Resonant Cavity Enhanced Ge Photodetectors for 1550 nm Operation on Reflecting Si Substrates

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***Abstract*—We have fabricated and characterized the first resonant cavity-enhanced germanium photodetectors on double silicon-on-insulator substrates (Ge–DSOI) for operation around the 1550-nm communication wavelength and have demonstrated over four-fold improvement in quantum efficiency compared to its single-pass counterpart. The DSOI substrate is fabricated using an ion-cut process and optimized for high reflectivity (>90%) in the 1300–1600-nm wavelength range, whereas the Ge layer is grown using a novel two-step ultra-high vacuum/chemical vapor deposition direct epitaxial growth technique. We have simulated a Ge–DSOI photodetector optimized for operation at 1550 nm, exhibiting a quantum efficiency of 76% at 1550 nm given a Ge layer thickness of only 860 nm as a result of both strain-induced and resonant cavity enhancement. For this Ge thickness, we estimate a transit time-limited 3-dB bandwidth of approximately 25 GHz.**

***Index Terms*—Absorption enhancement, bandgap narrowing, germanium, ion cut, photodetector, resonant cavity, silicon-on-insulator (SOI).**

I. INTRODUCTION

THE WIDESPREAD demand for high-speed data communications is driving the optical communications industry into devising more cost-effective ways of meeting these demands. Presently, full monolithic integration of photonic elements with the Si-based electronics of the optical communications infrastructure has become one of the major focuses of research within this industry. Therefore, Si-based optoelectronics, photodetectors in particular, have received considerable attention [1], [2]. Although major strides have been made in designing Si-based photodetectors for short-haul (850 nm) operation [3], [4], long-haul operation based around the 1300–1550-nm wavelength range still poses a great challenge. As is illustrated in Fig. 1, the lack of sensitivity Si possesses at wavelengths beyond 1100 nm makes it unsuitable for photodetection in the 1300–1550-nm wavelength range. The integration of other semiconductors with Si which are better suited for photodetection at these wavelengths has also been extensively explored, most notably through the methods of flip-chip bonding as well as direct heteroepitaxial growth onto Si. The Si optical bench (SiOB) technology, for example, has been successful in combining the high performance of Si electronics with the appealing optical properties of III-V semiconductors through a flip-chip hybrid integration technique [5], [6]. However, the inherent complexity of the required liftoff and micro-self-alignment process involved in this technique, especially on a large scale, makes it quite costly [7]. As for heteroepitaxial growth directly onto Si, the large lattice mismatch between III-V compound semiconductors and Si would make the growth of thick, uniform, high-quality III-V films extremely difficult. Methods involving the growth of thick buffer layers have been employed to dramatically reduce the concentration of threading dislocations within the III-V semiconductor film grown on Si. Unfortunately, there are high costs and fabrication complexities associated with this process. In addition, attempting to grow a compound semiconductor onto an elemental material such as Si often results in the formation of anti-phase domains within the compound semiconductor film, further degrading the quality of the film being grown.

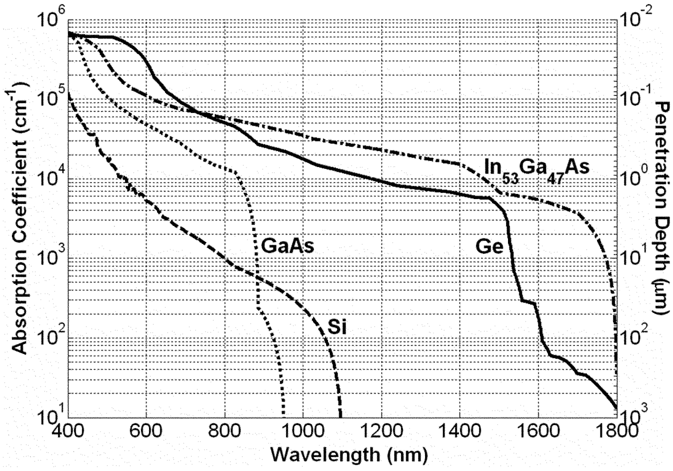

Fig. 1. Absorption coefficients for various semiconductors.

