Electrically pumped Metallic and Plasmonic Nano Lasers.

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Abstract

In recent years there have been a significant number of demonstrations of small metallic and plasmonic lasers. The vast majority of these demonstrations have been for optically pumped devices. Electrically pumped devices are advantageous for applications and could demonstrate concepts not amenable for optical pumping. However, there have been relatively few demonstrations of electrically pumped small metal cavity lasers. This lack of results is due to the following reasons: There are limited types of electrically pumped gain medium available. There is a significantly greater level of complexity required in the fabrication of electrically pumped devices. Finally, the required components for electrical pumping restrict cavity design options and furthermore make it intrinsically more difficult to achieve lasing. This review looks at the motivation for electrically pumped nanolasers, the key issues that need addressing for them to be realized, the results that have been achieved so far including devices where lasing has not been achieved, and potential new directions that could be pursued.

Keywords: 42.55.Px Semiconductor lasers; laser diode, 42.55.Sa Microcavity and microdisk laser, 42.82.-m Integrated optics

Introduction

There is interest in the continued miniaturization of light sources from both a scientific perspective, understanding the properties of such small light sources, and also from the utilization of such light sources. In particular nano scale lasers have been predicted and shown to have very high modulation speeds and low power [1], attributes which lend themselves well to future applications such as: On chip optical communications [2] where low power, high speed and small size are important. Furthermore nano lasers are needed in the continued miniaturization of integrated photonic systems, which could be employed in diverse areas such as optical sensing systems, or digital processing of optical information [3].

Of all the types of small cavities so far employed to form lasers or resonant cavity LEDs (light emitting diodes), metallic cavities are unique in offering both sub wavelength confinement of the light and a small overall footprint for the device [4], figure 1. Furthermore, the field of plasmonics primarily involves using metal structures to guide, confine and concentrate light into small regions often much smaller than the diffraction limit [5]. These highly concentrated fields not only offer the possibility of further miniaturization of photonic devices, but also much stronger light matter interaction due to the high optical field strengths produced.

A key issue common to both plasmonics and the use of any small metallic cavity is that of the high optical losses caused by the free electrons in the metal. It has been shown that these metallic losses can be compensated through the use of optical gain medium and clever design of the metallic cavity or waveguide [6-15]. The optical loss compensation can occur while still achieving a small device size and subwavelength confinement of the light. Furthermore, coherent light emission has been confirmed in these metallic light emitters by studying the statistics of the emitted light [15,16]. Many of these demonstrations of loss compensation and lasing in metallic/plasmonic devices have occurred at cryogenic temperatures and/or employed optical pumping of the gain medium [7-15]. Operation at cryogenic temperatures has been shown to reduce the metal losses via reduced phonon scattering of the free electrons in the metal [7,10, 17,18]. Employing optical pumping allows a wider range of gain medium to be employed, and also avoids the losses and issues introduced with electrical pumping of the gain medium. These electrical pumping issues will be discussed in detail later.

While optical pumping and cryogenic temperatures have demonstrated many interesting devices, for most applications it is necessary to have devices which are electrically pumped and can operate at room temperature or higher. Electrical pumping is advantageous for many reasons including the following: Electrical pumping avoids the requirement of a secondary light source for pumping, and allows direct electrical modulation of the nanoscale light source. Furthermore electrical pumping permits gain material buried deeply inside metallic structures to be pumped. Finally, the energy for pumping can be directed efficiently into many possibly spatially separated nano scale regions of gain material via wires.

Electrically pumped room temperature operation is also an important contemporary topic for the smallest of dielectric lasers, photonic crystal lasers [19,20] . Typically in dielectric lasers metal contacts must be kept a considerable distance from the dielectric cavity. Metal based small lasers have an inherent advantage compared to dielectric cavity lasers when considering electrical pumping. Specifically, the metals used to form the cavity itself are available to transport the current to the gain medium.

Loss compensation for plasmonics in particular is an important issue as typically the losses when light is tightly confined in plasmonic waveguides or cavities is high, and light can only propagate a small distance before decaying [21]. (There are plasmon mode waveguides which allow long propagation distances, however they do not confine the light to small regions [21]). Widely employed integrated photonic systems typically have means of compensating the losses in their waveguides and of providing integrated laser sources, for example InP based photonic integrated circuits [3]. Alternatively, the losses in the photonic system need to be sufficiently small so that a meaningful number of manipulations of an optical signal can be performed before it is excessively attenuated, for example silicon on insulator photonic integrated circuits.

Hence loss compensation in plasmonic systems is important to permit more complex systems to be built and provide integrated sources of coherent plasmons. An electrically pumped means of loss compensation which can provide large numbers of coherent plasmon sources is particularly important.

