Efficient Rate Enhancement of Spontaneous Emission in a Semiconductor nanoLED

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Abstract: Optical antennas drastically increase the spontaneous emission rate of a semiconductor LED, yielding 30x improvements in quantum efficiency. Their nanoscale size, high efficiency, and fast emission rate make them good candidates for ultra-low power communication.

1. Introduction

The speed of traditional light-emitting diodes (LEDs) is limited by the spontaneous emission rate of bulk semiconductors. Enhancement of spontaneous emission rate has been demonstrated by coupling the emitters to metallic structures (surface plasmons) [1,2], metal optic cavities [3], photonic crystal cavities [4], and optical antennas [5–7]. The optical antenna approach is particularly interesting because it can provide up to several orders of magnitude speedup while maintaining a high efficiency. Antenna enhanced emission was first demonstrated with dye molecules [5], however, dye molecules cannot be electrically pumped or directly modulated at high speed. Dipole antennas have been integrated on top of semiconductor quantum wells and 8x enhancement in photoluminescence was observed [6]. However, the antenna-quantum well coupling is weak and the enhancement measurement is complicated by light trapping in the semiconductor substrate. Recently, we have reported a dipole antenna-coupled nano-ridge LED with 20x enhancement [7]. The nano-LED is fabricated on a metallic ground plane with a thin (370nm) InP spacer layer to increase the radiation into free space, though the thin InP spacer still traps some light.

In this paper, we report a “free-standing” dipole-coupled nano-ridge (35nm wide x 35nm tall) LED with total substrate removal and complete elimination of light trapping. We also remove the ridge outside the antenna to further suppress the un-coupled emission. Photoluminescence measurements show quantum efficiency enhancements of 30x due to a corresponding decrease in the spontaneous emission lifetime. The emission peak wavelength agrees well with antenna length.

2. Rate Enhancement Measurement

The spontaneous emission rate enhancement of a dipole antenna can be determined by its equivalent circuit model [7]. The rate enhancement is found to be a function of the antenna length (L) and gap spacing (d):

$$\frac{\tau_o}{\tau} = \frac{1}{4}\left(\frac{L}{d}\right)^2$$

A 400nm long antenna with a 35nm gap should therefore enhance the spontaneous emission rate by 32x. In a real metal, the radiation losses will compete with the ohmic losses. For a 400nm long, 50nm wide gold antenna operating at 1400nm, the corresponding ratio of radiative to ohmic losses gives an antenna efficiency of 67%.

Time resolved photoluminescence is often used to determine the emission rate enhancement, although it can prove challenging at long wavelengths with such low-power emitters. If the semiconductor recombination rate is limited by non-radiative recombination, then the quantum efficiency of the emitter can be used as proxy for rate enhancement. This is the case for a nano-ridge of InGaAsP without surface passivation where surface recombination dominates. It is crucial however, to eliminate all sources of external efficiency enhancement such as light extraction which can enhance extraction efficiency from a high index (n) substrate by $4n^2$ without altering the spontaneous emission rate.

Another concern in rate enhancement measurements is signal from uncoupled semiconductor. An optical antenna only couples to material in very close proximity (within ~10s of nm). Removing all emitter material far from the antenna will therefore give a better indication of the antenna-induced rate enhancement.

3. 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 ridge length is kept small to minimize the amount of semiconductor far from the antenna (and therefore not coupled to it). The antennas are fabricated in staggered arrays of 1400nm pitch. Unlike previously reported structures, these arrays are flip-chip bonded to a glass slide with epoxy and the substrate is completely removed to eliminate light trapping effects.

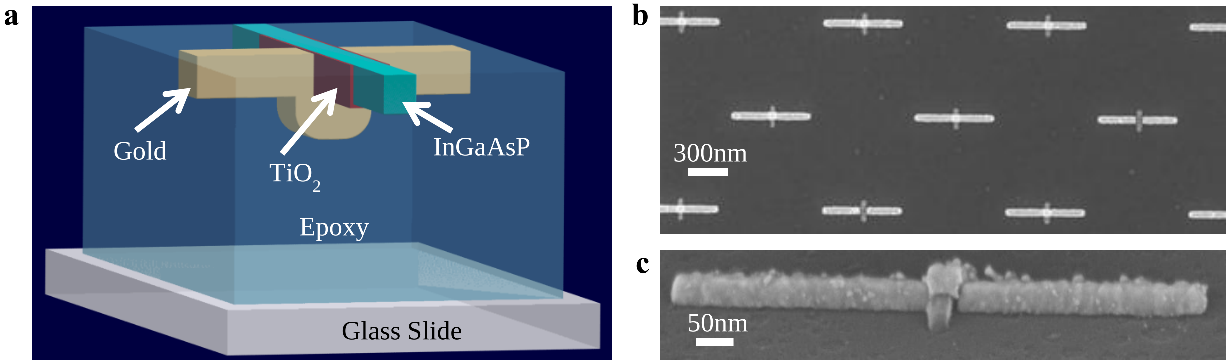

Figure 2. a, Perspective view of nanoLED structure after being bonded to glass with epoxy. **b,** SEM of antenna arrays before flip-chip bonding. **c,** perspective SEM of single optical antenna. Antennas are 500nm long and 50nm wide; InGaAsP ridges are 35nm wide and 150nm long.