II. GERMANIUM ON SILICON

Germanium is a viable candidate for integration on Si, given its sensitivity around the 1300–1550-nm wavelength range as well as its compatibility with integrated circuit technologies. However, the relatively small absorption coefficient ($\alpha \approx 460\ \mathrm{cm}^{-1}$) of Ge at 1550 nm would necessitate a thick active region in order to achieve high efficiency, resulting in

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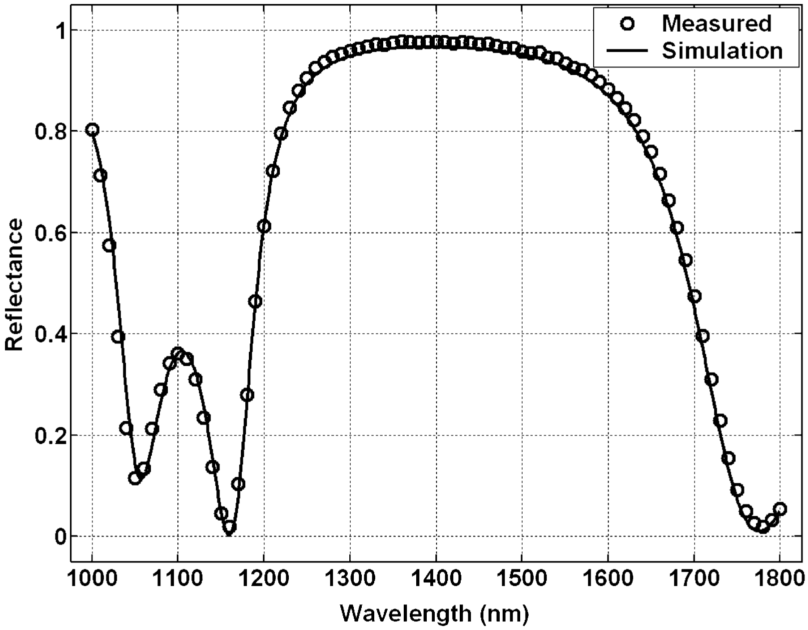

Fig. 2. Simulated and measured free-space reflectivity of the DSOI structure in the NIR.

a slow device. For example, given a Ge layer of thickness equal to its penetration depth ($1/\alpha \approx 22~\mu$m), a 40% quantum efficiency is attainable at 1550 nm in a single-pass configuration, taking into account reflectance at the air/Ge interface. However, this same Ge thickness yields a carrier transit time of greater than 1 ns. One way to effectively enhance the response of a weakly absorbing medium, without sacrificing the device bandwidth, involves placing the absorbing region within a Fabry–Pérot, or resonant, cavity [8]. In a resonant cavity-enhanced (RCE) configuration, a multiple-pass photodetection scheme is created, which effectively reduces the absorbing region thickness required to obtain a given η at a particular wavelength, thereby reducing the carrier transit time and, in turn, enhancing the device bandwidth. For example, an RCE Si-based vertical p-i-n photodetector has been recently demonstrated [4], where a 2-μm-thick Si active region is epitaxially grown on a distributed Bragg reflector (DBR) consisting of two periods of Si–SiO$_2$, or double-SOI (DSOI), optimized for high reflectivity over a broad range of wavelengths centered at 850 nm. At 850 nm, this photodetector exhibited a η of 40%, with a 3-dB bandwidth in excess of 10 GHz.

