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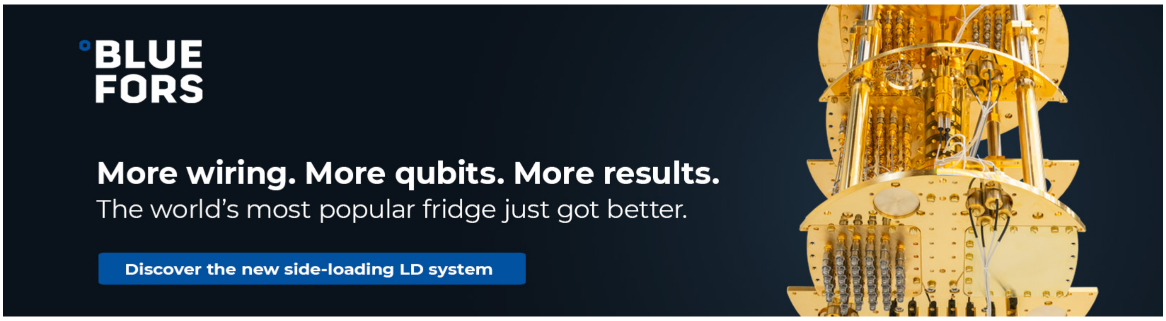

40 Gb/s surface-illuminated Ge-on-Si photodetectors

Johann Osmond,[1] Laurent Vivien,[1,a)] Jean-Marc Fédéli,[2] Delphine Marris-Morini,[1] Paul Crozat,[1] Jean-François Damlencourt,[2] Eric Cassan,[1] and Y. Lecunff[2]
[1]*Institut d'Electronique Fondamentale, Université Paris Sud, CNRS UMR 8622, Bât. 220, 91405 Orsay Cedex, France*
[2]*CEA-DRT/LETI, 17 rue des Martyrs, 38054 GRENOBLE cedex 9, France*

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This paper reports on surface illuminated Ge photodetectors monolithically integrated on Si substrate operating in the *C* and *L* wavelength bands. The responsivity at a wavelength of 1.5 μm ranges from 0.08 to 0.21 A/W without bias voltage for Ge mesa diameter ranging from 10 to 25 μm, respectively. The measured -3 dB cut-off frequency is as high as 49 GHz under a reverse bias of 5 V at a wavelength of 1.5 μm. An open eye diagram up to 40 Gbit/s is also demonstrated. © *2009 American Institute of Physics*. [doi:10.1063/1.3243694]

In the scope of reaching complementary metal oxide semiconductor (CMOS) electronics and Si photonics integration on the same platform,[1] necessary building blocks are developed from passive components such as waveguides[2] to active components, such as modulators[3] or photodetectors.[4–14] Among group IV materials, germanium is a good candidate to absorb light in the near-infrared range. Indeed, germanium does not present contamination issues, allowing the integration of Ge-based devices with CMOS circuits.[15] Ge photodetectors monolithically integrated on silicon have shown impressive advances during the last years and are now the most mature devices among these active building blocks. However, if large bandwidths combined to large responsivities were already reported for waveguide integrated Ge photodetectors,[8,9] it is not the case for surface illuminated photodetectors. Photodetectors with very high bandwidth were already reported but with low optical quantum efficiencies.[4,6] In surface illuminated configuration, the coincidence of the directions of carrier collection and of light absorption leads to a trade-off between optical responsivity and bandwidth of the photodetector.[10] Some photodetectors on the other part were reported with very high optical responsivity values but with small optical bandwidths.[11] We have chosen here a configuration allowing a high bandwidth with usable optical responsivity values at the same time. This result has been allowed by optimizing the structure of the photodetector and its processing. In this paper, we present a surface illuminated photodetector engineered to have responsivity larger than 0.1 A/W around a wavelength of 1.55 μm, an acceptable value for receiver sensitivity in telecom applications,[10] and a high bandwidth at the same time. It makes this photodetector usable for optical communications with high frequency operation.

