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Ge-on-Si Integrated Photonics: New Tricks from an Old Semiconductor

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Abstract: We review recent progress in Ge active photonic devices for electronic-photonic integration on Si, demonstrating new tricks in optoelectronics from this “old” semiconductor material used for the first transistor more than 60 years ago.

1. Introduction

Germanium is an “old” semiconductor material used to fabricate the first bipolar transistor in 1940s, which marked the beginning of the Information Age. However, due to relatively high thermal noise associated with its small band gap and lack of a stable thermal oxide, Ge gave its place to Si in large scale integrated circuits based on complementary metal oxide semiconductor (CMOS) transistors. In recent years there has been a revival of interest in Ge due to its applications in high mobility CMOS transistors and Si-compatible photonic devices. These research efforts show that it is promising to achieve high performance electronic-photonic integrated circuits on Si using Ge-based photonic devices. In this paper we will review recent progress in active Ge photonic devices on Si, including photodetectors, electroabsorption modulators, and lasers, whose performance has been enhanced or enabled by new tricks in band engineering such as tensile strain and n-type doping.

2. Band-engineering of Ge for photonic applications

Although Ge is commonly known as an indirect gap material, its direct gap at Γ valley is only 136 meV higher than the indirect bandgap (Fig. 1a). The direct gap of 0.8 eV corresponds to a wavelength of 1550 nm, the most technically important wavelength in optical communications. These properties make Ge a good candidate for photonic devices in the near infra-red (NIR) regime. The difference between direct and indirect gaps of Ge can be further reduced by introducing tensile strain, as shown in Fig. 1b. With biaxial tensile stress, both direct and indirect gaps shrink faster. Therefore, Ge transforms from an indirect gap material towards a direct gap material with the increase of tensile strain. Furthermore, the top of the valence band is determined by light hole band under biaxial tensile stress, which increases hole mobility. These changes in band structure induced by tensile strain can greatly enhance the optoelectronic properties of Ge. A thermally induced tensile strain of 0.2-0.3% can be incorporated into epitaxial Ge-on-Si utilizing the difference in thermal expansion coefficient between Ge and Si [1], which extends the absorption range of Ge photodetectors from C band (1528-1560 nm) to L-band (1561-1625 nm) [2]. The absorption contrast of electroabsorption effect in Ge is also significantly improved by tensile strain [3]. To obtain efficient light emission from the direct gap transition of Ge, n-type doping has been applied to tensile-strained Ge in order to fill the states in indirect gap L valleys so that the energy difference between direct and indirect gaps is compensated (Fig. 1c) [4]. Therefore, band-engineering by tensile strain and n-type doping enables high performance Ge active photonic devices on Si.

3. Ge-on-Si photonic devices

Photodetectors: Ge-on-Si photodetectors have achieved rapid progress in recent years. Free-space detectors with performance comparable to III-V devices at 850 and 1310 nm have been demonstrated [2,5]. Integration with Si waveguides further enhances bandwidth-efficiency product by separating the photon absorption path in the longitudinal direction along the waveguide from carrier collection path in the transverse direction [6]. A bandwidth-efficiency product as high as 30 GHz has been achieved in waveguide-coupled Ge photodetectors [7]. Combining the merits of Si in carrier multiplication and Ge in highly efficient light absorption, Ge/Si avalanche photodiodes have achieved a
gain-bandwidth efficiency of 340 GHz, exceeding the performance of their III-V counterparts [8].

**Modulators:** Ge electroabsorption modulators (EAMs) based on strain-enhanced Franz-Keldysh effect [9,10] and quantum confined Stark effect (QCSE) [11,12] have both been demonstrated in recent years. Compared to Mach-Zehnder interferometer modulators based on carrier-injection induced refractive index changes, Ge-based EAMs are based on an ultrafast (<1 ps) and highly efficient field-induced change in absorption near the direct band edge, which enables a very compact device size and ultralow capacitance. These advantages lead to a very low energy consumption in the order of tens of fJ/bit, which is ideal for high performance, high energy-efficiency large-scale electronic photonic integration.

**Lasers:** As discussed in Section 2, band-engineering by tensile strain and n-type doping can effectively compensate the energy difference between direct and indirect gaps of Ge. Modeling has shown that the optical gain from the direct gap transition can well overcome the free carrier absorption introduced by n-type doping and carrier injection [4]. Indeed, n-type doping has improved room-temperature photoluminescence of Ge by nearly two orders [13]. With $1 \times 10^{19}$ cm$^{-3}$ phosphorous and 0.24% thermally induced tensile strain in Ge, an optical gain coefficient of $\sim 50$ cm$^{-1}$ has been demonstrated [14]. The performance of an optically pumped, edge-emitting Ge-on-Si waveguide laser is shown in Fig. 2 [15]. With the increase of pump power, the spectrum evolved from a broad emission band dominated by spontaneous emission to sharp emission lines featuring stimulated emission. Correspondingly, the polarization evolved from a mixed TE/TM to predominantly TE with a contrast ratio of 10:1 due to the increase of optical gain, as expected for typical lasing behavior. A clear threshold behavior is demonstrated in the inset of Fig. 1a. Fig. 2b shows a high resolution scan of the emission line at 1593.6 nm using a spectral resolution of 0.1 nm. Periodic peaks corresponding to longitudinal Fabry-Perot modes are clearly observed in the spectrum. The longitudinal mode spacing of 0.060±0.003 nm is in good agreement with the calculated Fabry-Perot mode spacing of 0.063 nm for a 4.8 mm-long Ge waveguide cavity.

**Conclusions**

We have shown that Ge, an “old” semiconductor used for the first bipolar transistor in the world, is finding new applications in Si based photonics due to band-engineering of its direct gap transitions. The achievements of high performance Ge-on-Si photodetectors and modulators, together with the first demonstration of Ge-on-Si lasers, indicate that Ge photonic devices are ideal for monolithically integrated optoelectronics on Si.

**References**