博士論文（要約）

Control of Light Emission from Silicon by Using Photonic Crystals

（フォトニック結晶を用いたシリコンの発光制御に関する研究）

A Dissertation

Submitted to the Graduate School of

the University of Tokyo

in Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in Electrical Engineering

中山　茂

Shigeru Nakayama

July 2012

Silicon photonics has attracted much attention as a significant alternative to solve the electrical interconnects bottleneck limiting dense integration of metal wires and delaying signals. Optical interconnection has been already well demonstrated for fiber optics used in long distance communication. As of today, it is opening a way to board to board, chip to chip, furthermore intra chip communication, attracted as the silicon photonics which targets the system into integrated circuits. Various optical devices such as light sources, modulators, waveguides, amplifiers, detectors are desired to be compatible to current mainstream silicon electronics.

Achieving efficient light emission from silicon or other group IV materials has been one of the most challenging issues in silicon photonics. It would realize the optoelectronic circuits with all silicon-based materials and attribute to low manufacturing cost and monolithic integration on complementary metal oxide semiconductor platform. However, the problem is, owing to the material property of indirect bandgap, that crystalline silicon shows quite low emission efficiency. Thus, light sources for silicon photonics applications has focused on the use of III-V direct bandgap material grown or bonded on silicon, silicon related materials such as silicon nanocrystals, doped erbium ions, germanium nanostructures, and nonlinear effects including stimulated Raman scattering.

Research efforts have been devoted into luminescence enhancement of crystalline silicon with photonic nanostructures because of the potential for aforementioned silicon photonics with the light emitting devices compatible with current silicon CMOS technology. One of widely studied structures for improving the light emission properties of silicon is photonic crystal, having periodic modulation of dielectric constant with the period of the order of the wavelength of light. In particular, photonic crystal nanocavities enable the lowest mode volume of the electric and magnetic field among photonic nanostructures such as microdisks and microrings, and attributing to enhancement of spontaneous emission due to Purcell effect. Furthermore, radiation pattern of the emitted photon can be controlled, which resulting in high coupling efficiency to collection lens in the optics system.

This thesis discusses our experimental results of controlling and improving light emission from crystalline silicon with photonic crystals and photonic crystal nanocavities. Advanced nanofabrication technologies, sophisticated optical characterization systems enough to observe low power luminescence and numerical analysis based on the finite difference time domain method were essential in our demonstrations.

Chapter 1 introduces research background of silicon photonics mainly discussing the required light sources, and our objective of this thesis.

Chapter 2 describes basic theory of light emission properties of indirect bandgap materials and photonic crystal structures. First, emission spectra and dynamics of both silicon and germanium are presented. Next, photonic band diagrams and cavity modes are presented. Then, mechanisms of enhancing emission intensity by using the structures are described, including the ways to modify the radiation patterns and to localize light to small footprint space in the material, giving rise to emission rate.

Chapter 3 presents the results of photoluminescence of indirect bandgap materials with photonic crystals. Fabrication of the silicon and germanium photonic crystal and measurement of the photoluminescence from the structures are described. From both of photonic crystals and photonic crystal nanocavities, emission was enhanced. In the former case, the main contribution for the enhancement is improvement in extraction efficiency. On the other hand, increase of internal quantum efficiency is suggested in the case of nanocavities.

In Chapter 4, experimental investigation of photoluminescence from silicon photonic crystal nanocavities with different mode volumes at room temperature are discussed. The integrated cavity mode intensity, which was estimated from the observed photoluminescence signal by considering extraction and collection efficiencies for each cavity mode, increased as the cavity mode volume decreased, which suggests that smaller cavities have larger mode emission efficiency per volume than that for larger cavities at room temperature.

In Chapter 5, demonstration of silicon light emitting diodes with photonic crystal is reported. It shows stronger electroluminescence from them than a non-patterned silicon on insulator LED at room temperature. Enhancement ratio of integrated intensities up to 14 was obtained from photonic crystal on SiO2 LED. Numerical simulations on extraction and collection efficiencies with and without photonic crystal pattern well explained the peak enhancement. Furthermore, air-bridge photonic crystal slab LED was fabricated by removing buried oxide layer and resulted in 134-fold enhancement ratio.

In Chapter 6, successful demonstration of photonic crystal nanocavity silicon LED is reported. The device is composed of a lateral p-i-n junction along the nanobeam, providing electron-hole recombination mainly in a cavity in contrast to photonic crystal cavity LEDs without specific designs of p-, and n-doped areas. The nanobeam photonic crystal cavities exhibit cavity resonant peaks in electroluminescence spectra at room temperature. The peak electroluminescence intensity from the cavity is 80 times stronger than that from a nanobeam LED without patterns. The enhancement factor due to the collection and extraction efficiency is approximately 15. The remaining 5-fold enhancement can be considered as the enhanced internal quantum efficiency. The Purcell effect possibly improves the emission efficiency for the cavity mode.

Finally, Chapter 7 offers conclusions and outlooks for the work in the thesis.