A schematic view of surface illuminated vertical pin Ge diode is presented in Fig. 1(a). Starting from a silicon-on-insulator substrate p^+-Si, p^+-Ge, *i*-Ge and n^+-Ge layers were successively epitaxially grown by reduced pressure chemical vapor deposition[16] with the following thicknesses: 160, 40, 300, and 150 nm, respectively. These thicknesses were chosen to achieve a good trade off between high responsivity and large bandwidth. The p^+-Ge was grown at 400 °C, following layers at 800 °C and no thermal annealing was performed. *In situ* doping during growth was achieved with doping levels of about 10^{20} cm^{-3} for silicon and about 10^{19} cm^{-3} for germanium. Mesas were defined by a deep-UV (DUV) lithography step followed by a reactive ion etching (RIE) step down to p^+-Si film (bottom contact). Diameters of mesa ranged between 10 and 25 μm. A passivation/antireflection coating was deposited by plasma enhanced chemical vapor deposition. A second step of DUV lithography and RIE was performed to define bottom and top contacts. The metal stack used for contacts was Ti/TiN/AlCu. The microscope view in Fig. 1(b) shows the final surface illuminated pin diode. The used technological processes are fully compatible with CMOS technology.

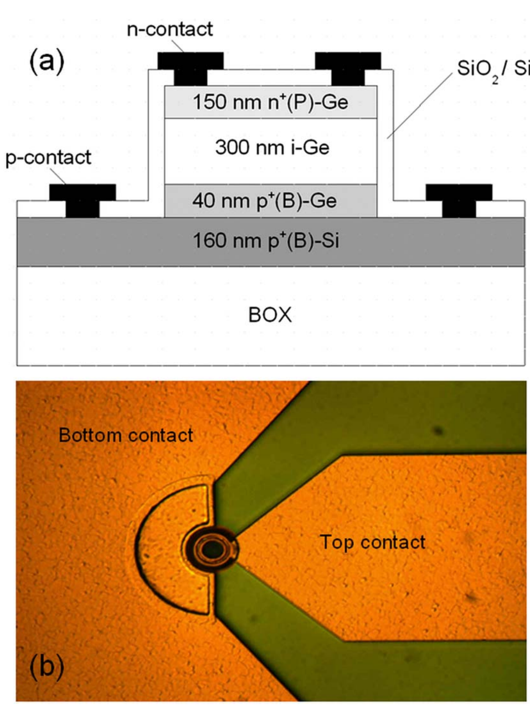

FIG. 1. (Color online) (a) Schematic and (b) optical microscope views of the surface illuminated pin photodetector. The mesa diameter is 15 μm. The thicknesses are 160, 40, 300, and 150 nm for p^+-Si, p^+-Ge, *i*-Ge and n^+-Ge layers, respectively.

a)Author to whom correspondence should be addressed. Electronic mail: laurent.vivien@u-psud.fr.

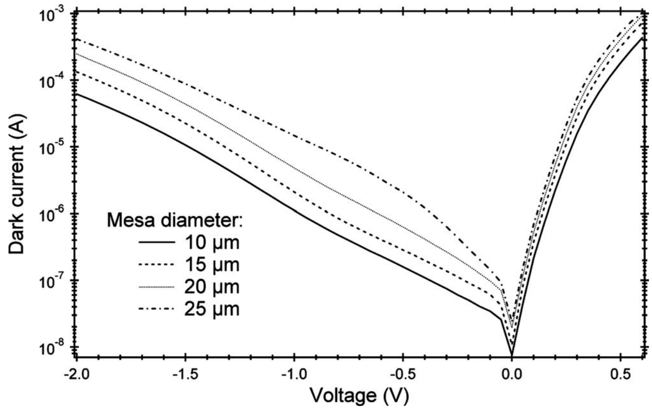

FIG. 2. Dark current as a function of the applied bias of photodetectors of different diameter: 10, 15, 20, and 25 μm.

