FABRICATION AND CHARACTERIZATION OF QUANTUM-WELL AND QUANTUM-DOT METAL CAVITY SURFACE-EMITTING NANOLASERS

By

Eric Wei

Senior Thesis in Electrical Engineering
University of Illinois at Urbana-Champaign
Advisor: Shun Lien Chuang

May 2013
Abstract

Nanolasers have the advantages of low power consumption and ultrahigh density integration for the next generation intrachip optical interconnects. The ultimate goal is to make millions of semiconductor nanolasers on a single chip to perform the functions of transistor integrated circuits. To maintain the optical energy within a nanocavity, metal is used to enhance the optical confinement down to the wavelength scale of photons. Optical gain is achieved through the use of groups of quantum wells, while quantum dot structures are also explored due to their higher differential gain and lower surface recombination. Our fabricated lasers possess a hybrid distributed Bragg reflector (DBR) silver mirror with an active region consisting of InGaAs quantum wells or submonolayer quantum dots surrounded by a silver cavity with a diameter as small as 1 μm.

The lasers possess a vertical cavity surface emitting laser structure with over 20 pairs of top and bottom DBR. Our microlasers lase at room temperature by electrical injection for a diameter of 4 μm for continuous wave operation and 1 μm for pulsed operation. To shrink down the cavity size, a structure using 4 top and bottom DBR is investigated for light emission through fabricating light emitting diodes with an aperture of over 100 μm. Further design planning and processing needs to be achieved for lasing at room temperature and electrical injection down to 1 μm. These results give promise to the advent of nanolasers for optical interconnects designed for intrachip data communication.

Subject Keywords: semiconductor lasers, nanolasers, plasmonics, nanocavity, vertical cavity surface emitting lasers
Acknowledgments

The author would like to thank Pengfei (Michael) Qiao, Chien-Yao Lu, and Professor Chuang for insight and guidance for the project and the members of Professor Chuang's group, Thomas O'Brien, Ben Kesler, Daniel Zuo, Guanlin Su, and Shu Chen, for deliberations and processing help.
# Contents

1. Introduction ............................................................................................................................................ 1

2. Motivation, Theory, and State of the Art ................................................................................................. 2
   2.1 Theory of Surface Plasmons ............................................................................................................. 2
   2.2 Plasmonic Lasers .............................................................................................................................. 3
      2.2.1 SPASERs .................................................................................................................................... 3
      2.2.2 Metal-cavity Photon Based Lasers .......................................................................................... 4

3. Laser Design and Fabrication .................................................................................................................. 6
   3.1 Laser Design Rules ............................................................................................................................ 6
   3.2 Fabrication of Lasers ......................................................................................................................... 9

4. Experimental Results .................................................................................................................................. 10
   4.1 Experimental Setup ......................................................................................................................... 10
   4.2 Optical Characterization of Lasers .................................................................................................... 10
   4.3 Study on Metal Cavities .................................................................................................................... 11

5. Conclusion and Future Work .................................................................................................................... 14

References ....................................................................................................................................................... 15
1. Introduction
The search has been ongoing for a laser with the smallest cavity achievable, which is half a wavelength in all three directions. Interest towards small cavity lasers has been rampant due to the desire for a laser with small threshold current, low power consumption, and high modulation speeds [1]. Nano-cavity lasers have also been sought out for applications such as inter and intrachip optical interconnects, photonic integrated circuits, and single photon sources. Several different strategies have been pursued in order to scale down the dimensions of the cavity. Beginning from the ruby laser by Maiman [2], edge-emitting semiconductor lasers and microdisk lasers have shrunk the laser cavity to microns in length. The advent of the vertical cavity surface emitting lasers (VCSELs) further reduced the cavity size. The formation of technologies such as photonic crystal lasers have allowed for the cavity size to inch closer towards the size scaling of the wavelength of light. However, reducing the cavity size further down to beyond the wavelength of light introduces a fundamental barrier. When the cavity is reduced below the wavelength of light, high diffraction loss from the small aperture creates the inability for lasing. Thus novel means must be necessary to create lasers on the wavelength scale of light.

