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Review Article

Surface-Emitting Metal Nanocavity Lasers

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There has been considerable interest in metallic nanolasers recently and some forms of these devices constructed from semiconductor pillars can be considered as surface-emitting lasers. We compare two different realized versions of these nanopillar devices, one with a trapped cutoff mode in the pillar, another with a mode that propagates along the pillar. For the cutoff mode devices we introduce a method to improve the output beam characteristics and look at some of the challenges in improving such devices.

1. Introduction

Since the invention of the first laser by Maiman [1] in 1960, different lines of development have yielded lasers the size of buildings, or as small as a few tens of nanometers. Perhaps the greatest impact on society has been had with making lasers smaller. In particular, the invention of the semiconductor laser [2] has allowed small, electrically driven lower power coherent light sources. One of the later developments in the miniaturization of the laser has been the vertical cavity surface-emitting laser or VCSEL [3]. The VCSEL was the first laser with dimensions which approached the wavelength scale. The VCSEL has found many applications due in part to the following characteristics: electrical pumping, room temperature operation, reasonable efficiency, small threshold current, useful output beam characteristics, and ease of test and manufacture owing to the surface normal output.

In the last few years the use of metals to form nanoscale resonators for lasers has been explored. Metals have allowed a dramatic decrease in both the size of the optical mode and also the overall size of the laser. Some of the initial devices are given roughly in chronological order in [4–12]. Some of these devices involve plasmonic waveguide modes [5, 7]. Others show lasing with a nanoparticle as a resonator [6]. Others involve the encapsulation of small pillars of semiconductor material [4, 10, 12]. In these particular devices, light escapes from one end of the pillar. Such devices can be considered as surface-emitting lasers. In this article we will look at a number of aspects of such devices.

2. Pillar-Based Metal Nanolasers

Two main types of surface-emitting devices have been proposed thus far. The first sort of device involves encapsulating a heterostructure pillar [4, 10], which has a higher index in the center of the pillar, Figure 1(a). In the devices we have made, the lower index material consists of InP and the higher index InGaAs. The mode of interest which resonates in such a pillar has a frequency close to the cutoff frequency of the circular waveguide with the InGaAs core. Since the cutoff frequency of the waveguide above and below the InGaAs region is higher than the resonant frequency, the mode is trapped on the InGaAs region, see Figure 1(b). The modal energy in such a cutoff waveguide is actually bouncing back and forth between the sidewalls of pillar. This can be seen in the Figure 1(b), where the Poynting vector is shown. Due to the optical losses of the encapsulating metal, net energy flow is into the sidewalls of the pillar. However, due to the finite length of the bottom InP region in the pillar, there is some coupling of the modal energy into the substrate below the pillar. The amount of power emitted into the substrate can be tuned by adjusting the amount of cutoff waveguide below the InGaAs, and this will be discussed in a later section. The light escaping from the aperture at the base of the pillar