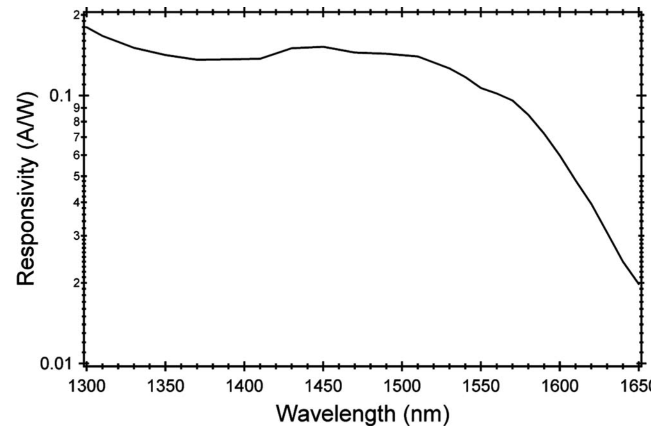

FIG. 4. External optical responsivity as a function of wavelength for 15 μm diameter photodetector at 0 V bias.

The dark current as a function of the applied bias voltage was first measured for each photodetector. Under -1 V bias, dark currents of 1.1, 2.1, 4.8, and 14.7 μA were measured for photodetector diameters of 10, 15, 20, and 25 μm, respectively (Fig. 2). These values are decreased by performing thermal annealing after Ge layer growth to reduce threading dislocations density in Ge film.[17,18] Indeed, dark current in a Ge/Si photodiode has been proven to scale linearly with threading dislocation density N_{TDD}.[19] After thermal annealing dark currents of 225, 373, 527, and 952 nA were measured for diodes of 10, 15, 20, and 40 μm diameter, respectively.

External optical responsivity was measured by calibrating the power at the output of a cleaved optical fiber (mode diameter of about 10 μm at $1/e^2$) and measuring photocurrent of the photodetector. The responsivity is retrieved by dividing the photocurrent by the input optical power. Responsivity increases as the diode diameter increases, scaling roughly with diode area, starting from 0.06 A/W for 10 μm diameter and reaching 0.22 A/W for 25 μm diameter photodetectors, as shown in Fig. 3. This responsivity increase is related to the increase of the surface illuminated of the diode and thus the light absorption increase for a given input beam diameter. Quasisimilar responsivities were obtained for 20 and 25 μm mesa diameters because the input beam diameter corresponds to their active surface. The saturation of the optical responsivity values already at 0 V bias reveals that this photodetector configuration allows a complete photogenerated carrier collection without bias.

The spectrum of the optical responsivity reported in Fig. 4 for the considered device shows that for a 15 μm diameter photodetector, the external responsivity value is about 0.15 A/W for a wavelength of 1500 nm and is always higher than 0.1 A/W up to 1570 nm. For a wavelength of 1600 nm, the measured value of optical responsivity is still 0.05 A/W. This photodetector is thus enabled to be used in *C*- and *L*-wavelength bands optical communications detection.

The 3-dB bandwidth was determined using a RF set-up based on a vector network analyzer working up to 50 GHz.[14] Optical signal at a wavelength of 1.5 μm was modulated and was coupled to the photodetector under vertical incidence using a lensed optical fiber in order to increase the signal/noise ratio. 50 GHz rf probes were used to collect photo-generated carriers and measured by lightwave component analyzer. Normalized optical response for each mesa diameters under a bias of -5 V is shown in Fig. 5. Bandwidths of 49 GHz, 40 GHz, 33 GHz and 25 GHz were measured for photodetector diameter of 10, 15, 20, and 25 μm, respectively. For a 10 μm diameter photodetector 25, 34, and 49 GHz 3 dB bandwidths were measured for reverse biases of 3, 4, and 5 V, respectively.

