High-Efficiency p-i-n Photodetectors on Selective-Area-Grown Ge for Monolithic Integration

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***Abstract*—We demonstrate normal incidence p-i-n photodiodes on selective-area-grown Ge using multiple hydrogen annealing for heteroepitaxy for the purpose of monolithic integration. An enhanced efficiency in the near-infrared regime and the absorption edge shifting to longer wavelength is achieved due to 0.14% residual tensile strain in the selective-area-grown Ge. The responsivities at 1.48, 1.525, and 1.55 μm are 0.8, 0.7, and 0.64 A/W, respectively, without an optimal antireflection coating. These results are promising toward monolithically integrated on-chip optical links and in telecommunications.**

***Index Terms*—Germanium, photodiode, selective, strain, tensile.**

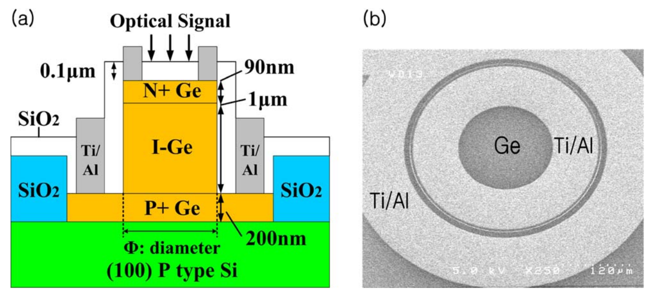

Fig. 1. (a) Schematic diagram of the cross section of normal incidence Ge/Si p-i-n photodiode. (b) Scanning electron micrograph of the circular mesas of the photodiodes. The circular p-i-n device has the ring-shaped contact with a ring width of 50 μm.

I. INTRODUCTION

SI-BASED devices for optical applications have been widely researched. However, a Si photodetector that operates in the 1.3–1.55-μm wavelength range is a challenging task because of its relatively large indirect ($\sim$1.1 eV) and direct ($\sim$3.4 eV) bandgap energies. Since Ge naturally has a smaller direct bandgap energy of 0.8 eV, corresponding to $\sim$1.55-μm wavelength, it is, however, a strong candidate for this application. Moreover, Ge is easy to integrate with the existing Si CMOS technology, further making it an attractive material for optical applications.

In particular, Ge optical detectors on Si are being aggressively researched as a potential solution for optoelectronic integration application. As a result, several heteroepitaxial techniques have been introduced to grow Ge on Si. For example, employing superlattice buffer layers to grow Ge layers effectively reduced the large lattice mismatch between Si and Ge, yielding optical detectors with a quantum efficiency of 40% at 1.3 μm [1]. Cyclic thermal annealing is another method of heteroepitaxial growth, which reported a responsivity of 0.56 A/W at 1.55-μm wavelength on 1-μm-thick Ge films grown on Si [2]. Moreover, molecular beam epitaxy is yet another method to grow Ge on Si, and it can create thin strain-relaxed buffers on silicon substrate. This method showed an external quantum efficiency of 2.8% at 1.55 μm [3]. These methods are focused on the bulk heteroepitaxial growth on Si. However, selective-area heteroepitaxy is a promising approach for the monolithic integration of Ge-based optoelectronics on Si CMOS VLSI platform and thus needs to be thoroughly studied. Several integration methods based on selective-area heteroepitaxy have been suggested for monolithic integration with waveguide. An evanescently coupled Ge waveguide photodetector demonstrates a responsivity of 0.89 A/W at 1550 nm and a dark current density of 25 mA/cm^2 at -1 V [4]. A butt-coupled Ge photodetector integrated in SOI rib waveguide showed a responsivity as high as 1 A/W at a wavelength of 1550 nm and a low dark current density of 60 mA/cm^2 [5].

In this letter, we demonstrate a normal incidence *p-i-n* Ge photodiode by selectively growing Ge through patterned SiO_2 on Si using the multiple hydrogen annealing for heteroepitaxy (MHAH) technique. We report a high-efficiency p-i-n photodiode with a high responsivity over a broad detection spectrum, making monolithically integrated on-chip or chip-to-chip optical links more feasible.