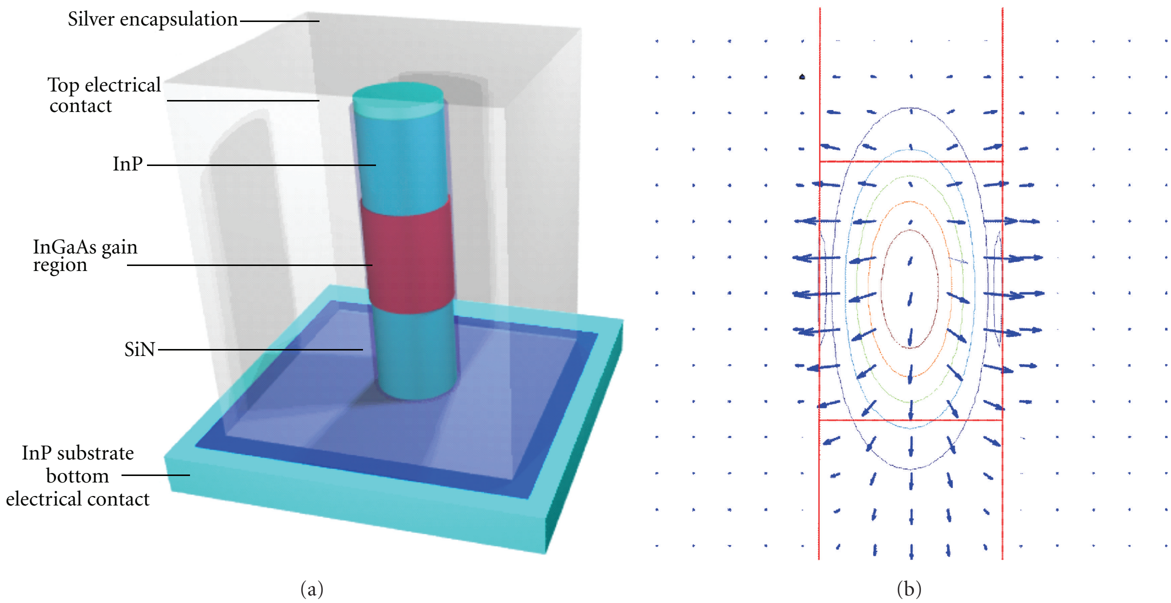


Figure 1: (a) One approach for metallic nanolasers with surface-emitting properties is to encapsulate a semiconductor heterostructure pillar in an insulator then a low optical loss metal such as silver or aluminium. Such an approach is particularly suitable for electrical pumping of the laser. In the figure shown an InP/InGaAs heterostructure is used with SiN insulator. Some light in the optical mode escapes through the bottom of the pillar and the substrate. (b) The optical mode in such structures is trapped on the InGaAs gain region in the center of the pillar due to refractive index differences. The figure shows just the center section of the pillar containing the InGaAs. The contour lines show $|E|^2$ of the trapped optical mode in a slice through the pillar center, with color giving intensity. The arrows show the magnitude and direction of the time averaged Poynting vector for this slice of the mode and show that the energy of the mode is mostly being dissipated as heat in the metal sidewalls.

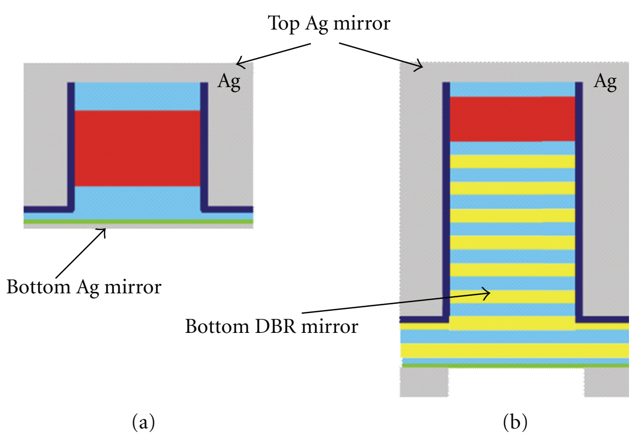


Figure 2: Another form of a pillar cavity appears very similar to that of Figure 1. However, here the mode propagates up and down in the pillar, and the resonant wavelength is always below the cutoff wavelength in the pillar waveguide [12, 13]. The mirror at the pillar top is formed by the silver contact. (a) In one case, the mirror at the bottom of the pillar is formed by a thin silver film. (b) In another case, the bottom mirror is formed by a Bragg reflector, similar to a traditional VCSEL. The red indicates the active region.

propagates with a component in the vertical direction, and hence the device can be used as a form of surface-emitting laser. More will be said on controlling the emission direction of the light later.

By adjusting the size and shape of the cross-section of the pillar different resonant modes can be obtained. At present, perhaps the most interesting modes are the lower order modes of such cavities, for example HE11 or TE01 modes [4, 10], as these modes result in the smallest device and modal volumes. The benefits of small device and modal volumes include high Purcell factors helping to reduce threshold and nonradiative losses, smaller active regions reduce power and also improve prospects for heat sinking, and finally a large free spectral range to ensure single mode operation.

