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CMOS photonics based on SiGe and Ge for near and mid-infrared photonic integrated circuits

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Abstract

We present contributions of the heterogeneous integration of SiGe and Ge on Si to near and mid-infrared integrated photonics. Strained SiGe enables high-efficiency Si-based optical modulators. Ge offers a novel photonic platform to extend available wavelength to mid-infrared spectrum.

1. Introduction

Photonic integration based on Si photonics technologies are going to be one of the standard approaches for building low-power and ultra-small optical interconnect chips through CMOS compatible process. To extend functionalities on Si photonics platform, heterogeneous integration of Ge and III-V semiconductors on Si has developed significantly, enabling, for example, Ge photodetectors (PDs) and III-V lasers on Si platform. Since Si industry is also pursuing to develop SiGe/Ge/III-V based CMOS circuits to utilize their high hole and electron mobility, CMOS photonics based on the heterogeneous integration is an enabling technology to develop high-performance electronic-photonic integrated circuits through CMOS compatible process.

In this paper, we discuss the benefits of the introduction of SiGe and Ge for near and mid-infrared CMOS photonics. We present strained SiGe opens the way for strain engineering in optical modulators as well as CMOS electronics. We also discuss Ge CMOS photonics for mid-infrared integrated photonics beyond Si photonics.

2. SiGe optical modulator

The free-carrier effects in Si such as the plasma dispersion effect and free-carrier absorption mainly contribute to build Si optical modulators through carrier modulation by accumulation, injection and depletion. Many practical Si optical modulators have been demonstrated so far. However, they are suffering from low modulation efficiency due to the weak free carrier effects in Si. To enhance the free-carrier effect with keeping CMOS compatibility, we have proposed to introduce strain SiGe into Si waveguides [1]. The free-carrier effects are basically described by the Drude model, suggesting that the free-carrier effects are enhanced by reducing effective masses of electron and hole. It is well known that compressively strained SiGe possesses lighter hole effective mass. The strained SiGe channel has already been used in commercial products for high-performance p-channel metal-oxide-semiconductor (MOS) transistors. We have proposed the concept of similar strain engineering for Si optical modulators. Fig. 1 shows the numerically analyzed free-carrier effects in strain SiGe. As shown in Fig. 1, the enhancements in the free-carrier effects increase as the Ge content in SiGe increases because of the reduction in hole effective mass. When the Ge content is 50%, 3 times and 4.2 times enhancements are predicted for the refractive index change (Δn) and absorption change (Δα), respectively.

To investigate the enhanced free-carrier effects in strained SiGe, we have developed carrier-injection SiGe optical modulator [2, 3]. As a cross-sectional TEM image of the SiGe optical modulator in Fig. 2, a strained SiGe layer is embedded in the Si waveguide mesa. When carriers are injected through a lateral PIN junction, electrons and holes are accumulated in the SiGe layer, contributing the free-carrier effects. Fig. 3 shows attenuation modulation characteristics in the SiGe and

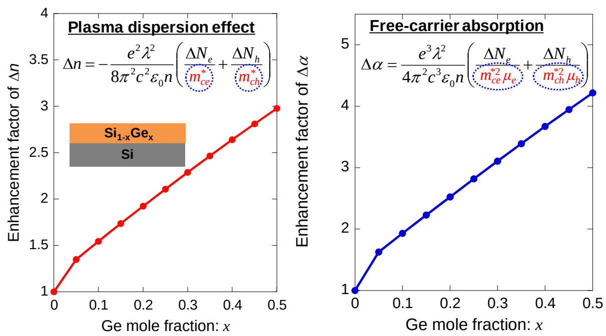

Fig. 1 Enhancements in the free-carrier effect of strained SiGe as a function of Ge content.

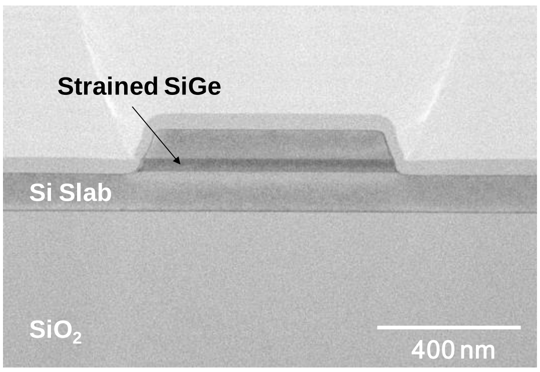

Fig. 2 Cross-sectional TEM image of SiGe optical modulator.