Ideally, assuming that good crystalline quality Ge can be grown on a DSOI substrate which is optimized for high reflectivity around 1550 nm, a high-performance RCE Ge photodetector with a responsivity much greater than that of a conventional single-pass device can be designed. However, the growth of high-quality Ge films on Si can prove to be challenging. The difficulty in Ge heteroepitaxy on Si stems from the 3.96% lattice mismatch between Ge and Si. The misfit and threading dislocations resulting from such a lattice mismatch severely limits the thickness of high-quality Ge films obtainable. In addition, a Ge photodetector with a high threading dislocation density would suffer from large leakage currents, as well as reduced responsivity resulting from carrier recombination at the dislocation defect sites within the Ge layer. As in the case of III-V semiconductor heteroepitaxy on Si, a thick buffer layer can be grown between the Ge film and Si substrate, isolating much of the threading dislocations below the Ge active region. One can then design a high-quality Ge photodetector above the buffer layer in a single-pass configuration. This buffer layer is usually a SiGe compound semiconductor, where the Ge content is carefully graded from low concentration at the Si interface to high concentration at the Ge interface [9]. However, such a structure would not be suitable in an RCE scheme, where the SiGe buffer layer, along with the threading dislocations, would be effectively reintroduced into the photodetector active region. Recently, a two-step ultrahigh vacuum/chemical vapor deposition (UHV/CVD) direct epitaxial growth technique was developed for Ge growth onto Si, along with a cyclic annealing process which dramatically reduces the threading dislocation density within the heteroepitaxially grown Ge film [10]. In this process, a thin low-temperature Ge buffer layer is grown at a temperature of 375 °C to a thickness of about 30 nm. Afterwards, the growth temperature is increased to around 600 °C, and the growth of a thick uniform Ge film is performed. To reduce the threading dislocation density within the Ge film, the structure is temperature cycled between 780 °C and 900 °C. By using this two-step UHV/CVD growth technique, combined with cyclic annealing, the heteroepitaxial growth of high-quality Ge films on Si can be achieved.

III. RCE PHOTODETECTOR DESIGN

Placing a Ge layer within a resonant cavity in order to enhance its effective absorption at 1550 nm will first require a DBR structure optimized for high reflectivity around 1550 nm. Fig. 2 illustrates the simulated and measured reflectivity of a DSOI structure we have designed to be highly reflective in the 1300–1600-nm wavelength range [11]. This DSOI substrate

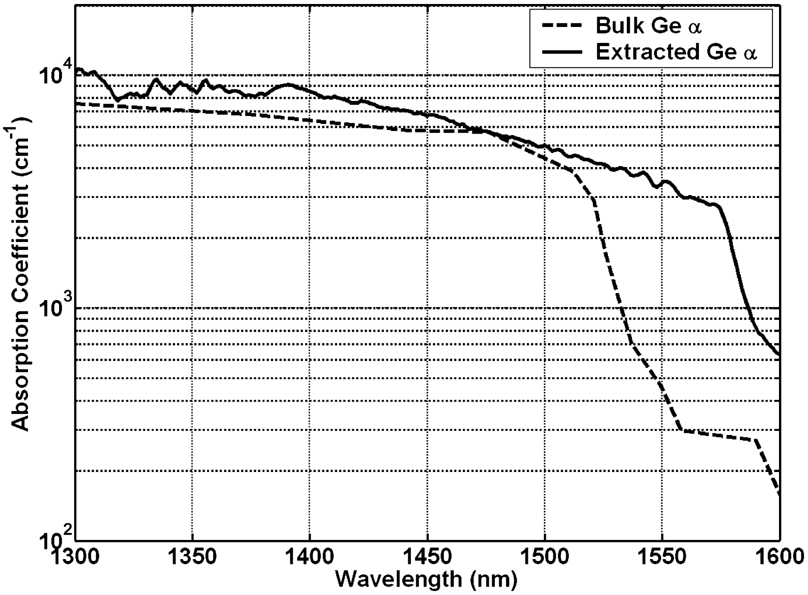

Fig. 3. Comparison of the extracted strained-Ge absorption coefficients to bulk-Ge values. Extracted values were from an undoped Ge–Si sample, and bulk-Ge values were obtained from [15].

is fabricated through an ion-cut process [12], [13], where the basic mechanism is based on the blistering of Si. For our DSOI substrates optimized for high reflectivity around 1550 nm, the thicknesses of the Si and SiO_2 layers are 300 and 250 nm, respectively. Requiring only two periods of Si–SiO_2 because of the high index contrast between the Si and SiO_2 layers (at 1550 nm, $n_{Si}/n_{SiO2} \approx 2.4$), the DSOI structure is designed to provide greater than 90% free-space reflectivity over a 325-nm spectral range centered around 1400 nm, with 92.7% reflectivity at 1550 nm.