The rest of this review will look at the following aspects of electrically pumped metallic and plasmonic nanolasers: Firstly the critical issues that need to be addressed to obtain loss compensation and lasing in small metal structures are examined, then the key elements required for electrical pumping which typically impact nano-laser design are identified. Examples will be given of some of the optically pumped metal cavity nanolasers and how they achieve lasing. Then examples of electrically pumped devices will be given, and it will be shown how the requirements for electrical pumping increase the challenge of overcoming the metal losses. A comprehensive review of the latest electrically pumped devices (including those which may fall short of achieving lasing) will be given. There is also a considerable amount of literature providing only simulation or theory results about electrically pumped nano-lasers. This simulation and theory literature will also be reviewed to see what is possible in electrically pumped nano-lasers and what could be the future directions for their development.

Critical issues for loss compensation and lasing in metal structures

The dielectric function, ε_m, of the metals employed for metal nano lasers and plasmonic waveguides is both negative and complex, i.e. $\varepsilon_m = \varepsilon_m' + i\varepsilon_m''$. Silver is the metal with lowest losses at wavelengths of most interest for plasmonics and nanolasers and thus is employed in many nano laser demonstrations. However, even for silver the loss due to ε_m'' is significant, ($\varepsilon_m = -130 + i3.3$ at 1550nm wavelength [22]). The decay of light in a metallic cavity or along a metallic waveguide depends on how much of the electric field of the mode overlaps the metal. In general for optical modes which are tightly confined by the metal structures, propagation lengths and decay times are short [21]. For less confined optical modes propagation lengths along waveguides can be in the order of a millimeter [21].

A nanolaser consists of two main components; a nano cavity or resonator, and optical gain medium which overcomes the optical losses in the nano cavity. The nano cavity can be characterized via a photon lifetime τ_p which gives the time the optical power in the cavity mode decays to 1/e of its initial value [23]. τ_p is related to the cavity quality factor Q, resonant wavelength λ_0, and the speed of light *c* [23].

$$\tau_p = \frac{Q\lambda_0}{2\pi c}$$

The cavity Q and thus τ_p are determined by the optical losses caused by the cavity metal itself and also by leakage of energy out of the cavity. The component of Q associated with loss in the metal can be denoted Q_m, and the component associated leakage of energy out of the cavity Q_r, both of which are related to the cavity Q by [23,24]:

$$\frac{1}{Q}=\frac{1}{Q_m}+\frac{1}{Q_r}$$

Optical gain to compensate loss in the laser cavity can be provided by a number of different materials; solid state crystals [25], organic dyes [9,26], colloidal quantum dots [27] and inorganic semiconductors [7,8,10,11-15]. For electrical pumping inorganic semiconductors are most interesting due to their high gain and ability to form diode structures which permit electrical pumping. In this review only the use of inorganic semiconductors is considered. Additionally, there could be other methods for producing coherent photons or plasmons in metal structures which don't rely on a gain medium [28,29], however they also are not considered here.

The semiconductor gain medium is characterized by the material gain G_a . The confinement factor Γ is defined as the proportion of the laser mode energy which overlaps the optical gain medium [23].

The G_a required to overcome the cavity losses and so create a laser G_{th} , is related to the other cavity parameters [23]:

$$G_{th}=\frac{n}{c\Gamma\tau_p}$$

Where *n* is the group index of the gain material. In many cases the nano laser cavity should be designed to have G_{th} as low as possible, as often G_{th} is high compared to dielectric cavity lasers and approaches the maximum G_a available. To decrease G_{th} requires that Γ be increased as much as possible and that the cavity losses from the metal and energy leakage are minimized. Losses from the metal are reduced by decreasing the proportion of modal energy that overlaps the confining metal. Typically there is a tradeoff between achieving a high Γ and reducing the modal overlap with the metal [24].

In [24] this tradeoff between metal losses and Γ is explored to achieve a sufficiently low G_{th} that lasing can be achieved at room temperature [11], even when higher optical loss metals such as aluminum are employed. In [11] a thick dielectric spacer between the metal and gain material is employed to reduce the overlap of the optical mode with the confining metal.

In [10, 26] the surface plasmon modes typically involve just one surface of the metal or the metal stripe is very thin. Furthermore the refractive index of the majority of the surrounding dielectric is low, which greatly reduces the amount of optical energy in the metal compared to having a high refractive index material adjacent to the metal [30]. Typically these plasmon modes are called long range surface plasmons [21], due to their significant propagation distance.

Another feature that occurs in both [11] and [10] that enables a large Γ is the low refractive index of the dielectric material which completely surrounds the relatively high refractive index semiconductor gain material. In [11] SiOx (n~1.5) and air (n~1) surround the gain material (n~3.5), which leads to the optical mode being strongly confined on the gain material.

The strategy of having the gain medium surrounded by a low index dielectric has been very successful in producing nano-lasers [10-12], however it requires that the gain medium is optically pumped. Typically low index materials are insulators and no pathways exist to carry current to the semiconductor gain medium.

Requirements for electrical pumping

To move from optically to electrically pumped nanolasers two key issues must be solved. First there needs to be a way to efficiently inject electrons and holes into the semiconductor from metal electrodes. Typically what is desired is to form low resistance ohmic contacts between metal electrodes and a particular n or p doped semiconductor. Considerable effort over the last 50 years has gone into developing such low resistance ohmic contacts to many types of semiconductor [31]. In fact, the ability to efficiently inject electrons and holes into a particular semiconductor via electrodes determines whether or not it is suitable for use in laser diodes or energy efficient LEDs. The second key issue is that there often needs to be semiconductor pathways from the electrode contact regions to the semiconductor gain material.

