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Lasing in metal-insulator-metal sub-wavelength plasmonic waveguides

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Abstract: We demonstrate lasing in Metal-Insulator-Metal (MIM) waveguides filled with electrically pumped semiconductor cores, with core width dimensions below the diffraction limit. Furthermore these waveguides propagate a transverse magnetic (TM₀) or so called gap plasmon mode [1-4]. Hence we show that losses in sub-wavelength MIM waveguides can be overcome to create small plasmon mode lasers at wavelengths near 1500nm. We also give results showing room temperature lasing in MIM waveguides, with approximately 310nm wide semiconductor cores which propagate a transverse electric mode.

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OCIS codes: (250.5403) Plasmonics; (250.5960) Semiconductor Lasers.

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The coupling of radiative emitters to the surface-bound electromagnetic waves supported by metals (surface plasmons) is an important topic in nano-optics [5] from several perspectives. The interaction between semiconductors and surface-plasmon polaritons (SPP) at nanometer scale is of great interest in the fundamental physics of light-matter interaction. Here a question of particular importance is: what is the smallest limit at which light can be confined. From the point of view applications, there is an interest in generating high intensity, localized coherent fields [6]. A further aspect of this topic is the overcoming of high propagation losses in nano-scale plasmon mode waveguides, and making nano-lasers from these waveguides. Such lasers will be crucial in future complex nano-photonics systems. Indeed, there have been attempts to overcome metallic losses in plasmon mode waveguides for near-infrared and visible frequencies [7,8]. A recent successful demonstration of overcoming losses in a thin silver film supporting a SPP mode was given in [9]. Among the various types of plasmon mode waveguides the Metal-Insulator-Metal (MIM) structures are interesting in that they allow true deep sub-wavelength confinement of light, guiding a transverse magnetic (TM₀) or so called gap plasmon mode [1–4]. Light emitting material has been previously incorporated into MIM waveguides [10]. Introducing gain into MIM and other metallic waveguides to overcome loss has also been proposed [11,12]. Here we construct MIM (or more accurately Metal Insulator Semiconductor Insulator Metal, MISIM) waveguides containing electrically pumped semiconductor gain medium cores. This work builds on our previous work of electrically pumped metallic nano-lasers [13] and is a step towards eventual plasmon mode lasers with waveguide core sizes of a few tens of nanometers in two dimensions [4].

Our MISIM waveguide consists of a rectangular cross-section InP/InGaAs/InP pillar with a conventional double hetero structure surrounded by a 20nm thick insulating silicon nitride (SiN) layer. The pillar is then encapsulated in silver as shown in Fig. 1(a). The InGaAs layer of height $h = 300\text{nm}$ forms the gain medium. Furthermore the index contrast between it and the InP confines the light vertically in the waveguide [3]. Electrons are injected via the top of the pillar, and holes are injected via the p-InGaAsP layer and a large area lateral contact. Rectangular pillars were made in lengths l , of three or six micrometers (for a small cavity free spectral range), and with the semiconductor core width d , varying between ~ 90 ($\pm 20\text{nm}$) and 350nm , in steps of $\sim 20\text{nm}$, Fig. 1(b). The devices were made by employing epitaxy, electron beam lithography, dry etching, and various material deposition techniques [13].

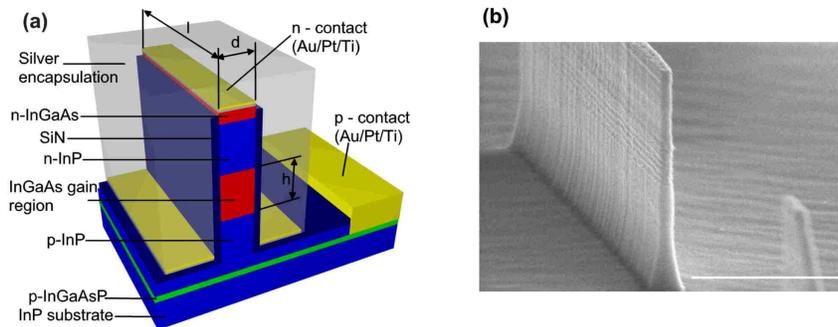


Fig. 1. Structure of cavity formed by a rectangular semiconductor pillar encapsulated in Silver. (a) Schematic showing the device layer structure. (b) Scanning electron microscope image showing the semiconductor core of one of the devices. The scale bar is 1 micron.