Another concept in metallic surface-emitting devices has also been demonstrated recently [12, 13], Figure 2. Although similar to the concept presented in Figure 1, in that both are round pillars containing heterostructures, there are a number of fundamental differences. In particular, the device of Figure 2 does not rely on a trapped cutoff mode in the center of the pillar. Rather, the resonant mode has a frequency above the cutoff frequency of the cylindrical metal waveguide. The mode is propagating up and down the waveguide. The resonator is formed by having mirrors at either end of the cylindrical waveguide. Typically, the top mirror is formed by the metal of the top contact. In the examples given in [12, 13], the bottom mirror can be formed by a Bragg grating or by a partially reflective metal mirror. This concept is closer to the original concept of a VCSEL, nanowire lasers, and also numerical studies of looking at lasing in metal coated nano-wires [14]. In this particular concept, the frequency of laser oscillation is determined by the length of the cavity in the vertical direction, in combination with any frequency selective mirrors that may be employed. Original VCSEL designs also incorporated metallic mirrors [15]. However, the metallic propagating mode devices here also constrain the opti-cal mode in the lateral direction, via the thick metallic waveguide. The lateral metallic confinement can lead to smaller size and better heat sinking compared to VCSELs. There are a number of advantages and disadvantages of this second approach compared to the cutoff mode devices discussed previously. In the following, these are listed to allow comparison between the two approaches. Aspects of each form of cavity can be considered an advantage or disadvantage depending on the application and point of view. For example, in the cutoff waveguide mode device, the pillar cross-section diameter determines the resonant frequency, which allows many different wavelength lasers to be easily produced on one wafer. However, the wavelength is also then sensitive to the lithographic precision employed in defining the pillar cross-section.

Cutoff Mode Cavity Advantages:

(i) widely tunable wavelength and modal characteristics via pillar cross-section dimension;

(ii) critical low resistance electrical contacts well separated from optical mode;

(iii) good modal overlap between optical mode and gain medium;

(iv) coupling of mode to free space can be tuned by cutoff region length;

(v) optical mode properties independent of pillar length, emission pattern can be independently modified by horns or segments;

(vi) do not require Bragg mirrors or critical metallic mirrors.

Cutoff Mode Cavity Disadvantages:

(i) wavelength strongly dependent on lithographic control of pillar cross-section dimension;

(ii) cannot make pillar width independent of wavelength and mode choice;

(iii) energy flow in optical mode is not in the vertical direction;

(iv) longer pillar required than for some propagating mode devices.

Propagating Mode Cavity Advantages:

(i) wavelength better controlled over whole wafer due to Bragg mirrors or constant etch depth;

(ii) mode energy propagation in direction of emission;

(iii) waveguide (pillar) width independent of resonant wavelength and mode choice;

(iv) smaller pillar height for some designs.

Propagating Mode Cavity Disadvantages:

(i) wavelength difficult to widely tune via lithography;

(ii) require special mirrors on the pillar base;

(iii) the critical top electrical contact material will form part of the optical cavity;

(iv) possibly smaller modal overlap with gain material.

The VCSEL has become a very successful form of semiconductor laser and it is good question to ask why should some other form of surface-emitting device be explored that could potentially replace it. The metallic cavity structures discussed above do have some significant positive features compared to conventional VCSELs and these are discussed below in point form.

(i) Heat sinking. Having a nanoscale device encapsulated in a potentially large heat sink allows excellent heat removal from the active semiconductor material. In fact, simulations indicate that pumping densities into the MA/cm^2 region should be feasible, with only a few tens of degrees rise in device core temperature. Indeed, already current densities approaching 1 MA/cm^2 have been shown at low temperature for continuous operation [4] and at room temperature for pulsed operation [5]. Other experiments have reported excellent thermal characteristics for these devices [12]. The high pump densities possibly allow semiconductor gain material to be pushed close to its limits.

(ii) High Purcell factor. A number of experiments have demonstrated that these cavities have a significant Purcell factor [4, 10]. Others have also pointed out that these cavities can have high Purcell factors over a broad bandwidth and that even for light-emitting diode applications they are interesting [16].

(iii) Transfer to various substrates. The small size and malleable metallic encapsulation may be of benefit when transferring the devices to substrates such as Si or metals [12, 13].