A schematic of an electrically pumped double heterostructure ridge waveguide is given in figure 2a. Consider for the moment that the encapsulating silver in figure 2a is removed, and we just focus on illustrating solutions to the metal contact and pathway issues. The double heterostructure waveguide concept enabled the first electrically pumped room temperature lasers and is still used in some form in most electrically pumped lasers. The device of figure 2a employs the InP/InGaAs (indium phosphide / indium gallium arsenide) material system which covers near infra-red wavelengths. Heavily doped low bandgap energy semiconductors are typically employed to form the electrical contact regions. In the case of figure 2a a heavily n-doped InGaAs (bandgap ~0.75eV) on top of the ridge forms the n electrode contact. At the base there is a heavily p-doped InGaAsP layer which forms the p electrode contact. The semiconductor gain region consists of undoped (intrinsic) InGaAs. To transport the electrons to the intrinsic InGaAs region from the n contact there is a region of n doped InP (bandgap ~1.34ev), and similarly to transport holes from the p contact there is a region of p doped InP. Holes and electrons are trapped in the lower bandgap undoped InGaAs gain region where they can recombine creating optical gain. The InGaAs also has a slightly higher refractive index than the InP so the optical mode is typically centered on the undoped InGaAs region. To keep the optical mode away from the contact regions, the length of the InP regions employed to transport current to the gain region is often on the order of microns. The double heterostructure ridge waveguide solves the problem of having the optical mode centered on the gain region and separated from the contacts in a way that is easy to implement with epitaxy and standard processing techniques.

The two requirements of contacts and transporting current from contacts to gain region create three key problems that optically pumped metal cavity nanolasers don’t suffer from.

Firstly stable low resistance electrical contacts to semiconductors typically involve a number of metals which have optical losses much higher than metals such as silver. These metals, examples of which are titanium and platinum, among other tasks provide adequate adhesion of the contact to the semiconductor and prevent diffusion into the semiconductor of other metals which form part of the contact. The key point is that the metal contact regions exhibit extremely high optical losses. The optical mode of the nanolaser must be kept away from the contact regions to avoid high cavity losses which can't be compensated by the gain medium, similar to a dielectric cavity laser. Some low optical loss contact metallization schemes have been investigated [32] and may play a role in the future.

Secondly, the refractive index contrast between the semiconductors which transport the carriers from the contacts and the gain medium, is typically quite low. For example the refractive index n of InP is 3.17 compared to 3.6 of InGaAs, at 1.55 microns wavelength. Most optically pumped nanolasers have dielectrics such as air or SiO_2 (n~1 to 1.5) adjacent to the semiconductor gain medium. The main result of the much lower index contrast is that it is harder to obtain a high Γ in electrical pumped nanolasers. Additionally, the higher refractive index of the materials next to the metal results in a larger amount of optical mode energy in the metal, so metal cavity losses are also increased [30].

Thirdly, resistive heating from both the electrical contacts and the semiconductors transporting the carriers to the gain medium, will be detrimental to the operation of the nano laser.

State of the art of electrically pumped metal nanolasers – including LEDs

While there has been a wide variety of optically pumped metallic nano laser structures, only a comparatively few forms of electrically pumped metallic nano laser have been demonstrated. The first metallic nanolasers demonstrated were electrically pumped and based on the concepts of the double heterostructure ridge waveguide laser, figure 2a. In figure 2a electrical contacts are separated from the InGaAs semiconductor gain medium by a few hundred nanometers of InP. As in conventional electrically pumped lasers the InP regions transport the carriers from the electrode contacts to the gain medium. The pillar or ridge which forms the core of the nanolaser is encapsulated first in a thin dielectric layer, then a noble metal such as gold or silver. The thin dielectric layer prevents the noble metal layer short circuiting the pillar structure and also stops diffusion of any noble metal into the semiconductor. The noble metal shell forms part of one electrical contact at the top. The optical cavity is formed by the presence of the higher index InGaAs and the metal shell. In the case where the etched semiconductor structure is a pillar [7] the wavelength of the resonant mode is at the cutoff wavelength of the waveguide formed by the InGaAs filled metal pillar. The mode is localized at the center due to the fact that the cutoff wavelength in the InP regions is smaller than in the InGaAs region. Essentially the light is bouncing between the vertical walls of the pillar.

Where the etched semiconductor region forms a ridge [8], light is guided in an MIM (metal insulator metal) waveguide. These particular MIM waveguide lasers employ the MIM waveguide concept explored in [33], but with the MIM structure now vertical instead of horizontal [33].

