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Surface plasmon enhancement of photon extraction efficiency by silver nanoparticles: with applications in laser cooling of semiconductors

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ABSTRACT

Laser cooling of materials has been one of the important topics of photonic research during recent years. This is due to the compactness, lack of vibration, and integratibility of this method. Although laser refrigeration has been achieved in rare earth doped glass, no net cooling of semiconductors has been observed yet. The main challenge in this regard is the photon trapping inside the semiconductors, due to its high refractive index, which prevents the extraction of the energy from the material. Various methods have been proposed to overcome photon trapping but they are either not feasible or introduce surface defects. Surface defects increase the surface recombination which absorbs some portion of the photoluminescence and converts it to heat. We exploit the surface plasmons produced in silver nanoparticles to scatter the PL and make the extraction efficiency significantly higher without increasing the surface recombination. This is also important in the semiconductor lighting industry and also for enhancing the performance of solar cells by coupling the sunlight into the higher index absorbing region. Finite difference time domain simulations were used to find the total power extraction efficiency of the silver nanoparticles. It is also proposed for the first time to use the silver nanoparticles as mask for dry etching. The results for both etched and unetched cases were compared with each other. We also refer to a method of silver nanoparticle fabrication which is easy to apply to all kinds of cooling targets and is relatively cheaper than deposition of complex anti-reflective coatings.

1. INTRODUCTION

Laser cooling of rare earth doped materials has been achieved by the principle of anti-stokes blueshift of radiation [1, 2]. In this method after photon absorption the energy of the electron hole pair is increased by absorption of phonons. Consequently when the electron-hole pair is recombined the energy of the resulting photon will be higher which can lead to cooling of the device. The efficient interaction of phonons with electrons in rare earth doped materials leads into a higher internal quantum efficiency[1]. Moreover the refractive index of the host material (which is near to unity in most cases) leads to efficient extraction of the light from the rare earth doped glass. Despite success in laser cooling of these kind of materials, anti-stokes laser cooling of semiconductors has not been achieved yet. The internal luminescence efficiency of semiconductors η is defined as [3]:

$$\eta = \frac{Bn^2}{An + Bn^2 + Cn^3} \tag{1}$$

In which B is the binomial radiative coefficient, and A and C are Shockley- Read-Hall and Auger recombination coefficients, respectively. The internal quantum efficiency has been reported to be as high as 97 percent [4] for high quality semiconducting materials. The advances in increasing the internal luminescent efficiency suggests that laser cooling of semiconductors is also feasible if efficient ways of light extraction is implemented. The methods of light extraction that were used by researchers usually leads to the increase of surface defects and hence the surface recombination [5]. The increase in surface recombination is not desirable since it reduces the internal luminescence efficiency which is in opposite direction of laser cooling [6].

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If the light cannot be extracted from the material, photon trapping and recycling happens, leading to heat generation. This was the main reason behind failure of the previous attempts in laser cooling of semiconductors [7]. In this paper we propose a simple and efficient way to increase the light efficiency with minimal surface damage. This method is based upon light scattering from silver nanoparticles that is necessary in order to transfer light from a higher index medium (semiconductor) to a lower index environment (air). In section II, The fabrication steps leading to the formation of silver nanoparticles is described. According to the SEM and AFM images obtained after fabrication, 3D Finite difference time domain (FDTD) simulations were used to simulate the structure. The theoretical prediction for excitation efficiency of nanoparticles for different sizes was obtained and compared to the case of a simple one layer Anti-Reflection coating. The enhancement of radiation to the outside of the material due to scattering by the silver nanoparticles is evident.