II. EXPERIMENT

Fig. 1(a) shows the schematic cross section of a Ge *p-i-n* photodiode. A 500-nm-thick SiO_2 film was thermally grown on a lightly doped p-type (100) Si substrate at 1100 °C. The SiO_2 film was then patterned by a combination of dry etching followed by wet etching to define the desired locations for Ge growth. Ge epitaxial layers in a *p-i-n* structure were selectively grown directly on Si in windows opened through the SiO_2 layer. To obtain abrupt junctions and good electrical contact, a 200-nm-thick heavily *in situ* boron-doped Ge layer was deposited initially [6] at 400 °C and 8 Pa. This was followed by annealing for 30 min at 800 °C in H_2 ambient. The growth temperature was then increased to 600 °C for the formation of 1-μm-thick intrinsic Ge layer, followed by another 800 °C hydrogen anneal. Finally, a heavily doped 90-nm-thick

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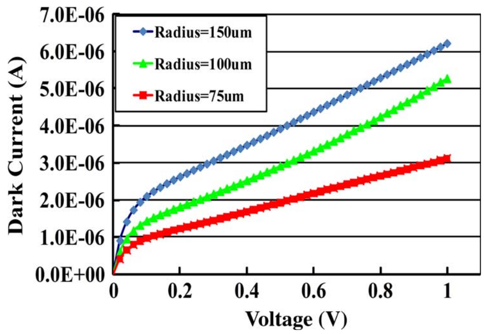

Fig. 2. Dark current versus reverse-bias curves of the circular-shaped mesa Ge/Si p-i-n photodiodes.

n^+-type Ge layer was grown at 600 °C. To avoid recombination in the n^+ Ge layer, we needed a shallow n^+ layer and an abrupt n^+/i junction. To achieve this with a high level of n-type dopant activation, this layer was *in situ* doped with diluted 1% phosphine. The resultant n^+ junction has a depth of 97 nm and a peak electrically activated concentration of 2×10^{19} cm^{-3}. Because fast n-type dopant diffusion during the high-temperature process makes it difficult to fabricate p-i-n structure in Ge photodiodes, we fabricated the topmost n^+ layer without post hydrogen annealing to prevent phosphorus from diffusing inside the 1-μm-thick intrinsic Ge layer [7]. The root-mean-square roughness of the resulting film was determined to be ~0.67 nm by 10×10 μm^2 area atomic force microscopy scans [8], [9]. The samples annealed in nitrogen at 825 °C exhibited no reduction in surface roughness. Due to the selective heteroepitaxy and hydrogen annealing, the Ge layer had a low threading dislocation density count of 1×10^7 cm^{-2} based on the plan-view TEM, which is suitable for optoelectronic applications [10]. The *p-i-n* Ge photodiodes were realized as mesa structures from 150- to 300-μm diameter. The mesa structures were patterned by HBr/Cl_2 reactive ion etching of the Ge layer to a depth of 1 μm. On top of this Ge film, a 100-nm-thick low-temperature silicon oxide layer was deposited at 300 °C for surface passivation. Windows for the contacts were then patterned in the oxide and etched in HF, followed by metal deposition using electron-beam metal evaporation and photoresist liftoff. About 25 nm of Ti was used as contact material, topped with ~45 nm of Au. Fig. 1(b) shows the SEM top view of the resulting *p-i-n* Ge photodiode.

III. Results and Discussion

The dark current density of the photodiode not only indicates the material quality but also determines the optical receiver sensitivity [11], [12]. Fig. 2 shows the dark current–voltage I–V characteristics of photodiodes with various mesa radii. For large photodiodes with a radius of 150 μm, the dark current density is 9.9 q at a reverse bias of 1 V. The dark current can be related to bulk dark current density (J_{bulk}) and the peripheral surface leakage density (J_{surf}) through

$$I_{\text{dark}} = J_{\text{bulk}} Area + J_{\text{surf}} B \sqrt{Area}$$

where B is the $\sqrt{4\pi}$ for a circular photodiode.

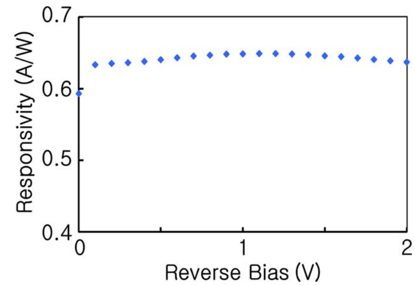

Fig. 3. Photodetector responsivity at $\lambda = 1.55$ μm versus reverse bias for the mesa Ge p-i-n photodiodes with a radius of 100 μm.

For the diode operating at 1-V reverse bias, the extracted J_{bulk} and J_{surf} are shown to be 3.2 mA/cm^2 and 62 μA/cm, respectively. This very low bulk current density of 3.2 mA/cm^2 confirms the excellent Ge crystal quality and the shallow and abrupt n^+ junction in Ge with a high level of activation of n-type dopant, using *in situ* phosphorus doping during the epitaxial growth [13], [14]. This is one of lowest reported dark current density values among the Ge *p-i-n* photodiodes [2], [3], [15]–[17].