(iv) Lack of complex Bragg mirrors. The metallic mirrors required are in principle easy to construct and work over a very wide range of wavelengths.

(v) Wide range of wavelengths on a single substrate.

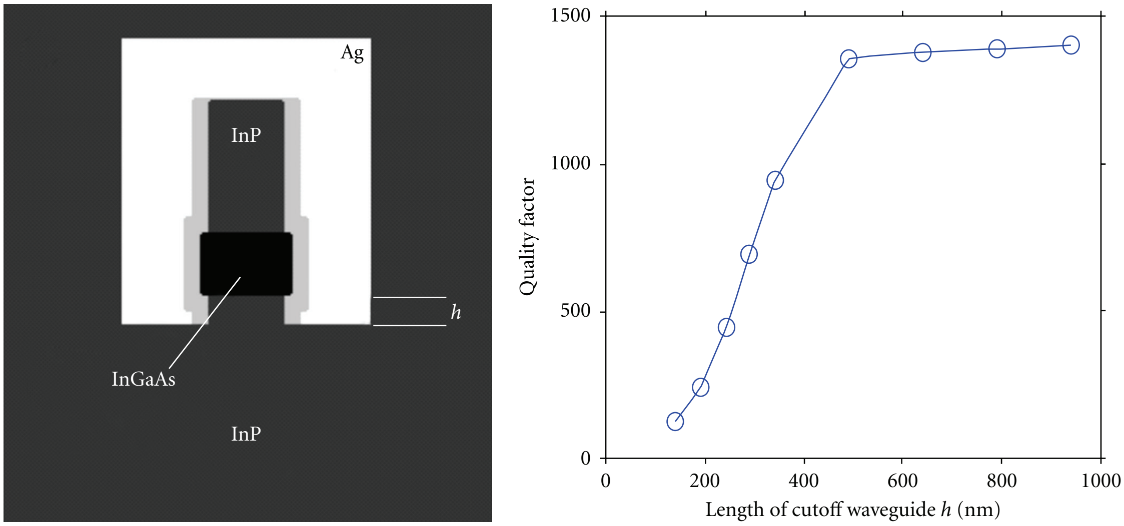
(vi) Potentially high intrinsic speed due to high Purcell effect and high pump density possible. Here we consider modulation of the laser by injection of optical signals, which is of interest in optical signal processing applications. Electrical modulation bandwidth may be significantly less due to limitations imposed by gain compression effects [17].

(vii) Low power due to smaller active region.

(viii) Closer packing of devices without interference, due to the strong lateral metallic mirrors, possibly allowing arrays of independent devices with subwavelength pitch.

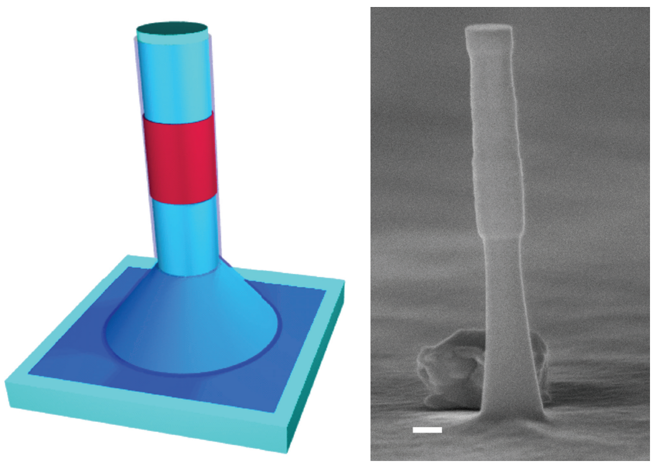
3. Efficiency and Output Beam Quality

For applications, it is clearly desirable that any laser converts electrical energy into light which can be utilized, with as close



(a) (b)