2. FABRICATION

The wafer was grown by MOCVD on an InP substrate. The active region consists of a 300 nm thick active region of quantum wells with an effective bandgap of 0.88 eV. All of the layers are lattice matched to InP. The active region was capped with a p-doped InP layer with the thickness of 1.5 μm. There is a thin etch stop layer of InGaAs which is sandwiched inside the cap layer and is located half a micron above the active region. The capping layer is usually etched up to the etch stop layer for making ridge waveguides, therefore we consider only a capping layer with the thickness of 0.5 μm in all of our simulations. We followed the same method as Ref [8, 9] in order to make the silver nanoparticles. First 30 nm of silicon nitride was deposited on the surface of the sample by PECVD, then 17 nm of silver was deposited by electron beam deposition followed by 90 minutes annealing under nitrogen purge. The nano islands of the silver form because of poor surface adhesion of silver to silicon nitride. The SEM images of the particles are shown in Figure 1 . Next we have done an AFM measurement in contact mode in order to find the average height of the nanoparticles as shown in Figure 2. This information was used in order to do the simulations as outlined in the next section.

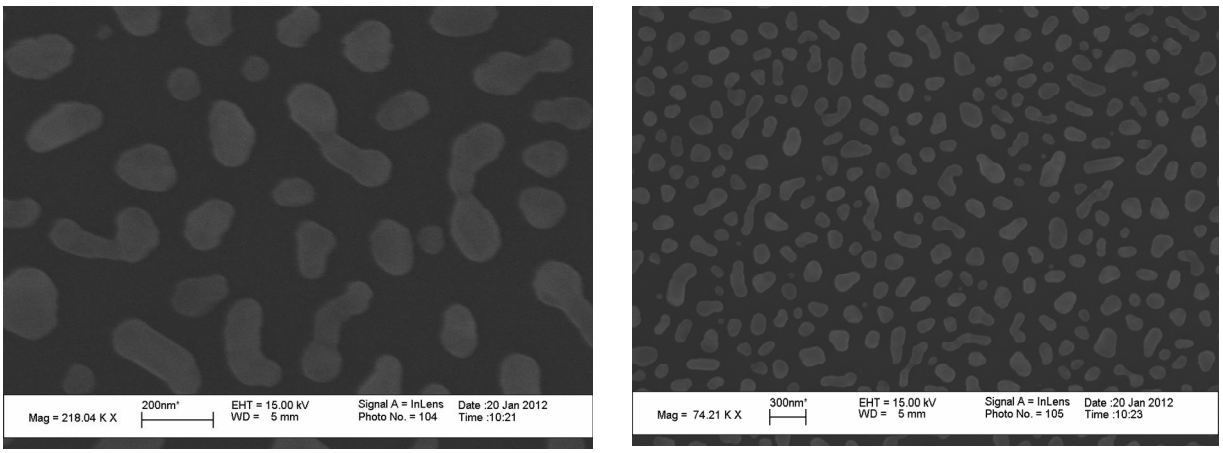

Figure 1 SEM photo of the fabricated silver nanoparticles for two different magnifications.