Metal has been proposed as a solution to this problem. Utilizing the plasmonic effect at the semiconductor-metal interface, the effective index can be made very large and leads to the confinement of light inside a cavity on the order of a few nanometers. They also allow for good thermal dissipation and contact for electrical injection. The caveat is that metal introduces high absorption loss which must be counteracted with high gain in order to achieve lasing. Several strategies using metal have been experimented to ultimately produce devices working at room temperature and continuous-wave (CW) electrical injection with varying degrees of success. To counteract the significant optical losses, quantum dots can be utilized in the gain region to provide advantages such as high differential gain and reduced surface recombination to minimize the losses within the system and reduce the threshold gain.

This paper will introduce current results and progress for metal-cavity quantum dot and quantum well nanolasers and microlasers. It will also detail the fabrication and characterization of the nanolasers produced with room temperature continuous wave electrical injection operation. Finally, remarks about future progress on the continuing shrinking of cavity size will be made with design considerations.
2. Motivation, Theory, and State of the Art

The motivation for pursuing metal-cavity and plasmonic lasers is to provide means for amplification of optical modes smaller than the diffraction limit of light. Because of the diffraction limit from the small aperture, the cavity volume is limited by half the optical wavelength in all dimensions using traditional dielectric-semiconductor mirrors. This barrier can be surpassed using a cavity surrounded by metal to greatly confine the optical mode. This brings promise to possible electromagnetic radiation for semiconductor lasers at the nanoscale, which may be used in applications such as intrachip optical interconnects, photonic integrated circuits, sensors, bio-medical uses, and ultra-fast spectroscopy [3].

2.1 Theory of Surface Plasmons

Figure 1  (a) Illustration of the surface plasmon electromagnetic wave and surface charge characteristics at the dielectric-metal interface (b) Decay of field within the dielectric and metal regions. Penetration within the metal region is determined by the skin depth (c) Dispersion curve for surface plasmon mode and free space photon, with a gap in momentum seen for the same frequency [4]

The utilization of metal for high optical confinement is derived from the presence of surface plasmon polaritons (SPPs) at the metal-dielectric interface. Surface plasmons are electromagnetic waves propagating along the interface and result from the negative refractive index of metal. They have been extensively studied for over 60 years, but are now gaining attraction due to increase interest in nanoscale devices. Metals, as a conductor, possess free electrons at the surface which couple with an electromagnetic wave at the interface to produce surface plasmon polaritons (SPPs). This creates a resonance interaction and local enhancement of the field component perpendicular to the interface. This coupling between the surface charge and electromagnetic field produces a SP dispersion relation shown below [5]

\[ k_{sp} = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} \]  \hspace{1cm} (2.1)
where $\varepsilon_m$ is the permittivity of the metal and $\varepsilon_d$ is the permittivity of the dielectric. For the formation of a surface plasmon, the two permittivities must have opposite signs. Since metals behave as plasmas at optical frequencies, they possess a negative and complex permittivity. This causes a momentum mismatch between light and surface plasmons at the boundary and requires mechanisms to provide this missing momentum, such as surface scattering, for coupling into the plasmon mode.

### 2.2 Plasmonic Lasers

Metal cavity resonators, due to the negative index for metal, possess high dissipative loss and thus small quality factors, typically less than 100, compared to typical laser resonators. Thus, emphasis is placed on the gain medium and pump mechanism. With a mode volume below the diffraction limit, a gain coefficient up to $10^5 \text{ cm}^{-1}$ may be required to compensate. Thus not only does the gain medium need to be robust, but the design of the cavity must be able to direct most of the initial spontaneous emission into the designated laser mode. This also causes the linewidth of the laser spectrum to be larger than that of conventional lasers. These challenges require creative design of the cavity in order to produce lasing of the surface plasmon mode, or a spaser.

