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High performance germanium-on-silicon detectors for optical communications

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We demonstrate fast and efficient germanium-on-silicon *p-i-n* photodetectors for optical communications, with responsivities as high as 0.89 and 0.75 A/W at 1.3 and 1.55 μm, respectively, time response <200 ps and dark currents as low as 1.2 μA. Ge was epitaxially grown on Si by chemical vapor deposition, employing a low temperature buffer and cyclic thermal annealing to reduce the dislocation density. The overall performance is well suited for >2.5 Gb/s integrated receivers for the second and third fiber spectral windows.
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Thin film germanium photodetectors fabricated on silicon substrates have recently gained widespread interest due to their potential use in low-cost monolithic transceivers for optical communications.[1] The high absorption coefficient at the wavelengths of interest (1.3–1.55 μm), the good transport properties, and the compatibility with silicon technology qualify germanium as the ideal candidate for silicon-compatible near-infrared light detection. To this extent, Ge films have been epitaxially grown with different technologies, aiming at reducing the defects caused by the lattice mismatch with silicon.[2] To date, the best detectors have been obtained employing a low temperature buffer layer associated with cyclic thermal annealing.[3] More recently, a different approach has been demonstrated, based on the growth of Ge islands embedded in a Si *p–n* junction. The latter technology, however, while suggesting the possibility of dark current reduction, at the moment yields detectors with a limited conversion efficiency.[4,5]

Hereby we report on a fast and efficient Ge *p-i-n* detector, epitaxially grown on a silicon substrate and capable of operation at the 2.5 Gb/s "OC-48" standard of optical communications. In order to effectively exploit the compatibility with silicon technology, the goal of the present work was the demonstration of photodiodes exhibiting optimal performances in terms of both responsivity and speed at low voltage biases.

Germanium was epitaxially grown on silicon by ultrahigh vacuum chemical vapor deposition with a base pressure of 3×10^{-9} Torr. In order to minimize the dislocations associated with the large lattice mismatch, a thin relaxed low-temperature Ge buffer was deposited on Si at 350 °C with 10 sccm of GeH_4 (15% in Ar). The buffer layer was meant to promote the insertion of dislocations as a mechanism for strain relaxation (rather than island growth).[6] Its thickness typically ranged from 30 to 60 nm. Then the reactor temperature was incresead up to 600 °C, and about 4 μm of Ge were deposited on Si. In order to further reduce the residual dislocation density, a cyclic thermal annealing (ten cycles between 900 and 780 °C) was performed. Details on the material growth and its characterization can be found in Ref. 7.

The fabricated devices are *p-i-n* photodetectors, with the top *n*-type contact and the intrinsic layer made of epitaxial Ge, while the bottom *p*-type contact is the highly doped silicon substrate (resistivity 0.008 Ω cm). For the realization of the top *n* contact, phosphorous was implanted at 30 keV with a dose of 4×10^{15} cm^{-2}. The *n* contact was about 200 nm thick, as evaluated by secondary ion mass spectroscopy. After ion implantation, the samples were thermally activated through a 5 min anneal at 600 °C. The *p*-type substrate was chosen in order to get the most favorable band alignment for the collection of the photogenerated carriers.[3] The incorporation of one of the doped layers in the substrate eliminates the need for doping gases during Ge growth, while simplifying the electrical connections to the diode. Round mesas of areas ranging from 1.4×10^{-4} to 2.7×10^{-3} cm^2 (diameters from 135 to 585 μm, respectively) were fabricated by standard photolithography and wet chemical etching, and subsequently passivated by spin-on glass. Top and bottom contacts were photolithographically defined on a sputter-deposited aluminum layer. Finally, the samples were annealed to obtain ohmic contacts.

