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

Olufemi I. Dosunmu, Douglas D. Cannon, Matthew K. Emsley, Lionel C. Kimerling, and M. Selim Ünlü

Abstract—**We have designed and fabricated high-speed resonant cavity enhanced germanium (Ge) Schottky photodetectors on a silicon-on-insulator substrate. These back-illuminated detectors have demonstrated 3-dB bandwidths of more than 12 GHz at 3-V reverse bias and a peak quantum efficiency of 59% ($R = 0.73$ A/W) at the resonant wavelength of ~1540 nm. Time domain measurements of our Ge photodetectors with diameters of up to 48 μm show transit-time limited impulse responses corresponding to bandwidths of at least 6.7 GHz, making these detectors compatible with 10-Gb/s data communication systems.**

Index Terms—**Germanium (Ge), photodetectors, resonant cavity enhanced (RCE), silicon-on-insulator (SOI).**

I. Introduction

THE MONOLITHIC integration of photodetectors designed for operation around the long-haul communication wavelengths (1300, 1550 nm) with silicon-based technologies has been a long-standing goal within the optical communications industry. Although a number of methods exist for the integration of photodetectors with electronics, such as flip-chip bonding, a more attractive solution involves direct monolithic integration, given the relative ease of fabrication and potential cost advantage associated with this approach. Si-based photodetectors would be ideal for monolithic integration with Si-based electronics; however, such detectors would not be viable for operation around the long-haul communication wavelengths, given the Si energy bandgap cutoff wavelength of 1100 nm. The use of a semiconductor which is sensitive around the 1300–1550-nm wavelength range would be required in designing a photodetector for long-haul operation.

Germanium (Ge) is a good candidate for designing such photodetectors, given its smaller direct energy bandgap of 0.8 eV, as well as its compatibility with silicon. However, bulk Ge is still a relatively weak absorbing material at 1550 nm when compared to semiconductors such as InGaAs, which is traditionally used for photodetection at this wavelength. As a result, a thick Ge active region would be required to obtain a certain level of quantum efficiency η, resulting in a slow device. 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 [1]. Resonant cavity enhanced (RCE) photodetectors have been successfully demonstrated for a range of operating wavelengths, including Si-based detectors optimized for 850 nm [2] and InGaAs-based detectors designed for operation around 1550 nm [3]. Common to most RCE detectors is the use of a distributed Bragg reflector for at least one of the cavity mirrors. In the case of the Si RCE detector [2], for example, the Si active region is grown atop a highly reflective two-period silicon-on-insulator (SOI) substrate.

Fabricating a Ge photodetector on a similar SOI reflective substrate would not only enhance the photodetector bandwidth and efficiency, but also demonstrate the viability of monolithically integrating such a detector with other Si-based components. However, the heteroepitaxial growth of high-quality Ge films on Si is very challenging, given the 3.96% lattice mismatch between these two semiconductors. One method which allows for the heteroepitaxy of thick high-quality Ge films directly onto Si involves the growth of a thin low-temperature Ge buffer layer between the underlying Si substrate and Ge film. This particular method is usually combined with a cyclic annealing process to reduce the threading dislocation density within the Ge film [4]. A number of Ge photodetectors have been reported [5], [6] which employ the low-temperature Ge buffer layer method described above. Ge-on-Si (Ge–Si) photodetector responsivities of up to 0.75 A/W at 1550 nm have been demonstrated, with a temporal response <200 ps at 1320 nm [7].

In this letter, we report on high-speed and high-efficiency RCE Schottky Ge photodetectors fabricated directly on an SOI substrate. These Ge photodetectors are designed for bottom-illuminated operation around the 1550-nm wavelength range.

II. Device Design and Fabrication

The basic structure of our Ge RCE photodetector consists of a Ge layer heteroepitaxially grown on a double-side polished SOI substrate. The SOI substrate itself is fabricated through an ion-cut process [8]. The thicknesses of the Si (340 nm) and SiO_2 (200 nm) layers provide adequate back-illuminated reflectivity (55%) around the 1550-nm wavelength range. Prior to Ge growth, the ion-implantation of Boron into the top Si layer is performed to form the bottom P-contact of the Ge photodetector. After ion-implantation, a 1450-nm-thick Ge film is grown on

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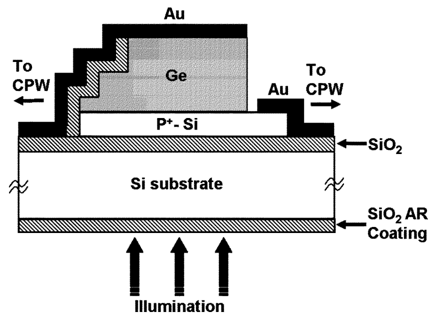

Fig. 1. Cross-sectional view of the back-illuminated Ge–SOI Schottky photodetector.

the SOI substrate through the aforementioned low-temperature Ge buffer layer technique. To reduce the threading dislocation density within the Ge layer, the Ge–SOI structure was cyclic annealed.

