Ge Active Photonic Devices on Si for Optical Interconnects

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Abstract
Near-infrared active photonic devices, using Ge layers epitaxially grown on Si, are presented from the viewpoint of short-reach optical interconnects.

1. Introduction
Si photonics is a technology to integrate photonic devices on a Si CMOS platform. As a Si photonics product, active optical cables, where Si-based optical transceiver chips terminate a silica optical fiber, have been applied to rack-to-rack interconnects in supercomputers. Advantages in the optical communications – large capacity, low-power consumption, and small signal delay – would be effective also for emerging shorter-reach interconnects including chip-to-chip and on-chip ones [1].

Although low-loss optical waveguides (WGs) of Si for on-chip near-infrared (NIR) communications (1.3 - 1.6 μm) have been fabricated from Si-on-insulator (SOI) wafer, monolithic integration of group-IV active photonic devices, such as light emitters, remains as a challenge. Ge is an old but new group-IV material in electronics, as renewed for high-end transistors on Si. In this work, a photonic device technology is presented, where Ge plays an enabler to realize active photonic devices integrated on a Si platform.

2. Optical Properties of Ge
Similar to Si, Ge is an indirect bandgap material, and the gap energy is 0.66 eV at the L point, as in Fig. 1. The indirect nature prevents efficient light emissions, while the direct gap energy of 0.80 eV at the Γ point leads to a large optical absorption for the wavelength below 1.55 μm. As shown below, Ge photodetectors on Si have been applied to NIR optical communications [2]. Electro-absorption optical modulators to generate optical signals have been also proto-typed, based on the Franz-Keldysh (FK) effect [3]. Attempts have been also performed for Ge light emitters on Si [4], since Ge can be regarded as a “quasi-direct” bandgap material: the energy difference between the L and Γ points in the conduction band is as small as 0.14 eV.

3. Epitaxial Growth of Ge on Si
In spite of a large lattice mismatch of 4% between Ge and Si, device-quality Ge can be grown on Si using chemical vapor deposition (CVD) techniques with an insertion of low-temperature buffer layer of pure Ge [5]. Uniform Ge layers are obtained, as in Fig. 2(a), and the threading dislocation density is reduced from 10^7 cm^-2 to < 10^5 cm^-2 by a post-growth annealing, as in Fig. 2(b). Selective area growth of Ge with SiO_2 masks can simplify the process for the integration with WGs, as in Fig. 3 [6, 7].

It is important that a biaxial tensile strain of 0.1 - 0.2% is present in Ge [2]. In contrast to the compressive strain in pseudomorphic Ge (~1 nm) on Si, a tensile strain is accumulated during the cooling from the growth/annealing temperature because of the thermal expansion mismatch between Ge and Si. The tensile strain decreases the direct gap from 0.80 eV to ~0.78 eV, expanding the optical absorption towards longer wavelengths. Further increase of tensile strain in Ge up to ~2% theoretically makes a transition from the indirect material to the direct one, suggesting highly efficient light emissions.
4. Active Photonic Devices Based on Ge pin Diodes on Si Current-Voltage (I-V) Characteristics

Typical I-V characteristics for Ge pin diodes on Si are shown in Fig. 4. Rectifying diode characteristics were observed. Reduction of threading dislocation density by a post-growth annealing is found to be effective to decrease the reverse leakage current. Photonic device functions, i.e., photodetection, optical modulation, and light emission, are described below.

Photodetection

A typical responsivity spectrum in the 1.55 µm range is shown in Fig. 5(a), which was measured with the normal incidence of light. High responsivities more than 0.1 A/W were obtained for < 1.57 µm, indicating high quantum efficiencies. The absorption edge for the experimental one is found to shift towards the longer wavelength in comparison with the theoretical one (1.55 µm, i.e., 0.80 eV) for unstrained Ge. This reflects the narrowing of direct bandgap due to the tensile strain. The red shift is crucial to cover the L band (1.56 - 1.62 µm) as well as the C band (1.53 - 1.56 µm) in the wavelength division multiplexation (WDM) communications. As for the on-chip interconnects, Ge pin photodiodes have been successfully integrated with Si waveguides, as in Fig. 3, and the high-speed operation with the bit rate more than 10 Gbps has been realized [7].

Optical Modulation

Electro-optic optical modulators of Si have been investigated, using Mach-Zehnder interferometer (MZI) configurations. Free carrier injections to Si WGs of MZI arms modify the refractive index, leading to the optical intensity modulations. However, the large device size of > 100 µm has been used for the high extinction ratio, causing large energy consumptions (> 1 pJ/bit) unfavorable for the short-reach interconnects. One approach to overcome this issue is to develop electro-absorption modulators with a reduced size. As in Fig. 5(b), applying high electric fields to Ge pin diodes on Si, optical absorption is enhanced above the 1.58 µm due to the FK effect. Based on this effect, Ge optical modulators with a reduced power (0.05 pJ/bit) have been proto-typed [3].

Light Emission

Under high level of carrier injections, Ge layers on Si show a light emission in the 1.55 µm range due to the direct transition around the Γ point, as in Fig. 6. In order to increase the emission efficiency, heavily n-type doping was performed to fill the conduction band at the L valley by electrons. A net optical gain as well as an electrically pumped laser has been reported due to the efficient direct recombination of electrons injected to the Γ valley [4]. The tensile strain of 0.1 - 0.2% in Ge layers is also responsible for this enhancement, since the energy difference between the L and Γ points in the conduction band is reduced. Increase of tensile strain up to ~2% theoretically makes a transition into the direct bandgap material, suggesting highly efficient light emissions. In order to introduce such a large strain, an approach using micro-mechanical structures of Ge/Si [8] will be discussed.

Fig. 4 (a) Schematic structure of Ge pin diode on Si and (b) typical I-V curves.

Fig. 5 (a) A typical responsivity spectrum at a reverse voltage of 1 V for a Ge pin diode with an as-grown Ge layer of 800 nm, and (b) responsivity spectra at reverse voltages of 1.5, and 9 V.

Fig. 6 Typical electroluminescence spectra from a Ge pin diode (20 µm in diameter).

5. Summary

A photonic device technology, using Ge epitaxial layers on Si, was described. This technology should play an important role in the future short-reach optical interconnects in Si CMOS electronics.

References