Electrically pumped gap-plasmon mode semiconductor core lasers

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ABSTRACT

We will examine progress in electrically pumped Metal-Insulator-Metal (MIM) waveguide laser devices. Such structures allow the concentration of both electrically injected carriers and the optical mode into a gain region of just a couple of tens of nanometers in size in two dimensions. We will show results from such waveguide devices, demonstrating the presence of propagating optical modes in these devices. Another aspect of MIM waveguides is their use in Bragg gratings to form distributed feedback lasers. Results will be shown from such Bragg grating devices and key issues in their design discussed.

Keywords: Plasmonics, Semiconductor lasers, nano-lasers.

1. INTRODUCTION

Over the last year or so there has been considerable progress by a number of groups in reducing the size of lasers by employing metallic nano structures to from the laser resonant cavity. Some of these devices are coming close to being useful light sources, and it may only be a few years before we see lasers based on metallic nano structures in applications.

One direction of investigation has been to push the laser mode size to the smallest size possible. In particular where the mode size is below the diffraction limit and the optical modes have a surface plasmon polariton (SPP) component. Here it has been shown that it is possible for gap-plasmon modes in metal-insulator-metal waveguides to lase at near infra-red wavelengths [1], for devices which form an SPP like mode between a silver/insulator/semiconductor nano-wire sandwich to lase at blue wavelengths [2]. Furthermore for SPP in a metal/semiconductor microdisk to lase at near infra-red wavelengths [3]. Finally the concept of the SPASER [4] has been realized with gold nano-particles at green wavelengths [5].

Another direction has been to look at devices with enclosed cavities which typically emit through an open bottom of the cavity. These devices typically employ modes sizes which are just below or above the diffraction limit. There has been rapid progress here from the first of these pillar devices [6]. Recently room temperature pulsed optical pump operation was shown for this sort of device operating in a TE mode [7]. Also continuous wave electrically pumped room temperature operation has been shown in devices which also incorporate a Bragg mirror under the active layer [8]. Finally, so called nano-patch devices have been demonstrated with optical pumping [9]. These sort of devices, either with or without the use of additional Bragg mirrors may soon replace vertical cavity surface emitting lasers (VCSELs) for some applications. In particular the use of metal cavities in these devices may provide significant advantages such as: arrays of independent lasers with sub-wavelength pitch, good heat sinking of the devices allowing very high pumping levels and high output powers, good control over individual laser wavelengths in large arrays, and easier fabrication of the mirrors compared to Bragg gratings for some wavelength ranges.

2. SURFACE EMITTING DEVICES

In particular and contrary to popular belief such lasers could be made as efficient light emitters by making the correct design tradeoffs. For example, at near infra-red wavelengths, with silver as the metal, and exploiting TE modes in the cavity such pillar devices can have quality (Q) factors at room temperature of over 3000 [7]. Furthermore by adjusting the length of cutoff waveguide below the active gain region on which the optical mode is centered the coupling of the optical mode to free space can be varied. Hence, the optical losses from the cavity can be tuned from being entirely due

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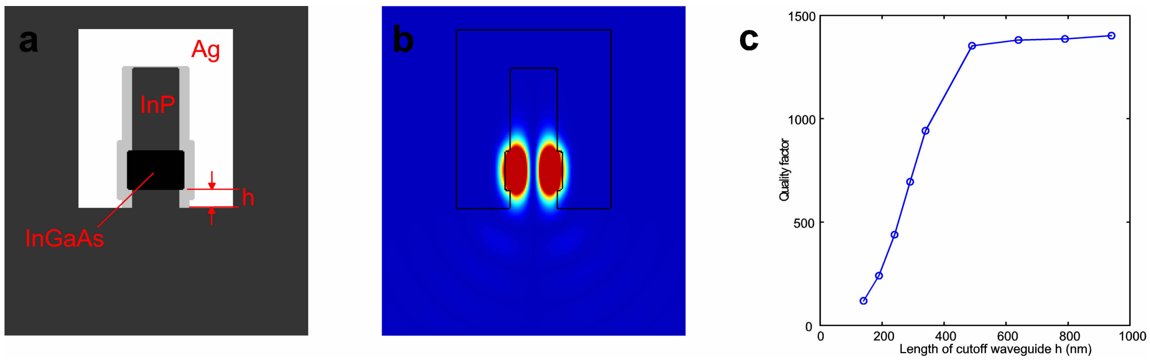

Figure 1a). Structure of silver encapsulated semiconductor core pillar device. b) FDTD simulation results showing E^2 plot, indicating a TE mode centered on the InGaAs and leaking power to the substrate. C) Plot of quality factor of cavity versus length of InP stub under the InGaAs. Shows trade off can be made between Q and emission efficiency.

to metal absorption, to being mostly due to emission to free space. This can be seen in figure 1c where for little coupling to free space the Q is 1400. By decreasing the length of the waveguide underneath the active region the Q can be reduced to around 100. Room temperature operation of electrically pumped metallic cavity devices with Q's on the order of several hundred have already been shown [1,8], hence it is possible that metallic nano lasers can be made with a good efficiency of emission of light to free space. Furthermore, even for applications that don't require lasing, the high Purcell effect of such structures [6,7], along with optimized coupling of the mode to free space, may provide efficient light emitting diodes.

