Spontaneous Emission Rate Enhancement using Gold Nanorods

Nikhil R. Kumar*, Kevin Messer, Michael Eggleston, Ming C. Wu, Eli Yablonovitch
UC Berkeley Department of Electrical Engineering
*Nikhil.RKumar@gmail.com

Abstract:
We present a 7nm bare InGaAsP quantum well coupled to a gold nanorod. Photoluminescence measurements show an increased spontaneous emission rate of at least 4.5x without sacrificing efficiency.

I. Introduction
High-speed optical communication has been dependent on lasers due to their high modulation bandwidth. However, the modulation speed of lasers is inherently limited to <50GHz by nonlinear gain saturation. Lasers also must be operated above their threshold current to achieve this bandwidth. Light Emitting Diodes (LEDs) on the other hand are limited by spontaneous emission, a rate that is dependent upon the emitter's electromagnetic environment. LEDs also have no minimum threshold current for achieving their maximum switching speed enabling low power communications. Recent work has shown that the modulation speed of LEDs can potentially be much faster than that of lasers by taking advantage of small modal volumes and/or high Q optical cavities [1]. However, recent devices often sacrifice efficiency for modulation speed; a tradeoff that can always be made even in conventional devices[2].

Optical antennas have been shown to greatly increase the spontaneous emission rate from dye-molecules[3]. In this work, we show that the overall efficiency-bandwidth product of a semiconductor can increase by coupling the active material (InGaAsP) to a gold nanorod. When the metallic structure is resonant at the emission wavelength of InGaAsP, an increase in photoluminescence (PL) and hence rate enhancement is observed.

The spontaneous emission of the InGaAsP semiconductor can be modeled as light emission from several oscillating dipoles with a dipole moment of around $0.4A^0$. Because of the mismatch between the dipole moment of the material and the wavelength of emitted light, spontaneous emission is typically weak. Our device acts as a half-wavelength dipole antenna with the semiconductor dipole acting as an oscillating current between the two tips. Coupling the emitting material to an antenna improves the power transfer from the oscillating dipoles in the semiconductor to free-space, thus increasing the rate of spontaneous emission[4].

II. Structure
Fig 1 is a schematic of the fabricated structure. The gold nanostructures are patterned with e-beam lithography on a 7nm layer of InGaAsP before flip-chip bonding with epoxy onto glass and etching away the substrate. A second e-beam lithography step creates a mask to etch away most of the semiconductor material that is not coupled to the gold nanorod.

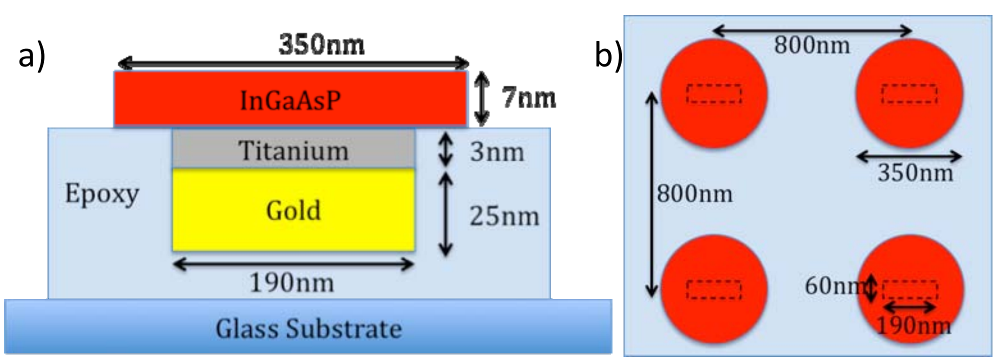

Fig 1. a) cross-sectional view of the fabricated structure, b) top-view

Reducing the amount of excess semiconductor serves two purposes. First, It reduces background photoluminescence revealing the full enhancement of the spontaneous emission due to the gold nanorods. Second, it prevents the gold structures from simply scattering out waveguided light in the epitaxial layer, an effect that would increase the total amount of PL observed but would not indicate an increase in rate. The latter purpose allows us to use enhancement in PL as a proxy for enhancement in rate. The antennas are fabricated 800nm apart to reduce coupling between the structures.

