High-Efficiency, 10 GHz Bandwidth Resonant-Cavity-Enhanced Silicon Photodetectors Operating at 850 nm Wavelength

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Resonant-cavity-enhanced (RCE) photodetectors have been the focus of extensive research over the past decade in the design of high bandwidth-efficiency product devices [1,2]. Silicon-based photodetectors for applications in optical communications in the near-IR wavelength range between 800-900 nm suffer from low bandwidth-efficiency products due to the long absorption length necessitated by the small absorption coefficient. Increasing the bandwidth-efficiency product is the inherent benefit of a RCE structure, which relies on the constructive interference of a Fabry-Perot cavity to enhance the optical field inside the photodetector at specific wavelengths. For semiconductor photodetectors, such a resonant cavity can be formed using a buried reflector consisting of alternating layers of semiconductors and the air/semiconductor top interface. Due to the availability of heterostructures, compound semiconductors have been the focus of RCE photodetector development [1]. Formation of buried mirrors and resonant cavities have remained as a challenge in Si technology.

Various attempts to fabricate Si RCE photodetectors included chemical vapor deposition (CVD) as well as molecular beam epitaxy (MBE) [3] of Si on top of dielectric mirrors, which resulted in a polycrystalline device layer, due to the amorphous seed layer. Photodiodes fabricated on a polycrystalline device layer typically suffered from high dark currents. Schaub et al. [4], has reported silicon RCE photodiodes with low dark currents that achieved a bandwidth in excess of 34 GHz – the highest speed recorded for Si pin photodiodes. Although the merged epitaxial layer overgrowth (MELO) process may not be a commercially viable technique, the results in themselves are significant. Schaub has shown that use of RCE for Si photodiodes can lead to significant leaps in device performance.

To our knowledge there is only one report of purposely-manufactured reflecting Si substrates. Ishikawa et al. [5] used a combination of separation by implantation of oxygen (SIMOX) and MBE to develop a 5-period DBR with a peak reflectance of 90%. Recently, we introduced a Si wafer with a more than 90% reflectance buried DBR for the fabrication of RCE optoelectronic devices [6]. The process uses the Smart-Cut technique for fabricating silicon on insulator (SOI) wafers commercially available from SOITEC SA [7]. Previous x-ray measurements also showed that these reflective SOI wafers were of high crystalline quality. In this paper, we present the responsivity and high-speed measurement results on photodiodes fabricated on these reflecting SOI wafers, showing feasibility of RCE Si detectors for 10 Gb/s optical communication applications at 850 nm.

After the buried DBR fabrication, single crystalline silicon was grown on the double-SOI substrate using a standard low-pressure chemical vapor deposition (LPCVD) epitaxy process. RCE pin photodetectors are fabricated in the epitaxial device layer, which was approximately 2.1μm in total thickness, using standard silicon device fabrication techniques. The structure has a buried n+ implant and a p+ implant on the surface, while the epitaxial silicon layer is left undoped yielding the vertical pin diode. To contact the buried n+ layer a trench was formed using RIE technique with SF6 reactant and He ambient. A high dose n+ implant was then performed in the trench to achieve low contact resistance to the n+ silicon. Contacts were formed using Al patterned by a photoresist lift-off technique. The final device structure is shown schematically in Fig. 1.

For on-wafer testing, photodiodes with various dimensions were fabricated with co-planar transmission lines. The photodiodes were tested for dark current performance as well as spectral quantum efficiency. The dark current density as measured on 200-μm-diameter photo-

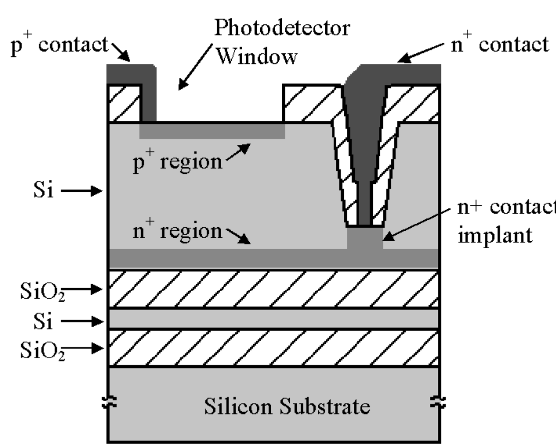

Fig. 1. Cross-section of RCE Si pin photodetector showing trench via for buried n+ contact.

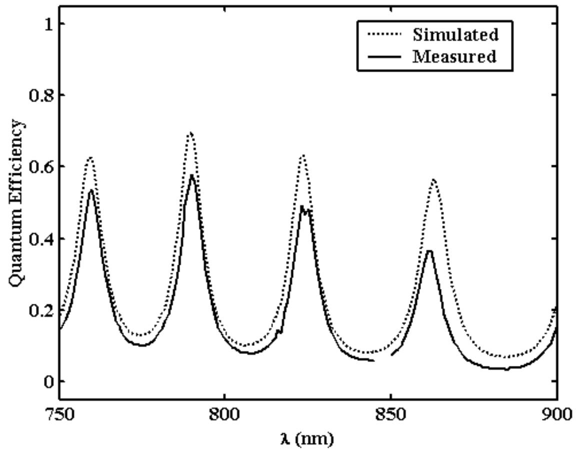

Fig. 2. Spectral quantum efficiency of RCE pin photodetector.

diodes varied from 1 to 3 μA/cm^2 at reverse bias of 1V to 3V. On 30-μm-diameter devices, the dark current is measured as 70 pA to 120 pA at reverse bias of 1V and 3V, respectively. As seen in Fig. 2, the measured spectral quantum efficiency agrees well with the simulation and that the efficiency near 860 nm is approximately 40%, which corresponds to a responsivity of 260 mA/W.

