Semiconductor Plasmonic Nanolasers

(Invited Paper)

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Abstract **We present recent results on modeling, fabrication, and characterization of semiconductor nanolasers based on semiconductor-metal core-shell waveguides. In particular, results of lasers with a sub-diffraction-limit thickness will be presented under electrical injection.**

I INTRODUCTION

Future photonic or optoelectronic integrated circuits for computing, sensing, imaging, and other applications require on-chip light sources or waveguides that have sizes compatible with electronics or in sub-wavelength regime. All-dielectric or semiconductor waveguides are incapable of such significant size reduction and are eventually limited by the diffraction limit. Metallic structures are known to allow wave confinement to a much smaller spatial scale. Thus hybrid metal-dielectric or metal-semiconductor structures provide not only an interesting solution, but practically the only feasible solution for achieving lasers or other active photonic devices with size significantly smaller than the wavelength involved.

Metallic waveguides have been used as laser cavities in mid or far infrared, where the metal loss is relatively small and can be overcome by optical gain provided by semiconductors. But it is far less clear if such cavities can be used for the near infrared and shorter wavelengths, where significant excitation of surface and bulk plasmons is involved. As a result, optical loss in metals becomes a few orders of magnitude higher than for mid- and far-infrared. It is therefore necessary to study both theoretically and experimentally the interplay between the plasmonic loss and semiconductor gain near and around plasmonic resonances.

In this paper, we will first present our theoretical and modeling results on semiconductor-core metal-shell waveguides [1-4] and demonstrate how enough modal gain can be achieved to reach laser threshold, despite significant metal loss. Some unconventional features of modal gain and confinement factor in a metallic waveguide will be presented. We will then present our recent results on fabrication and experimental characterization of core-shell nanolasers [4-6]. Our results include lasing demonstration for a rectangular pillar structure with a thickness of semiconductor core as thin as 90 nm and room temperature demonstration of lasing for a 300 nm pillar core.

II THEORETICAL RESULT

We have studied several issues recently theoretically. The first one is the possibility of overcoming metal loss by semiconductor gain using an example of semiconductor-metal core-shell structure [1]. While the compensation of metal loss by gain material was studied at 1.5 micron wavelength previously, the shorter wavelengths were not considered for propagating surface plasmon polariton (SPP) wave, especially near the SPP resonance. Our recent study showed several interesting features. The first is the possibility of a net gain near the cut-off frequencies of various modes [1] at sufficiently high levels of material gain in semiconductors. The material gain required is relatively high, near the upper limit of what is achievable with high quality III-V semiconductors, around 6000 cm^{-1} at room temperature. At this level of material gain, the net modal gain near the SPP resonance remains negative. With the further increase of material gain to the level of 8000 cm^{-1}, the net gain becomes positive near the SPP resonance [3]. The required material gain is too high for many semiconductors, but is achievable for some wide gap II-VI semiconductors and for nitrides. The required material gain can be significantly reduced at lower temperature, where material gain of semiconductor is higher, while the metal loss is much lower. A somewhat surprising realization [4] is that the resulting net modal gain is not only positive, it is huge, a few orders of magnitude larger than the material gain, once the loss is over compensated. The order-of-magnitude larger modal gain than material gain indicates that the confinement factor (which is the ratio of modal gain to the material gain) is a much larger than unity [4]. This peculiar feature is one of several counter-intuitive characteristics of a plasmonic waveguide near SPP resonance. All of these unique features will be discussed in detail in the talk and a more tutorial discussion is given recently in Ref. [3].

III EXPERIMENTAL RESULT

The first experimental demonstration of lasing in a structure similar to what has been simulated [1] was performed by Hill

et al [5] in the infrared wavelength regime. While the effects of surface plasmons were not completely clear there, this first experiment did demonstrate that the metal loss can be sufficiently overcome by a standard gain structure to exceed the laser threshold. This was the laser demonstration using a metallic cavity with the shortest wavelength. Subsequent experiment [6] showed that a substantially smaller laser can be made than the diffraction limit of half-medium wavelength and the surface plasmons play a non-trivial role in the realization of lasers. This was the first experimental demonstration of any metallic structure laser with deep sub-wavelength size due to the substantial involvement of surface plasmons. Fig. 1 shows one example of basic laser behavior where the thickness of the semiconductor core is only 90 nm. The optical thickness of this device (semiconductor core and dielectric isolation layers) is around 360 nm. This should be compared with the half-wavelength (or diffraction limit) in this case, which is 670 nm. Obviously there is also a finite penetration of the field into the metal (silver) layers on either side of the dielectric medium (SiN). But the penetration depth and the index of refraction of the silver at 1.5 micron are sufficiently small so that the contribution to the overall optical thickness remains small.
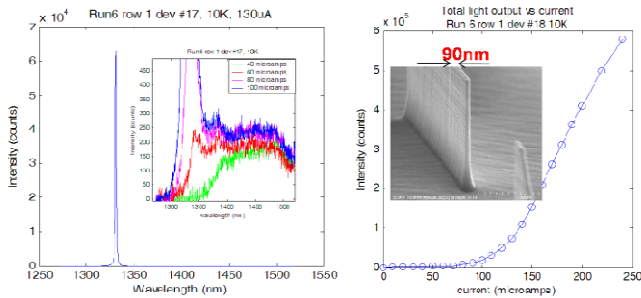

Figure 1 Power spectrum of the laser output (left panel) with inset showing an enlarged view near the laser line for several pumping levels and L-I curve (right panel) with inset showing the scanning electron micrograph of the semiconductor pillar of 90 nm in thickness. (see Ref. [6] for details).

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