#### 2.2.1 SPASERS

While the effects of SPs have been known for decades, it was only recently proposed to couple energy into the surface plasmons through lasing and generate a coherent light scale for focusing of optical energy beyond the diffraction limit of light [3]. The idea of a spaser, or surface plasmon amplification by stimulated emission radiation, was to be analogous to a laser in which instead of emitting photons, coupling into the surface plasmon mode could generate a coherent light field within a cavity at the nano-scale. This phenomena has been utilized to create nano-cavity plasmonic lasers.

The notion of plasmonic lasers have shown to be experimentally viable. However, it is currently unclear what criteria can be used to identify a plasmonic laser, and thus a clear delineation must be made to what constitutes a spaser [6]. Spasers, like conventional lasers, possess a gain medium, a resonator, and a pump, but provide feedback for SPP modes instead of optical modes. Lasing occurs above a pump threshold and can be seen from spectral narrowing and increased coherence for the output. However, plasmonic structures have the ability to modify the gain spectrum for spontaneous emission and thus the spectral narrowing may be incorrectly interpreted as lasing. When "spasing," mode competition occurs for the different SPP modes and allows for the distinguishing of stimulated emission amplification. Radiation occurs in the form of surface plasmons, which like photons are bosons, and can be confined at the nanoscale. The energy of the electric field can be quantized for the surface plasmon
system and the transitions can be formulated along with a net stimulated emission of surface plasmons can be derived [7].

<table>
<thead>
<tr>
<th>Structure</th>
<th>Metal Ridge</th>
<th>Nanoparticle</th>
<th>Nanosquare</th>
<th>Coaxial Laser</th>
<th>Nanofilm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension/Mode</td>
<td>0.42 (\lambda^3)</td>
<td>44 nm diameter</td>
<td>(\sim 0.05 \lambda^3)</td>
<td>500 nm diameter</td>
<td>(\sim 0.03 \lambda^3)</td>
</tr>
<tr>
<td>Volume</td>
<td>1418 nm</td>
<td>525 nm</td>
<td>508.4 nm</td>
<td>(\sim 1500) nm</td>
<td>510 nm</td>
</tr>
<tr>
<td>(\lambda_{nm})</td>
<td>200 - 10 K</td>
<td>14.8</td>
<td>97</td>
<td>120 - 4.5 K</td>
<td>13</td>
</tr>
<tr>
<td>Cavity Q</td>
<td>140 - 77 K</td>
<td>53 - 295 K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>CW Electrical</td>
<td>Optical at 488 nm</td>
<td>CW Electrical</td>
<td>Optical at 1064 nm</td>
<td>Optical at 405 nm</td>
</tr>
</tbody>
</table>

Figure 2  Summary of key parameters for different plasmonic laser designs. We include a comparison of cavity volume, resonant wavelength, cavity quality factor, and pump mechanism [8-12].

Several design methods for plasmonic lasers have been realized to produce nanocavities. From the first instance of using metal-insulator-metal waveguide as a means for optical confinement [8], several different cavity configurations have been designed to ensure optimal gain to overcome the large absorption losses associated with metal. More recently, a nanofilm structure has been utilized consisting of a GaN nanorrod shell and an InGaN core for its gain medium between atomically smooth silver films that are epitaxially grown [12]. The InGaN, which emits in the green, is chosen due to its high gain and a thin silicon dioxide layer is also added to confine the electromagnetic field in the oxide gap which reduces the absorption loss from silver. Using optical pumping at 78 K, two lasing peaks can be seen spectrally at 510 and 522 nm, and the threshold is found to be at 2.1 and 3.7 kW/cm² for 8 K and 78 K respectively. Utilizing an atomically smooth silver allows for a reduction in losses, but lasing ceases for temperatures above 130 K. Through emission from coupling with the surface plasmons at the semiconductor metal interface, the use of metal provides the necessary avenue to produce lasers at the nanoscale.