III. Results and Discussion

The samples were pumped with a Ti-Sapphire laser tuned to 1080nm and polarized perpendicular to the long axis of the antennas. The resulting PL was measured using a liquid nitrogen cooled InGaAs CCD. The spectra for different cases of alignment between the antennas and semiconductor for emission in both the antenna and perpendicular polarizations are shown in Figure 2. We see an increase in PL in the antenna polarization when the InGaAsP is aligned with the antennas. The magnitude of this increase is 4.5x when compared to patches of InGaAsP with no antennas present. By reducing the amount of background semiconductor, this enhancement factor can be improved. As expected, there is no increase in PL in the perpendicular polarization, since this is the null of the antenna mode.

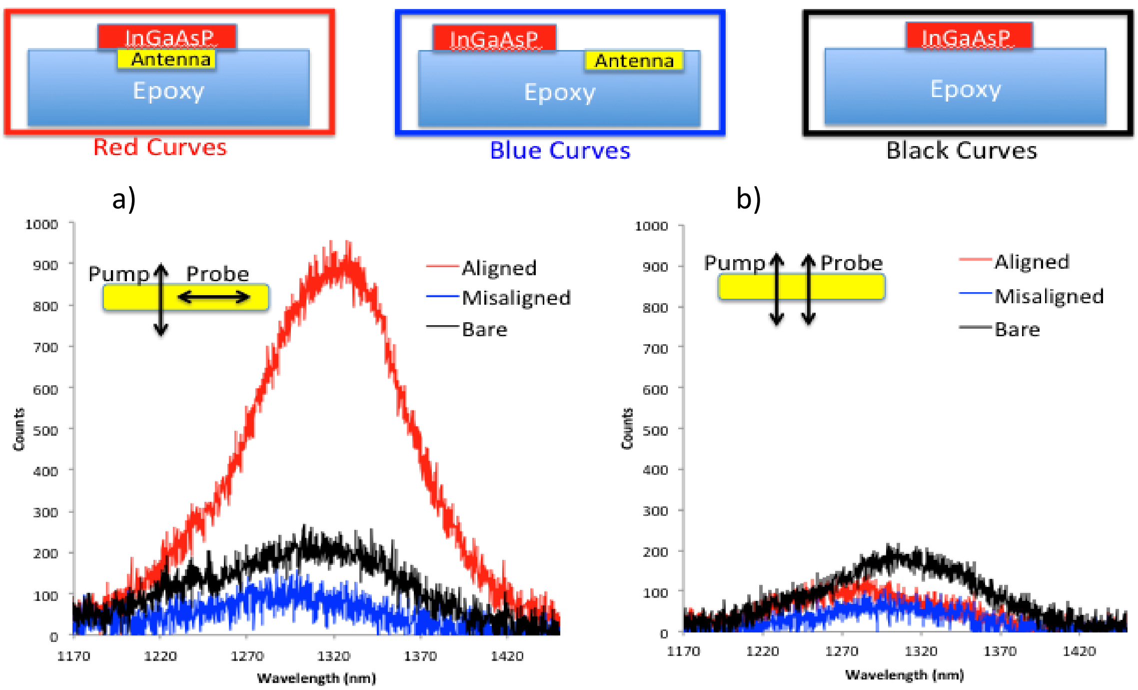

Fig 2. Spontaneous emission spectrum from aligned (red), misaligned (blue) and bare (black) devices. a) emission parallel to the long axis of the antenna, b) emission perpendicular to antenna

[1] 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.

[2] G. Shambat, B. Ellis, A. Majumdar, J. Petykiewicz, M. A. Mayer, T. Sarmiento, J. Harris, E. E. Haller, and J. Vučković, “Ultrafast direct modulation of a single-mode photonic crystal nanocavity light-emitting diode,” *Nature Communications*, vol. 2, p. 539, Nov. 2011.

[3] 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.

[4] M. Eggleston, N. Kumar, L. Zhang, E. Yablonovitch, M. C. Wu;, “Enhancement of Photon Emission Rate in Antenna-Coupled nanoLEDs” Semiconductor Laser Conference (ISLC), 2012 23rd IEEE International. (Manuscript accepted for publication).