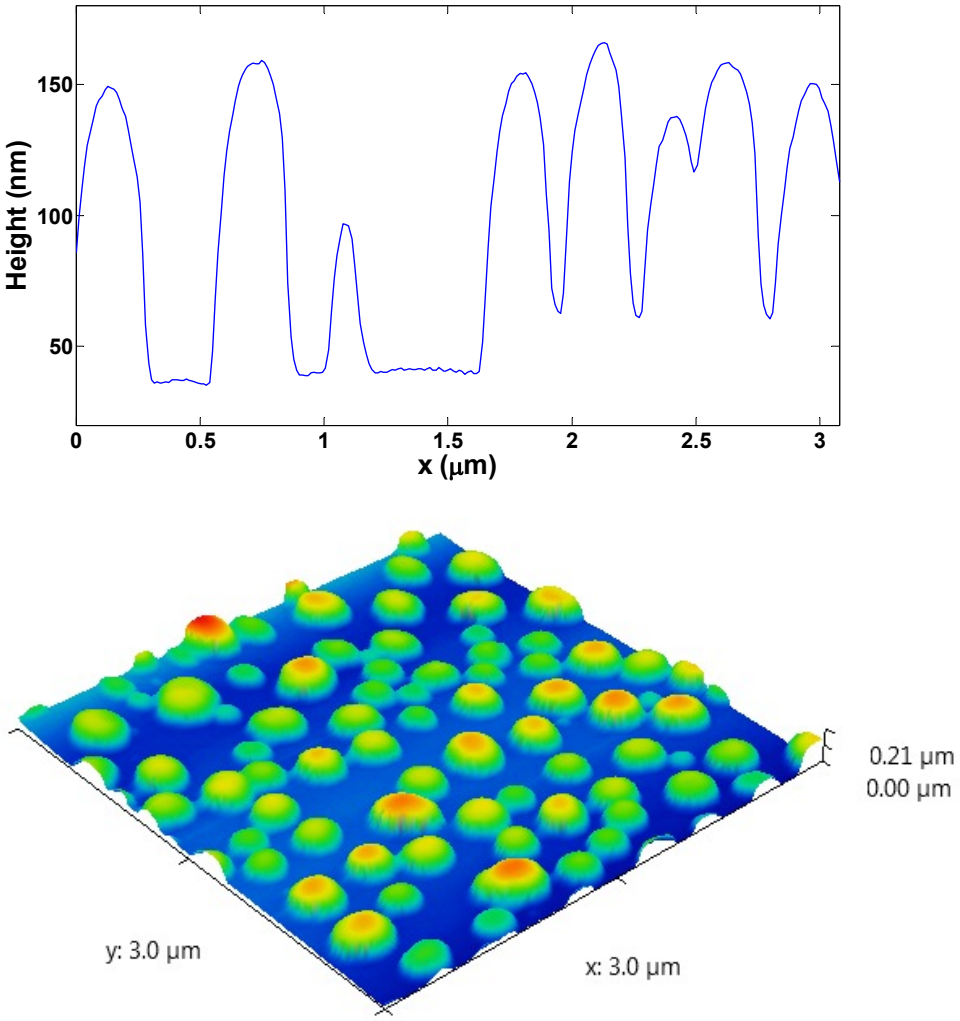

Figure 2 AFM micrograph of the sample showing the relative height of each silver nanoparticle.

3. SIMULATION

The FDTD method was used to simulate the structure as shown in Figure 2. A half cylinder was used to represent an arbitrary particle. Perfect matched layers (PMLs) boundary conditions are imposed on all boundaries in order to minimize the reflection. A power monitor was placed on the top of the structure in order to collect the power of the photoluminescence. The photoluminescence of the sample was modeled by a single point source with polarization parallel to the surface of the wafer according to Ref [10]. Ideally the simulation area should be large enough to reduce the effect of PML boundaries on the final results. However because of this, the computational burden becomes significantly high. In order to avoid this problem we adopted the same method as Ref [11]. In this case since the distance from the nanoparticles to the quantum well region is large, Plasmon-exciton interaction is very low and can be neglected. Therefore the nanoparticles act as scattering centers and don't affect the exciton energy therefore the PL spectra retains its shape and it is only amplified by silver nanoparticles as shown in Figure 3.