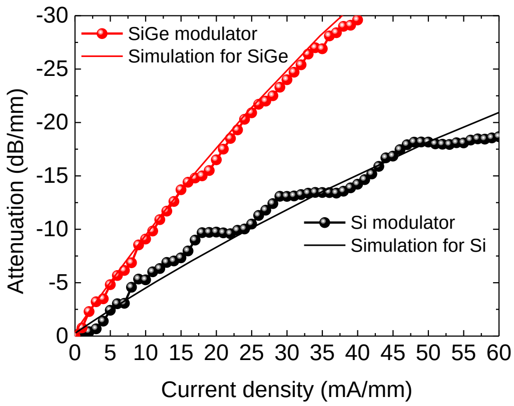

Fig. 3 Attenuation characteristics in SiGe and Si devices.

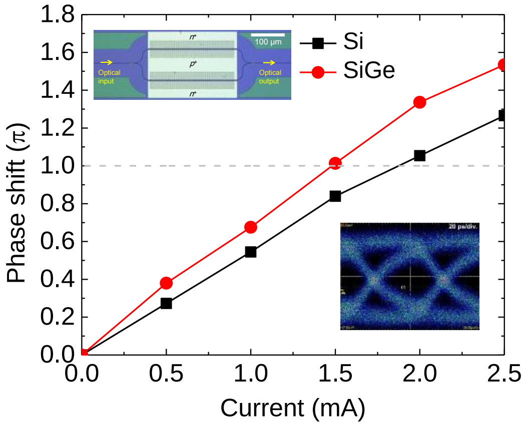

Fig. 4 Phase shift in SiGe optical modulator.

Si devices. The SiGe devices shows significantly larger attenuation than the Si device. Thus, we have successfully demonstrated the enhanced free-carrier absorption in strained SiGe. We have also measured a phase shift in the SiGe asymmetric Mach-Zehnder interferometer optical modulator [4]. As shown in Fig. 4, the enhanced plasma dispersion effect in strain SiGe is confirmed for the first time. We have also achieved a clear eye operation at 10-Gbps modulation.

3. Ge CMOS photonics

Ge has been intensely investigated as PDs for Si photonics. Recently Ge attracts much attention for its potential in mid-infrared photonics applications because Ge is transparent to mid-infrared light. In terms of the free-carrier effects, nonlinearity, and thermo-optic coefficient, Ge is superior to Si. To take full advantage of the Ge properties for mid-infrared photonics, we have proposed the Ge CMOS photonics platform as shown in Fig. 5. A Ge-on-Insulator (GeOI) wafer with a thick buried oxide layer (BOX) allows us to monolithically integrate Ge-based waveguide devices and Ge CMOS. We have successfully fabricated a high-quality photonic GeOI wafer by direct wafer bonding and Smart-Cut™ [5]. A transmission in a Ge waveguide on the GeOI wafer for a 2-μm wavelength is confirmed for the first time [6]. A sharp Ge bend waveguide shown in Fig. 6(a) exhibits negligible bend loss owing to the strong optical confinement in the GeOI platform, enabling ultra-small mid-infrared photonic integrated

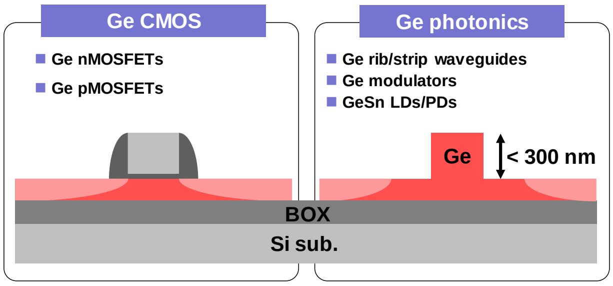

Fig. 5 Concept of Ge CMOS photonics platform.

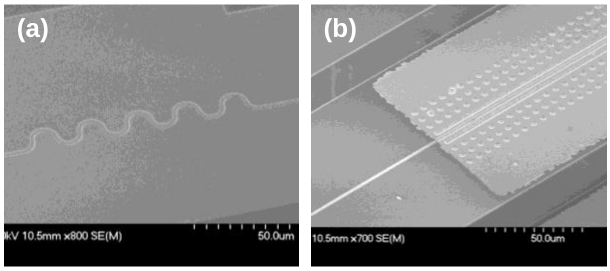

Fig. 6 (a) Ge bend waveguide and (b) carrier-injection Ge variable optical attenuator fabricated on GeOI wafer.

circuits. We have successfully fabricated carrier-injection Ge variable attenuator on the GeOI wafer for the first time as shown in Fig. 6(b). Ge strip waveguide-based passive components including a grating coupler, MMI coupler and ring resonator have also been successfully demonstrated [7].

4. Conclusions

We have presented that strain engineering by SiGe is also applicable to enhance the modulation efficiency in Si-based optical modulators. Ge on an SiO_2/Si wafer is emerging as a new platform for mid-infrared photonics. The heterogeneous integration of SiGe and Ge on Si can extend possibilities of photonic integrated circuits based on Si photonics technologies.

Acknowledgements

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