Ultra-Fast Ge-on-Si Photodetectors

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Abstract: A Ge-fin photodetector in which un-doped germanium is laterally sandwiched between complementary in situ-doped silicon is demonstrated, allowing for unprecedented 3-dB bandwidths up to 265 GHz. Here, we review our work on ultra-fast Ge photodiodes.

1. Introduction

Progress of silicon photonics technology has been an important enabler for datacenter interconnect or metro applications in recent years. Further enhancement of opto-electrical bandwidth is highly desirable in view of anticipated symbol rates approaching 200 GBaud. Already in 2015, germanium photodetectors (Ge PDs) with >67 GHz opto-electrical (OE) bandwidth and responsivity of 0.9 A/W were demonstrated [1]. However, further Ge PD improvement has been impeded since and 67 GHz OE bandwidth remained the benchmark for a long time. Conventional Ge PD approaches usually deploy relatively broad Ge regions where the p- and n- doped (Si and/or Ge) parts of the PDs are defined by means of ion implantation [2-4]. Photo-carrier generation in doped Ge regions is eventually inevitable. In consequence, minority carriers, which are subject to diffusion, negatively affect the OE bandwidths. In [1, 5] the negative impact of minority carrier diffusion on the frequency response of Ge PDs has been discussed. In our unique device approach, doping of the Ge region is mostly prevented as the formation of the p-i-n diode is realized by in situ-doped Si layers. Ion-implantation into Ge is entirely circumvented which eventually allows for very efficient suppression of minority carrier diffusion effects.

Our unique fabrication approach allows for drastically narrowed lateral width of the Ge region, which is a significant differentiator from our previous work [1, 6] or any other state-of-the-art Ge PDs [2-4, 7, 8]. In [9] we demonstrated for the first time a PD with a Ge-fin width of about 100 nm, leading to highest electric-fields and shortest photo carrier drift times. Both measures, the abandonment of ion-implantation through the introduction of in situ-doped silicon regions together with the implementation of narrow Ge-fins eventually enabled, for Ge PDs unprecedented, OE bandwidths of 265 GHz, which was achieved under reverse bias of 2 V and at a rather high DC photocurrent of 1.0 mA (λ = 1550 nm). Thus, these Ge PDs are, in terms of OE bandwidths, on par with state-of-the-art III-V devices or even outperform their InP-based counterparts.

2. Fabrication

Our approach is based on an initially few-micrometer-wide germanium body with a height of ~400 nm, which is thick enough to ensure sufficiently good crystalline quality. This is a distinctive feature compared to vertical drift field diodes, where the epitaxial growth of thin germanium layers (<100nm) with low defect density is very difficult, and thus the fabrication of photodiodes with reasonably low dark currents is quite challenging [10].

The fabrication of this novel PD is schematically sketched in Fig. 1 (a-d): similar to our prior PD generations, we start with selective Ge epitaxy that is conducted on an exposed SOI waveguide (WG) (a). Encapsulation of the Ge by a thin Si layer helps to protect the Ge from abrasive chemicals. By anisotropic dry etching a prior deposited SiO2 layer and the Ge body is patterned, such that a trench is formed. Subsequently, an in-situ doped Si layer is deposited, e.g. by non-selective epitaxy (b). SiO2 deposition is carried out to fill the trench and by chemical mechanical polishing (CMP) the topography of the trench is planarized. The Si layer outside of the trench is then removed by CMP as well (c). Anisotropic dry etch of the hard-mask layer and the Ge on the opposite side is performed (d), followed by deposition of an in-situ doped Si layer with the inverse doping species, with respect to the first Si layer. The relative position of the first and second hard-mask patterning and Ge dry etchings define the actual width of the Ge fin. Similar to the prior process, subsequent steps are conducted for filling, planarization and removal of the protruding Si. Finally, both in-situ doped Si offshoots are exposed, enabling $CoSi_2$ or NiPtSi formation and fabrication of the back-end-of-line process [6,9].

