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Analysis of temperature dependence of Ge-on-Si p–i–n photodetectors

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ABSTRACT

We investigate the temperature dependence of p–i–n photodetectors realized in germanium on silicon. The dark current increases by a factor 1.6–1.9 every 10 °C and is typically dominated by generation in the space charge region, with diffusion contributing in the best samples. The near infrared (NIR) responsivity decreases with temperature in devices with a large defect-density, but is more stable in high-quality photodiodes. These findings provide a relevant insight on the design of Ge-on-Si NIR detectors to be operated above room temperature.

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1. Introduction

Germanium on silicon heterostructures are quite promising for light detectors in the near-infrared (NIR) fiber communication spectrum, where the most common solutions are hybrid subsystems based on III–V semiconductors. Germanium is characterized by good optical absorption as required in WDM applications (1.3–1.6 μm) and is compatible with silicon and silicon microelectronic circuits, enabling its integration in NIR monolithic optoelectronics circuits [1,2]. Much effort, in fact, has been devoted to high-responsivity and high-speed devices for integrated photoreceivers. Recent achievements include normal-incidence p–i–n detectors with 39 GHz bandwidth [3], p–n photodiodes with responsivity ≈0.6 A/W at 1.3 μm and bandwidths up to 19.5 GHz [4], normal-incidence Ge-on-Si p–i–n operating up to 10 Gbit/s at 1.55 μm [5]. More recently, guided-wave detectors have been proposed, including p–n Ge/Si heterojunction diodes operating at 2.5 GHz with responsivity $R = 0.1$ A/W [6], p–i–n operating at 7.2 GHz with $R \approx 1.1$ A/W [7], and p–i–n at 30 GHz with $R \approx 1.2$ A/W [8]. Most reported devices meet the telecom requirements in terms of dark current, responsivity and speed; however, little is known about their temperature behaviour in the range of operation typically specified for data-com transceivers, i.e. 0–70 °C or even −20 to 85 °C [9]. Morse and co-workers [10] measured an increment by a factor nine in the dark current of Ge/Si p–i–n photodiodes as the temperature was increased from 25 to 85 °C. Other researchers observed a similar trend and studied the temperature dependence of a receiver with a Ge-on-SOI photodiode wire-bonded to a CMOS trans-impedance amplifier [11]. To date, no systematic investigation was carried-out on responsivity versus temperature. In this work, we address the temperature dependence of both dark current and responsivity in Ge-on-Si p–i–n, reporting on samples with rather different Ge quality. Our results show that the dark current increases by 0.16 and 0.19/°C in low- and high-quality samples, respectively; the responsivity grows with temperature at wavelengths above the direct band-edge but, depending on Ge quality, can become either larger or smaller at shorter wavelengths.

2. Device fabrication

The p–i–n photodiodes were fabricated by chemical vapor deposition (CVD). A first batch of samples (denoted 5026 [12]) were grown by ultra-high-vacuum CVD with a base pressure of 3×10^{-9} Torr. A thin relaxed low-temperature Ge buffer was deposited on p^+–Si at 350 °C. Then the reactor temperature was ramped up to 600 °C and about 2 μm of Ge was deposited on Si. In order to reduce the residual dislocation density (TDD), cyclic thermal annealing was performed between 900 and 780 °C [13]. Another batch (denoted 56B1 [14]) was fabricated by reduced-pressure CVD with a similar low/high-temperature approach. In addition, in order to minimize the residual TDD, a thick Ge buffer was used and followed by thermal annealing. Finally, the p–i–n structure with a 2-μm-thick intrinsic layer was deposited [15]. We

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intentionally selected two wafers with relatively different defect densities. The threading dislocation density of the best samples (56B1) is about $5–7\times10^6/cm^2$, while that of 5026 is about one order of magnitude larger.

3. Results and discussion

The quality of the investigated samples could be assessed by the dark current density J_d at room temperature with reverse bias V_R of 1 V: such density differs by more than one order of magnitude between 5026 and 56B1, with typical values 28 and 2.2 mA/cm^2, respectively. Fig. 1 displays the dark current at $V_R = 1$ V versus temperature. In both cases J_d increases by more than one order of magnitude as the photodiode is heated from 20 to 70 °C, but with slightly different dependencies. The trend of batch 5026 corresponds to a J_d increase by a factor 1.6 every 10 °C, while it scales by 1.9/10 °C in 56B1. In both cases these rates are slightly larger than in a previous study [10], most likely due to random variations in the defect-density of films realized by highly mismatched heteroepitaxy [16]. In order to understand the nature of the dark current and its temperature variation, we measured the activation energy. Fig. 2 shows the Arrhenius plots of J_d (in logarithmic scale) versus $1/kT$ for various bias voltages. For samples 5026, the activation energy E_a around half the Ge band-gap ($E_g/2 = 0.33$ eV) suggests a transport process dominated by generation in the space charge region [17], the latter prevailing on diffusion due to the relatively large defect-density [16]. The small change in E_a with reverse bias is consistent with an energy distribution of defects around the mid-gap, with voltage-dependent activation and deactivation.

Samples 56B1 exhibit a similar behaviour, but the activation energies can be larger than in lower-quality samples 5026. $E_a > E_g/2$ and up to the germanium band-gap E_g demonstrates the role of diffusion current as well. This voltage dependence of the dark current is most likely due to the coexistence of diffusion at lower bias and generation at higher bias. The relevance of diffusion in 56B1 (with respect to 5026) is consistent with their superior quality, as the dark current in small band-gap semiconductors (like Ge) is typically dominated by diffusion.

