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RESEARCH HIGHLIGHTS

A new 3-dB bandwidth record of Ge photodiode on Si

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Si photonics is a promising technological approach to realize a photonic integrated circuits on Si substrate with small footprint, high performance, low cost, and being highly compatible with Si complementary metal oxide semiconductor (CMOS) technology[1]. Because of good compatibility of Si and the relatively high absorption coefficient in the near-infrared region, Ge waveguide photodiode on Si is almost the only option for optical receiving in Si photonic integrated circuits. For a high performance Ge photodiode, the critical parameters are optical responsivity, 3-dB bandwidth, and dark current. In order to guarantee an acceptable optical responsivity and low dark current, Ge waveguide photodiodes with 300–400 nm-thick intrinsic-Ge is a normal tradeoff choice[2–5]. As the length of the Ge is longer than 10 μm, optical responsivity larger than 0.8 A/W can be realized in 1550 nm. The dark current of these photodiodes is from several to dozens nA which depends on the crystal quality of Ge layer and device structure. The bandwidth of the Ge photodiode is mainly dominated by the carrier transit-time-limited bandwidth (f_T) and resistor–capacitor (RC) bandwidth (f_{RC}) in the active region. f_T, f_{RC} and 3-dB bandwidth ($f_{3\text{-dB}}$) can be approximated using the following equations[6]:

$$f_T \approx \frac{0.45 v_{sat}}{d_i}, f_{RC} = \frac{1}{2\pi\left(R_L + R_S\right)C}, f_{3\text{-dB}} = \sqrt{\frac{1}{1/f_T^2 + 1/f_{RC}^2}}, \tag{1}$$

where v_{sat} is the saturated hole velocity (Ge v_{sat}= ~0.65 × 10^7 cm/s)[7], d_i is the intrinsic layer, C is the capacitance of the device, R_L is the load resistance (50 Ω in most case), and R_S is the series resistance. Calculated 3-dB bandwidth of Ge p–i–n photodiode with various thickness and active area is shown in Fig. 1. The f_T of the 300–400 nm-thick intrinsic-Ge is about 70–100 GHz, consequently 3-dB bandwidth of most high-speed Ge waveguide photodiode is 50–70 GHz. These Ge waveguide photodiodes are qualified for most optical communications which require a good responsivity to maintain a high sensitivity of optical receiving system. However, photodiode with bandwidth around 50–70 GHz is far from enough in some applications, such as terahertz generation and sensing, which needs a photodiode with bandwidth higher than 100 GHz at least[8, 9]. Because of the relatively low hole velocity, Ge photodiode is absent from this ultrahigh bandwidth field which is dominated by InP-based uni-travelling-carrier (UTC) photodiode ($In_{0.53}Ga_{0.47}As$ electron drift peak velocity is 3.1 × 10^7 cm/s)[10]. According to the theory of the bandwidth, there are mainly two approaches to improve the bandwidth of the photodiode. The first approach is decrease of carrier transit-time, which needs a thin intrinsic layer. The second approach is reduction of size of active area and series resistance. However, a narrow intrinsic-Ge layer not only leads low responsivity and large dark current, but increases the junction capacitor per unit active area. Small size also has negative effect in responsivity. Moreover, there is no doubt that both approaches will bring challenges in device design and fabrication.

Recently, Lischke, Peczek, and their colleagues reported an ultrafast Ge photodiode with 3-dB bandwidth of 265 GHz in Nature Photonics[9] (https://doi.org/10.1038/s41566-021-00893-w). This exciting result creates a new 3-dB bandwidth record of the waveguide Ge photodiode. This waveguide Ge photodiode has a lateral Si–Ge–Si p–i–n junction. Inspired by well-known FinFET transistors, an undoped narrow Ge fin is sandwiched between two complementary Si layers. The width, height, and length of Ge fin is 90–100 nm, 400 nm, and 10 μm, respectively. The Ge fin is fabricated by dry etch of a 400 nm-thick selective grown Ge film, which avoids the poor quality of thin Ge film on Si. Due to the activation temperature of n-type or p-type ion implantation in Si is higher than the temperature budget of this sandwich structure, in situ-doping is employed to doping in Si grown process. The in situ-doped Si layers not only provide the sharp doping profile

