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Record performance of electrical injection sub-wavelength metallic-cavity semiconductor lasers at room temperature

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Abstract: We demonstrate a continuous wave (CW) sub-wavelength metallic-cavity semiconductor laser with electrical injection at room temperature (RT). Our metal-cavity laser with a cavity volume of 0.67 $\lambda^3$ ($\lambda = 1591$ nm) shows a linewidth of 0.5 nm at RT, which corresponds to a Q-value of 3182 compared to 235 of the cavity Q, the highest Q under lasing condition for RT CW operation of any sub-wavelength metallic-cavity laser. Such record performance provides convincing evidences of the feasibility of RT CW sub-wavelength metallic-cavity lasers, thus opening a wide range of practical possibilities of novel nanophotonic devices based on metal-semiconductor structures.

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Truly nanoscale coherent light sources [1] with sub-wavelength (wavelength in vacuum) dimensions are of great importance in both fundamental science and future technological applications. Plasmonic sub-wavelength scale lasers or spasers [2] represent the ultimate verification and utilization of the fundamental understanding of nanoscale physics processes involving the interactions of plasmons in metals or heavily doped semiconductors, excitons and electron-hole pairs in semiconductors, and photons confined in a cavity. Such nanolasers will potentially lead to large scale integration of photonic and electronic functionalities, thus enabling unprecedented capabilities in a wide range of future technologies from computing and communication to sensing and detection. Recent years have witnessed a rapid progress in nanoscale lasers since the proposal of spasers [2] and of the semiconductor-metal core-shell laser architecture [3], which was soon demonstrated with a top-down approach under electrical injection [4]. This paradigm shift in laser development represented by the use of metallic cavities operating in visible and near infrared wavelength ranges for reducing the device size down to the sub-wavelength scale, has since been further solidified with a myriad
of designs and variations [5–18]. Many of metallic-cavity lasers, especially the recently demonstrated electrical injection plasmonic lasers with 90-nm wide semiconductor cores [10], have characteristic dimensions already comparable to state-of-the-art transistors. Despite great success and various breakthroughs, the holy grail of this endeavor has remained out of reach, which is to achieve RT, CW operation of a sub-wavelength metallic-cavity laser under electrical injection. While various aspects of this ultimate goal have been demonstrated, the simultaneous achievement of all these attributes would have far-reaching consequences. While optically and electrically pumped pulse operation at RT has been demonstrated, CW operation under electrical injection is fundamentally different due to exacerbated heat generation. This is also true, even for other pure dielectric sub-wavelength lasers. Sub-wavelength microdisk lasers have been demonstrated at RT, but in pulse mode in visible [19] and near infrared [13] wavelength ranges. But CW operation [20] is still limited to low temperature. Therefore an unambiguous demonstration of a RT CW nanolaser with electrical injection represents a significant advance in the development of nanoscale lasers. While our recent work [21] has demonstrated CW operation under electrical injection with linewidth as broad as 3–4 nm, this progress itself raised new questions: Would such sub-wavelength metallic-cavity lasers ever be able to show features of light output similar to a typical semiconductor laser with the expected narrow linewidth, among others. This issue becomes especially important, since a few other reported metallic-cavity lasers [7, 18] showed even broader linewidth under RT CW operation and most of the proposed applications of nanolasers such as on chip sensing and communication require narrow linewidth [22, 23].

Most importantly, the smooth and gradual transition near threshold in that demonstration also leads one to wonder: Is this smooth transition an intrinsic feature of such lasers due to large spontaneous emission factor associated with their small sizes and metallic cavities, or because of the non-ideal performance of a device incapable of operating far above threshold due to significant heating? All these questions are related to the fundamental features of such nanolasers and will ultimately determine the extent of all the potential applications of such lasers mentioned above.

In this paper, we intend to address all these questions by demonstrating a new generation of sub-wavelength lasers with record performance. As we will show, sub-wavelength metallic-cavity lasers (Fig. 1) are capable of showing similar features of a typical laser, such as narrow linewidth and well-defined threshold, but with a cavity volume as small as 0.67 \( \lambda^3 \) (\( \lambda = 1591 \) nm). The linewidth of our lasers is reduced by a factor of 13 from below to above threshold, with transition behavior similar to that of a typical semiconductor laser. To have a fair comparison of linewidth of lasers operating at different wavelengths, the concept of lasing Q-factor \( Q = \lambda / \Delta \lambda \) [24](identical to the total Q [25] or observed Q [26] including all losses and gain) can be used a good measure of improvement of a laser mode above threshold from below threshold (cavity Q). Our Q-factor of 3182 under lasing condition is the highest reported of any sub-wavelength metallic-cavity laser under RT CW operation. Such Q-value is comparable to or better than most pulse operation metallic-cavity lasers at RT. We believe that this work can finally clear the doubts and concerns about the feasibility of CW RT operation of metallic-cavity lasers with sub-wavelength sizes, and paves the way for eventual applications of such lasers.