High-speed measurements are performed on a microwave probe station by using 1.6 ps full-width at half-maximum (FWHM) pulses from a Ti:sapphire laser using a 50 GHz sampling oscilloscope. Figure 3 shows the temporal response obtained at 9 V reverse bias from 30 μm- and 100 μm-diameter circular devices with respective measured FWHM values of 29 ps and 57 ps. The FWHM of 29 ps suggests a bandwidth well above 10 GHz. However, in these particular devices, a long tail in the photocurrent response is observed indicative of a diffusion component. To limit the diffusion current due to absorption in doped neutral regions, we have used very thin (less than 0.2 μm) contact regions. The incomplete depletion of the unintentionally doped absorption region is expected to be the main reason for the diffusion current and resulting reduction in the device speed.

To study the frequency response, measured temporal

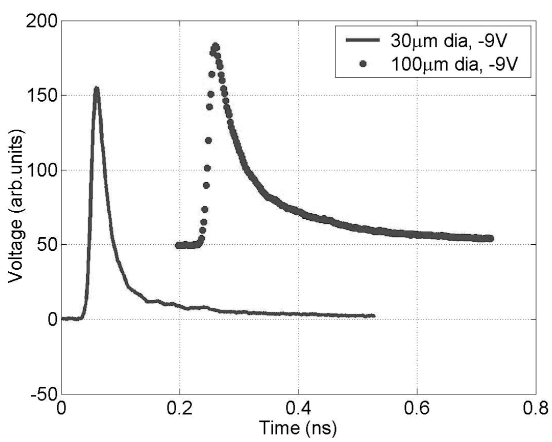

Fig. 3. Measured temporal responses of 30 μm- and 100 μm-diameter photodiodes.

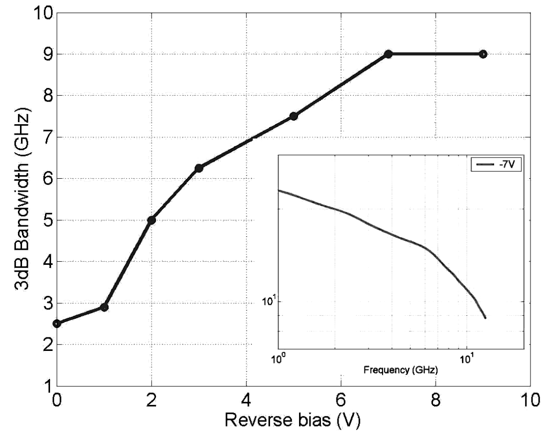

Fig. 4. Frequency bandwidth of 30-μm-diameter device at various bias values calculated from temporal response. The inset shows the bode plot for 7 V reverse bias.

response data for various size devices at different bias values are converted to frequency domain using fast Fourier transform (FFT). Figure 4 shows the 3 dB bandwidth obtained from a 30 μm-diameter detector under different bias conditions.

In summary, we presented RCE Si pin photodetectors capable of quantum efficiency of ~40% and bandwidth of ~10 GHz at 850 nm with a buried distributed Bragg reflector fabricated by means of a double-SOI technique. The reflecting wafers are commercially reproducible and have single crystalline silicon device layers for fabricating silicon RCE photodiodes with high bandwidth efficiencies as well as low dark current. These wafers are well suited for VLSI integration and are compatible with standard CMOS processing making them ideal for monolithic integration of receiver circuits with photodetectors.

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[1] M.S. Ünlü, S. Strite, *Applied Physics Reviews*, vol. 78, no. 2, pp. 607-638, (1995).

[2] J.C. Campbell, *Proceedings of IEEE International Electron Devices Meeting*, Washington, DC, 10-13 December 1995, pp. 575-578.

[3] J. C. Bean, et al., *IEEE Photonics Technology Letters*, vol. 9, no. 6, pp. 806-808, (1997).

[4] J.D. Schuab, R. Li, C.L. Schow, J.C. Campbell, *IEEE Photonics Technology Letters*, vol. 11, no. 12, pp. 1647-1649, (1999).

[5] Y. Ishikawa, N. Shibata, S. Fukatsu, *Applied Physics Letters*, vol. 69, no. 25, pp. 3881-3883, (1996).

[6] M. K. Emsley and M. S. Ünlü, *Proceedings of IEEE Lasers and Electro-Optics Society 2000 Annual Meeting*, Rio Grande, Puerto Rico, 13-16 November 2000, vol. 2, pp. 432-433.

[7] M. Bruel, *Electronics Letters*, vol.31, no.14, pp.1201-1202, (1995).