Photoluminescence measurements were performed by pumping the semiconductor ridge arrays with a Ti:Sapphire laser with center wavelength of 720nm polarized perpendicular to the antennas. Emitted light was passed through a polarizer aligned either perpendicular or parallel to the antennas and then sent through a spectrometer and collected on a LN-cooled CCD.

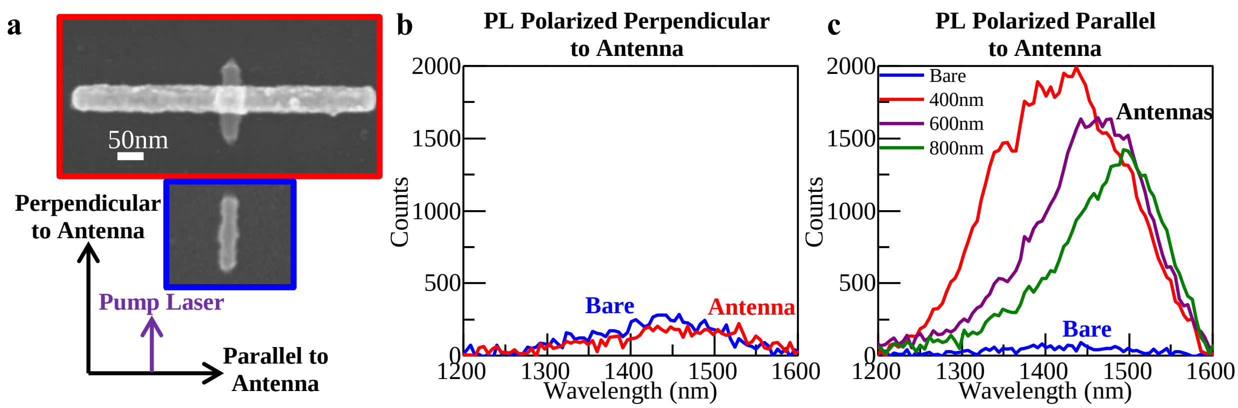

Figure 3. a, SEM micrographs of a bare InGaAsP ridge (blue) and an antenna coupled ridge (red). **b,** PL of the ridges for light emitted polarized perpendicular to the antenna and **c,** PL of the bare ridge and three different length antennas for light emitted polarized parallel to the antennas.

As shown in Figure 3, antenna coupled ridges show almost no change in light emitted polarized perpendicular to the antenna as compared to the bare ridge. Light polarized parallel to the antennas, however, shows a significant increase when an antenna is present. A 30x broadband increase is seen for 400nm long antennas with longer antennas showing enhancements at longer wavelengths. The antenna resonance wavelength does not increase linearly with antenna length due to the effect of the LC matching arch. Since these structures are surface recombination rate dominated, this 30x increase in PL can be directly attributed to an increased spontaneous emission rate. This corresponds well with the 32x rate increase predicted with antenna theory. Such large rate enhancements make these devices good candidates for high-speed nano-emtters in ultra-low power applications.

4. References

[1] A. Neogi, C.-W. Lee, H. Everitt, T. Kuroda, A. Tackeuchi, and E. Yablonovitch, "Enhancement of spontaneous recombination rate in a quantum well by resonant surface plasmon coupling," *Phys. Rev. B*, vol. 66, no. 15, Oct. 2002.

[2] V. J. Sorger, N. Pholchai, E. Cubukcu, R. F. Oulton, P. Kolchin, C. Borschel, M. Gnauck, C. Ronning, and X. Zhang, "Strongly Enhanced Molecular Fluorescence inside a Nanoscale Waveguide Gap," *Nano Letters*, vol. 11, no. 11, pp. 4907–4911, Nov. 2011.

[3] E. K. Lau, A. Lakhani, R. S. Tucker, and M. C. Wu, "Enhanced modulation bandwidth of nanocavity light emitting devices," *Optics Express*, vol. 17, pp. 7790–7799, 2009.

[4] D. Englund, D. Fattal, E. Waks, G. Solomon, B. Zhang, T. Nakaoka, Y. Arakawa, Y. Yamamoto, and J. Vučković, "Controlling the Spontaneous Emission Rate of Single Quantum Dots in a Two-Dimensional Photonic Crystal," *Phys. Rev. Lett.*, vol. 95, no. 1, Jul. 2005.

[5] A. Kinkhabwala, Z. Yu, S. Fan, Y. Avlasevich, K. Müllen, and W. E. Moerner, "Large single-molecule fluorescence enhancements produced by a bowtie nanoantenna," *Nature Photon*, Oct. 2009.

[6] D. Arbel, N. Berkovitch, A. Nevet, A. Peer, S. Cohen, D. Ritter, and M. Orenstein, "Light emission rate enhancement from InP MQW by plasmon nano-antenna array," *Optics Express*, vol. 19, no. 10, May 2011.

[7] M. Eggleston, N. Kumar, L. Zhang, E. Yablonovitch, and M. C. Wu, "Enhancement of Photon Emission Rate in Antenna-Coupled nanoLEDs," in *Semiconductor Laser Conference (ISLC), 2012 23nd IEEE International*. Accepted for publicaton.