Optical Antenna Based nanoLED

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Abstract: An optical antenna based nanoLED design that enhances photoluminescence of a semiconductor emitter by more than 10x is presented. The small mode (0.015 $(\lambda_0/2n)^3$) and physical ($3x10^{-4}\ \lambda_0^3$) volumes are attractive for on-chip optical interconnect applications.

I. Introduction

Spontaneous emission has been considered slower and weaker than stimulated emission. As a result, light-emitting diodes (LEDs) have only been used in applications with bandwidth < 1 GHz. Spontaneous emission is inefficient because the radiating dipole is much smaller than wavelength (~ $2.5x10^{-4}\ \lambda_0$ where λ_0 is the free space wavelength). Such short dipoles are poor radiators. By attaching an optical antenna to the radiating dipole at the nanoscale, the emission rate can be significantly increased. Theoretically, very large bandwidth, in excess of 100GHz or even approaching THz, is possible when the emitter size is in the nanoscale (< 0.01 $(\lambda_0/2n)^3$) [1]. This type of device has only been demonstrated with dye molecules as active media [2], [3], however, dye molecules cannot be electrically pumped or directly modulated at high speed. Recently, metal optics has been combined with semiconductor gain media to demonstrate nanolasers [4-6]. However, the mode volumes of such cavities are still too large for the nanoLED.

In this paper, we report on a novel optical antenna-based nanoLED in the infrared regime (~ 1550nm wavelength). The effective optical mode volume is as small as 0.015 $(\lambda_0/2n)^3$, and the optical Q is ~7. We have observed enhancement of photoluminescence by more than 10x. The nanoLED is also physically small (50nm x 60nm x 350nm, or $3x10^{-4}\ \lambda_0^3$), making them attractive for on-chip optical interconnect applications.

II. Device Design

An optical antenna provides a simple and effective way of making a nanoLED with very small volume. A simple structure to make is a half-wave dipole antenna with matching circuit. The driving source in this antenna is the gain material and it is therefore located in the gap of the antenna. For a high-efficiency device the radiation Q should be lower than the metal loss Q to minimize energy dissipated as heat in the metal. Using a matching circuit allows the frequency and radiation Q to be tuned independently of each other. Figure 1 shows the basic antenna design. It consists of a semiconductor ridge passivated with a thin oxide layer that is covered by a gold bar laid perpendicularly over it. As shown in Figure 1(b), 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. By adjusting the length of the antenna arms and the dimensions of the arch the device parameters can be tuned. For the device shown the radiation Q has been matched to the metal loss Q of 14 for a total Q of 7.

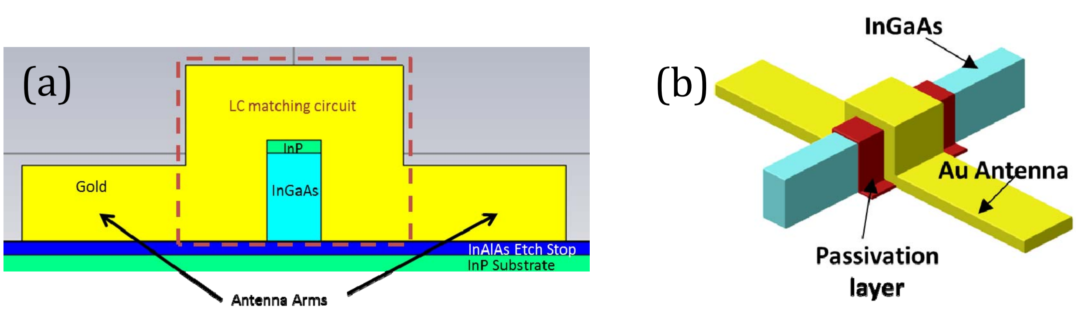

Fig.1 nanoLED design. (a) Side-view of nanoLED showing antenna components. (b) Perspective View of nanoLED.

III. Experimental Characterization

The epitaxial layers are grown by MOCVD and consist of an InAlAs etch stop, a 30nm-thick InGaAs active layer, and a 5nm-thick InP cap. Devices were fabricated using e-beam lithography and reactive ion etching (RIE) to define an array of semiconductor ridges followed by e-beam patterning and metal lift-off to define the metal antennas. Devices with ridges as narrow as 24nm were fabricated. The ridges are 35nm high and the optical antennas are 350nm long, 50nm wide, and 30nm thick. Figure 2 shows scanning electron micrographs (SEM) of the fabricated structure.