2.2.2 Metal-cavity Photon Based Lasers
While using metal as a means to couple into surface plasmon modes provides a novel avenue to creating nanoemitters, metal has been used in laser and nanocavities since the very beginning. The first ruby
laser by Maiman utilized silver coatings to increase the mirror reflectivity for sufficient lasing [2]. Lasing in metal nanocavities was first produced by using a pillar encapsulated in gold [13]. Despite being optically lossy, a cavity surrounded fully by metal exhibits good thermal dissipation necessary for room temperature operation as well as shortening the photon lifetime in the cavity to produce higher modulation speeds [3]. Metal also provides a natural contact for electrical injection of carriers as well as preventing crosstalk between devices for dense integration on-chip. Photon based lasers using metal cavities have already exhibited lasing at room temperature and electrical injection. However, more work must be done to minimize the cavity size, reduce the threshold current, and improve the mode shape for waveguide coupling. The lasers introduced in this paper have been fashioned with these factors in mind and work towards an ultimate solution to create working lasers suitable for inter- and intrachip optical interconnects.
3. Laser Design and Fabrication
The proposed devices are air post VCSELs surrounded by silver. Figure 3 illustrates the strategy for reducing the cavity size vertically. The prominent first device structures use over twenty top and bottom distributed Bragg reflector (DBR) pairs of alternating GaAs/AlGaAs to act as high reflectivity mirrors to achieve sufficient feedback into the cavity. The most recent designs possess just 4 pairs of top and bottom DBR along with top covered silver to form a hybrid DBR/metal reflector. For each generation of devices, an active region sandwiched of either groups of multiple quantum wells (MWQ) or submonolayer quantum dots (SML QD) are explored. The advantages of this design include the flexibility for substrate removal and wafer bonding onto and a circular beam shape for optimal coupling.

![Image](image.png)

Figure 3 (a) Design for thick top and bottom DBR device (b) Design for hybrid DBR/metal mirror device (c) Design for DBR-free device [14]

3.1 Laser Design Rules
The structures are grown using metal organic vapor phase epitaxy (MOVPE) and each layer of material, including the DBR, active region, etch stop, and metal, must have the thickness tuned to ensure the roundtrip phase is preserved for the designed wavelength of the cavity. To confirm the resonant wavelength for the layer structure, the transfer matrix method [5] was used to model the roundtrip phase condition and DBR reflectivity as well as to plot the electric field standing wave pattern for the electric field. To ensure constructive interference for a roundtrip, the resonant wavelength must satisfy

\[\Phi_{p-DBR} + 2k_0n_{AR}d_{AR} + \Phi_{n-DBR} = 2m\pi\]  \hspace{1cm} (3.1)

which accounts for the phase shift of the propagating wave through the top and bottom DBR as well as the active region.
The transfer matrix method analyzes the propagation of the wave as it traverses through each layer. Using the model shown in Equation (3.2) and placing the necessary parameters for the refractive index and layer thickness, the phase through the top DBR, bottom DBR, and active region can be modeled for engineered thicknesses at the resonant design wavelength. Figure 5 confirms that using the design wavelength of 985 nm for the thin DBR cavity, the total phase is found to be zero which allows for the sustainment of the mode at that wavelength.

\[
\begin{pmatrix}
E_0 \\
T E_0
\end{pmatrix}
= B_{01} B_{12} B_{23} \ldots B_{(N-1)N} B_{Nt}
= \begin{pmatrix}
b_{11} & b_{12} \\
b_{21} & b_{22}
\end{pmatrix}
= \begin{pmatrix}t E_0 \\
0
\end{pmatrix}
\]  

(3.2)

Figure 4  Modeling of transfer matrix method as a means to measure transmission and reflection over a series of layers.
Aside from the phase condition, another important parameter to consider for the design of the laser is the threshold gain condition. For a VCSEL, the threshold gain is described by Equation 3.3, which accounts for the optical absorption loss and diffraction loss due to the mode mismatch while propagating at the mirrors. Due to the short active region length, a large reflectivity is required to minimize the threshold gain required for lasing. For devices with a thick DBR (over 20 pairs), a reflectivity of over 99.9% can be achieved. For devices with a few DBR pairs, a top metal reflector must be used to increase the reflectivity. Figure 6 shows the reflectivity of the hybrid metal DBR mirror, which shows comparable reflectivity with a system with many more DBR pairs.