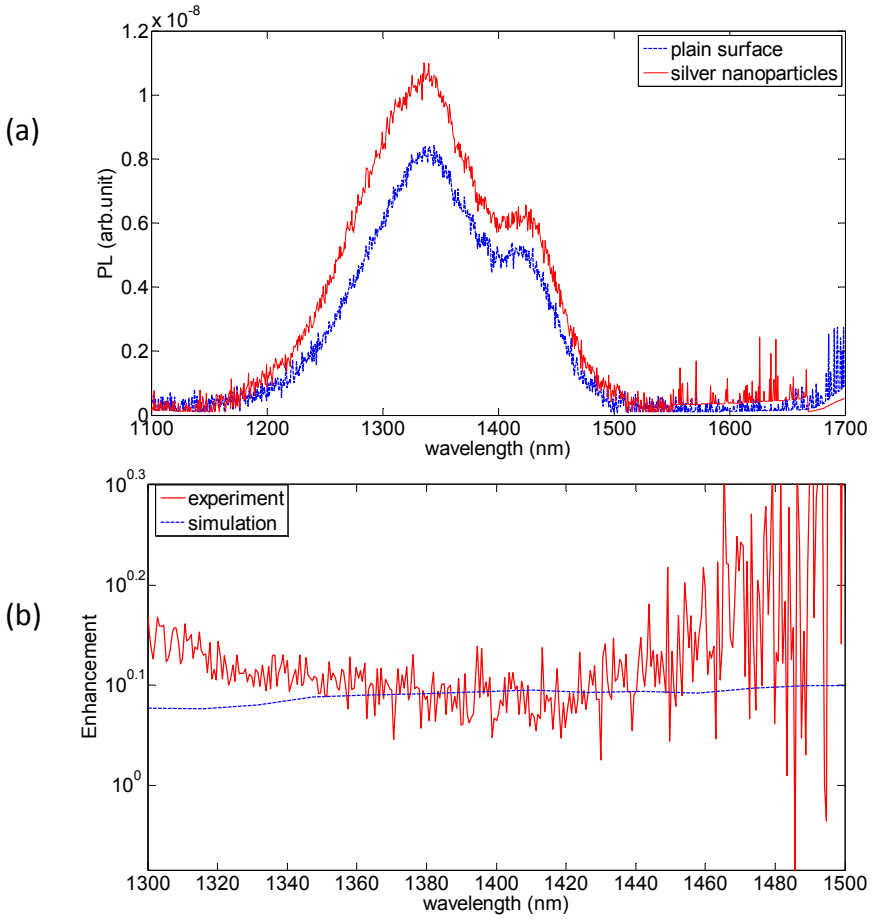

Figure 3 (a) measured PL spectra on the regions with and without silver nanoparticles.(b) the dashed line shows the calculated values of the enhancement of output power with respect to the single layer AR. The solid red line is the corresponding data obtained by measurements.

A 980 nm laser is used in order to excite the material with photons which have energies much higher than the bandgap energy. The use of the 980 nm laser as a pump source leads to strong PL signals and enables us to measure the PL power with high accuracy and signal to noise ratio but for laser cooling purposes, the material is pumped with photons which have energies close to the bandgap and the emission energy. For this reason we are only interested in scattering properties of silver nanoparticles near emission wavelength (~1400nm) and point source has a center wavelength exactly equal to the emission wavelength. The extraction efficiency is defined as fraction of the power which is coupled to the outside of the semiconductor. In the experiments the PL power spectra was measured for the parts with and without silver nanoparticles as shown in Figure 3(a). The ratio of the PL powers of both regions is defined as the enhancement. Figure 3(b) Shows that the measured and simulated enhancements agree very well over the PL wavelength range in which the experimentally determined enhancement doesn't have large fluctuations. The extraction efficiency is shown to be approximately 20 percent higher for the region with silver nanoparticles.

It is evident that using the silver nanoparticles will enhance the transmission of PL out of the structure. It has been reported that this method doesn't introduce surface damages and doesn't lead to surface recombination at the metal semiconductor interface because the silicon nitride layer acts as the protection layer [12].

4. EXPERIMENTAL SETUP AND METHODOLOGY

Silver nanoparticles scatter both incoming 980 nm laser light and the PL emitted from the active region (near 1400 nm) which makes it impossible to measure PL using ordinary methods used for planar surfaces. In order to address this problem, a new measurement setup is designed. The methodology for measuring the total PL power of the sample is explained in this section and is applicable to different kinds of samples. It is important to note that this method will also be useful to measure the total luminescence emitted by LEDs. The diagram of the experimental setup is shown in Figure 4. It is comprised of an inverted microscope and an upright microscope. The sample is polished from the side which is not covered by silver nanoparticles in order to allow the 980 nm pump beam to enter the active region without scattering. The absorption of the active region at 980 nm is approximately 4×10^4 cm^{-1} as a result 80 percent of the pump beam is absorbed before reaching the silver nanoparticles. Therefore the scattering of the pump beam by the silver nanoparticles can be neglected. The inverted microscope is used to focus the 980 nm laser beam to a small spot with a diameter of 2μm whereas the upright microscope is used the collect the PL signal from the front side of the sample. The collimated 980 nm laser goes through a beam splitter which provides a path for the infrared camera to see the surface of the sample simultaneously using the inverted microscope. The upright microscope has the same structure as the inverted microscope

