Enhancement of Photon Emission Rate in Antenna-Coupled nanoLEDs

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Abstract: Using a simple antenna model, we show a semiconductor coupled to an optical antenna can significantly increase spontaneous emission rate. Our experimental measurements shows a 20x increase in photoluminescence, which agrees well with the theory.

I. Introduction

Many attempts to create a fast modulated LED focus on removing carriers from the device in a non-radiative way, such as by sweeping the carriers out using a BJT type structure[1] or through surface recombination[2]. Although modulation bandwidths up to 7 GHz have been achieved, it was at the sacrifice of the device quantum efficiency. Metal structures have also been attempted, such as coupling gain material to surface plasmons[3], however the inability to efficiently couple light out from surface plasmon modes results in low efficiency devices. To obtain a fast and efficient device, the radiative lifetime must be shortened while maintaining a relatively long non-radiative lifetime. Theoretically, by coupling to a low-Q resonator such as an optical antenna, very large bandwidth, in excess of 100GHz or even approaching THz, is possible when the emitter size is in the nanoscale[4]. Antenna enhanced emission has only been demonstrated with dye molecules as active media[5], however, dye molecules cannot be electrically pumped or directly modulated at high speed.

In this paper, we demonstrate an optical dipole antenna that is coupled to a ridge (34nm wide x 35nm tall) of semiconductor material. A simple antenna-based analysis predicts photon emission enhancements from this device of 20x. Photoluminescence measurements confirm this by showing quantum efficiency enhancements of 20x due to a corresponding decrease in the spontaneous emission lifetime.

II. Theory

The spontaneous emission rate enhancement of a dipole antenna can be determined by its equivalent circuit model. In this model, the semiconductor is taken as a collection of individual oscillating dipoles that act as a current source to the coupled antenna. The antenna will have an associated reactance, ohmic resistance, and radiation resistance:

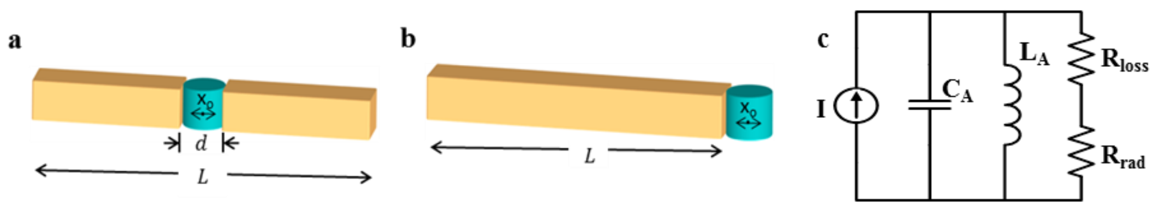

Figure 1 | Semiconductor coupled to an Optical Antenna. a, Parallel plate capacitor coupled dipole antenna. **b,** End-coupled antenna and **c,** circuit model of an optical dipole antenna.

The current generated in the circuit can be found by Ramo's theorem[6] which states the current induced by an oscillating charge in a parallel plate capacitor is a function of the plate spacing (d), oscillation frequency (ω), and the dipole length (x_o), $I = \frac{q x_0 \omega}{d}$. On resonance, the antenna capacitance exactly cancels out its inductance. The radiation rate is then proportional to $I^2 R_{rad}$, where R_{rad} is known for a dipole antenna of arbitrary length (L):

$$\frac{1}{\tau} = \frac{2I^2 R_{rad}}{\hbar\omega} = \frac{q^2\omega}{2\hbar}\left(\frac{x_0}{d}\right)^2 \frac{\pi}{6} Z_o \left(\frac{L}{\lambda}\right)^2 n$$

Dividing this quantity by the emission rate in a material of index n gives the total enhancement:

$$\frac{\tau_o}{\tau} = \frac{2\frac{q^2\omega}{\hbar} n \left(\frac{x_0}{d}\right)^2 \frac{\pi}{6} Z_o \left(\frac{L}{\lambda}\right)^2}{\frac{\mu_o \omega^3 n}{3\pi\hbar c}(q x_0)^2} = \frac{1}{4}\left(\frac{L}{d}\right)^2$$

Note that the enhancement is determined by geometric factors: it is proportional to the square of the antenna length to its gap spacing. A 300nm long antenna with a 34nm gap should therefore enhance the spontaneous emission rate by 20x. Similar analysis of an end-coupled antenna shows only slightly reduced enhancement for ridges 34nm wide.

III. Experimental Characterization

Figure 2 shows the basic antenna design. It consists of a semiconductor ridge that is covered by a gold bar deposited perpendicularly over it. This creates a dipole antenna with the gain material in the gap and an arch over the top that acts as an LC matching circuit. The antenna is fabricated on top of a gold reflector plane and an InP spacer layer designed to direct the radiation upwards[7]. The antennas are fabricated in an array with a 700nm pitch.