Figure 5  Measure of the phase through the top DBR, bottom DBR, and active region as well as total phase using the transfer matrix method

$$\Gamma g = \alpha + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right)$$  \hspace{1cm} (3.3)

Figure 6  Reflection spectrum of hybrid DBR/silver mirror.
3.2 Fabrication of Lasers

The fabrication process for the nanolasers involve microelectronic fabrication techniques. The fabricated lasers were created in the cleanroom in the Micro and Nanotechnology Laboratory at the University of Illinois. Figure 7 describes the major steps required for forming the airpost VCSELs. First, silicon nitride is deposited on the layer structure using plasma enhanced chemical vapor deposition (PECVD) and the mask is patterned using Freon reactive ion etching (RIE). The GaAs system materials are then etched through using inductively coupled plasma (ICP) RIE to form the air posts. Next, a layer of thin silicon nitride is deposited to act as insulation for the top contact as well as passivating the side walls. Finally silver is deposited to form the metal cavity and top contact. The devices can then be measured, and the substrate is free to be removed and transferred to a substrate of choice using flip chip bonding.

As with the production of many nanoscale structures, there are several obstacles that must be considered during the fabrication process. The use of metal warrants the danger of short circuiting the device if the top contact becomes electrically connected to the bottom DBR. Thus the cleanliness of the device surface as well as etching chambers must be prioritized to ensure unwanted residue and structures are not formed on or near the device.

Figure 7  Summary of steps for fabrication of nanolasers.

Figure 8  SEM of 10 μm device after ICP-RIE etch through top DBR into active region (left). Device pads after wet etch through bottom DBR to separate device mesas (right).
4. Experimental Results
Once the fabrication of the lasers is complete, the optical and electrical properties of the lasers are then characterized for validation of operation at room temperature and CW electrical injection. Experimental results are shown for several quantum-well and quantum-dot laser designs. A brief study is then issued to determine the thermal effects for metal-coated cavities.

4.1 Experimental Setup

![Experimental setup for characterization of fabricated nanolasers.](image)

The lasers are characterized using a probe setup designed for temperature controlled measurements at room temperature as well as CW and pulsed current injection. A pair of probes are set onto the p-contact and n-contact to enable forward biasing of the p-n junction and the injection of current through a current source. The source can be set for both pulsed measurements with varying pulse width and duty cycle as well as CW electrical injection. For measurement of light output, a germanium detector is used for detecting light in the infrared regime at around 980 nm. For spectrum measurements, the output is coupled into a multimode fiber instead. A thermoelectric cooler (TEC) is utilized to maintain room temperature and curtail effects from junction heating. The data is collected through the use of a LabVIEW program that controls the current source and TEC through the computer. The current signal and the detected light can be then fed into a lock-in amplifier, and the LabVIEW program then records the output signal.

4.2 Optical Characterization of Lasers
The initial check for light emission is accomplished by measuring the light output for a given injected current, or the LI curve, for each fabricated device. Through these measurements, light emission at room temperature was achieved for quantum-dot metal-coated devices down to 1 μm at room temperature CW electrical injection. Thus at the very least, the devices created can function as light emitting diodes (LEDs) for room temperature operation. To check for lasing, the LI curve can be studied...
to display a clear threshold behavior for the transmission from spontaneous to stimulated emission characteristic for lasing.