Prior to the fabrication of the Ge photodetectors, the Ge layer is etched back to a thickness resonant around 1550 nm under back-illumination. Afterwards, circular mesas of varying sizes are patterned into the Ge layer through reactive-ion etching (RIE), forming the main photodetector structures. To prevent the detectors from shorting out during metallization, a 500-nm-thick SiO_2 insulating layer is evaporated onto the entire wafer surface, and later patterned for subsequent metallization. Ti–Au metal pads are then patterned onto the SiO_2 layer to form coplanar waveguide (CPW) contacts to the Ge photodetectors, allowing for on-wafer high-speed characterization. To reduce the influence of the bottom Si substrate cavity on the measured Ge photodetector response, a SiO_2 antireflection coating is sputtered onto the bottom Si surface. A cross-sectional view of this bottom-illuminated Ge photodetector structure is illustrated in Fig. 1, where the resonant cavity is formed between the top Au mirror and the SOI substrate. Here, the metal pads form an ohmic contact to the P-type Si layer, whereas a Schottky contact is formed between the top Au contact/mirror and Ge film.

III. Results and Analysis

Back-illuminated Ge–SOI photodetectors of sizes ranging between 10 and 78 μm in diameter were fabricated. The best measured current–voltage response from a 10-μm diameter Ge detector revealed a dark current of 380 nA at a reverse bias of 5 V.

An important byproduct of Ge heteroepitaxy on Si is tensile strain within the Ge film, resulting in the shrinkage of the Ge bandgap, and extending the absorption edge of the strained Ge layer to longer wavelengths [9], [10]. This effect has been shown to increase the Ge absorption coefficient at 1550 nm by almost an order of magnitude, to around 3.4×10^3 cm^{-1}[11]. As a result, we expect the response of these Ge photodetectors to be enhanced both by the resonant cavity effect as well as the strain-induced Ge bandgap narrowing.

Spectral quantum efficiency measurements of our Ge photodetectors were performed with the use of a tunable continuous-wave laser source. The measured quantum efficiency of a 78-μm diameter detector at 0- and 0.5-V reverse bias is shown in Fig. 2, along with the simulated response which takes into account the strained Ge enhanced absorption coefficients obtained from [11]. At 0.5-V reverse bias, the peak quantum efficiency η of

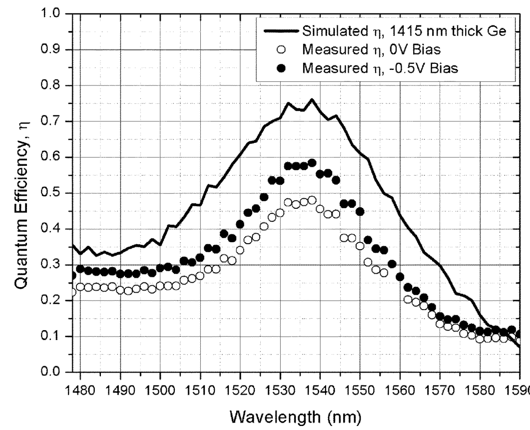

Fig. 2. Simulated versus measured η of a 78-μm diameter Ge–SOI photodetector, resonant at 1538 nm. The measured η at 0- (open circles) and -0.5-V bias (filled circles) are illustrated.

59% ($R = 0.73$ A/W) is measured at 1538 nm. It should be noted that the measured η remains constant beyond 0.2-V reverse bias for all wavelengths. Although not exactly resonant at 1550 nm, the 1538-nm resonant peak still falls well within the 1528–1565-nm C-band used in long-haul optical communications. In addition, the resonant peak full-width at half-maximum (FWHM) is around 50 nm, allowing this single detector to be highly responsive throughout the entire C-band.

We believe the bias dependence of the measured η is due to recombination at the threading dislocation defect sites within the Ge film. Much of the carrier recombination occurs near the Ge–Si interface, where carrier trapping increases the interaction time between the photogenerated carriers and defect sites, ultimately resulting in increased carrier recombination. Reverse biasing of the photodetector effectively reduces the carrier trapping time at the Ge–Si interface.

The discrepancy between the measured and simulated η can be attributed, in part, to the diffusion of Si into the Ge layer during Ge growth. The Si out-diffusion would effectively shift the absorption edge of the Ge region near the Ge–Si interface to shorter wavelengths, resulting in the reduction of the Ge absorption coefficient at longer wavelengths, including 1550 nm.