3. METAL INSULATOR METAL WAVEGUIDE DEVICES

The unique properties of metal cavities is that light can be confined to regions smaller than the diffraction limit.. One of the few metallic structures that permit true deep sub-wavelength confinement of light is the MIM waveguide structure [10]. Here the light can be confined to inside an arbitrarily small insulator layer between two metal slabs. Penetration into the metal on each side of the insulator is typically also limited to a few tens of nanometers [10], allowing in principle tightly packed waveguides [11]. We are working on a number of aspects of lasing in MIM waveguides. Our future focus involves making both smaller and more complex electrically pumped MIM waveguide devices. One of the key requirements in future plasmonic lasers will be precise control over the operation wavelength and the form of the optical mode. In conventional semiconductor lasers precise wavelength control is often achieved via Bragg gratings used to form distributed feedback (DFB) or distributed bragg reflector (DBR) lasers. A method proposed in the literature to form Bragg grating reflectors in MIM waveguides is to modulate the waveguide width [12]. This method has been employed by us to create plasmonic DFB nano-lasers. The modulation of the MIM waveguide width is achieved by modulating the semiconductor waveguide core width during the lithography. Figure 2 shows one of these waveguide cores before metal encapsulation. In [13] it is shown that indeed it is possible to make DFB lasers in MIM waveguides, with below diffraction limit widths and based on gap-plasmon modes. Results on these devices will be given in the presentation.

Our ultimate aim is to further reduce both the size of the optical mode and the active region down to a few tens of nano-meters in two dimensions. This is possible in the encapsulated heterostructure concept we employ with slight modifications. In particular we have indented the sidewall around the active region as shown in figure 3, for a InP/InGaAs heterostructure [14]. The indentation strongly localizes the optical mode in the vertical direction [15,16], while the metal sidewalls confine the mode in the horizontal direction. A plot of the simulated electric field magnitude is shown in figure 3b.

Key issues in constructing such devices are: the shaping of the sidewalls via chemical processes. Sidewall roughness reduced to the nano-meter scale. The deposition of high quality conformal silver layers. Finally, the coating of the semiconductor form with thin dielectric layers This is in particular is a critical step as a significant amount of the modal

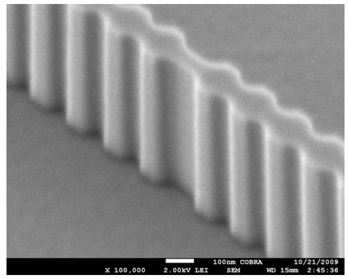

Figure 2 Semiconductor core with modulated width to used to form plasmonic DFB lasers as reported in [13].

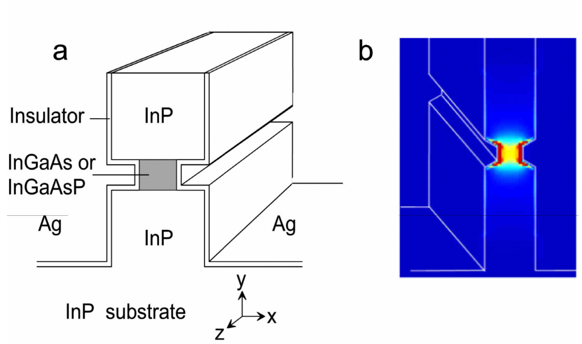

Figure 3. a) Structure of an active surface plasmon polariton gap waveguide. Lithography, dry etching and selective wet etching can be used to form the three dimensional nano structure. Metal can be deposited by evaporation around the form to complete the waveguide and provide a top electrical contact. b) Plot of $|E|^2$ from FDTD simulation of such a structure, showing tightly confined mode.

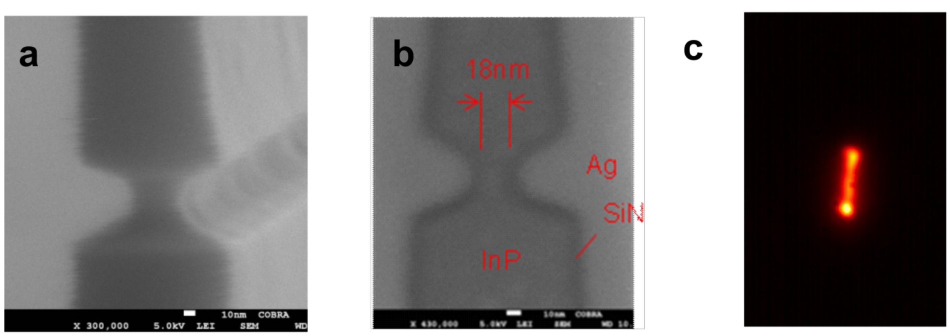

Figure 4. a) Actual fabricated semiconductor InP/InGaAS semiconductor core. b), cross-section of a completed waveguide which has been encapsulated in silver. c) emission through substrate of a waveguide similar to b) with the active region width of 25nm, and the waveguide 20 microns long.

energy can be contained in the dielectric layer between the semiconductor and the metal. The goal here is to make the dielectric layer as thin as possible and also with a high refractive index to minimize the energy contained in it. Figure 4 shows scanning electron microscope images of a bare waveguide core with a sidewall indentation. Furthermore figure 4 shows a completed waveguide that has been encapsulated in a dielectric, then silver.

Figure 4 also show the emission of light through the substrate of one of our initial attempts at making these extremely small MIM waveguide devices. The InGaAs gain region in the waveguide core is approximately 18nm thick by 25nm wide, and the waveguide section is 20 micrometers long. With electrical pumping emission of light and filling up of the semiconductor bands can be seen, indicating that the extremely small semiconductor gain region is operating correctly. Furthermore the stronger light emission at the ends of the cavity points to the fact that emitted light is being coupled into propagating waveguide modes [1]. However, we have yet to achieve lasing in these devices.

4. CONCLUSIONS

Rapid progress is being made in the miniaturization of lasers to sizes below the diffraction limit. It is likely that in the near future such devices will be useful in important applications. Our approach in based on encapsulated electrically pumped hetero-structures, and in particular we are focusing on employing the MIM waveguide structure as a basis for our devices.

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