The structure of our sub-wavelength metallic-cavity lasers shown in Fig. 1 is similar to those in our previous publication [21]. It consists of an InP/InGaAs/InP rectangular core and a SiN insulating layer, encapsulated in a silver shell. More details of the structure can be found in Ref. 21. Our main focus here is to optimize the device design through adjusting SiN thickness and to refine the entire fabrication process. Realizing sub-wavelength metallic-cavity lasers that could operate significantly above threshold under CW RT condition poses significant challenges. The large loss in a metallic cavity leads to an intrinsic high threshold. The small device size requires extremely precise fabrication. Even small fabrication imperfection would mean a large relative error and thus makes the already high threshold unattainable or device could barely operate above threshold. During the fabrication of this new generation of device, extensive efforts were made to optimize the fabrication process to
minimize such imperfections and to fabricate devices close to ideal situations. Instead of PMMA as in our previous fabrications, we employed hydrogen silsesquioxane (HSQ) as resist in electron beam lithography (EBL) process to reduce the pattern edge roughness to within 2 nm [27], much smoother than those obtained using PMMA. Another important factor affecting device performance is the tilting of the sidewall of semiconductor pillar, which leads to severe radiation loss of the cavity [28]. To reduce such loss, we optimized the pillar dry etching parameters to restrict the sidewall tilting angle within 1 degree. One of the most significant fabrication challenges is to achieve near single-crystal silver quality. Our optimized deposition and post annealing process eventually led to silver with grain size up to 1 µm, comparable with the device feature size, as can be seen in Fig. 1(c). This will result in significantly reduced metal loss [29]. Given the large surface-to-volume ratio and presence of several interfaces, it is critically important to achieve high surface quality with low surface recombination. We performed more thorough surface treatment involving a combination of oxygen plasma and dilute phosphoric acid processes to reduce surface recombination. Finally, SiN thickness is a critical design optimization parameter. Though using thicker dielectric layer to reduce metal loss and improve the Q factor of a metallic cavity has been demonstrated [8], we did observe severe degradation of device performance in our own lasers with thick SiN (120 nm) due to insufficient heat dissipation and high surface recombination [30]. In this new generation of devices, we slightly increased the SiN thickness from 20 nm to 30 nm which led to an increase of cavity Q factor from 372 to 428. The improved device performance proved that this SiN thickness is a better trade off among metal loss, surface quality, and heat dissipation.

Fig. 1. Structure of the sub-wavelength metallic-cavity semiconductor laser. (a) Semiconductor pillar with a rectangular cross section is encapsulated in silver to form a metallic cavity. (b) Scanning electron microscope (SEM) image of the semiconductor core. (c) SEM image of the pillar after coating SiN and silver. Scale bars in (b) and (c) are both 1 µm.

Devices were mounted to a heat sink which also formed a p-contact and were forward biased by a DC voltage source. Measurement was conducted at 294 K. Emission from the backside of the substrate was collected by an objective lens and detected by a spectrometer equipped with a liquid nitrogen cooled InGaAs array detector. The light output versus current (L-I curve) for a device with optical cavity dimensions (including the SiN layer) of 1.15 (W) × 1.39 (L) × 1.7 (H) µm³ = 0.67 λ³ (λ = 1591 nm) is shown in Fig. 2(a). The L-I curve shows a clear turn-on threshold around 1.1 mA. Above the threshold, the integrated lasing mode intensity increases linearly with injection current. The integrated spontaneous emission intensity initially increases faster than the lasing mode intensity but shows a gradual clamping trend afterwards, giving way to the lasing mode. Well below threshold and close to transparency, the full width at half maximum (FWHM) of the lasing peak is 6.8 nm, corresponding to a cavity quality factor of 235. The FWHM shows a rapid decrease with increasing current and further drops to 0.5 nm at 2.02 mA as shown in the inset of Fig. 2(b). Such intensity and linewidth behavior is typical of a laser transition from below to above...
threshold as pumping current increases. As shown in Fig. 2(b), the threshold behavior is accompanied by a significant blue shift of the laser wavelength from 1601 nm (well below threshold) to 1591 nm (above threshold) due to the band filling effect. Result from the polarization resolved measurement (Fig. 2(c)) shows that the far field emission measured directly normal to the substrate is predominantly linearly polarized along the length direction (Z direction) of the cavity. We were able to drive the device to about twice of its threshold but not higher, due to overheating. The dielectric breakdown of thin SiN layer at high voltage (~5-6 V) is another constraint.