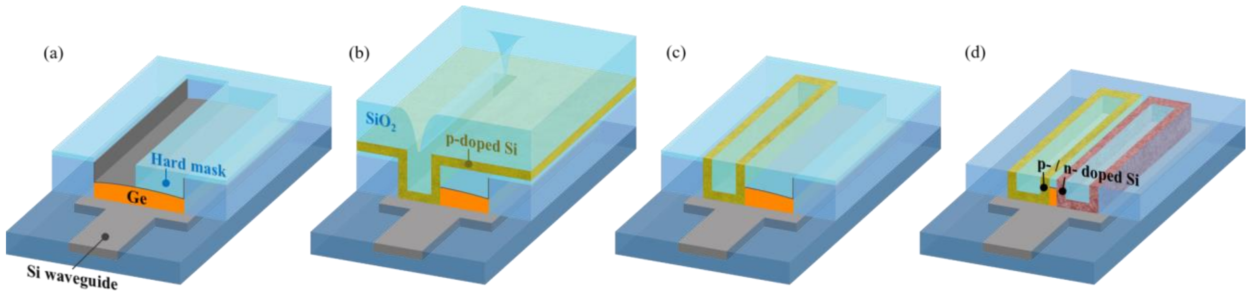

Fig. 1: Schematic process flow of germanium-fin photodetectors: an (undoped) Ge-fin is realized by subsequent germanium dry etching. Eventually, the Ge-fin is sandwiched between two complementary in situ-doped silicon layers, such that a lateral Si–Ge–Si p–i–n diode is formed, without the need for ion implantation. The p- and n-doped regions create laterally oriented offshoots, which at the end enable the low-ohmic contacts to access the photodiode [9].

3. Results and Discussion

A cross-sectional image of a Ge-fin PD including the contacts and the first metal layer and corresponding frequency response are provided in Fig. 2(a). The nominal width of the Ge-fin is about 100 nm (termed 'Ge100_10') while at the narrowest point it is only ~60 nm wide. Results from heterodyne measurements, calibrated up to 325 GHz, for two devices termed "Ge100_10" and "Ge150_10" are shown in Figures 2(b) and (c). Device Ge100_10 achieves a 3-dB bandwidth of 265 GHz at a DC photocurrent of 1.0 mA. A PD with a slightly broader Ge fin, device Ge150_10, shows a 3-dB bandwidth of 240 GHz at the same DC photocurrent of 1.0 mA [9].

Under consideration of a resistance of 59 Ohm (sum of series resistance and the 50-Ω load from the measurement set-up) and a capacitance of ~6.5 fF, the RC cutoff frequency is >400 GHz for Ge100_10. With an effective width of 80 nm (assuming that the biggest fraction of the light would be absorbed nearby and in the center of the Ge fin), the transit time cutoff-frequency yields to ~360 GHz, leading to an overall cutoff frequency of f_{3dB} = 271 GHz which matches very well to the measured 3-dB bandwidth [9].

Photocurrents, measured at various optical input power (at fiber tip) and bias voltages as well as dark currents are shown in Fig. 3a for Ge150_10. The dark currents in the range of 100 nA at room temperature are three to four orders of magnitude below the photocurrents in the range of 0.1-1.2 mA. Plots of the photo-current vs. the optical power are provided in figures 3b and 3c, each measured at bias -2 V. It is worth to note that no saturation is seen up to high photocurrents of 2.5 mA (at 8 dBm at fiber tip, equals 6.3 mW). For the estimation of the internal responsivity, grating coupler losses of ~3.9 dB at 1550 nm were considered. While device Ge100_10 features internal responsivity of 0.3 A/W at 1550 nm, the device Ge150_10 exhibits R_{int} =0.45 A/W. This Ge PD shows bandwidth-efficiency product of 86 GHz, which, to the best of our knowledge, is the highest reported value for Ge PDs so far. A comparison of key parameters of various state-of-the-art waveguide-coupled as well as side-illuminated photo detectors can be found in [9].