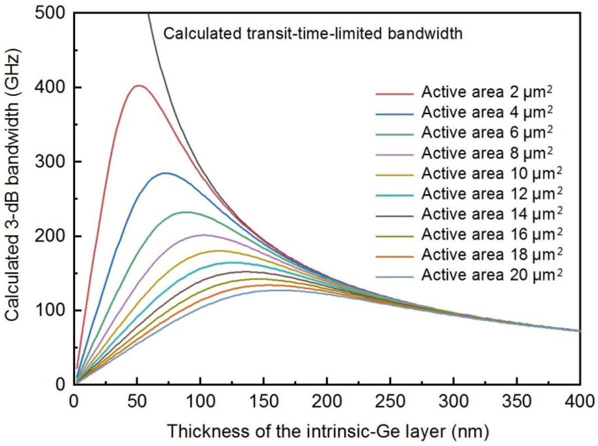

Fig. 1. (Color online) Calculated 3-dB bandwidth of Ge p–i–n photodiode with various thickness and active area. Calculated transit-time-limited bandwidth is also shown for comparison.

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and strong electric field for Ge fin, but also realize a waveguide structure with acceptable optical confinement. Because of the broad bandgap of Si (1.1 eV), this structure can minimize the intrinsic optical absorption of 1550 nm (0.8 eV) in n-type and p-type layer which improve the responsivity of the device. Due to the small size and delicate structure of the Ge photodiode, the fabrication processes are very challenging including highly precise alignments, three times epitaxy, twice Ge etching, twice Si chemical-mechanical polish (CMP) and so on.

The 3-dB bandwidth of the Ge photodiode is obtained by calculation and experimental measurements. Due to the small series resistance (9 Ω) and small active area (4 μm^2, corresponding to the capacitance of 6.5 fF), f_{RC} of the device reaches 415 GHz. Small series resistance suggesting the superb fabrication processes in doping and Ohmic contact. The narrow Ge fin guarantees the f_T as high as 358 GHz. Therefore, the calculated 3-dB bandwidth is 271 GHz. In experimental measurements, frequency response within 0–67 GHz is measured by 67-GHz lightwave component analyser and heterodyne measurement, frequency response larger than 67 GHz is measured by a heterodyne measurement. The experimental 3-dB bandwidth of the Ge photodiode is 265 GHz, which is in a good agreement of calculation. Although the 3-dB bandwidth is greatly benefited from the narrow Ge fin, the cost is the sacrifice of dark current and responsivity. The dark current of the Ge photodiode is below 200 nA at –2 V. Although the dark current is acceptable, it still one order higher than the normal Ge photodiode[2, 4, 11]. This dark current may originate from local high electric field in narrow Ge fin, crystal damage created by the Ge etch process, and defects induced by Ge/Si lattice mismatch in extra two Ge/Si interfaces. The responsivity of the Ge photodiode is only 0.3 A/W which is attributed to insufficient light absorption in the narrow Ge fin. Although the responsivity of the device is low, it is still an amazing result for such narrow and short Ge fin.

In summary, this ultra-fast Ge photodiode is a milestone of Si photonics in ultrahigh bandwidth field which is usually dominated by InP-based photodiode. It proves that the performance of Ge waveguide photodetector fabricated by the conventional Si technology can match or even better than that of InP-based counterpart. The device structure and fabrication processes are very impressive, and will influence the development of the Ge photodiode. According to the calculated results in Fig. 1, the Ge photodiode with the 3-dB bandwidth as high as 400 GHz is also possible by further reducing the thickness and active area of Ge. However, this downscaling will need higher requirements in device fabrication. In the meanwhile, maintaining a good responsivity and low dark current in the ultrafast Ge photodiode is still a big challenge.

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