Semiconductor Optical Microcavities for Chip-Based Cavity QED

Thesis by

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To my friends and family

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Abstract

Optical microcavities can be characterized by two key quantities: an effective mode volume V_{eff}, which describes the per photon electric field strength within the cavity, and a quality factor Q, which describes the photon lifetime within the cavity. Cavities with a small V_{eff} and a high Q offer the promise for applications in nonlinear optics, sensing, and cavity quantum electrodynamics (cavity QED). Chip-based devices are particularly appealing, as planar fabrication technology can be used to make optical structures on a semiconductor chip that confine light to wavelength-scale dimensions, thereby creating strong enough electric fields that even a single photon can have an appreciable interaction with matter. When combined with the potential for integration and scalability inherent to microphotonic structures created by planar fabrication techniques, these devices have enormous potential for future generations of experiments in cavity QED and quantum networks.

This thesis is largely focused on the development of ultrasmall V_{eff}, high-Q semiconductor optical microcavities. In particular, we present work that addresses two major topics of relevance when trying to observe coherent quantum interactions within these semiconductor-based systems: (1) the demonstration of low optical losses in a wavelength-scale microcavity, and (2) the development of an efficient optical channel through which the sub-micron-scale optical field in the microcavity can be accessed. The two microcavities of specific interest are planar photonic crystal defect resonators and microdisk resonators.

The first part of this thesis details the development of photonic crystal defect microcavities. A momentum space analysis is used to design structures in graded square and hexagonal lattice photonic crystals that not only sustain high Qs and small V_{eff}s, but are also relatively robust to imperfections. These designs are then implemented in a number of experiments, starting with device fabrication in an InAsP/InGaAsP multi-quantum-well material to create low-threshold lasers with Qs of 1.3×10^4, and followed by fabrication in a silicon-on-insulator system to create passive resonators with Qs as high as 4.0×10^4. In the latter experiments, an optical fiber taper waveguide is used to couple light into and out of the cavities, and we demonstrate its utility as an optical

probe that provides spectral and spatial information about the cavity modes. For a cavity mode with $Q \sim 4 \times 10^4$, we demonstrate mode localization data consistent with $V_{\text{eff}} \sim 0.9(\lambda/n)^3$.

In the second part of this thesis, we describe experiments in a GaAs/AlGaAs material containing self-assembled InAs quantum dots. Small diameter microdisk cavities are fabricated with $Q \sim 3.6 \times 10^5$ and $V_{\text{eff}} \sim 6(\lambda/n)^3$, and with $Q \sim 1.2 \times 10^5$ and $V_{\text{eff}} \sim 2(\lambda/n)^3$. These devices are used to create room-temperature, continuous-wave, optically pumped lasers with thresholds as low as $1\,\mu$W of absorbed pump power. Optical fiber tapers are used to efficiently collect emitted light from the devices, and a laser differential efficiency as high as 16% is demonstrated. Furthermore, these microdisk cavities have the requisite combination of high Q and small V_{eff} to enable strong coupling to a single InAs quantum dot, in that the achievable coupling rate between the quantum dot and a single photon in the cavity is predicted to exceed the decay rates within the system. Quantum master equation simulations of the expected behavior of such fiber-coupled devices are presented, and progress towards such cavity QED experiments is described.

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Acronyms

cQED, or **cavity QED** Cavity quantum electrodynamics

DBR Distributed Bragg reflection

DWELL Epitaxy consisting of a layer of quantum dots embedded in a quantum well (dot-in-a-well)

EL Electroluminescence

FEMLAB Commercial software, written by the Comsol Group, for solving partial differential equations by the finite element method

FDTD Finite-difference time-domain

FSR Free spectral range

ICP-RIE Inductively coupled plasma reactive ion etch

MBE Molecular beam epitaxy

MQW Multi-quantum-well

NA Numerical aperture

OSA Optical spectrum analyzer

PC Photonic crystal

PCWG Photonic crystal waveguide

PECVD Plasma enhanced chemical vapor deposition

PL Photoluminescence

Q Quality factor

QC Quantum cascade

QC-PCSEL Quantum cascade photonic crystal surface-emitting laser

QD Quantum dot

SEM Scanning electron microscope

SOI Silicon-on-insulator

TE Transverse electric polarization, defined in this thesis to have electric field components predominantly in-plane and a magnetic field primarily out-of-plane

TM Transverse magnetic polarization, defined in this thesis to have magnetic field components predominantly in-plane and an electric field primarily out-of-plane

$V_{\mathbf{eff}}$ Effective mode volume

WGM Whispering gallery mode

WG Waveguide