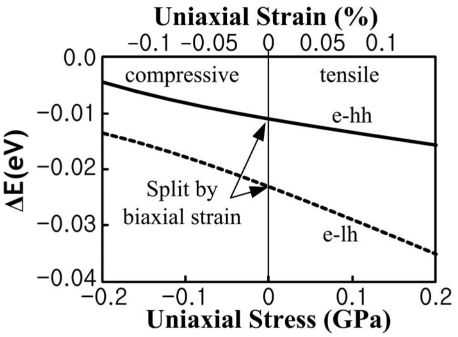

FIG. 4. Bandgap energy shift of uniaxially strained p-i-n Ge photodiodes as a function of uniaxial strain in $\langle 110 \rangle$ direction of simulation.

spectrum shift in the absorption edge toward higher energy. Under the uniaxial tensile strain, such remarkable increase in responsivity greatly shows the high efficiency Ge photodiodes.

In conclusion, we have demonstrated a uniaxial tensile and compressive strained Ge p-i-n photodiode integrated on Si by using four-point bending structure. The responsivity at 1550 nm increases from 0.67 to 0.75 A/W with uniaxial tensile strain and decreases to 0.477 A/W under compressive strain. These uniaxial tensile or compressive strains cause the absorption spectrum to shift toward lower or higher energy because they reduce or increase the direct bandgap of the Ge layer, respectively.

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