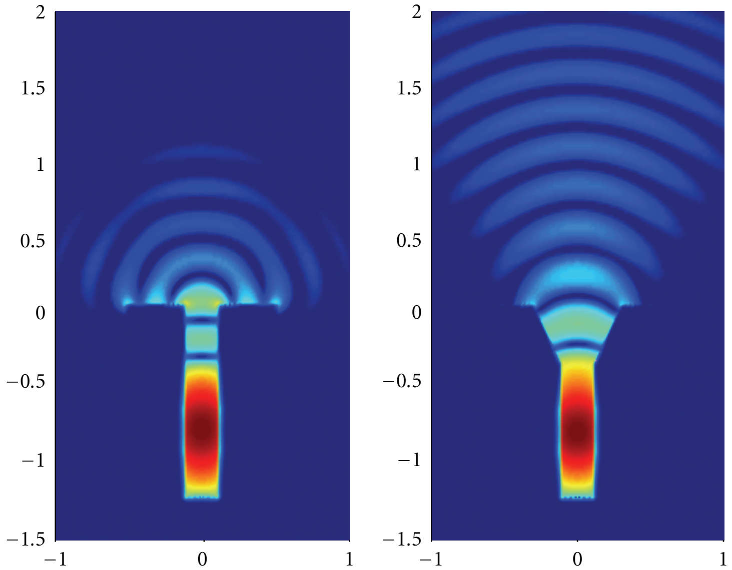
Figure 3: (a) Slice through silver-encapsulated semiconductor core pillar device, showing details of its structure used in a simulation. The height of the InGaAs core is 300 nm. The light gray region between the InGaAs core and silver is the dielectric. The substrate below the pillar is InP. The height parameter h can be varied to modify the Q of the cavity, allowing more or less light from the cavity mode to leak to the outside of the cavity. (b) Plot of quality factor of cavity (Q) versus length of InP stub under the InGaAs. Values were obtained via FDTD simulations. Shows trade off can be made between Q and emission efficiency. The particular mode simulated here is the TE01 mode, and due to less interaction with the metal, it has a reasonably large maximum Q.



(a) (b)

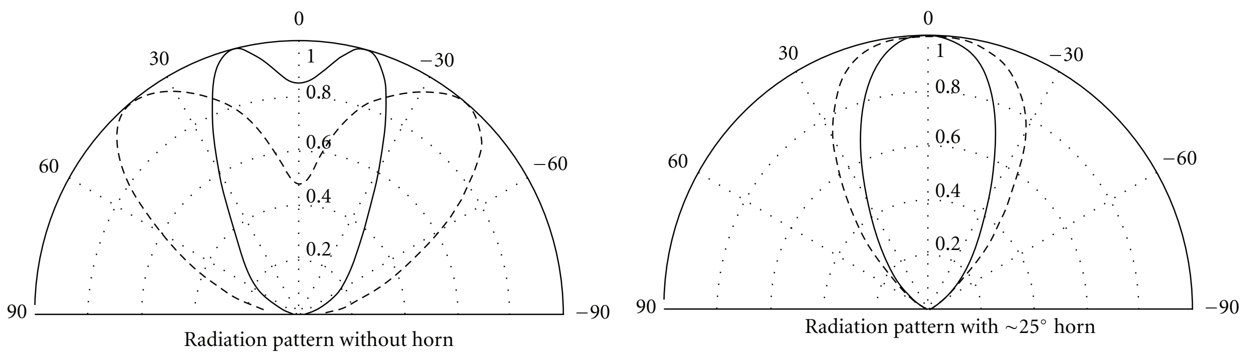
Figure 4: (a) The core of a cutoff mode pillar device with a horn antenna structure at the base of the pillar. The horn can radically change the output radiation pattern. (b) Scanning electron micrograph (SEM) of a semiconductor core of a pillar device, before encapsulation in dielectric and metal. The scale bar is 100 nm. The InGaAs region in the center can be seen, and has a slight bulge to enhance confinement. The base of the pillar flares out as often happens in reactive ion etch processes. Furthermore, the process parameters can be adjusted during the etch process to increase the sidewall slope and create horn-like structures at the pillar base.

