論文の内容の要旨

論文題目:

Compact photonic crystal cavities and microdisk InGaAs LEDs for on-silicon monolithic light sources

シリコン上のモノリシック光源に向けた省面積フォトニック結晶共振器とInGaAs微小ディスクLEDの研究

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ABSTRACT

Large scale systems integrating photonics and electronics at low cost is a future target of the semiconductor industry with potential application areas ranging from single chip gas sensors to sophisticated biological sensors, and to optoelectronic communication systems for distances down to the millimeter scale. Photonics/electronics convergence on a silicon platform is ideal since silicon has low substrate cost, mature processing technologies and dominates the electronics industry. photonic integrated circuits (PIC) implemented in silicon-on-insulator (SOI) is already an established technology with several key advantages such as strong confinement of light and low absorption at near-infrared (NIR) wavelengths useful for optical communication and sensing. However, due to silicon's indirect bandgap nature, silicon is not an efficient light emitter. Thus for truly convergent photonics/electronics systems, it is necessary to realize an efficient light source on silicon. Current solutions entering the market space rely on wafer- and chip-scale bonding of III/V materials onto silicon. These wafers are not homogeneous, bulk III/V material, but require epitaxial growth to realize functional optoelectronic devices such as lasers and photo-detectors. Intuitively, costs can be saved by removing the bulk III/V wafers from the equation and growing III/V material directly on silicon.

Previous works have established the growth of InGaAs microdisks on (111) oriented silicon by micro selective-area growth (μSAG) using metalorganic chemical vapor deposition (MOCVD). These disks have high crystalline quality and are grown with lateral overgrowth to diameters as large as 8 μm and with thicknesses as thin as 200 nm having been demonstrated. This makes these disks ideal for in-plane silicon photonics integration where the device layer is typically on the order of 200 nm to 300 nm. However, previous studies of these disks have focused only on growth with no demonstrations of functional electro-optical components. Due to the disks compact size, their direct band-gap nature and selective area growth, they are excellent candidates for future integration as on-silicon light sources.

In this dissertation, the first opto-electronic devices in the form of proof-of-concept NIR light emitting diodes (LEDs) are demonstrated. By introducing dimethylzinc (DMZn) and hydrogen sulfide (H_2S) into the growth, *p*- and *n*-doped regions can be formed, respectively. Room temperature electroluminescence (EL) is demonstrated from ensembles of 300 to 400 microdisks with *pin* junctions. The luminescence spectra has a maxima at 1.78 µm which is attributed to recombination in the doped regions. A local maxima at 1.65 µm is attributed to recombination in the un-doped region. As a first order approximation, this indicates a indium content of 47 %. The spectrum is broad banded with a full-width at half-maximum (FWHM) of 290 nm. This broadness is attributed to inter- and intra-disk variations in composition. The structure presented here was not optimized and for future applications, it is necessary to perform optimization with regards to reducing FWHM and supressing the long wavelength peak.

In addition to exhibiting EL, the microdisk ensembles were also found to detect infrared (IR) light. Under IR illumination with photon energies smaller than the silicon bandgap, a weak, but reproducible shift in the I-V characteristics indicating the generation of a photo current in the InGaAs disks. Again, further optimization of the growth and the device is required to improve performance.

For the realization of a future, hypothetical InGaAs-on-silicon laser, it is proposed that a cavity is formed using photonic crystals (PhCs). The advantage of using photonic crystal cavitys (PhCCs) is the possibility of high quality factors (Q-factors) and small mode volumes which for laser applications generally reduces the threshold current and improves modulation speed due to both the quantum mechanical Purcell effect as well as a pure reduction of the modal density. PhCCs also allows a high degree of field tailoring allowing a certain flexibility in the design of the mode profile.

However, despite potentially sub-cubic-wavelength mode volumes the total device area is generally large because a large number of PhC lattice periods are required to provide strong confinement. This makes it challenging to realize compact PhCCs. Within constraints determined by the hexagonal shape of the InGaAs-on-Si disks, a novel PhCC is proposed. Since few reports have been published on the challenges of compact PhCCs the problem is here approached in a manner which elucidates the general challenges of compact PhCCs in optically thin slabs. This part of the research is carried out using well established computational methods such as finite-difference time-domain (FDTD) and plane wave expansion method (PWEM) for solving Maxwell's equations.

The cavity design is inspired by line defect heterostructure PhCCs. Such cavities can be optimized using a gentle confinement method where the field at the surface is shaped to have a Gaussian envelope in order to maximize the confinement to the slab by total internal reflection. This methodology has been applied to larger scale PhCCs achieving record high Q-factors on the order of 1×10^9, but here it is shown that the methodology can also be applied to compact cavities with diameters of less than 8 µm. For the case of an air suspended cavity, relatively high Q-factors of 75 100 are achieved. However, a strong dependence on the boundary is identified. A suboptimal boundary thickness between the outermost rows of holes and the surrounding cladding, can reduce the Q-factor by more than a factor of six. It is suggested that the optimum boundary width can be estimated using a simple Fabry-Pérot model. It is believed that this lesson on the importance of boundary optimization is general to all compact PhCCs.

One major advantage of the proposed design and optimization strategy is that the cavity can be designed for a specific resonance wavelength by using the computationally cheap PWEM. Deviation between the design wavelength and the resonance frequency calculated by FDTD was 0.5 %, or 8 nm when scaling the cavity to a C-band resonance wavelength of 1538 nm.

In conclusion, it has been shown that InGaAs-on-silicon disks do have potential as a future on-silicon light source. Although the LED structure was not optimized, clear EL could be observed at room temperature. Furthermore, it has been shown that it is possible to design a sophisticated PhCC within the constraints of the InGaAs microdisk geometry. This open ups the possibility of creating complementary metal-oxide-semiconductor (CMOS) compatible on-silicon lasers with in-plane coupling for advanced applications utilizing monolithic silicon photonics and electronics circuits.