The Ge-on-Si p–i–n photodiodes from series 5026 and 56B1 exhibited typical 1.55 μm responsivities at reverse voltage $V_R = 1$ V of 0.4 and 0.5 A/W, respectively, at room temperature. Based on the temperature dependence of optical absorption in Ge, only a moderate increase is expected at wavelengths below the direct band-edge, whereas a large increase should take place close to the band-edge [18]. Fig. 3 shows the short-circuit spectral responsivity of detectors 5026, measured at various temperatures in 10 °C steps. While the expected increase with temperature is visible at long wavelengths, at shorter wavelengths the responsivity reduces, with a maximum drop of about 25%. This can be explained by resorting to the temperature-dependent recombination in the Ge layer.

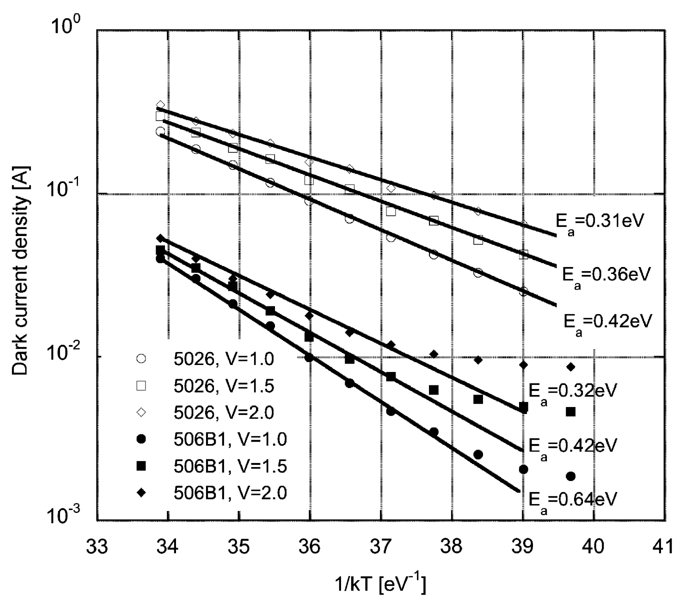

Fig. 2. Dark current density (log scale) versus $1/kT$ at various reverse biases (Arrhenius plot). The indicated activation energy E_a is extrapolated from the fit.

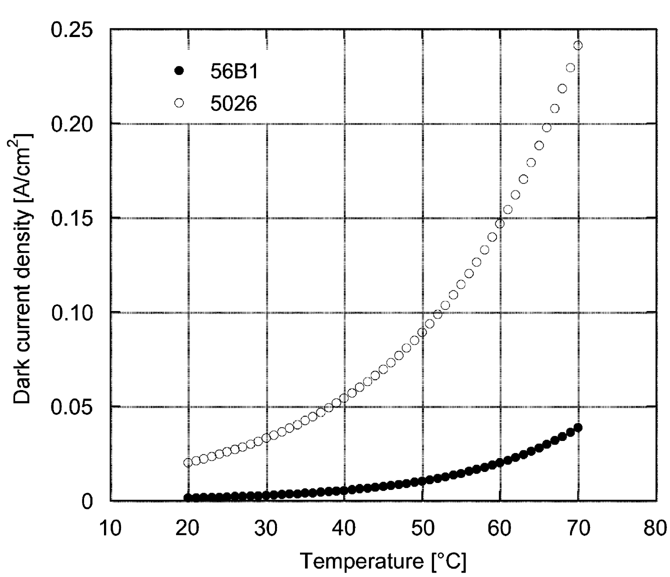

Fig. 1. Dark current density versus temperature for low- (circles) and high-quality samples (dots).

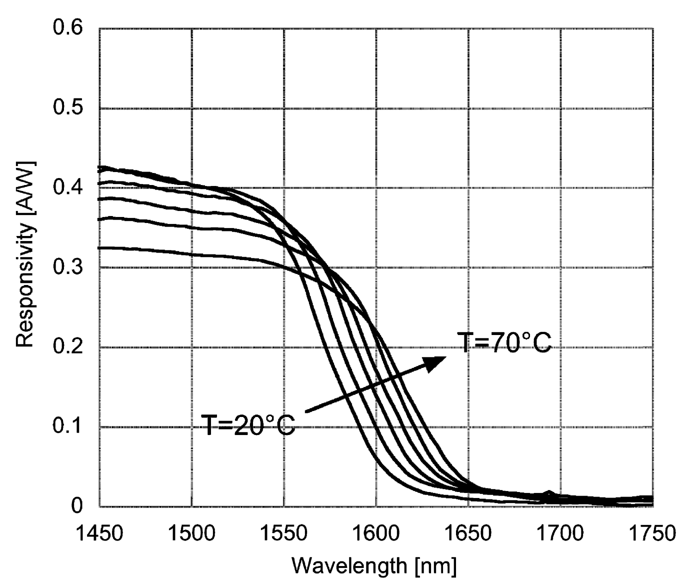

Fig. 3. Short-circuit spectral responsivity of samples 5026 measured between 20 and 70 °C at increments of 10 °C.

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