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PHOTODETECTORS

Ultrafast on-chip germanium photodiode

The demonstration of a germanium-based photodiode with a 3 dB bandwidth of 265 GHz and compatibility with silicon photonics and CMOS fabrication offers a cost-effective route to faster channel data rates for optical communications.

Léopold Virot

In order to address the ever-growing needs for higher data rates in communications systems, integrated photonics is spreading into more parts of the network, all the way from data-centres to long-haul transmission systems¹. However, in order to circumvent the limited speed of single-channel components (laser, modulators, photodetectors and drivers), the complexity of communication systems has increased in order to provide the necessary data transmission rates. As a result, systems employing devices with modest speeds (with tens of gigahertz of bandwidth) are now able to achieve bitrates of hundreds of Gbit s⁻¹ thanks to the use of wavelength division multiplexing (WDM) and advanced coherent modulation formats based on intensity and phase modulation². Nevertheless, if one can increase the intrinsic speed of the components in such systems, it will directly allow faster bitrates without the need for other approaches.

Presently, the speed of optical transceivers is limited to a few tens of gigahertz due to several factors such as the design, the materials and technologies used. In the last decade, silicon photonics has emerged as a cost-efficient technology for optical transceivers, benefiting from the enormous, well-established complementary metal-oxide-semiconductor (CMOS) fabrication industry³. It has thus been widely adopted, despite the lack of silicon integrated sources and photodetectors in the O-band (1,260–1,360 nm) and C-band (1,530–1,565 nm) parts of the WDM spectrum. To date, to serve these wavelength windows, high-performance, fast photodetectors have required the use of other specific materials such as III–V alloys or germanium. Importantly, the latter benefits from the possibility to use it in a CMOS fabrication line, allowing wafer-scale integration with silicon.

In the research community, state-of-the-art ultrafast devices have been achieved by using specific materials such as graphene and plasmonic technology for modulation and detection at high speed (beyond 100 GHz)^{4,5}, but those approaches

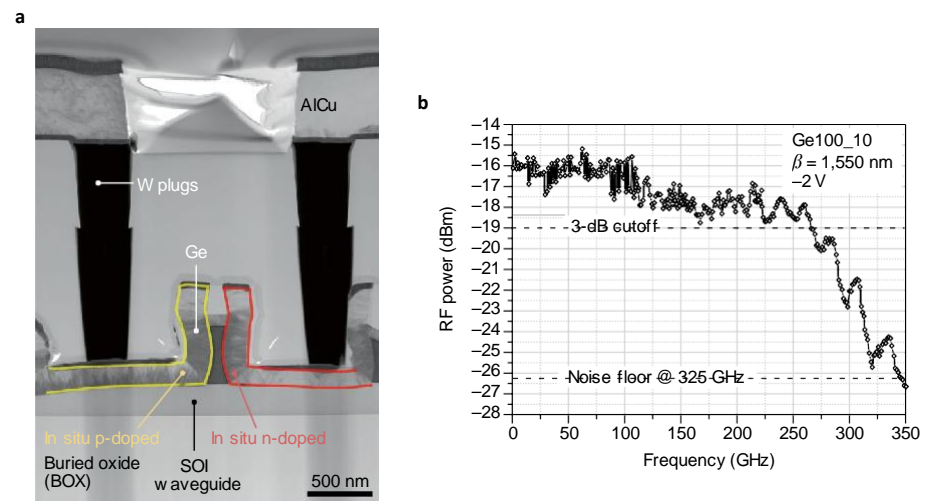


Fig. 1 | Cross-sectional view and frequency response of the photodiode reported by Lischke et al. **a**, Cross-section by scanning transmission electron microscopy of the Ge photodiode featuring in situ-doped Si p and n contact regions. SOI, silicon on insulator. **b**, Frequency response of the photodiode obtained by heterodyne measurement. Credit: Adapted with permission from ref. ⁶, Springer Nature Ltd.

are still some way from being a commercial solution. In the photodetection domain, III–V-based photodetectors remain the best available technology for optical communications. However, with the rise of silicon photonics, germanium-based photodetectors have proven that they are serious challengers performance-wise, with the advantage of easier silicon integration and cost.