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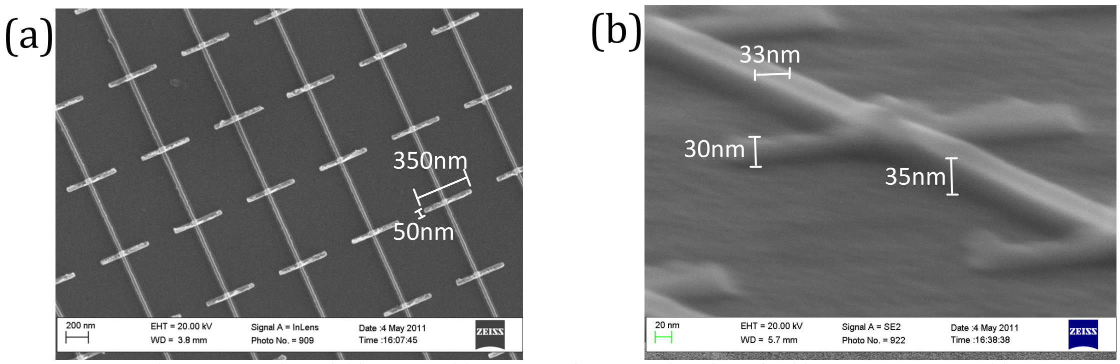

Fig 2. (a) Top view of ridge array with antennas. (b) Perspective view of gold antenna on InGaAs ridge

The measured reflection spectrum of the optical antennas clearly shows a resonance around 1550nm, as shown in Fig. 3(a). Photoluminescence (PL) of the ridges both with and without antennas was measured using a custom-built microscope with cooled InGaAs detector integrated with a spectrometer. Devices were optically pumped using a 1064nm diode laser far from the antenna resonance. Increased PL can be attributed to decreased carrier lifetimes in the gain material and therefore larger modulation bandwidths. The PL spectrum for an array of 33nm wide ridges both with and without antennas is shown in Figure 3 (b) and (c), respectively.

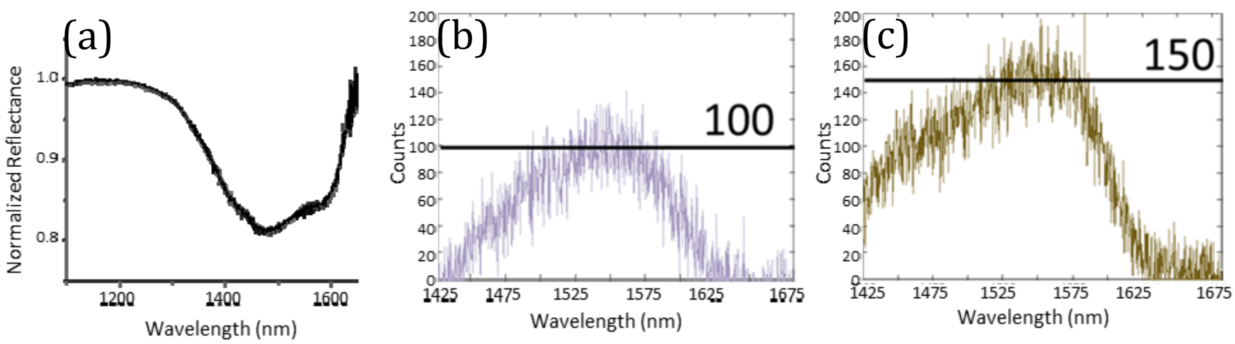

Fig.3. (a) Reflectance measurement of antenna array showing antenna resonance. (b) PL of ridges without antenna. (c) PL of ridges with antenna.

Fig. 3(b) and (c) demonstrates an increase in PL intensity for the array with antennas. PL enhancement will only occur at the intersection of the metal antenna and the semiconductor ridge. The area of the ridge covered by an antenna, and therefore exhibiting enhanced luminescence, only accounts for 7% of the total ridge area. The 1.5x increase can then be attributed to a large enhancement from these few high emission regions. The antenna structure induced enhancement is then easily calculated as ~8x. 24nm wide ridges were also measured with enhancement ~15x, however these devices required cooling to accommodate the very large pump powers necessary to generate sufficient signal for detection.

IV. Conclusion

We have demonstrated an optical antenna based nanoLED design capable of large modulation bandwidths. Fabricated devices with ridge widths of 24nm have shown PL increases greater than 10x. The large bandwidth and small size of these emitters make them strong candidates for use in integrated nanophotonic systems such as on-chip optical interconnects.

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