

Rapid melt grown Germanium p-i-n photodiode wrapped around a Silicon waveguide

Ryan Going*, Tae Joon Seok, Ming C. Wu

Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720

*rwgoing@berkeley.edu

Abstract: We report on a compact germanium photodiode design where single crystal germanium wraps around a single mode silicon waveguide. A 32 μm long, 626 aF, p-i-n device has 0.8 A/W responsivity at 1550 nm.

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1. Introduction

Low capacitance photodiodes with high responsivity together with CMOS compatible materials and silicon photonics integration are needed for future optical interconnects [1]. Many groups have made germanium p-i-n photodiodes with direct epitaxial growth of germanium on silicon [2]. However with the first 50-100 nm of Germanium during growth being highly defective, direct epitaxy places strong constraints on the minimum size and geometry of the photodiode [2]. Recently groups have reported using rapid melt growth [3] to obtain defect-free germanium on silicon oxide [4, 5]. We propose a germanium photodiode, which uniquely takes advantage of this crystallization technique. The 150 nm thick photodiode wraps around a single mode silicon waveguide for enhanced optical coupling with a small volume and sub-fF capacitance.

2. Design and Fabrication

The photodiode, schematically shown in Fig. 1(a), consists of a 150 nm thick layer of germanium, which is deposited conformally with an LPCVD furnace around a 500 nm x 220 nm silicon waveguide on 2 μm of buried oxide. Between the waveguide and germanium is 20nm of thermally grown SiO_2 for electrical isolation. Separate from the waveguide is an isolated island of silicon, which the germanium is in contact with and acts as a crystal seed for the rapid melt growth [3]. The germanium is dry etched to 1.7 μm wide, capped with low temperature oxide (LTO) and then melted at 1000°C for 1s and cooled to crystallize by rapid melt growth. Contact vias are etched, and the germanium is then ion implanted with Boron for the p-junction, and Phosphorus for the n-junction. Rapid thermal annealing of 500°C for 10 s is performed to activate the phosphorus with limited diffusion. 50 nm of Titanium, followed by 400 nm of Aluminum is deposited and etched to form metal contacts to the device.

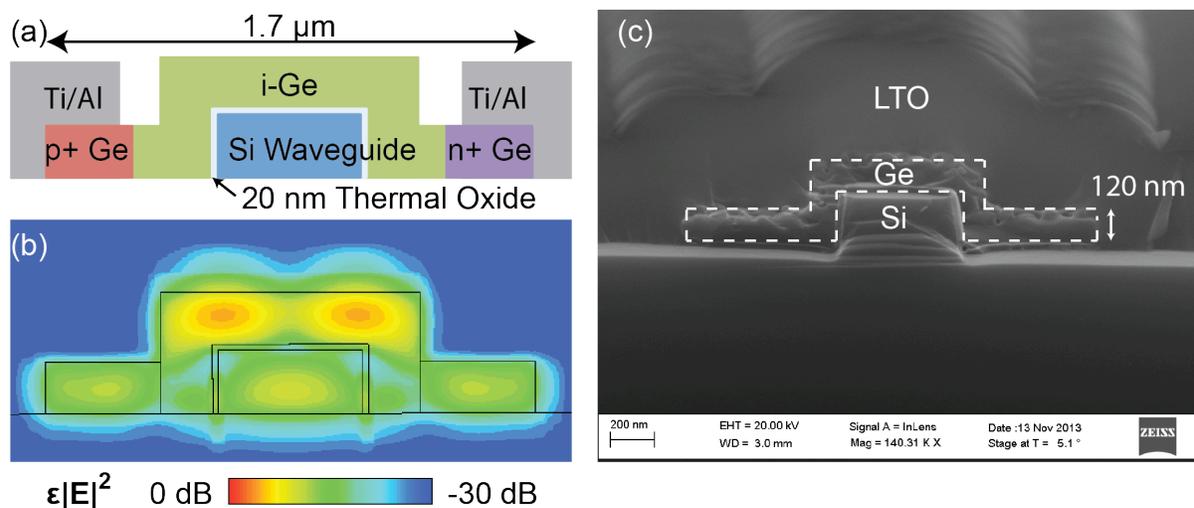


Fig. 1 (a) Schematic cross-section of germanium p-i-n. (b) FDTD simulation showing electrical energy present in the waveguide and germanium. (c) Scanning electron micrograph of fabricated germanium before the contact via etch.