Data operation was observed for 10 μm diameter photodetector using a 40 Gb/s pseudo random bit sequence with transmitted patterns of $2^{15}-1$ length. A non-return-to-zero

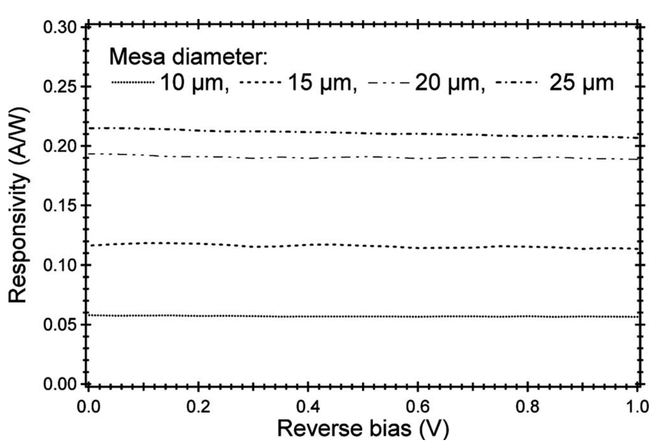

FIG. 3. External optical responsivity as a function of the reverse applied bias of photodetectors of different diameters: 10, 15, 20, and 25 μm.

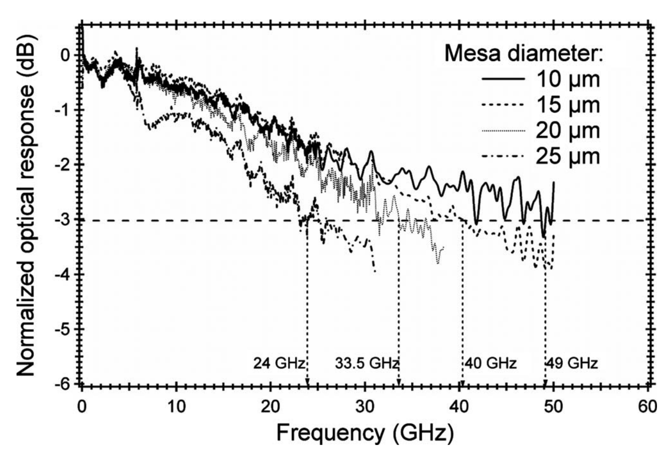

FIG. 5. Normalized optical response as a function of frequency for surface illuminated photodetector of different diode diameters under -5 V bias.

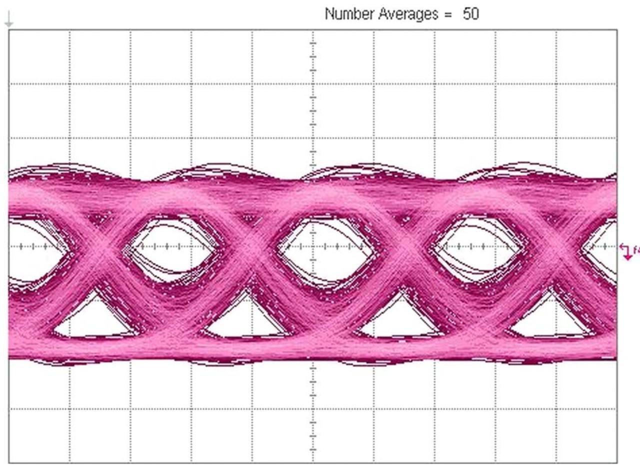

FIG. 6. (Color online) Eye diagram at 40 Gb/s for a 10 μm diameter photodetector under 5 V reverse bias.

(NRZ) open eye diagram presented in Fig. 6 shows operation at 40 Gb/s of the photodetector at -5 V bias.

To conclude, we have demonstrated surface illuminated photodetectors operating up to 40 Gb/s and with optical responsivity reaching 0.1 A/W. These results allow considering such a photodetector as a viable solution for high speed optical communication applications at telecom wavelengths.

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