![Fig. 2. CW characteristics at 294K. (a) Light intensity (■: lasing mode and ●: spontaneous emission) and linewidth under DC bias. (b) Spectra (offset for clarity) at different currents with a zoom-in shown in inset at 2.02 mA with a resolution of 0.2 nm. (c) Laser intensity vs. polarizer angle with Z-direction at 180 degree.](image)

Optical mode properties in this device were investigated through three-dimensional finite-difference time-domain (FDTD) simulations. A mode (E_{106}, corresponding to 1, 0 and 6 E-field nodes in x, y, and z direction of the cavity) with Q-factor of 428 is identified as the lasing mode. Using the surface equivalence theorem [31], the far field radiation in the direction normal to the substrate for this mode is calculated and shows linear polarization along the Z direction, which matches the polarization measurement results. The effective mode volume is estimated to be $V_{\text{eff}} = 10.29(\lambda/2n_{\text{eff}})^3$, and the confinement factor is 0.645. The mode profile is shown in Fig. 3(a). The Q-factor from experiment is significantly lower than in the simulation, and the difference is likely due to the imperfections of the fabrication, such as deviation of the EBL pattern from a perfect rectangle, non-vertical cavity sidewalls.

To understand the lasing behavior, the experimental results were fitted to the rate equations (REs) described in Ref. 32. By RE fitting and separate calculation of Purcell factor [33] for our laser structure (with a value of 13.88), we determined a Purcell enhanced spontaneous emission factor, $\beta$, of 0.048. Figure 3(b) shows the L-I curve on a log-log scale, where we also indicated different slopes (S) in the three regions of pumping, representing the evolution of device output from spontaneous emission to threshold transition and eventually above-threshold lasing. Due to the change of slopes around threshold in the log-log scale L-I curve, it is interesting to plot the slope as function of pumping current. As expected, a peak is observed on such a plot (Fig. 3(b), right Y axis). Since this peak represents the most dramatic transition of the laser behavior from amplified spontaneous emission to lasing, we think it is a good measure of laser threshold and can be extracted from the experimental L-I measurement directly. Below the threshold transition region, we observed a slope of 2 in the log-log scale L-I curve. Well below threshold, the lasing mode emission is dominated by spontaneous emission and a linear scaling is expected if current is also dominated by spontaneous emission. The $S = 2$ scaling below threshold indicates that the current contains significant contributions from non-radiative recombination such as surface recombination and Shockley-Read-Hall (SRH) process. In such a sub-wavelength device, we estimate the surface recombination lifetime is on the order of nanoseconds. Typical bulk SRH recombination lifetime in metal organic chemical vapor deposition (MOCVD) grown high quality intrinsic III-V semiconductors is hundreds of nanoseconds [34], so SRH process is negligible compared to surface recombination and therefore ignored in our rate equation analysis.
surface recombination velocity (SRV) of $5 \times 10^4$ cm/s is obtained through RE fitting. This value is lower than typical SRV of InGaAs structures produced by dry etching processes which is $1\sim 2 \times 10^5$ cm/s [34, 35], and approaches the lowest value reported to our knowledge [36].

![Fig. 3. (a) $|E|^2$ patterns of $E_{106}$ mode in various planes. (b) L-I curve on a log-log scale (red circle $\bullet$ from measurement and solid line from RE calculation) with slopes (S) given for three regions. Right Y axis: slopes of log-log LI curve (black diamond $\diamond$ from measurement and solid lines from RE calculation, from top to bottom for $\beta = 0.01, 0.048, 0.132$, respectively).](image)

In summary, we demonstrated record performance of a RT CW sub-wavelength metallic-cavity semiconductor laser, comparable to conventional semiconductor lasers, thus achieving a long sought goal in such lasers. The linewidth is almost an order of magnitude narrower than the previously reported value [21], and the Q value under lasing condition is comparable to some of the best previous RT lasing demonstrations with pulse optical pumping [6, 8, 9]. We believe that this more convincing demonstration is critical in many respects. This demonstration proves that such sub-wavelength metallic-cavity lasers are capable of RT operation with similar characteristic performance to a conventional semiconductor laser. Overcompensating metal loss at RT by semiconductor gain also has a profound impact on other active plasmonic devices and metamaterial structures, especially under CW electrical injection. Overcoming major technical challenges in the fabrication of sub-wavelength devices represents a significant advance in micro/nanofabrication. In terms of technological applications, RT CW electrical injection operation represents a key milestone for the practical implementation of such devices as one key component of future nanophotonic systems. Currently, the lifetime of our laser is still limited at RT, possibly due to degradation of the surface quality of InGaAs under the large injection current at RT. Improved processing techniques for better surface passivation or new device designs, for example using quantum wells as the active medium to lower the threshold current, are possible solutions for such problem. We believe that, with further advances in processing techniques and device designs, fully developed metallic nanolasers suitable for practical applications will be realized in the near future, thus opening new vistas for nanophotonic applications.

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