The concept of figure 2a maintains the electrical contacts sufficiently distant from the optical mode to minimize their losses. Furthermore a low resistance path is provided from the contacts to the gain medium by the InP. However, localization of the mode on the InGaAs is much poorer than in optically pumped nanolasers due to the low index contrast between InP and InGaAs, particularly with non-ideal pillar shapes. Improvements to the mode localization have been proposed and realized by making the InP regions thinner [34, 35]. Furthermore, the presence of high index semiconductors everywhere increases optical mode penetration in the metal and hence losses. In spite of these shortcomings the etched pillar concept of figure 2a has been employed in a number of demonstrated electrically pumped nanolasers. In particular it has been used to demonstrate small plasmonic distributed feedback lasers [36] and non plasmon mode lasers which show room temperature lasing [37]. It has also been the basis of a simulation study which showed in theory it is possible to create very fast plasmon mode amplifiers [38].

Another form of etched structure which has similarities to that of figure 2a has also produced useful electrically pumped small lasers [39,40]. The structure of this laser is shown in figure 2d. The central core of the structure consists of a pillar with a central gain region which is coated with a thin dielectric layer and encapsulated in metal. Here the optical mode travels up and down the pillar at wavelengths below the cutoff wavelength. Bragg or metal mirrors constitute the end sections of the pillar and confine the optical mode to the central gain region. The Bragg mirrors also keep the optical mode away from the electrode contacts and transport carriers to the gain region. Note that the structure has a relatively large height (several microns) due to the depth of the Bragg mirrors. Furthermore the diameter of the pillar is also of the order of a micron. Nevertheless, reliable room temperature lasing has been achieved in these structures. A progression from using Bragg mirrors to a much smaller device size using only metal mirrors has been proposed [41] .

A horizontal MIM structure has also been used to create mid and far infra-red wavelength lasers (approximately > 3 microns) [42]. Here, the semiconductor gain medium is sandwiched between two pieces of metal which form the electrical n and p-type contacts. Generally a thin layer of titanium or other adhesive metal is used between the semiconductor and gold to assist adhesion of the metal to the semiconductor. Also there are often specific doped semiconductor layers close to the metal to achieve a low contact resistance between the metal and semiconductor [42]. For the longer wavelengths which such devices operate at, the metal losses are low and the extra losses due to the titanium layer are acceptable. Furthermore the semiconductor layer between the metal is typically several microns thick. The thickness of this layer permits the use of n and p doped contact layers in the semiconductor, while still having a significant proportion of the semiconductor as undoped gain medium.

In [43] a variation of the MIM structure for far infra-red lasers involved introducing circuit concepts to create the resonant cavity. Here sections of MIM with different aspect ratios are used to form inductor and capacitor like elements. It would be interesting to see how such resonators based on circuit concepts could be employed for much shorter wavelengths.

The dimensions of these far infra-red wavelength MIM laser structures are far from nanoscale. Reducing this horizontal MIM structure down to nanoscale dimensions and shorter wavelengths while still achieving lasing is difficult due to the high optical losses of the metal contact regions close to the optical mode. Nevertheless these long wavelength MIM lasers highlight an important advantage of electrically pumped devices; that is the confining metal structures themselves can be employed as electrical connections.

There have been a number of demonstrations of light (or surface plasmon) emitters which employ such horizontal MIM structures, with nanoscale dimensions and shorter wavelengths. It is worthwhile looking at these structures considering that the number and variety of demonstrated electrically pumped metallic and plasmonic nano lasers is so small. As highlighted by a number of authors [44], nanoscale metal cavity SPED (surface plasmon emitting diodes) or LED sources may provide useful sources in themselves. At the very least they can provide an interim solution for small plasmon sources until technology develops sufficiently for the challenges of metal cavity nanolasers to be overcome in a wide variety of configurations.

One of the first demonstrations of surface plasmon emission in a MIM structure was reported in [45], figure 3a. Here electrons tunnelled through a thin (~100nm) aluminium oxide layer which was sandwiched between gold contacts. The aluminium dioxide layer contained silicon nanocrystals, which were electrically pumped when electrons tunnelling between the gold contacts collided with the nano crystals. The spontaneous emission from the silicon nanocrystals couples to the gap plasmon mode which propagates in the MIM waveguide.

Compound III-V semiconductors have also been employed for small surface plasmon emitters, forming SPEDs (surface plasmon emitting diodes). In [46] (figure 3b), a quantum well emitter is placed in close proximity to a slot in a MIM waveguide. One of the diode electrodes was formed by one of the metal plates in the MIM waveguide. Spontaneous emission from the quantum well coupled to the gap plasmon mode inside the MIM waveguide, to generate propagating gap plasmons.

Another demonstration of a nanoscale SPED was given in [44] (figure 3c), here again a quantum well emitter was employed. However, the emitter was placed inside the MIM waveguide. Here the SPED had truly nanoscale dimensions of 130x60nm. Furthermore a number of circuits formed with the MIM waveguides were demonstrated by employing the SPED source.

In [47] an electrical pumped quantum well emitted has also been placed next to a thin gold layer. The idea was to fully compensate the metal losses for the long range surface plasmon supported by the gold layer. However loss compensation was not able to be achieved.