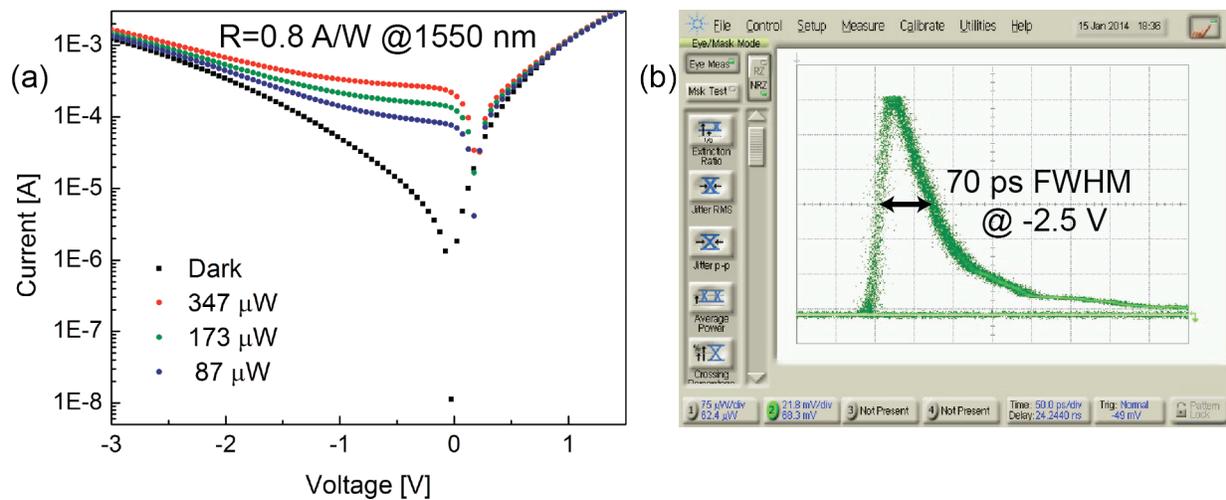


Fig. 2(a) I-V curve showing dark current and illuminated diode response at 1550 nm. (b) Electrical impulse from illumination by a 500 fs fiber laser.

Finite difference time domain (FDTD) simulations show in Fig. 1(b) the optical mode from the silicon waveguide easily couples into the germanium, with the majority of the optical energy in the intrinsic portion of the diode. This yields a theoretical responsivity of 1.15 A/W with only 32 μm of length, and 626 aF of calculated capacitance. This is because very little of the optical mode is present in the heavily doped regions of germanium or where the metal would contact the germanium.

3. Results

A fiber array probe was used to send light from a single mode fiber into grating couplers (7 dB insertion loss) which taper into single mode waveguides. A 32 μm length device was measured to have a responsivity of 0.8 A/W at 1550 nm with 347 μW of light incident on the diode, shown in Fig. 2(a). Although less than predicted, the reduced responsivity is likely due to scattering from the rough germanium, and a slightly thinner film (120 nm) than originally desired. The roughness in the germanium is due to the LPCVD deposition itself, and has since been corrected, although devices with the smoother germanium film have not yet been completed. The dark current at -1 V bias is 52 μA . The high dark current is believed to be due to incomplete phosphorus activation, and this is currently being investigated. Fig. 2(b) shows an impulse response when biased at -2.5 V, and illuminated with a 500 fs pulsed laser. The pulse width of 70 ps is much longer than the drift-limited calculation of 20 ps. This could again be due to the incomplete phosphorus activation or to saturation effects from the laser pulse power being too high.

4. Conclusions

This work demonstrates ongoing efforts to produce a compact, high responsivity germanium photodiode. The presented photodiode has a unique design which wraps single crystal germanium around a single mode waveguide for efficient coupling. The initial 32 μm long device measures 0.8 A/W responsivity at 1550 nm with 52 μA of dark current at -1V, and has a calculated junction capacitance of 626 aF.

5. References

- [1] D. A. B. Miller, "Device requirements for optical interconnects to silicon chips," *Proceedings of the IEEE*, vol. 97, no. 7, pp. 1166–1185, 2009.
- [2] J. Wang and S. Lee, "Ge-photodetectors for Si-based optoelectronic integration," *Sensors*, vol. 11, no. 1, pp. 696–718, 2011.
- [3] Y. Liu, M. Deal, and J. Plummer, "Rapid melt growth of Germanium crystals with self-aligned microcrucibles on Si substrates," *J Electrochem Soc*, vol. 152, no. 8, pp. G688–G693, 2005.
- [4] S. Assefa, F. Xia, S. W. Bedell, Y. Zhang, T. Topuria, P. M. Rice, and Y. A. Vlasov, "CMOS-integrated high-speed MSM Germanium waveguide photodetector," *Opt. Express*, vol. 18, no. 5, pp. 4986–4999, Jan. 2010.
- [5] C.-K. Tseng, W.-T. Chen, K.-H. Chen, H.-D. Liu, Y. Kang, N. Na, and M.-C. M. Lee, "A self-assembled microbonded germanium/silicon heterojunction photodiode for 25 Gb/s high-speed optical interconnects," *Sci. Rep.*, vol. 3, Nov. 2013.

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