The photodiodes were characterized in terms of dark current, speed of photoresponse and responsivity at both 1.3 and 1.55 μm. Figure 1 shows the typical dark current density as a function of voltage bias at room temperature. From the graph, current densities of 11 and 15 mA/cm^2 at 0.5 and 1 V are apparent, respectively. In particular, the smallest device (135 μm in diameter) exhibited a dark current of 1.2 μA, which compares well with commercial bulk-Ge photodiodes of equal area and dark currents in the range 0.1–1 μA.[2] The inset in Fig. 1 displays the dark current versus device area: the linear scaling indicates a bulk effect at the origin of the

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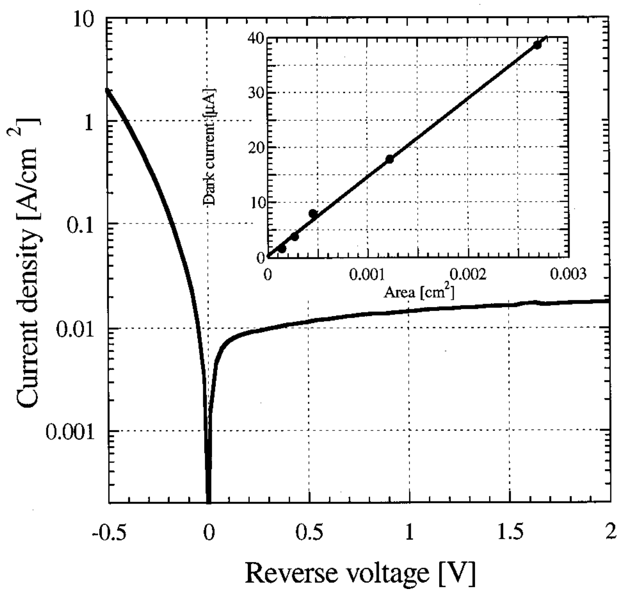

FIG. 1. Dark current density as a function of the applied reverse voltage at room temperature. Dark current vs device area is shown in the inset.

dark current (probably carrier generation in the intrinsic-Ge layer), while underlines the negligible contribution of surface leakage, even in small devices.

The measured dark current is larger than that reported in Ref. 5 for a lower responsivity Ge-island based photodiode, probably due to a larger dislocation count. To date, the larger dark current— and the associated shot noise— of Ge-based versus InGaAs detectors have penalized the former in telecommunication applications where high sensitivity is required. However, as the detector diameter is reduced in order to achieve high speed operation, the contribution of the photodiode on the total receiver noise becomes unimportant as compared to the transimpedance preamplifier. Moreover, for very small area devices (diameter <100 μm), the increasing perimeter to area ratio makes leakage dominate over diffusion/generation currents in the mesas, bleaching the differences due to band gap and transport characteristics of the employed semiconductor.

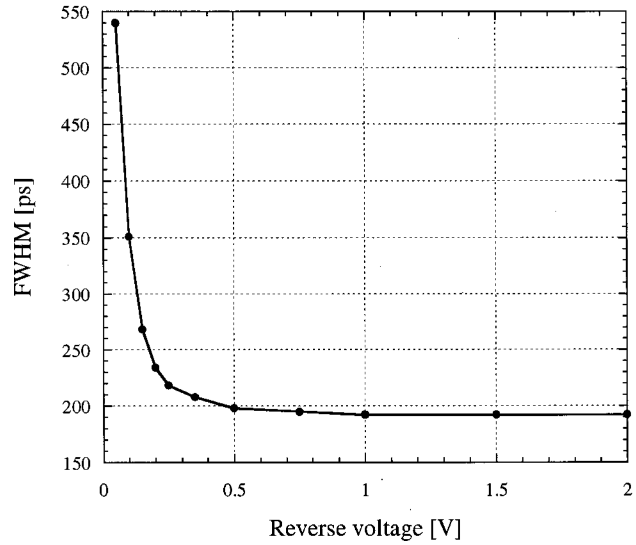

FIG. 3. FWHM of the photoresponse of the 135 μm diameter device vs reverse bias.

