博士論文（要約）

# Study on strain-induced enhancement of plasma dispersion effect and free-carrier absorption for SiGe optical modulators/attenuators

（**SiGe** 光変調器/減衰器に向けた歪誘起によるプラズマ分散効果及び自由キャリア吸収増大に関する研究）

**A DISSERTATION**
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The plasma dispersion effect and free-carrier absorption are well-known physical phenomena that change optical constants, the refractive index (*n*) and absorption coefficient ($\alpha$), of semiconductors, and are the most promising effects for silicon (Si) to build-up optical modulators, as previously shown in the study by Soref and Bennett. Currently most Si optical modulators, which are one of the fundamental building blocks of Si-based electronic-photonic integrated circuits (EPICs) for off-chip and on-chip optical interconnects, have been demonstrated using these free-carrier effects.

However, the weak plasma dispersion and free-carrier absorption in Si cause low modulation efficiency, resulting in large device footprints and power consumption. Thus, enhancement of the plasma dispersion and free-carrier absorption will be fundamentally important to improve the modulation efficiency of Si-based optical modulators for small device footprints and low power consumption. The plasma dispersion effect and free-carrier absorption are expressed by the Drude model, which describes the changes in the refractive index and absorption coefficient upon a change in the plasma frequency of free carriers, which is dependent on the number of free carriers and their conductivity effective masses. Since the effects are inversely proportional to the conductivity effective masses of electrons and holes, lighter conductivity masses result in a larger plasma dispersion effect and free-carrier absorption.

In the dissertation, we have theoretically and experimentally investigated the enhancement of plasma dispersion and free-carrier absorption by strain-induced mass modulation in silicon-germanium (SiGe). The introduction of compressive strain to SiGe reduces the conductivity hole mass, resulting in enhanced plasma dispersion and free-carrier absorption. We expect that compressively strained $Si_{0.7}Ge_{0.3}$, which can be coherently grown on Si, will exhibit approximately two times higher plasma dispersion and three times higher free-carrier absorption than Si. The enhancement of the plasma dispersion effect and free-carrier absorption in SiGe is experimentally examined using a Si/SiGe/Si double-heterostructure optical waveguide with a lateral *pin* junction for carrier injection in the near-infrared wavelength range from 1.3 to 1.6 μm, which is the most important range of wavelengths for optical communication.

We have experimentally proved that the effective mass modulation by using strain to SiGe is an effective way to enhance the plasma dispersion effect and free-carrier absorption. We have invented a novel strained SiGe optical modulator, which consists of Si/SiGe/Si heterostructure in waveguide core and successfully demonstrated the enhancement in the plasma dispersion effect and free-carrier absorption for the first time. We have experimentally demonstrated that the modulation efficiency can be enhanced twice by introducing strained SiGe in the telecommunication wavelength range from 1.3 to 1.6 μm.

Finally, we have also demonstrated the high-speed optical modulator and variable optical attenuator, taking advantage of the strain-induced mass modulation which is effective to improve the plasma dispersion effect and free-carrier absorption. The introduction of compressively strained SiGe is a promising method of boosting the modulation efficiency of Si-based optical modulators. As is well known, technology for enhancing mobility by strain has been widely used in most Si metal-oxide-semiconductor (MOS) transistors to enhance the transistor performance since the first mass production of strained Si MOS transistors by Intel. In a similar manner, the strain-induced enhancement of the free-carrier effects can soon be applied to Si-based optical modulators to improve their performances owing to the compatibility of SiGe with the standard complementary metal-oxide-semiconductor (CMOS) process.