In designing an RCE Ge–DSOI photodetector for operation at 1550 nm, the Ge layer thickness must be chosen not only to be resonant at 1550 nm, but also to optimize the detector bandwidth. However, before the optimum Ge thickness can be determined, the true absorptive properties of the Ge film have to be known. Using an undoped Ge–Si test sample where the Ge layer was grown through the aforementioned two-step UHV/CVD process, the absorption characteristics of the Ge layer were measured. Around 1550 nm, the measured absorption values were greater than those expected for bulk Ge of the same thickness. This increase in absorption is attributed to the tensile strain-induced bandgap narrowing within the Ge layer, resulting from the difference in the thermal expansion coefficients of Ge and Si [14]. Although the Ge layer is relaxed during growth, strain is introduced as the structure is cooled to room temperature. Because this strain-induced enhancement is a bulk effect [14], the enhanced effective absorption coefficients of the strained Ge layer can be extracted from the absorption data. Illustrated in Fig. 3 are the absorption coefficients of the strained Ge layer above 1300 nm, extracted from the measured absorption values of the undoped Ge–Si wafer sample. Here, the extracted strained-Ge absorption coefficient at 1550 nm is about an order of magnitude greater than the bulk Ge value [15]. X-ray diffraction measurements reveal a Ge film strain of 0.221% for the Ge–DSOI structure, as opposed to 0.2% strain reported for its Ge–Si counterpart [14]. This translates to an absorption edge red shift of only 5 nm for the Ge–DSOI structure with respect to the Ge–Si case and virtually no change in the enhanced absorption coefficient at 1550 nm. Therefore, the response of a Ge–DSOI structure optimized for 1550-nm operation can be simulated using the strained-Ge absorption coefficients extracted from the Ge–Si structure.

The quantum efficiency η of an RCE photodetector is given by the following [8]:

$$\eta = \left\{ \frac{(1+R_2 e^{-\alpha L})}{1-2\sqrt{R_1 R_2} e^{-\alpha L} \cos(2\beta L+\psi_1+\psi_2)+R_1 R_2 e^{-2\alpha L}} \right\} \times (1-R_1)(1-e^{-\alpha L}) \quad (1)$$

where α and L represent the absorption coefficient and thickness of the active region, respectively. Other variables represented in this expression are the top (R_1) and bottom (R_2) cavity mirror reflectivity, the top (Ψ_1) and bottom (Ψ_2) mirror phase shift, and the propagation constant $\beta = 2\pi n/\lambda_o$, where n and λ_o represent the refractive index and free-space wavelength, respectively. For the same RCE photodetector, the 3-dB bandwidth can be approximated by

$$f_{3\text{ dB}} = \left(\frac{1}{f_{tr}^2} + \frac{1}{f_{RC}^2} \right)^{-\frac{1}{2}} = \left[\left(\frac{L}{0.45\nu} \right)^2 + \left(\frac{2\pi R \varepsilon A}{L} \right)^2 \right]^{-\frac{1}{2}} \quad (2)$$

where f_{tr} and f_{RC} represent the transit time and capacitance-limited bandwidths, respectively. Also represented in this expression are the charge carrier velocity v, detector area A, and series resistance R. Given these two expressions, along with the extracted absorption coefficients for strained-Ge, we can design a Ge–DSOI photodetector with maximized bandwidth and efficiency at 1550 nm. Fig. 4 illustrates the simulated η of a strained-Ge–DSOI photodetector at 1550 nm with varying Ge thickness, while Fig. 5 shows the simulated 3-dB bandwidth of the same photodetector structure over a range of Ge thicknesses and detector areas. The resonant cavity of the simulated