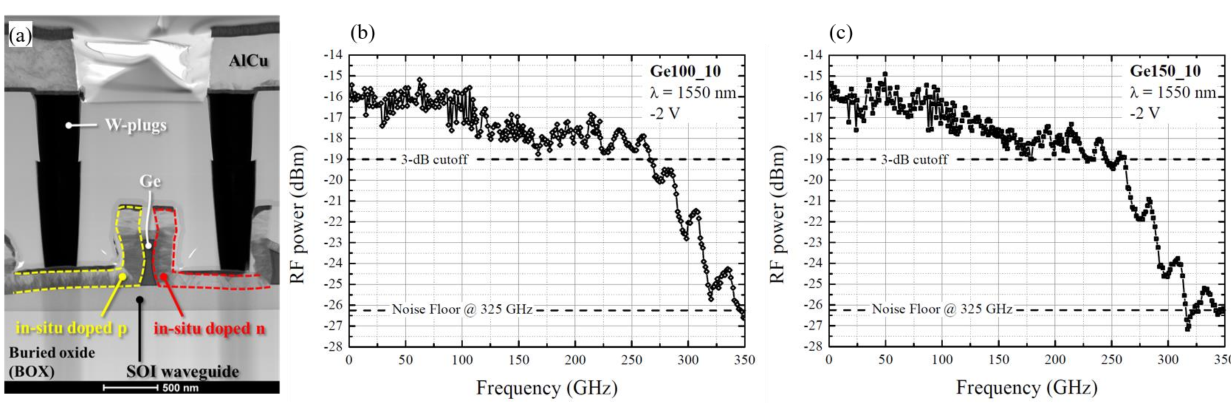

Fig. 2: Cross-sectional image (STEM) of a Ge-fin photodiode with nominal width of 100 nm (termed Ge100_10) featuring in situ-doped (different colors for p- and n-doping) Si contact regions (a); cross-sections cut perpendicular to the direction of light incidence. Frequency responses from heterodyne measurements for Ge100_10 (b) and Ge150_10 (c), each measured at a DC. photocurrent of 1 mA. Measurements were performed at a reverse bias of 2 V on diodes from the same chip and wafer. Photo-diodes with nominal Ge-fin widths of 150 nm and 100 nm yield 3-dB bandwidths of 240 GHz and 265 GHz, respectively [9].

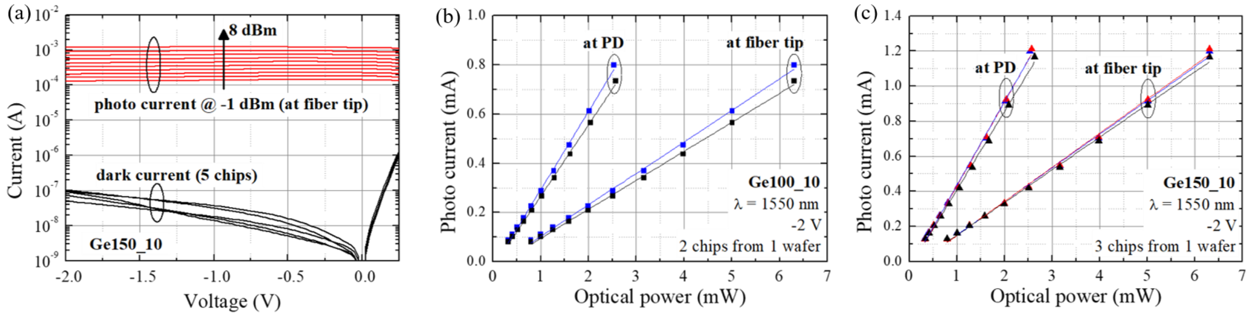

Fig. 3: Dark currents from photodiode Ge150_10 (measured on five chips) and photocurrents (for one representative chip) under an optical input power sweep at λ= 1,550 nm (a), photocurrents plotted versus optical power for the estimation of internal (at the photodiodes) and external (at the fiber tips) responsivities, each with linear fit, for Ge100_10 (b) and Ge150_10 (c) [9].

4. Conclusion

The outstanding enhancement of the 3-dB bandwidth was achieved by a novel construction in which a vertically aligned Ge-fin is sandwiched between two complementary in situ-doped silicon regions. Ion implantation can be waived completely, so unintended ion implantation into the light-sensitive germanium is avoided, which is very beneficial for high-speed performance, as minority-carrier diffusion effects are suppressed.

Our ultra-fast Ge PDs pave the way for silicon photonics-based receivers for applications with symbol rates of 400 GBd or even beyond. Fabrication was entirely conducted on IHP's 8-inch BiCMOS pilot line facilities, so our approach proves that the conventional silicon technology available for standard 200-mm or 300-mm silicon substrates can match or even outperform InP technology in terms of high-speed waveguide-coupled PD performance. Our unique fabrication approach enables ultra-high 3-dB bandwidths and high internal bandwidth–efficiency products together with moderate dark currents.

5. Acknowledgments

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6. References

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