Finally a recent demonstration of a LED involving a metal nanocavity was given in [48] (figure 3d). Here the actual cavity structure is similar to the encapsulated heterostructure in [7]. Such structures as in [48] when correctly constructed, should in theory be able to provide efficient electrically pumped nanoscale laser sources coupled to integrated photonic waveguides [34,49].

Relevant Simulation and Modelling Results

There has been a considerable amount of theory and simulation articles published about metal and plasmonic cavity nanolasers. It is worthwhile briefly examining some of this literature that is pertinent to electrically pumped devices and in particular those focused on semiconductor gain medium, figure 4. Simulation results provide an idea of what could be possible in the future if technology to manufacture metal nano lasers is perfected, and also identify interesting concepts to pursue.

Some of the initial theory to look at semiconductors amplifying surface plasmons at visible and near infrared wavelengths was given in [30], showing it was indeed likely that metallic losses could be overcome. Further work by the same group showed that using less confined transverse electric (TE) modes and dielectric spacers, some metal coated laser resonators can be formed with quite low threshold gain requirements which could be readily satisfied by semiconductors [24]. Other modelling work looked at Fabry-Perot metal nanocavities [23]. Again it was shown that in theory with current semiconductor gain medium it would be possible to obtain lasing in these cavities. However, all of the above mentioned simulations did not incorporate structures to permit electrical pumping of the gain medium.

A number of later simulations also looked at coupling metal nano cavities to waveguides and examining their potential as laser sources for on chip communications [34, 49], figure 4a,b. In particular these simulation studies took into account structures for electrical pumping which kept electrical contacts distant from the optical mode. Furthermore they showed that the light output from the nanolaser could be efficiently coupled to a photonic waveguide. As such they could form useful laser sources in the near future. The modes employed in these cavities were TE modes, so while the cavities were small their dimensions were not below the diffraction limit. Another study looked at coupling a plasmonic nano cavity laser to a photonic waveguide [50], figure 4d. However, electrical contacts were not separated from the plasmonic mode and estimates of threshold gain were not directly given.

A number of simulation studies have highlighted that considerable improvements in the performance of metal cavity devices are possible by optimizing or modifying their structure. In [51] it is shown how a simple change in the shape of the ends of a Fabry Perot cavity constructed with the waveguide of figure 2a, can significantly reduce metal losses. In [52] a different structure to that of figure 2a is shown where the electrical contacts are separated from the optical mode. In particular it shows that confinement of the optical mode and metal losses can be significantly improved compared to waveguides based on the structure of figure 2a. Furthermore it is shown that in terms of providing an amplifier with a small active region, it can have a figure of merit better than for the best conceivable dielectric waveguide. The improvements are due to the use of low index materials close to the metal and gain regions.

A number of theory and simulation studies have also examined the intrinsic modulation speed of both metal nano cavity lasers and LEDs [1, 53, 54]. All studies suggest that the metallic nano cavities can provide useful and high speed devices with distinct advantages in terms of size and speed over dielectric based cavity devices.

Some studies have made broad dismissive statements about perhaps about a particular single nanoparticle cavity [55], or a simplified one dimensional metal structure [56,57] being used for devices. However, it is dangerous to generalize these results to all possible structures that could exist. The theory and simulation studies cited above already indicate that metallic and plasmonic nano lasers are worthwhile pursuing, and they can have advantages in certain respects to dielectric cavity lasers. It is true, particularly for electrically pumped devices, that current experimental device performance is far from what theory predicts. However with improving manufacturing technology device performance should improve to approach that of theory, also new device structures with better performance may be found. Indeed already optically pumped devices are showing interesting results which indicate plasmonic laser devices do indeed have particular performance advantages over dielectric cavity devices, as their size goes below the diffraction limit [58].

Conclusions and Outlook

Future directions

From the published relevant simulation studies it appears possible to achieve useful small metal cavity lasers. However, many materials are pushed close to their limits to obtain lasing and so it is technologically difficult to make the laser structures. Improvements could occur on two fronts to make achieving electrically pumped small metal cavity lasers easier: Firstly, improvements could be made in the materials employed in the laser. Secondly, the design of the laser cavity could be improved so that useful small metal lasers could be made with current materials.

With regards to improvements in materials, plasmonic materials with lower loss than noble metals such as silver could be employed or created. In fact considerable effort in recent years has gone into developing new materials [59], in part due to the difficulty in compensating loss in metals such as silver. ITO (Indium Tin Oxide) is one material that has been suggested for use as a plasmonic material for plasmon mode lasers [59,60]. Indeed there has been proposals for using ITO for plasmonic lasers [61]. However, metals such as silver have many advantages such as good thermal and electrical properties and limited penetration of the electric field into the metal, allowing truly nanoscale devices. More studies should shed light on how well alternatives to silver will enable nanolasers to be realized. Recent results on using single crystal aluminum and silver have also shown considerable improvements in optically pumped nanolaser performance [62,63]. Applying single crystal metals to electrically pumped designs would be another avenue for improvement that could be pursued.

Other materials in the nano laser where improvements have been investigated are increasing the maximum gain from the semiconductor gain medium [64], and reducing the loss of the electrical contacts [32].

