論文の内容の要旨

論文題目: Fabrication and Characterization of Silicon-Germanium Field-Effect Ring Modulators and Germanium Light Emitters for the Integrated Group IV Photonics Platform
(IV族集積フォトニクスに向けたシリコンゲルマニウム電界効果リング光変調器およびゲルマニウム発光素子の作製と評価)

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The objectives of this thesis are threefold: The development of a silicon-germanium (SiGe) device fabrication process on the silicon (Si) platform as well as the design and realization of field-effect SiGe ring modulators and germanium (Ge) light emitters.

To these ends, we exploit the small direct-to-indirect conduction band edge separation of Ge-rich SiGe alloys. This property leads to significant direct band electro-optical interactions such as the Franz-Keldysh (FK) electromodulation or photon emission, both of which can be utilized for active SiGe devices.

Despite the quasi-direct nature of Ge, one disadvantage of Ge as an optical medium is the sub-ps intervalley scattering times in the conduction bands. We propose a new class of optoelectronic devices by which this loss mechanism is mitigated using strain generated from micromechanical structures. As a concrete example, we modeled the theoretical emission efficiency of strained Ge supported by a cantilever-like platform. Our simulations indicate that net optical gain is obtainable even in indirect Ge under a substrate biaxial tensile strain of about 1.5% with an electron-hole injection concentration of 9×10^{18} cm^{-3} while direct bandgap Ge becomes available at a strain of 2%. A large wavelength tuning span of 400 nm in the mid-infrared range also opens up the possibility of a tunable on-chip Ge biomedical light source.

To increase the material-light interaction time inside active microphotonic devices, an optical resonator, such as a ring filter, is often implemented. Ring filters, in contrast to standing wave resonators such as the Fabry-Perot resonator or the photonic crystal cavity, have good impedance matching to on-chip coupling waveguides and are ideally suited for integrated photonic circuits. We designed a novel concentric-ring optical buffer structure which retains this advantage but which also has twice the theoretical time delay-bandwidth of a single ring all-pass filter having the same footprint. In place of the computationally intensive 3D finite difference time domain simulations, we applied a combination of coupled-mode theory and a finite-difference-based solution of the full-vector waveguide equation to a 3-dimensional analysis of the problem. Optimization of the structure dimensions remains therefore a tractable problem despite the large degrees of freedom for parameter tuning. Such ring structures can be used in place of the simple ring modulator to further increase the bandwidth or optical interaction length within the resonator using the same area.

We also created a 5-layer technology process suitable for the heterogeneous integration of SiGe active devices and Si passive waveguides. Thanks to a 2-step dry and wet etch method, both Si and SiGe waveguides can be simultaneously created from substrates with blanket-grown SiGe. This allows for the rapid prototyping of photonic devices compared to selectively grown SiGe on substrates since the SiGe deposition is decoupled from the downstream processing. An automated electron beam mask generation procedure was also developed to optimize exposure speeds and resolutions during lithography.

Using the above process, we fabricated a SiGe microphotonic ring modulator and demonstrated for the first time, room temperature C-band electrorefraction in a waveguide-integrated SiGe ring. RF modulation was observed in through port transmission measurements around the optical wavelength of 1550 nm. The modulation mechanisms responsible are attributed to the Franz-Keldysh (FK) electrorefraction and -absorption by means of a novel optical measurement technique capable of detecting minute index shifts even with simultaneous absorption changes and a large background absorption.

Enhancement of direct bandgap emission from Ge ring resonators on silicon-on-insulator was also reported. As a consequence of optical strong confinement, a record high resonator quality factor, *Q* of 620 is obtained that is an order of magnitude higher than that previously characterized for crystalline Ge microcavities. We observe a pump power dependency of *Q* due to bandedge shifts not previously reported for Si- or Ge-based emitters. A decline in the relative peak to baseline intensities with lower *Q*s is attributed to the Purcell effect on account of the wavelength-scale dimensions and high index contrast of our samples. Our experiments suggest that Ge microresonators are promising as integrated light emitters since they are compatible with Si processes and their C-band emission can be easily transmitted along Si waveguides.