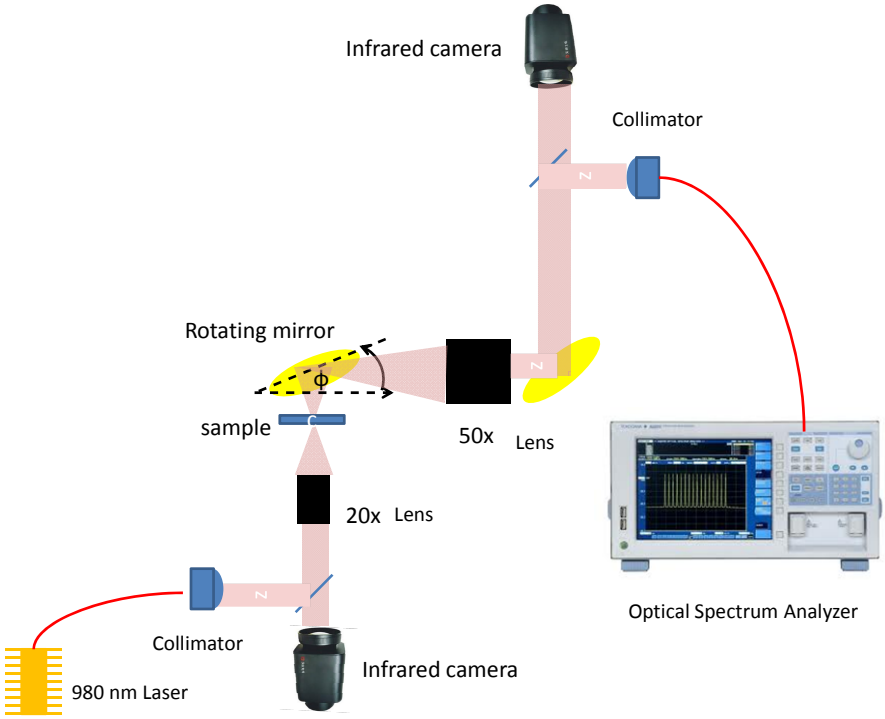

Figure 4 schematics of the measurement setup.

except that its lens has a magnification of 50x. The upright microscope is used for both collecting the PL and observing the surface of the sample. The carriers are generated by the pump laser and then they diffuse in the quantum well plane during the recombination. Therefore the PL is emitted by the sample over a large area. The diameter of this area is

approximately equal to twice of the diffusion length in this material (~80 μm). The objective lens of the upright microscope is oriented orthogonally with respect to the microscope axis using a fixed 45 degree mirror. The 50x objective lens sees the surface of the sample through a rotating mirror. The angular distribution of PL radiation can be investigated using this mirror. Whenever the orientation of the rotating mirror is changed, the sample surface may become out of focus for the upright microscope, therefore a translation stage is necessary to bring the sample in focus. It should be noted that the relative position of the sample and the inverted microscope objective remains unchanged as the mirror position is changed as a result the PL is obtained exactly at a fixed location on the surface of the sample. Using the described setup, the pump beam was focused on the regions with and without silver nanoparticles and the PL spectra was obtained using an optical spectrum analyzer as shown in Figure 3(a). The silver nanoparticles enhance the PL emission by 20 percent.

5. CONCLUSION

Silver nanoparticles act as efficient scattering centers for the light photoluminescence is produced inside the material. In this study we first introduced a simple and cost effective method to fabricate the nanoparticles, The dimensions of the fabricated silver nanoparticles were obtained using SEM and AFM microscopy. The AFM topography images were obtained under contact mode. Simulations were performed with the aforementioned obtained dimensions. The simulations agree closely with the experimental result. An enhancement of 20 percent near the telecommunication wavelengths was demonstrated experimentally. The experimental setup that is capable of measuring the PL was explained in detail. The use of two different objective lenses in two different microscopes enables to focus the pump beam to a small region while collecting the PL from a large area on the surface. A rotating mirror can be used to collect the PL from arbitrary angles. The setup is appropriate to study the angular properties of the PL for a wide variety of structures.

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