Now, writing in *Nature Photonics*, Lischke and colleagues report the demonstration of waveguide-coupled germanium-based photodiodes with record ~3 dB bandwidth of 265 GHz, and notably high responsivity of 0.3 A W⁻¹ at 1,550 nm wavelength⁶.

Not only does this impressive performance outperform their III–V counterparts, it's also a big step toward high-speed integrated receivers on the silicon photonics platform. One of the main achievements of the paper, apart from the record speed, is that it has been realized by using fabrication technologies that are

readily available in silicon photonics and/or CMOS foundries, allowing wafer-scale and volume production of such devices. Indeed, the fabrication was conducted on the 8-inch BiCMOS pilot line facilities at the Leibniz Institute for High Performance Microelectronics (IHP). The germanium region, which absorbs the near-infrared signal light, was defined through two lithography and etching steps, and the doped regions, on which the contacts are realized, were obtained thanks to silicon in situ-doped non-selective epitaxy (Fig. 1a).

This approach allows the realization of a very thin germanium layer that improves the transit time of the photo-generated carriers. Nevertheless, a trade-off between the detector's quantum efficiency and bandwidth exists, which intrinsically limits the performance in one of these key metrics. Despite the very thin absorption region, the internal quantum efficiency at 1,550 nm wavelength remains of the order of 25–36% for the demonstrated devices, leading to

bandwidth-efficiency products between 63 and 86 GHz, which are values not reached by any other waveguide photodetector. As germanium has a direct bandgap of 0.8 eV, its absorption coefficient is quite small at 1,550 nm relative to a shorter wavelength of 1,310 nm. It is thus expected that such a photodiode will have a much greater internal quantum efficiency for applications in the O-band, without any impact on the speed.

Using a heterodyne measurement approach, the frequency response of the fabricated photodiodes was characterized up to 350 GHz, showing a -3 dB cutoff frequency of 265 GHz (Fig. 1b), under a bias voltage of only -2 V. In these devices, the -3 dB opto-electrical bandwidth is limited by a combination of transit time and electronic delay (due to the resistance and capacitance of the device). The width of the Ge fin defines the transit time as well as the capacitance of the diode and the resistance is mainly determined by the quality of the contacts and the doping level of the silicon p and n regions. According to the authors, there is still room for improvement and even faster performance by limiting the size of the protruding silicon doped region that contributes to the total capacitance of the device, and also by increasing the doping level on the n-side. This should enable longer devices with improved internal

quantum efficiency without degrading the speed.

A direct application of such ultrafast photodiodes is the next generation of optical transceivers based on silicon photonics technology for use in data centres as well as in optical fibre communication systems. However, in order to reach channel rates of 400 GBaud or more, the availability of high-speed photodetectors is not enough and faster modulators and lasers will also be required. Fortunately, progress is also being made in both these areas and bandwidths of over 100 GHz have been demonstrated using either thin-film lithium niobate modulators⁷ or III–V semiconductor-based directly modulated lasers⁸.

Beyond the scope of the optical communication, such high-speed photodiodes may also find use in the terahertz (THz) domain for security, medical imaging, spectroscopy, and wireless communication applications, among others⁹. Indeed, photonics-based THz technologies allow the conversion from optical to THz waves by a photomixing technique. By coupling the photodiode to an integrated antenna, THz waves can be generated on chip, and this can be realized by making use of the silicon photonics platform with Ge-integrated photodiodes¹⁰.

The authors demonstrated a new record speed for waveguide-integrated photodetectors, almost ready for volume production in silicon photonics foundries. Those developments will enable the next generations of transceivers for optical communications, and could herald future developments in the THz domain as well as for metrology relying on high-speed photon detection. □

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Competing interests

The author declares no competing interests.