The devices' speed of response was investigated by recording the photocurrent generated by a train of 120 ps pulses at 1.32 μm, as produced by a cw actively mode-locked Nd: yttrium–aluminum–garnet (YAG) laser at 100 MHz. The diodes were biased through a 50 Ω resistor, and the signal was acquired by a dc-decoupled (via a 100 nF capacitor) sampling oscilloscope with a 12 GHz analog bandwidth. A 180 ps [full width at half maximum (FWHM)] pulsed photoresponse was measured at a reverse bias of 1 V on the 135 μm device, as visible in Fig. 2. Note that the residual oscillations are imputable to a nonperfect impedance matching with the probe. This result is consistent with a *RC* limited response, being the measured junction capacitance and the series resistance 0.7 pF and 250 Ω, respectively. The response FWHM is plotted in Fig. 3 versus reverse bias. Devices with larger areas exhibited proportionally slower responses; we can therefore infer that the response time is still

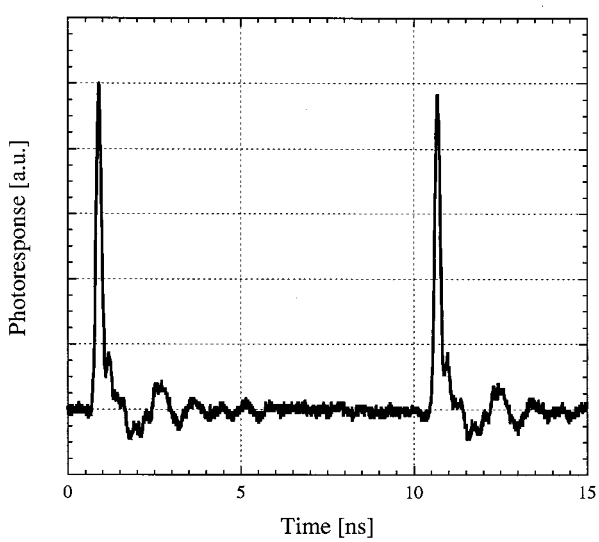

FIG. 2. Time response of the 135 μm diameter device to the 120 ps pulse train from a Nd:YAG laser emitting at 1.32 μm.

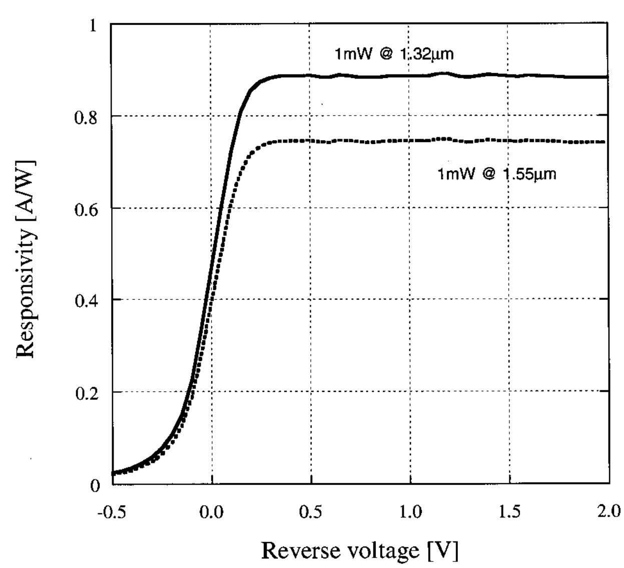

FIG. 4. Measured responsivity vs reverse bias at 1.32 μm (continuous line) and 1.55 μm (dashed line).

dominated by the junction capacitance, leaving space for further improvements by mesa-diameter reductions. The latter statement is also supported by an estimate of transit time from mobility, which yields 50 ps at a reverse bias of 1 V. The measured speed of photoresponse corresponds to a frequency cutoff higher than 2.5 GHz, and therefore enables our photodetectors to operate according to OC-48 at bit rates above 2.5 Gb/s.

Responsivities as high as 0.89 and 0.75 A/W at 1.3 and 1.55 μm, respectively, were evaluated using laser diode sources whose output power was measured by a calibrated power meter. Responsivity data versus reverse voltage are shown in Fig. 4. Notice that complete photocarrier collection (saturation in the curve) is achieved at reverse biases of about 0.3 V. An optimal performance in terms of responsivity and speed, even when operated at low voltages (<1 V), makes these photodiodes perfectly compatible with standard Si electronics and quite appealing towards their monolithic integration in modern, low voltage, electronic transceivers.

In conclusion, we demonstrated fast and efficient Ge p-i-n photodetectors integrated on silicon. Their overall performance compares well with that of commercial devices but, in addition, offers the advantage of complete integrability and voltage compatibility with Si-based high-speed electronics. We believe that these photodetectors will readily find applications in optical communication systems operating at and above 2.5 Gb/s.

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