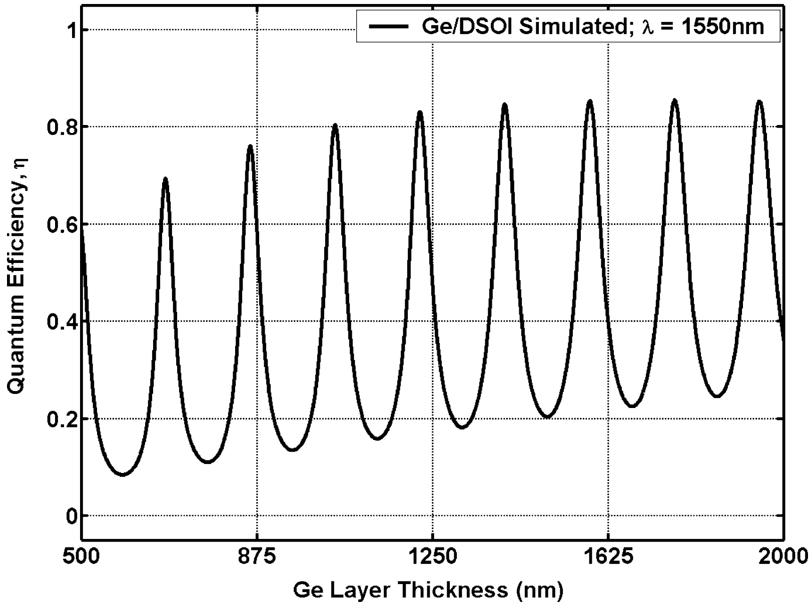

Fig. 4. Simulated η versus Ge layer thickness for Ge–DSOI structure. $\lambda = 1550$ nm.

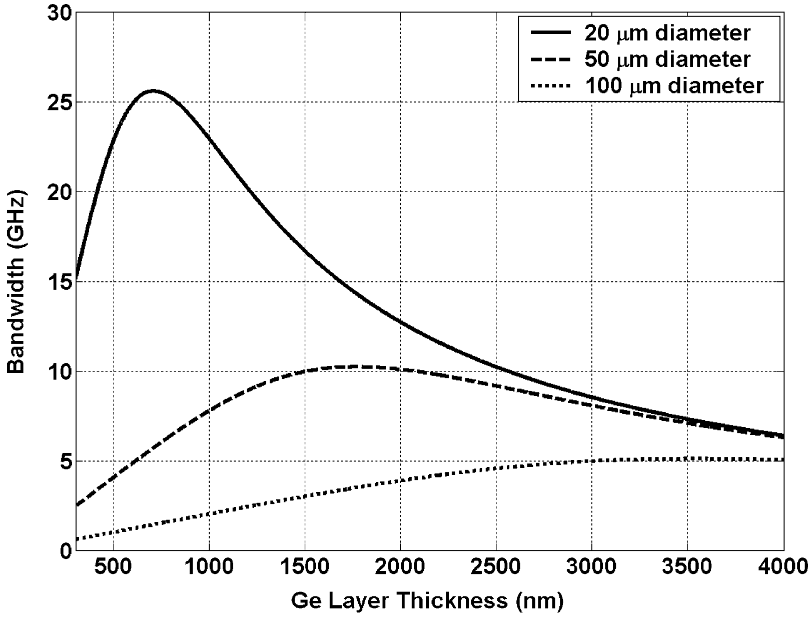

Fig. 5. Simulated 3-dB bandwidth versus Ge layer thickness for a Ge–DSOI structure. Bandwidth curves for three detector areas shown (20-, 50-, and 100-μm diameter).

Ge–DSOI detector structure is formed between the top air/Ge interface (R_1) and the bottom DSOI substrate (R_2). For the 3-dB bandwidth calculations, carrier saturation velocity is assumed, which is approximately 6×10^6 cm/s for Ge. Assuming a small area (<30 μm diameter) Ge–DSOI device, an optimum strained-Ge layer thickness of 860 nm is calculated for 1550-nm operation.