A mode travels along the waveguide until it reaches the end of the waveguide which is terminated by the encapsulating silver. At the waveguide ends light is reflected back into the waveguide, thus forming a Fabry-Perot cavity. The inhomogeneous waveguide core (SiN/InGaAs/SiN) of our MISIM waveguide distorts the propagating mode shape somewhat

from that of a homogeneous MIM core waveguide TM₀ mode. However as in the homogeneous core case, this distorted mode can still propagate in waveguides with d far below the diffraction limit. Additionally, the maximum energy flow along the waveguide occurs at the metal/insulator interfaces. Simulations indicate that quality (Q) factors in the range of 140 are possible for these cavities at room temperature. Higher Qs may be possible at lower temperatures due to reduced metal losses [13].

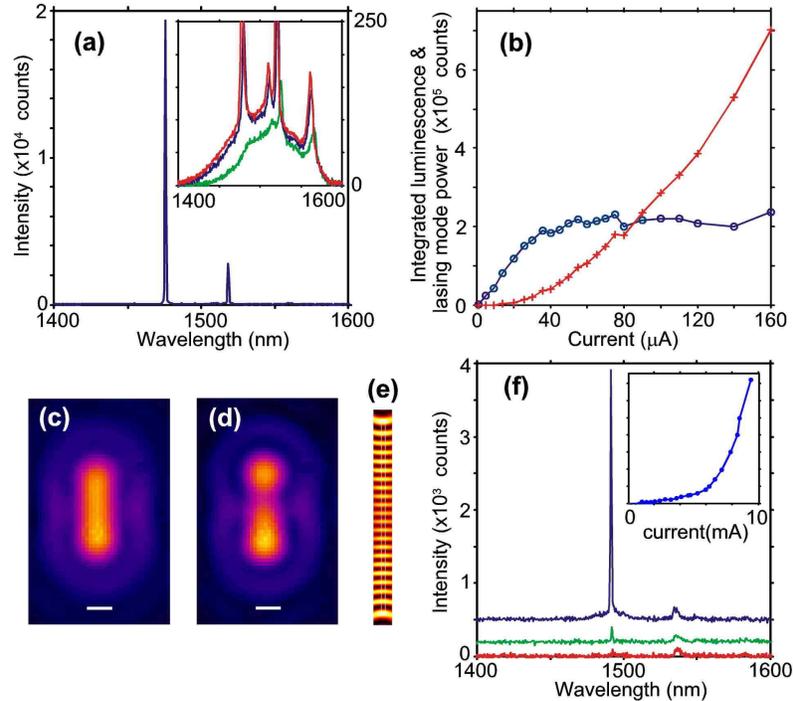


Fig. 2. Spectra and near field patterns showing lasing in devices. (a) Above threshold emission spectrum for 3 micron long device with semiconductor core width $d \sim 130\text{nm}$ ($\pm 20\text{nm}$), with pump current $180\ \mu\text{A}$ at 78K . Inset: emission spectra for 20 (green), 40 (blue) and 60 (red) μA , all at 78K . (b) Lasing mode light output (red crosses), integrated luminescence (blue circles), versus pump current for 78K . (c) Actual near field pattern (in x - y plane) for 6 micron ($d = 130\text{nm}$) device captured with $100\times$, 0.7 NA long working distance microscope objective and infrared camera, the scale bar is 2 micron, for below threshold $30\ \mu\text{A}$, and (d) above threshold $320\ \mu\text{A}$. (e) Simulated vertical (z) component of the Poynting vector taken at 0.7 microns below the pillar base, shows most emitted light at ends of device. (f) Spectra for a 6 micron long device with $d \sim 310\text{nm}$ at 298K , pulsed operation (28 ns wide pulses, 1MHz repetition). Spectra for peak currents of 5.2mA (red), 5.9mA (green) and 7.4mA (blue), (currents were estimated from the applied voltage pulse amplitude). The spectra for 5.9 and 7.4 mA are offset from 0 for clarity. Inset shows the total light collected by the spectrometer from the device for currents ranging from 0 to 10mA .