The temporal response of our high-speed Ge–SOI photodetectors was obtained using a microwave probe and 50-GHz sampling oscilloscope, as the photodetector is back-illuminated with 1.2-ps FWHM laser pulses, wavelength centered at 1550 nm. The measured temporal response of a 10-μm diameter Ge–SOI detector at 3-V reverse bias is shown in Fig. 3. Here, the measured FWHM of the detector response peak is 20 ps. Such a response suggests a 3-dB bandwidth of nearly 23 GHz. However, approximately 20 ps after the primary response peak is a satellite peak, which can be associated with charge-trapping at the Ge–Si interface. Another potential cause for this satellite peak is electrical reflections within the measurement system. Trailing the satellite peak is a diffusion tail, which can be attributed to carrier diffusion through the doped Ge region. We believe the Ge region near the Ge–Si interface is doped due to Boron diffusion during Ge growth. The temporal response of each photodetector is measured at two different time scales (200 ps, 10 ns) in order to extend the range of the calculated detector frequency response. Illustrated in the inset of Fig. 3 is the fast Fourier transform (FFT) of the detector temporal response. This curve is a fit

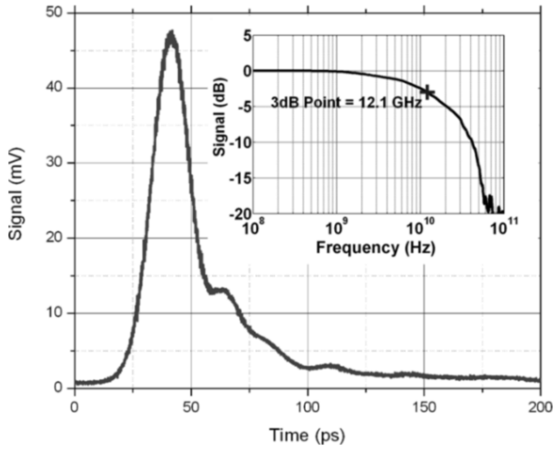

Fig. 3. Temporal response of a 10-μm diameter detector at -3-V bias and 1550-nm wavelength. Measured pulse FWHM is 20 ps. FFT of the temporal response is illustrated in the inset, which shows the 3-dB point at 12.1 GHz.

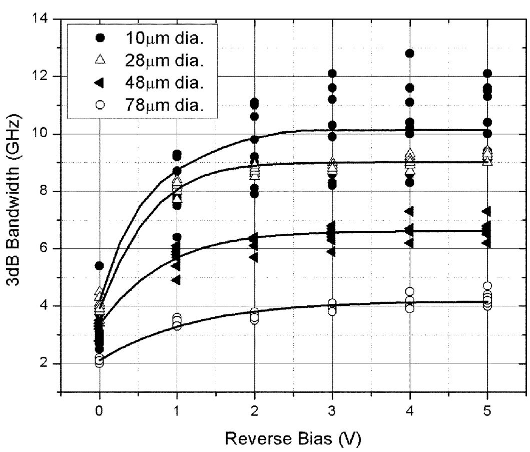

Fig. 4. 3-dB bandwidth at 1550 nm versus reverse bias for Ge–SOI detectors of sizes 10, 28, 48, and 78 μm in diameter. Empirical fit curves for each detector size group are included as trend lines.

to the FFT data obtained from the short (200 ps) and long (10 ns) time scans, and shows a 3-dB bandwidth of 12.1 GHz.

Theoretical maximum 3-dB bandwidths of 4.2, 9.0, 14.6, and 17.4 GHz were calculated for the Ge–SOI detector areas of 78, 48, 28, and 10 μm in diameter, respectively. These bandwidth calculations take into account transit time and capacitive effects, and suggest an increasingly capacitance-limited temporal response for the larger area devices. Fig. 4 shows the measured 3-dB bandwidths for several Ge–SOI photodetectors of sizes 10, 28, 48, and 78 μm in diameter, at reverse biasing ranging between 0 and 5 V. Included in Fig. 4 are empirical fit curves to the 3-dB points for each detector size group, where each group is comprised of ten individual photodetectors. Here, the average 3-dB values tend to decrease with increasing photodetector size, confirming the capacitance-limited nature of the larger area detectors. A maximum transit-time limited 3-dB bandwidth of 12.8 GHz is measured from a 10-μm diameter detector at 1550 nm and 4-V reverse bias. The discrepancy between the measured and theoretical bandwidths is most probably due to charge trapping at the Ge–Si interface, as well as parasitic capacitances. Under reverse biasing, the average measured 3-dB bandwidths for the 78-, 48-, 28-, and 10-μm diameter detectors are 4.2, 6.7, 9.2, and 10.4 GHz, respectively. As can be seen in Fig. 4, these detector bandwidths generally saturate around 2-V reverse bias, regardless of detector size.

IV. Conclusion

To our knowledge, we have demonstrated the fastest Ge photodetectors fabricated directly on Si for 1550-nm operation. These detectors exhibit quantum efficiencies of nearly 60% around 1540 nm, with a spectral resonant peak FWHM of 50 nm which encompasses the entire C-band. Ge–SOI photodetectors of sizes ranging from 10 to 78 μm in diameter were fabricated, with the smallest area devices exhibiting 3-dB bandwidths approaching 13 GHz. In addition, our larger area detectors—up to 48 μm in diameter—demonstrate 3-dB bandwidths compatible with 10-Gb/s data communication systems. The measured bandwidths of our Ge–SOI detectors, regardless of size, generally saturate around 2-V reverse bias, making these detectors attractive for Si integration.

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