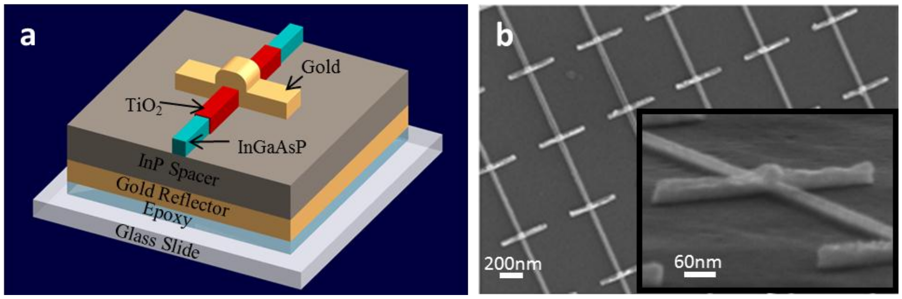

Figure 2 | nanoLED Structure. a, Perspective view of nanoLED structure with LC matching arch. **b,** SEM of antenna arrays and (inset) perspective SEM of single optical antenna. Antennas are 300nm long with ridge widths of 34nm.

Photoluminescence measurements were performed by pumping the semiconductor ridge arrays with a Ti:Sapphire laser with center wavelength of 1000nm polarized perpendicular to the antennas. Collected light was passed through a polarizer aligned either perpendicular or parallel to the antennas. Due to the geometry of the ridges, they absorb and therefore also emit light polarized almost completely in the direction of the ridge[8]. This allows for a separation of unenhanced PL (polarized parallel to the ridges) and antenna enhanced PL (polarized parallel to the antennas).

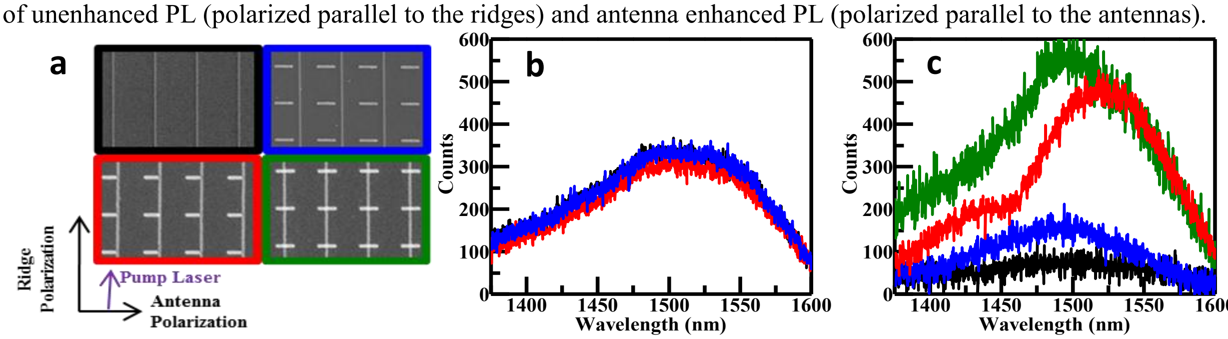

Figure 3 | Photoluminescense from InGaAsP nanoridge arrays. a, SEM micrographs of four arrays of ridges with no antennas (black), misaligned antennas (blue), end-coupled antennas (red), and parallel-plate coupled antennas (green). **b,** PL of the four arrays for light emitted polarized perpendicular to the antennas and **c,** PL of the four arrays for light emitted polarized parallel to the antennas.

As shown in Figure 3, antennas that are not touching the ridge show minimal enhancement in PL parallel to the antenna arrays, while antennas that are touching the ridge show significantly enhanced PL. This enhanced light emission can therefore not be attributed to increased light extraction from scattering trapped light out of the InP substrate since scattering trapped light would not be affected by the exact alignment of the antennas with respect to the InGaAsP ridges. Since the ridge itself cannot support waveguided modes, the large increase seen when the antenna is contacting the ridge must be due to an increased spontaneous emission rate. In all cases, the PL perpendicular to the antennas remains mostly unaffected by the presence or alignment of antennas. A 1.7x increase in total light out is seen in the parallel-plate coupled antennas versus the bare InGaAsP ridge arrays. The antennas are 60nm wide with a pitch of 700nm, therefore only about 8.5% of the total ridge area is emitting light at an enhanced rate. Taking into account this geometrical factor, the spontaneous emission rate from the area in contact with the ridge is enhanced by a factor of 20x, in good agreement with the theoretical value calculated using the antenna model.

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