Considering now improvements to the structure of the laser cavity, it is not trivial to find the optimum structure which minimizes the threshold gain required to overcome losses in a nano cavity or waveguide. Finding an optimum structure is particularly difficult when taking into account the electrical contact issues and if the cavity is a complex three dimensional structure consisting of metals, semiconductors and insulators. For example two dimensional structures which employ low refractive index materials each side of a semiconductor gain medium on a metal can have comparatively low amounts of energy loss in the metal, with good confinement of the optical mode in the gain medium [10, 52]. More work could be done searching for structures which localize the optical mode well on the gain medium, but minimize the amount of energy in the metal, while maintaining small overall size. Looking at small groups or arrays of plasmonic scatters [65] may prove useful or even circuit based cavity concepts could be looked at [43].

Conclusions

This review has examined the key issues involved for electrically pumped metal cavity nanolasers. Furthermore, how these key issues can impact on the already difficult task of obtaining lasing in metal nano cavities. It looked at the approaches taken to solve electrical pumping by the limited number of actually working laser devices fabricated.

Simulation studies were also reviewed to show that in theory useful electrically pumped nanolaser devices could be made with current materials. However, often the material gain required for lasing is close to the maximum possible, which leads to tight fabrication and material tolerances. In light of the difficult manufacturing technology, resonant cavity plasmon or light emitting diodes [44] may provide useful avenues for development in the interim.

Apart from improving the technology to build current nanolaser concepts, the review looked at possible advances in materials and cavity designs which could ease the difficulties involved in realizing electrically pumped metal nano-lasers.

Providing room temperature continuous wave electrically pumped metallic and plasmonic nanolasers with useful lifetimes and output power, typically coupled into a waveguide, is still a challenge to be solved. Furthermore, the structures and physics involved with such nano lasers are not trivial, so predicting what is achievable is not easy. However, recent simulation and experimental studies suggest that useful devices are indeed possible. Hence, metallic and plasmonic nanolasers are worthwhile pursuing as no other technology allows lasers and photonic systems to be miniaturized to dimensions smaller than the wavelength of light.

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Figures

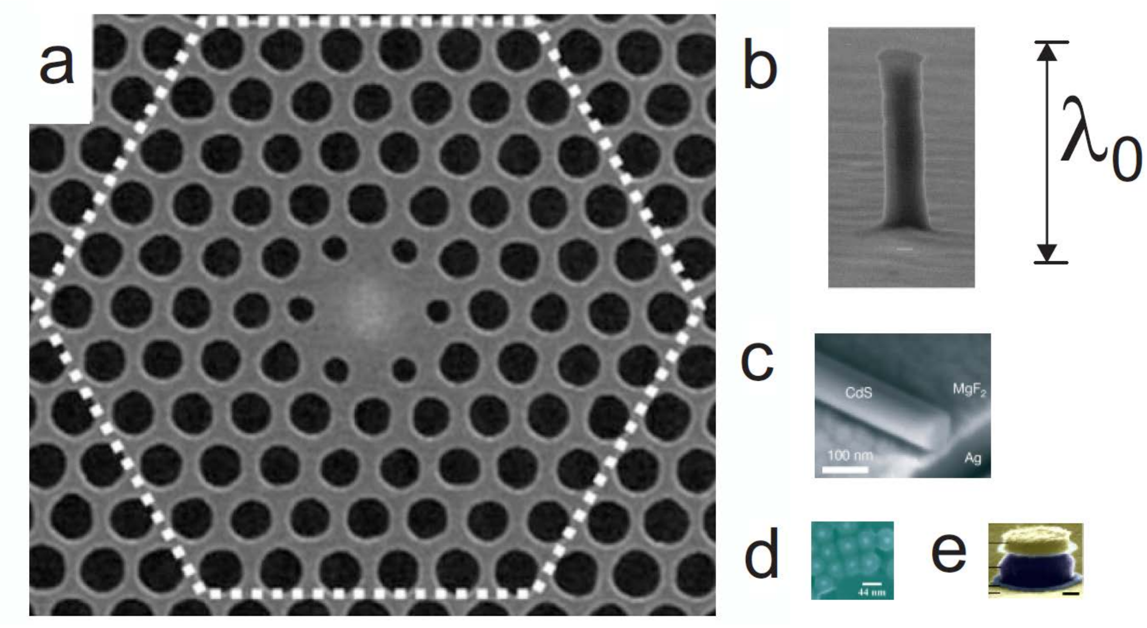

Figure 1. Size comparison of metallic and plasmonic nanolasers to dielectric nanolasers. The electron microscopy pictures are scaled to the free space emission wavelength λ_0 of each laser. **a)** A photonic crystal laser, a type of small dielectric cavity laser [66]. **b)** metallic non-plasmon mode laser [7]. **c)** metallic propagating plasmon mode laser [10]. **d)** localized plasmon mode laser [9]. **e)** Another metallic non-plasmon mode laser [12]. The metal cavity lasers developed recently exhibit a dramatic reduction in size compared to dielectric cavity lasers.