as possible to one hundred percent efficiency. In practice, most lasers fall well short of perfect conversion efficiency. The optical loss of the lasing cavity mode is a combination of light escaping into free space, and also internal cavity losses. For metallic nanolasers in particular efficiency has been a contentious issue, as the high internal losses due to the metal require significant gain to be compensated. Further compensating the increased cavity loss due to emitting a significant proportion of the optical mode energy to free space places even more demands on the material gain. However, a number of studies have shown that even with relatively strong confinement of the light, reasonable efficiency can be obtained with correct cavity design [18], and given published optical losses for the metal [19]. For the cutoff mode devices, larger pillars which employ higher order modes than the HE11 mode, and also have thicker dielectric layers, can



(a) (b)

Figure 5: Simulations showing the electric field intensity of a cutoff pillar device with and without a horn antenna structure at the output. Note in this case the base of the device is at the zero point on the vertical axes. The scale is in microns. The resonant mode is a HE11 mode, and resonant wavelength approximately 1.55 microns. (a) Without horn: showing strong divergence of the output light. (b) With a modest horn. Note that already the output beam is much more directional.



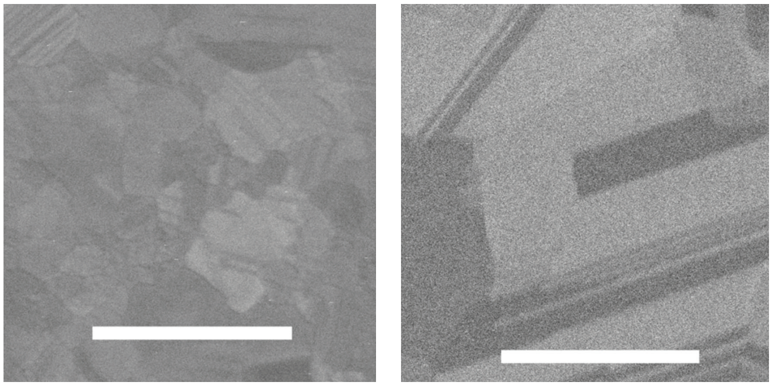
(a) (b)

Figure 6: Far field radiation patterns derived from the simulations of Figure 5. Note that the HE11 mode does not have circular symmetry so that radiation patterns for the two axes are shown. (a) Without horn, showing a significant beam divergence. (b) With a modest horn, showing a much narrower beam.

suffer less from the metallic losses [20]. For these devices high efficiency could in theory be achieved as the material gain required for lasing can be low as several hundred per centimeter. Considering that semiconductor gains can reach several thousands per centimeter, there is room to make devices where a large proportion of the lasing mode energy is coupled out. Others have also indicated that for both lasers and LEDs, such pillar structures can in theory have quite acceptable efficiencies, in the order of 50% [16, 21].

For the propagating mode devices, controllable out coupling is achieved by adjusting the transmission characteristic of one of the mirrors, which with a metal mirror means controlling its thickness [17]. For the cutoff mode devices, the amount of modal light coupled into the substrate can be controlled by adjusting the height of the cutoff waveguide under the gain region. Such a height adjustment can be readily achieved in fabrication. Figure 3 shows how such a change in height affects the cavity quality factor, Q. In the pillar devices the total Q, Q_{tot}, depends on the Q due to metal absorption, Q_{abs}, and the Q due to radiation out the pillar base Q_{rad} [18]. $1/Q_{tot} = 1/Q_{abs} + 1/Q_{rad}$. When the cutoff height is large, Q_{abs} dominates Q_{tot}. From Figure 3 it can be seen that for some modes Q_{abs} can reach into the thousands, allowing scope for significant out coupling of radiation.

A key advantage of the metallic devices described is that the resonant cavity has a subwavelength size. However,



(a) (b)

Figure 7: SEM images of deposited and annealed silver, showing different crystal sizes. The samples show the silver that occurs at the dielectric/silver interface, and the samples were prepared by removing the deposited and annealed silver films from the dielectric using adhesive tape. Both scale bars are 1 micron. (a) With 120 degrees C annealing for 2 hours. (b) With 400 degrees C annealing for 60 seconds. Note the much larger crystal grains, and also twinning defects.

the light exiting the cavity will in principle have to pass through some subwavelength aperture, which can lead to the light emitted over a wide solid angle. Some simulation studies have been done of these emission properties [21]. In many applications, a low divergence beam would be desired. The width of the propagating mode devices is independent of the mode choice, as long as the mode cutoff wavelength is longer than the lasing wavelength. Hence, here a wider device can be chosen to give less divergence in the output beam, although at the cost of a larger resonant cavity size.