Fig. 3 shows the responsivity $(\Re)$ versus reverse bias (V) for the Ge *p-i-n* photodiode operating at 1.55 μm with 140-μW incident power. The active absorption area of the device is $\pi \times 10^4$ μm^2, and the thickness of the absorbing Ge layer is 1 μm. A responsivity of ~0.64 A/W was measured for a reverse bias of 1 V, corresponding to 53.6% external quantum efficiency (η). The residual strain in this selectively grown Ge is 0.141%, as determined by a Raman spectra measurement, while that of the bulk grown Ge is 0.204%. The extracted tensile strains in both cases arise from the difference in thermal expansion coefficients between Ge and Si. During the cooling stage after Ge deposition, the decrease in the lattice constant of Ge is suppressed by that of the Si substrate, generating residual tensile strain in Ge layer [18]. The lower tensile strain value in the selectively grown Ge compared to bulk grown Ge can be explained by the Ge confinement by SiO_2, which has a compressive strain. However, a more detailed study will be necessary to verify this effect. This 0.141% tensile strain reduces the direct bandgap of Ge from 0.801 to 0.781 eV, extending the effective photodetection wavelength. The responsivity of the *p-i-n* Ge photodiode is further improved on the bulk grown Ge because of the higher tensile strain of the bulk grown Ge. This responsivity of 0.67 A/W at 1.55 μm is the highest value among the previously reported selective-area-grown Ge *p-i-n* photodiodes [15], [19]. The responsivity at 0-V bias is also about 93% of the maximum responsivity measured, indicating excellent carrier collection efficiency [20].

From the responsivity, the absorption coefficient (α) of the tensile-strained Ge can be derived. The responsivity $(\Re)$ and reflectivity (γ) of the device can be related to α at a certain photon energy by

$$\alpha = -\frac{1}{t_{\text{Ge}}} \ln\left(1 - E \bullet \frac{\Re}{(1-r)}\right)$$

where $t_{\text{Ge}} = 1$ μm is the thickness of undoped Ge film, and E is the photon energy. Fig. 4 shows the extracted absorption

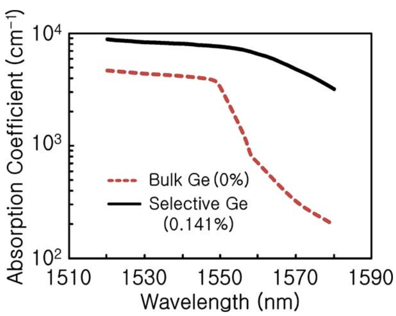

Fig. 4. Absorption coefficient at 2-V reverse-bias versus photon wavelength. The absorption coefficient (α) is extracted from the measured responsivity, assuming 90% internal efficiency. The α for bulk Ge is plotted for reference.

coefficient values versus wavelength. For comparison, the absorption curve of the unstrained Ge photodiodes is also included. The spectral responsivity shows that the optical characteristics of the selectively grown Ge layer is affected by the residual tensile strain [18]. It is clear that the absorption edge of strained Ge has shifted toward longer wavelengths. Spectral measurement verified the red shift of the absorption edge corresponding to 0.141% tensile strain, which leads to an enhanced absorption efficiency. The increase in absorption coefficients greatly improves the responsivity of the Ge photodiodes on the selectively grown Ge for monolithic integration on Si. Moreover, MHAH-Ge layers can absorb the same amount of light intensity in thinner layers, owing to the high absorption coefficient. For instance, at $\lambda = 1550$ nm, the intrinsic layer could be made half the thickness compared to that of bulk-Ge detectors, resulting in shorter transit times for carrier collection, hence higher speed of operation.

IV. Conclusion

We have demonstrated a 0.14% tensile-strained normal incidence Ge *p-i-n* photodiode selectively grown on Si for monolithic integration. A low bulk dark current density of 3.2 mA/cm^2 indicates good Ge film quality and a highly activated *in situ* doped n$^+$ layer. Responsivities of 0.64 A/W were achieved at 1.55 μm. The 0.14% residual tensile strain in the selectively grown Ge resulted in an enhanced efficiency in the near infrared regime and shifted the absorption edge to longer wavelengths. This high efficiency even at low reverse bias makes this technology a promising candidate for monolithic integration of Ge optoelectronics on Si for optical communication.

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