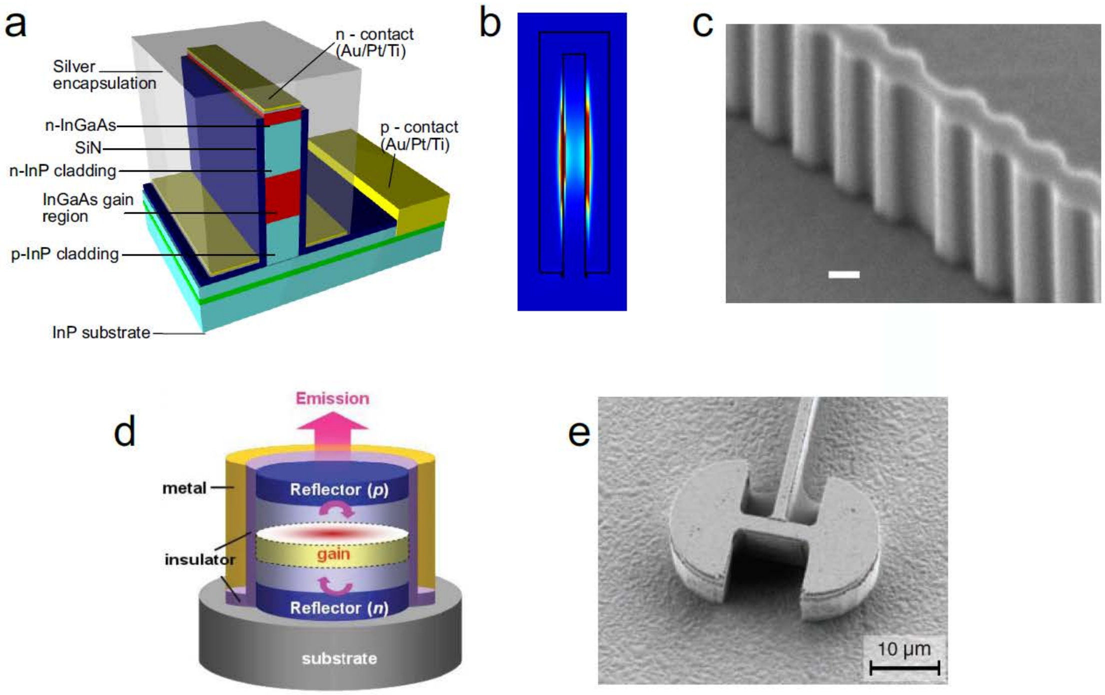

Figure 2. Different forms of small electrically pumped metallic and plasmonic lasers. a) A semiconductor heterostructure encapsulated in silver [8]. This structure has been used in many electrically pumped metal lasers. With the silver removed, the structure is similar to many dielectric waveguide heterostructure lasers. **b)** Plot of the magnitude of the electric field for a transverse magnetic 0 (gap plasmon) mode that propagates down the metal waveguide of a). Note red highest intensity to blue lowest intensity [8]. **c)** The semiconductor core which is encapsulated in silver in part a) can have many shapes, round pillars, straight waveguides, or as shown here with perturbations to form distributed feedback lasers [36], scale bar is 100nm. **d)** Another form of semiconductor heterostructure laser, but now having the mode travelling up and down the pillar which is equipped with mirrors at each end [39]. **e)** The structure of a far infrared laser which employs a MIM structure and circuit concepts to reduce the laser size well below the wavelength of the laser emission [43].