As is shown in Fig. 6, given a Ge layer thickness of only 860 nm, a quantum efficiency of 76% at 1550-nm wavelength is attainable, assuming that all the absorbed photons contribute to the measured photocurrent. This simulated η value is almost five times that obtainable with a strained-Ge–Si structure and 33 times the η of an unstrained-Ge/Si structure at 1550 nm, assuming equivalent Ge layer thicknesses. It should be noted that much of the noise seen in the η simulations of the strained-Ge structures is due to noise within the extracted absorption coefficient data. In terms of the device bandwidth, a Ge layer thickness of 860 nm would result in a transit-time limited bandwidth of approximately 25 GHz, making such a photodetector compatible with 10 Gb/s data communication systems.

IV. PHOTODETECTOR FABRICATION

We have fabricated the first resonant cavity enhanced Ge-on-DSOI photodetectors for operation around 1550 nm. As can be seen in the cross-sectional view in Fig. 7, our photodetector is a top-illuminated p-i-n structure, which consists of a Ge layer

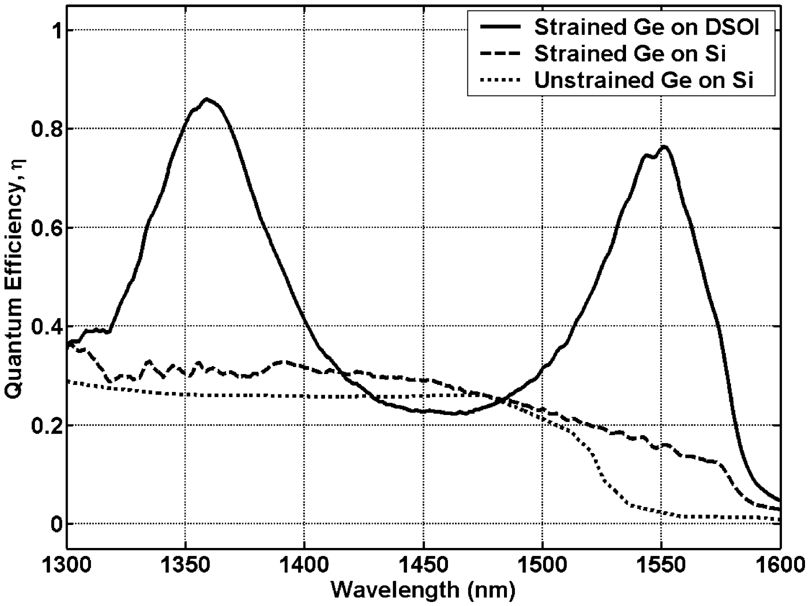

Fig. 6. Quantum efficiency simulation of a Ge–DSOI photodetector optimized for 1550-nm operation, compared to both strained and unstrained Ge–Si. Ge thickness: 860 nm; simulations assume 100% carrier collection.

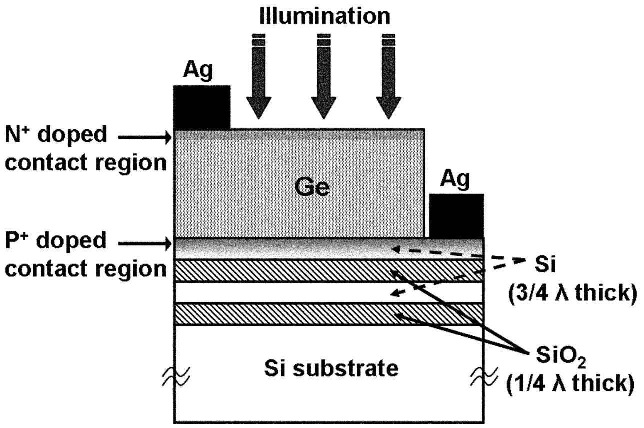

Fig. 7. Cross-sectional view of the top-illuminated Ge–DSOI vertical p-i-n photodetector.