The processed devices were placed in a variable-temperature Helium flow cryostat which was cooled to various temperatures between 10 K and 298 K. The devices were forward biased with a DC current source. The laser light escaping through the bottom of the device and the substrate was collected by a microscope objective. From the objective light was sent either to a spectrometer with a cooled InGaAs detector array, or an infrared camera. A range of devices were tested, with the semiconductor core width d , ranging from ~ 90 nm to 350 nm. The behavior of all but the thinnest devices was similar and the results for the $d = 130\text{nm}$ ($\pm 20\text{nm}$) and $l = 3\ \mu\text{m}$ device are given as a representative example. Figure 2(a) shows the spectra of the device around and far above threshold. It can be seen that the spectrally broad light from spontaneous emission increases until the laser threshold is reached ($\sim 40\ \mu\text{A}$), at which point further pump energy is directed into the spectrally narrow lasing mode. Just

below threshold the full width half maximum (FWHM) of the resonance is 4 nm, indicating a cavity Q on the order of 370 (at 78K). At 180 μ A the FWHM reduces to 0.7 nm. The spectrometer resolution is from 1 to 0.5 nm depending on the grating used and how the lasing wavelength falls on the detector array. The laser behavior can be best illustrated by plotting the spectrally integrated luminescence [14] outside the lasing mode, and the lasing mode power versus current. These plots (Fig. 2(b)) show that the laser mode power increases linearly after reaching threshold. The plot of integrated luminescence shows a leveling off above threshold, indicating carrier density pinning in the device [14], as is well known for a laser. Figure 2(c),(d) shows pictures of the near field radiation pattern of a 6 μ m long ($d = 130$ nm (± 20 nm)) device, below and above threshold, imaged with a microscope objective and infrared camera. Below threshold, when light is from spontaneous emission, there is rather even light emission over the device length. Above threshold, when light comes from stimulated emission in the lasing modes, the emission pattern is more structured and greatest at the device ends. This emission pattern is consistent with the lasing mode propagating along the MISIM waveguide and being scattered into the observation direction mostly at the waveguide ends. A simulation of the vertical (z) component of the Poynting vector below the base of the pillar confirms that greatest emission intensity should be expected at the device ends, for the lasing mode, Fig. 2(e).