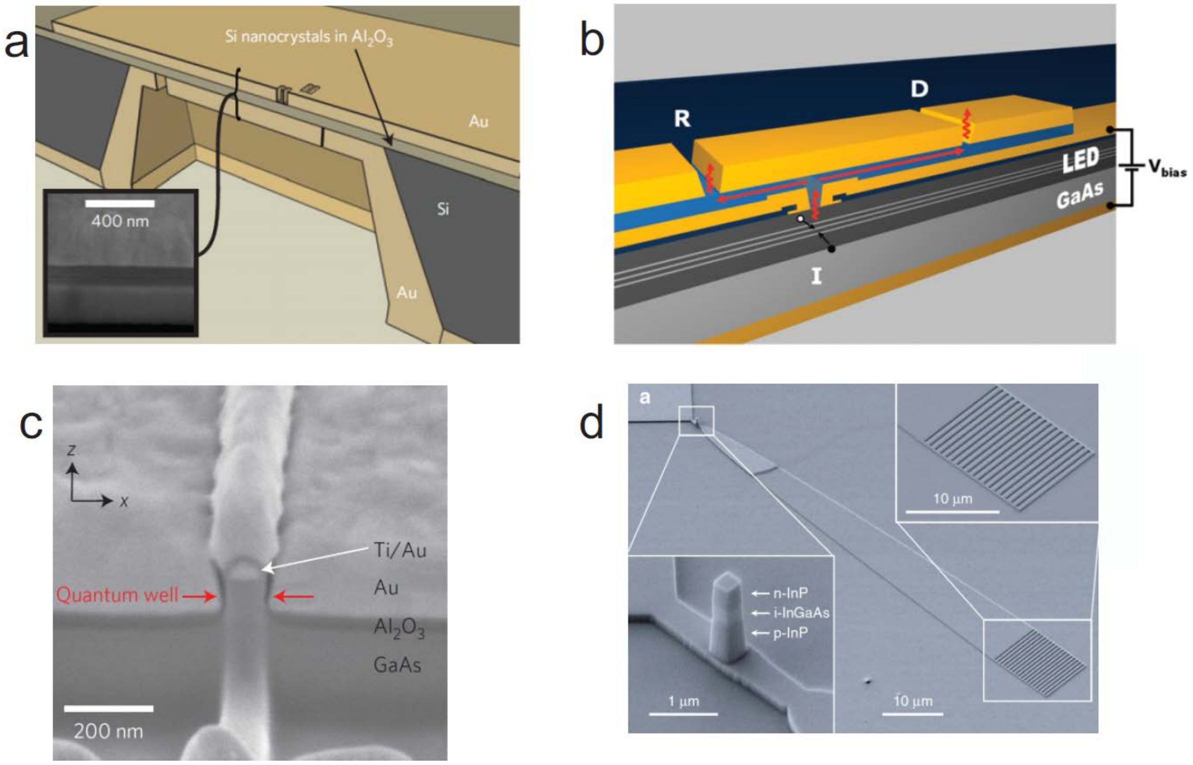

Figure 3. Some of the LED (light emitting diode) and SPED (surface plasmon emitting diodes) that have been realized. a) A MIM structure with silicon nanocrystals placed between gold electrodes [45]. **b)** Another MIM waveguide, but with semiconductor emitters placed outside the waveguide. Plasmons are coupled into the waveguide via a slit [46]. **c)** A quantum well semiconductor emitter inside a MIM waveguide [44] with the MIM layer orientation rotated 90 degrees with respect to those in parts a,b. **d)** Example of a metal clad nano cavity LED coupled to a dielectric waveguide [48].

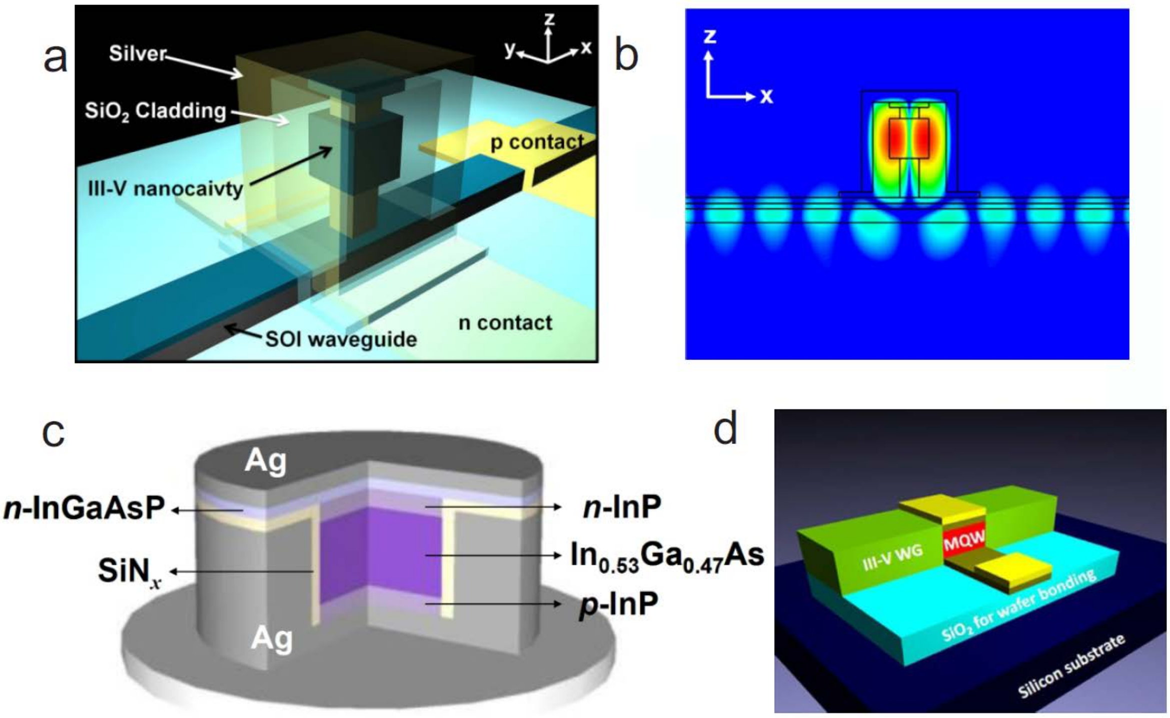

Figure 4. Some of the many small metallic and plasmonic lasers that that have been proposed. a) A metal clad laser that couples its light efficiently to a waveguide [34]. **b)** Simulation of the structure of part a) showing magnitude of the electric field and that laser light couples well to the waveguide [34]. **c)** A proposal for an extremely small 'nano coin' laser [41]. **d)** Another proposal for a waveguide coupled nano laser, but now employing a surface plasmon mode [50].