grown via the two-step UHV/CVD process onto our DSOI substrate described earlier, although it is important to note that this Ge–DSOI structure was not cyclic annealed. Scanning electron microscopic (SEM) imaging was performed on our Ge–DSOI structure to confirm the layer structure and thicknesses, but not to examine the crystalline quality within the structure itself. As a result, a very simple sample preparation was performed and a low-resolution image was obtained. The SEM cross-sectional view of the Ge–DSOI structure is illustrated in Fig. 8, where the Ge layer thickness is 755 nm. The contact regions are defined through the ion-implantation of phosphorus in the top 100 nm of the Ge film and boron in the top Si layer of the DSOI substrate. Photodetector mesas of various sizes ranging from 140 × 140 μm to 1 × 1 mm were formed through reactive-ion etching with a CF_4/O_2 plasma, and silver metal pads were patterned via liftoff to contact the ion-implanted P and N regions of the photodetector structure.

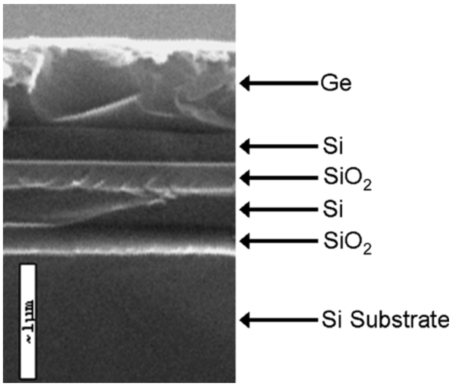

Fig. 8. SEM cross-sectional view of the Ge–DSOI structure; Ge thickness: 755 nm.

V. RESULTS AND ANALYSIS

Illustrated in Fig. 9 is the dark current–voltage response of one of our fabricated 140×140 μm area photodetectors, which shows a dark current of 54 μA at 1 V reverse bias. Such a large magnitude of leakage current is indicative of the high concentration of threading dislocations within the Ge layer, due primarily to the Ge–DSOI structure not being cyclic annealed. Spectral quantum efficiency measurements were performed with the use of a spectrometer as a wavelength tunable monochromatic light source. Fig. 10 compares the η of the same Ge–DSOI photodetector to its simulated response over a 1300–1600-nm wavelength range and at room temperature. Here, both the simulated and measured η of this detector are lower at 1550 nm than that simulated for the optimized detector simply because the Ge layer is not at the optimized resonant thickness of 860 nm. The resonant response of an RCE detector can be adjusted through recess etching, although care must be taken not to etch away the top contact region. To improve the response of this particular photodetector, the

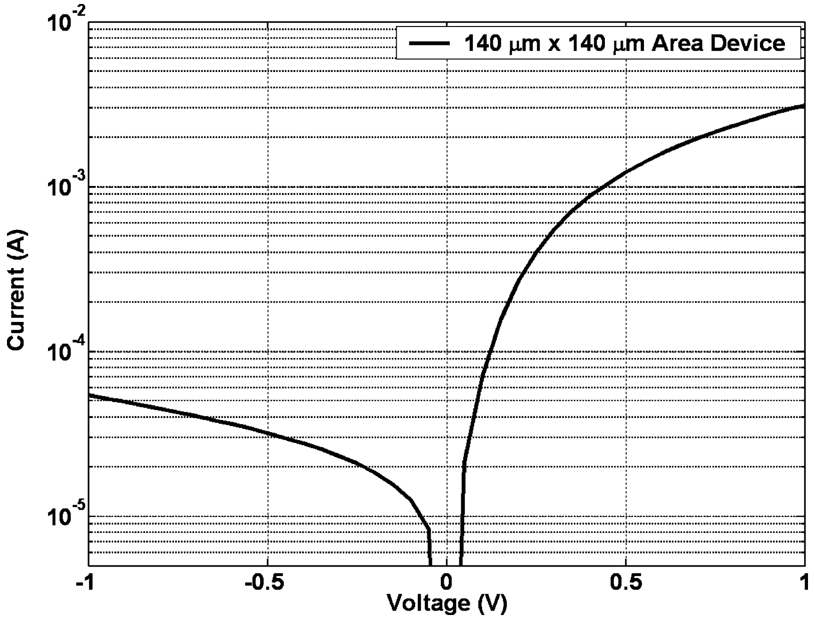

Fig. 9. Dark-IV characteristic of a 140×140 μm area Ge–DSOI photodetector.