Figure 10 shows the light output of lasers for fabricated thick DBR quantum-dot lasers measured at 293 K and CW electrical injection. For the smallest lasing device with a diameter of 4 μm, a threshold current of 1.6 mA and peak power of 38 μW is seen. Thermal rollover resulting from the off resonance of the cavity mode and gain peak is also witnessed from the decreasing light output. Another indication of lasing is the shortening of the broad spectral output of spontaneous emission to the sharp spectral characteristic of stimulated emission due to the photons having the same phase, energy, and polarization. Figure 10 displays the spectrum of a 2 μm thick DBR quantum-dot laser under pulsed injection at room temperature. The device exhibits a peak wavelength of 968 nm. These results confirm lasing for the fabricated devices under the specified conditions.

![Figure 10](image)

**Figure 10** LI for thick DBR quantum-dot lasers for varying diameters (left). Lasing spectrum for a 2 μm device taken at room temperature under pulsed injection (right).

### 4.3 Study on Metal Cavities

The notion of gain is critical for lasers with miniature plasmonic cavities. A motivation for the reduction of the cavity size is the decrease or elimination of the threshold current that allows for operation of lasers at lower power and a smaller footprint. However, the threshold current can increase at lower cavity size due to increased loss from junction heating and increased absorption loss into the metal region. These factors necessitate a robust laser design with consideration for the configuration of the active region.
Figure 11  Threshold current density for various cavity designs for quantum dot lasers.

Figure 11 displays the threshold current density for devices with three groups of quantum dots (DO-986) and four groups of quantum dots (DO-984) in the active region. Quantum dots have been preferred over quantum wells for better gain and temperature stability. Using four groups of quantum dots in the active region provides larger overlap of the standing wave with the gain region and provides increased gain. To confirm this notion, the fabricated lasers for both designs are measured to ascertain the threshold current and provide insight on the threshold current density. The threshold current density increases due to the increasing loss factors, but the larger gain from the four groups successfully exhibits a reduction in the threshold current density. By tailoring the active region, the threshold current can be minimized for lasing at room temperature for decreasing cavity size.

Figure 12  Time response of laser output for injected current for a metal-coated and BCB-coated cavity.

The use of metal has continuously been a point of contention due to the high optical losses associated with plasmonic cavities. However, metal possesses good thermal qualities that can be beneficial to smaller cavities that are riddled with an exorbitant amount of junction heating. This can be shown in
Figure 12, where a metal-coated cavity is compared to a cavity surrounded by Benzocyclobutene (BCB), a polymer-based dielectric used in microprocessing. The comparison reveals that the rise time of the laser output, which is determined by the detuning of the resonant mode to the gain bandwidth, for the modulated input current signal is shorter for the metal cavity due to dissipation of heat. Not only does this allow for optical confinement for room temperature operation, but potential increased modulation speeds that will be beneficial for high speed, high bandwidth applications for future interconnect applications.
5. Conclusion and Future Work
Figure 3 has outlined the plan from going from thick DBR devices down to an ultimate DBR-free structure. Ongoing efforts have been made with producing thin DBR devices with 4 pairs of top and bottom DBR with the starting of producing large VCSEL pads as shown in Figure 13. From these results, the wafers are confirmed for light emission and thus the next step is to produce light emission from the nanolaser structures. From measurements of a multitude of devices, it can be shown from the burn marks that the current may not be entering from the center device pillar, but from the surrounding regions that formed due to the nanopillars from processing. This can be improved in future processing generations from dismantling and cleaning the chamber prior to etching the top DBR which will eliminate the formation of nanopillars and increase the likelihood of light emission from the small VCSEL patterns.

Figure 13  Procedure for creating the large VCSEL pads to check for wafer quality shown (top). Resulting LIV measurements confirm light emission for the VCSEL structures (bottom left). Spectrum confirms spontaneous emission (bottom right).

Nanolasers have great potential for applications in communications and computing. We have shown operational lasers at room temperature for device diameters as low as 4 um for CW electrical injection and 1 um for pulsed operation. These results provide greater insight on producing working metal-cavity nanolasers for quantum well and quantum dot structures.
References