Alternatively, some other form of patterning or structure at the subwavelength output could transform the highly divergent beam into narrow beam [22]. One possibility that exists for the cutoff mode cavities is the inclusion of some form of waveguide horn antenna [23] structure in the lower part of the pillar, Figure 4(a). Such an arrangement has the advantage that the properties of the subwavelength resonant cavity such as Q, and modal volume can be made independent of the output beam divergence. Such horn structures could be realized as part of the pillar etching process by adjusting the process parameters. Sidewall angles greater than 10 degrees can be achieved in reactive ion dry etching with methane/hydrogen etchants due to either polymer byproduct deposition or mask erosion [24]. Figure 4(b) gives an idea about how during reactive ion etch the sidewall angle can change at different stages in the process, and more strongly angled pillar bases could be made.

Simulations of the effects of such a horn structure are given in Figures 5 and 6. Here a pillar with a HE11 resonant mode is simulated. The far field radiation pattern and the electric field intensity of the beam show what a dramatic effect that even a modest horn structure a few hundred nanometers long can have.

4. Technological Challenges

A number of teams have reported on attempts at producing these surface-emitting devices. However, often performance falls short of what theory would predict. Certainly for the smaller devices with a HE11 or TE01 mode, continuous electrically pumped room temperature operation has yet to be shown. What are the possible major hurdles to overcome in such devices? At first sight surface recombination and surface defects caused by manufacture would seem to be the most difficult obstacle. However, our experience has been that with well-controlled dry-etching techniques, and surface treatments, surface damage, and surface recombination can be kept in check [25].

Good electrical contacts are required to support the very high injection current densities necessary. Very low resistance n-type contacts are in principle possible, and we see that indeed with care contact resistances well below $10^{-6}\ \Omega\text{cm}^2$ can be obtained [26].

Likely, the largest deviation from theory in the manufactured devices that we see is the optical losses of the silver used as the confining metal. Estimates of cavity Q factor obtained from below threshold linewidths, in general yield a room temperature optical loss for the silver that is two to four times higher than some published measurements [19]. Other authors also report higher than expected optical losses in fabricated silver devices. Experiments have shown that the crystal structure of the metal can dramatically affect the optical losses [27]. Particular devices made from single crystal samples of metals have been shown to have much better performance than those made via deposition techniques such as evaporation [28]. Another aspect is that optical losses occur at the dielectric/metal interface where metal deposition starts, whereas most reported measurements are performed at the metal/air interface where deposition ends. In any case significant improvements in the metal dependent losses of the cavities are likely possible by improving the metal structure at the metal/dielectric interface. Figure 7 shows silver samples which were obtained by removing the treated silver layer from the dielectric (silicon nitride) surface via adhesive tape. The photos show the actual metal surface that in the device is responsible for optical losses, and they demonstrate the wide range of metal structure possible due to different process parameters.

5. Conclusion

The last couple of years have seen a dramatic reduction is the size of the laser through the use of metallic resonators. Some of these metallic devices can be designed to have a VCSEL-like operation with light being emitted from a wafer surface. Such metallic devices may have advantages over conventional VCSELs such as higher intrinsic modulation speed, better thermal characteristics, and easier fabrication for a wider range of wavelengths. Such small low power devices, or even larger arrays of these devices, may generate new applications due to their unique properties.

We looked at two similar approaches based on nanopillars. Both of these approaches have already been demonstrated. For both approaches, it is in theory possible to create efficient laser light emitters with useful output beam characteristics. However, there appears to be still some technological challenges to reach the device performance that is predicted by theory. One of the key issues is reducing the optical loss of the deposited silver. In spite of difficulties, significant progress has occurred, and in just a few years electrically pumped room temperature devices have been realized.

Acknowledgments

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