9:15am - 9:30am
WA3

Spontaneous Emission Engineering in Light Emitting Diodes

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For many years, spontaneous emission of light was considered a natural and immutable property of radiating atoms. Now we know that spontaneous emission is controllable by engineering the quantum zero point electromagnetic fields in the atom's environment. We can alter the electric fields and optical mode density which couple to the atom's dipole moment. using photonic crystal -artificial, multi-dimensionally periodic, structures which have a bandgap for electromagnetic waves. Photonic crystals can be used to tailor spontaneous emission, in order to forbid it in undesirable directions and to enhance it where needed.

It has been shown[1] that a thin freestanding slab of semiconductor material with a periodic array of holes can possess a forbidden gap for guided modes, at least for one polarization. This property makes such a structure a good candidate for LED's.. By choosing the right aspect ratio of the hole diameter to spacing, a photonic bandgap can be tailored in such a way that it inhibits spontaneous emission into the lateral guided modes, which happens to be the wrong direction for light extraction. At the same time, the semiconductor continues to emit light normal to the slab and into free space.

However not all guided modes in the finite structure are trapped, guided modes propagating normally to the edge of the structure are coupled to the free space in the same way as those propagating vertically. In figure 1 we present a design where only modes which can not escape are suppressed by photonic bandgap crystal. This structure would be less affected by the slowdown of spontaneous recombination, than in LED's where all guided modes are prohibited.. The spacing and hole diameter must be such that guided modes in M direction of the k-space are forbidden while X direction remains allowed. In reality one can not punch hole through the active region without having all carriers within the diffusion length of the free surface lost to surface recombination. For optical wavelength, the spacing between holes is of the order of 100nm, while the diffusion length of the materials is at least 1 micron. We show, using numerical modeling and millimeter wave modeling that one can have a gap for the "wrong"guided modes without punching the holes all the way through the active layer.

E. Purcell[2] predicted that an atom in the leaky cavity will radiate faster than in free space. Thus, in addition to prohibiting emission in wrong directions, we may think of enhancement of emission in the desirable directions. One-dimensional cavity enhanced LED's were introduced by F. Schubert[3],and implemented most successfully by H. de Neve *et al*[4].

Cavity enhancement could be extended to two and three dimensions. Then the total radiative recombination rate will significantly increase, allowing faster communications signals, and competing more effectively with residual non-radiative recombination. Cavity enhanced LED's could be useful both for their raw efficiency, as well as for future high-speed, broad-band, opto-electronic communications. Three dimensional cavity enhancement can be so substantial,

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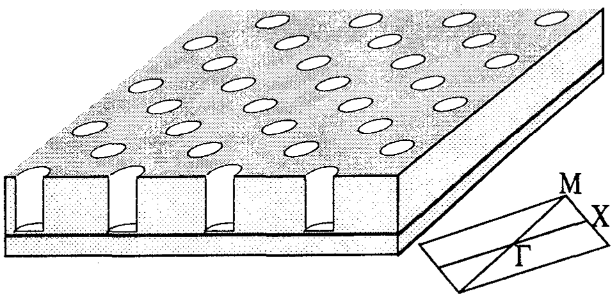

Figure 1: LED with suppression of emission in unfavorable directions.

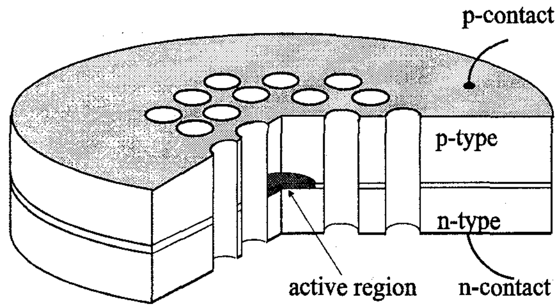

Figure 2 Two dimensional cavity enhanced LED

(~10-fold in the spontaneous emission rate), that the benefits of spontaneous emission inhibition can be abandoned without a severe penalty. Cavity enhancement of a three dimensional cavity is given by

$$\frac{Q\lambda^3}{8\pi V n^3}, \qquad (1)$$

where Q is a quality factor of the resonant mode, n is refractive index of the semiconductor and V is a volume of the cavity. Apparently, the cavity volume must be as small as possible for best results. The smallest volume that a cavity in a PBG material can have is $(\lambda/2n)^3$. All recombination away from the center of the cavity is not enhanced, that is why it's important to confine the active region to the cavity volume. At the optical scale that would require post-processing. In this case there is no harm in making holes in the photonic crystal go all the way through the structure. Analysis of the 2D resonant cavity LED shown in the Fig 2 shows that a quality factor Q~20 can be achieved. Mode confinement is provided by periodicity in the plane of the device and by total internal reflection in the vertical direction.

In conclusion, two new LED designs are proposed. One of them features resonant cavity enhancement of a two-dimensional continuum of modes coupled to a dielectric cavity and suppression of emission into confined modes of an LED structure. Use of photonic gap structures provides Q on the order of the material Q (about 20). Another design makes use of suppression of modes that can not escape the LED structure. Results of microwave-scale electromagnetic modeling of the LED structure along with numerical electromagnetic computations will be presented.

References:

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