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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 10^9 cm^{-2} to < 10^7 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.

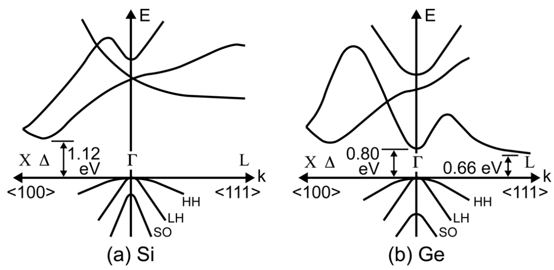

Fig. 1 Schematic band structures for (a) Si and (b) Ge.

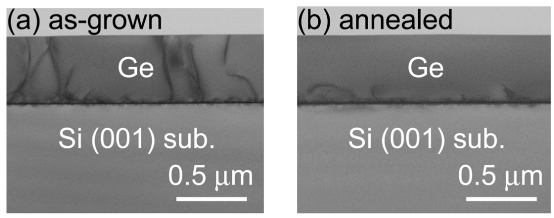

Fig. 2 Typical cross-sectional transmission electron microscope images for (a) as-grown Ge (600°C) and (b) annealed Ge (800°C).

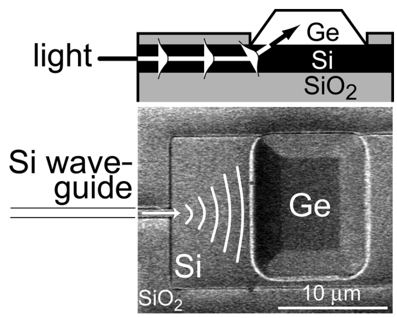

Fig. 3 A typical scanning electron microscope images for Ge selectively grown on an SOI layer.

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 multiplication (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.

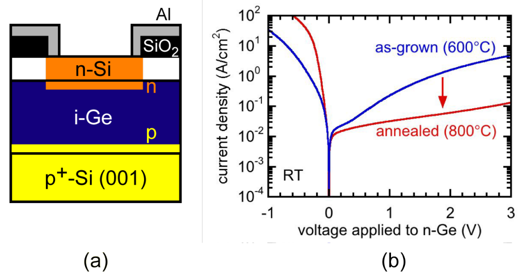

Fig. 4 (a) Schematic structure of Ge *pin* diode on Si and (b) typical *I-V* curves.

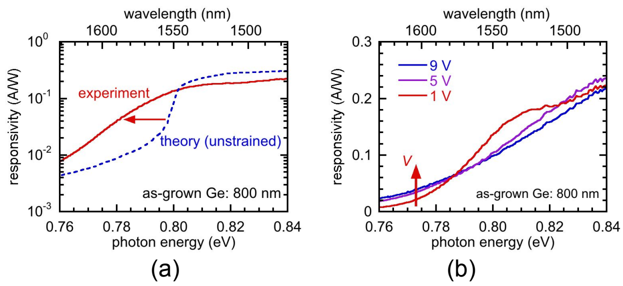

Fig. 5 (a) A typical responsivity spectrum at a reverse voltage of 1 V for a Ge *pin* diode with an as-grown Ge layer of 800 nm, and (b) responsivity spectra at reverse voltages of 1, 5, and 9 V.

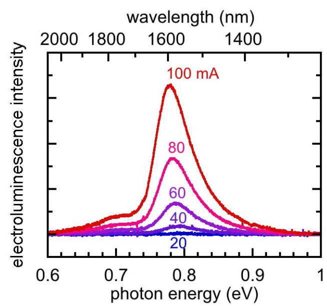

Fig. 6 Typical electroluminescence spectra from a Ge pin diode (20 μm in diameter).

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.

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