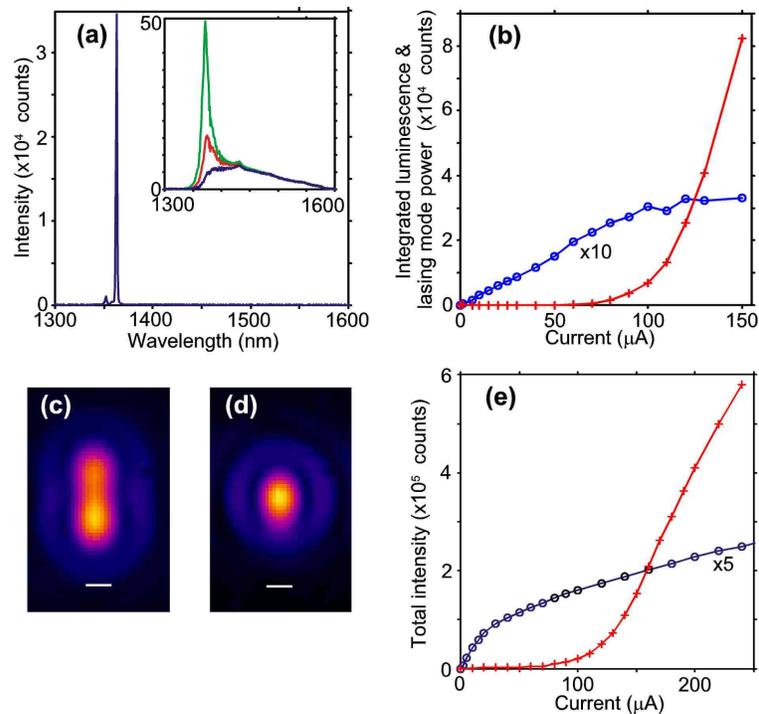


Fig. 3. Spectra and near field patterns showing lasing in thinnest devices. (a) Above threshold emission spectrum for 6 micron long device with semiconductor core with $d \sim 90$ nm (± 20 nm), with pump current 200 μ A at 10K. Inset: emission spectra for 55 (blue), 65 (green) and 75 (red) μ A, all at 10K. (b) Lasing mode light output (red crosses), integrated luminescence $\times 10$ (blue circles), versus pump current for 10K. (c) Actual near field pattern captured with an infrared camera, the scale bar is 2 micron, for below threshold 20 μ A, and (d) above threshold 240 μ A. (e) Total output intensity versus current at 10K as determined by integrated counts from the infrared camera. Red crosses show the 6 micron long $d \sim 90$ nm device. Blue circles, the 6 micron long $d \sim 130$ nm device, with output scaled 5x to show the shape better.

Most of the measurements were performed at cryogenic temperatures, to allow a large number of accurate spectra to be collected. However, most devices could operate at much higher temperatures, particularly in pulsed current mode. Figure 2(f) shows the spectra for a

device with $d = 310\text{nm}$ ($\pm 20\text{nm}$) operating in pulsed current mode at 298K. A significant narrowing of the spectra can be seen with higher currents, to a FWHM of 0.5 nm. Furthermore, the total light collected by the spectrometer shows super-linear behavior, indicating lasing at room temperature for these metallic nano-lasers. Below threshold linewidths indicate that the Q of this cavity is ~ 340 at 298K. These wider MISIM waveguides can support a transverse electric (TE) mode, which has lower loss than the TM₀ mode. Simulations indicate a room temperature Q of ~ 320 for this cavity. The use of silver which has the lowest optical loss of all metals, is an important factor to obtain lasing at 298K.

Figure 3(a) shows the spectra for a device with $d = 90\text{nm}$ ($\pm 20\text{nm}$) and $l = 6\ \mu\text{m}$, above and around threshold. Just below threshold the resonance FWHM is 8 nm ($Q \sim 170$) and at 220 μA it is 0.5nm. Figure 3(b) shows the plot of integrated luminescence and laser mode power versus current (at 10K). It can be seen that the device acts as a laser. For the same device the near field radiation patterns of the device, below and above threshold are given in Fig. 3(c),(d). It can be seen that above threshold the emitted light comes from a small spot in the middle of the device. This is in contrast to the larger devices, where light was scattered out at the cavity ends, Fig. 2(d).

We also find from measurements, that the light from the lasing mode of this device is collected much more efficiently than the larger devices. Comparing measurements from the $d = 90$, and 130nm devices, we find that lasing mode light collection is 38 times more efficient in the 90nm device than for the 130nm device. Figure 3(e) shows the total light collected, as measured by integrating the counts from the infrared camera, versus current, for $d = 90$, and 130nm. For the 130nm device, the slope of the curve decreases as the current increases past the lasing threshold. The slope change indicates that spontaneous emission is collected more efficiently than the lasing mode light, as the laser light is travelling back and forth in the cavity, perpendicular to the observation direction, similar to in [13]. In contrast, the $d = 90\text{nm}$ device showed an increase in the curve slope as the current increases past the lasing threshold.

In the laser spectra (Fig. 2(a), 3(a)), a number of longitudinal modes of the Fabry-Perot cavity can be seen. Knowing the mode spacing and cavity length, an estimate of the group velocity of light (or group index) in the MISIM waveguide can be found [15]. Figure 4 shows a plot of the estimated group index versus d , for a number of devices.

The results show a sharp rise in the group index with the smaller waveguides. Figure 4 also shows the group index obtained from FDTD (2D) simulations of MISIM structures with different semiconductor core sizes, with and without SiN cladding, and with different models for the semiconductor material. By including significant dispersion in the InGaAs model ($\partial\epsilon_r/\partial\omega$ ranging from 2×10^{-13} s to 2×10^{-14} s at the frequencies of interest) the experimental results can be reproduced, red curve Fig. 4. At low temperatures, bulk InGaAs can show significant dispersion over small wavelength ranges near the gain peak, according to the methods of [16]. The refractive index may also deviate significantly from the nominal value at low temperature for high carrier densities. The dispersion and refractive index deviation increase for lower temperature and higher carrier densities. The smaller devices had in general higher threshold current densities, and the two smallest were measured at $T = 10\text{K}$, hence we expect that dispersion will be higher the smaller the device.