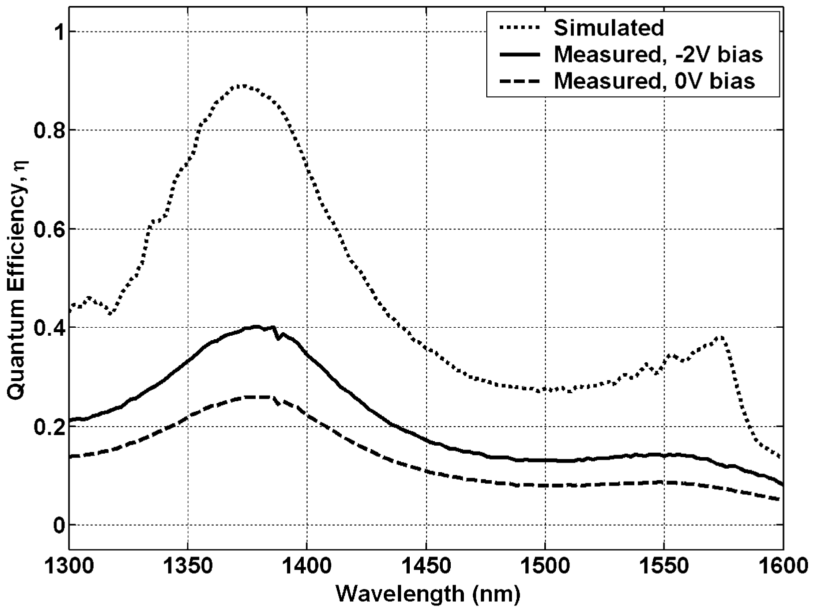

Fig. 10. Measured Ge–DSOI photodetector η at 0 and 2 V reverse bias versus simulated η. The 140×140 μm area device includes a 737-nm Ge layer, capped with a 300-nm SiO_2 layer. Simulation assumes 100% carrier collection.

Ge layer was etched back to a thickness of 737 nm. The off-resonance response of the photodetector at 1550 nm was further enhanced with a 300-nm-thick SiO_2 layer sputtered onto the detection area. At 1550 nm, the photodetector was measured having a 14% quantum efficiency at 2 V reverse bias, which is over four times the simulated η of 3.3% in a single-pass configuration without strain-induced absorption enhancement. However, this measured response is less than half the expected η of 33.3%. The discrepancy between the expected and measured η most likely stems from the photogenerated carriers not being collected efficiently at the contacts. A contributing factor to the loss of photogenerated carriers within this Ge–DSOI structure is carrier recombination at the threading dislocation sites within the Ge layer. To reduce recombination at these defect sites, the photodetector was reverse biased, thereby increasing the photogenerated carrier velocities and reducing the carrier interaction time with the threading dislocation sites. This is evident when compared to the photodetector response at zero bias, which falls to about 8.6% at 1550 nm.

VI. CONCLUSION

We have simulated and fabricated Ge–DSOI photodetectors which are suitable for operation around 1550 nm. Given a Ge layer thickness of only 860 nm, these detectors should exhibit quantum efficiencies of approximately 80% at 1550 nm, with a transit-time limited bandwidth approaching 25 GHz. The enhanced response of these detectors is attributed to both the resonant cavity effect as well as strain-induced bandgap narrowing within the Ge film. Although the measured η of the fabricated Ge–DSOI photodetector is approximately 50% lower than the simulated response at 1550 nm, we believe the photogenerated carrier collection efficiency can be improved through cyclic annealing of the photodetector structure.

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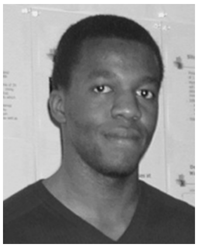

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