The shape of the experimental group index curve reflects the following behavior. For wider devices the confinement of modal energy in the InGaAs, Γ [1,2] is large, and there may also be less interaction with the metal cladding and hence lower losses. Hence the semiconductor carrier density and gain need not be so high for lasing, leading also to a lower dispersion, and finally to a lower group index in the region of 5. As d decreases, Γ decreases, due in large part to the SiN, as a significant amount of the propagating mode energy can be contained in the SiN layer [17], particularly for smaller d . Furthermore, losses may become higher via greater interaction with the metal cladding. So the semiconductor carrier density and gain must be higher for lasing, and along with this will come higher dispersion. This higher dispersion also increases the Γ [18], and leads to a high group index [18]. Dispersion should be included when assessing the possibility of lasing in MIM structures filled with semiconductor gain medium. Furthermore, when reducing d and h down to a few tens of

nanometers or less, quantum confinement effects may contribute to very high gain and dispersion [19], permitting lasing in such small devices.

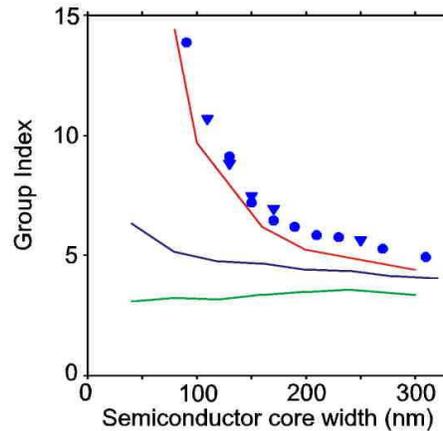


Fig. 4. Spectra and Group index, estimated from mode spacing in device spectra versus device semiconductor core width d . Blue circles – estimates from 6 micron long devices, blue triangles, estimates from 3 micron long devices. All measurements at 78K except for the two smallest d , which were at 10K. Blue, green and red curve, simulated group index. Blue - semiconductor only filled MISIM structures. Green - including the SiN layers. Red - include SiN layers and varying dispersion for the InGaAs core. InGaAs dispersion was varied from $\partial \epsilon_r / \partial \omega \sim 2 \times 10^{-13}$ s for the thinnest d , to $\partial \epsilon_r / \partial \omega \sim 2 \times 10^{-14}$ s for the thickest d .

Another semiconductor specific effect seen in the experiments is the lasing wavelength shifting to shorter wavelengths for smaller devices or higher operating temperatures. This is due to the fact that the material gain peak shifts to shorter wavelengths and increases at higher carrier densities, in bulk semiconductors [20].

A further feature of the experiment is the change in the near field pattern and emission of light from the bottom of the cavity for the smallest device (90nm core width). This feature is the subject of further investigation. This particular device required a much higher pump current density to obtain lasing than wider devices, and lased at a much shorter wavelength. It is possible that the high carrier density in the device caused significant refractive index deviations, and high (or even anomalous) dispersion, which altered the behavior of the device.

In summary, we have shown for the first time lasing in MISIM waveguides which confine light to waveguide core regions about half the diffraction limit in width ($\lambda/2n$, n is the refractive index of the core material). Based on the waveguide dimensions and matching of simulations to experimental results, the propagating mode in the waveguide structure is the TM₀ or so called gap plasmon mode, for the smaller devices. Furthermore we have shown room temperature lasing in MISIM waveguide devices which propagate a TE mode. However, more work needs to be done to show sub-diffraction limit TM₀ mode room temperature lasing in these waveguides. Our results show that it is not only possible to squeeze a propagating light mode in one direction to a space smaller than the diffraction limit, but the propagation can be amplified to lasing by a common semiconductor gain medium with electrical injection. It is likely that significant further miniaturization of these plasmon mode lasers will be possible in the future, by reducing the widths of both the semiconductor and insulating layers.

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