LIGHT-EMITTING DIODE EXTRACTION EFFICIENCY

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ABSTRACT

A model of optical processes in LED's was created that takes into account device geometry, light absorption in contacts and cladding layers, photon recycling, light randomization due to surface scattering and the benefit from encapsulation of the device into epoxy. Based on the results of our modeling, an optimization of the LED was proposed.

Also, photoluminescence measurements of internal quantum efficiency were performed on the epi-layers used for LED fabrication.

1.INTRODUCTION

Performance of light-emitting diodes is defined to the great extent by two figures of merit, namely internal quantum efficiency of the active region and light extraction efficiency. While the former quantity reflects the quality of an epitaxially grown structure and normally lies in the range 20-90%, the latter strongly depends on the particular design and can be as low as 2%. Improvement of the design performance of the requires extensive modeling of optical processes in the device. Moreover, since extraction of light is related to the internal quantum efficiency, the optimal design of the device can vary depending on the quality of the material that is used in the LED.

In this paper we report results of the light extraction efficiency modeling using the photon gas method and Monte-Carlo simulations.

2. THEORETICAL MODEL

A photon gas model[1] based on the statistical properties of the completely randomized photons in the bulk of the semiconductor device allows one to make estimates of the dependence of the LED light extraction efficiency on quality of the active layer material and geometric parameters such as aspect ratio and thickness of active layer. We consider a square chip with dimensions width L and height H, with the active layer of thickness d in the middle and reflecting electrical contacts on the top and bottom surfaces covering area $A_{contact}$. Top and bottom surfaces are assumed to be polished while four side edges are rough saw-milled. The design similar to that is used in fabrication of visible LED based on InGaAlP quaternary alloy[2] with L~200μm, H~250μm and d~1μm.

If there is a photon flux inside the LED

$$I=[\text{Density of photons inside LED}]\times\frac{c}{n}, \qquad (1)$$

where n is the refractive index of the semiconductor, there are four ways for a photon to disappear from the LED:

a) For the portion of photon whose direction lie in the escape cone, escape rate will be proportional to the surface area and the escape fraction $1/(4n^2)$:

$$A(\lambda)=\frac{(2L^2+4LH)T}{4n^2}I(\lambda) \qquad (2)$$

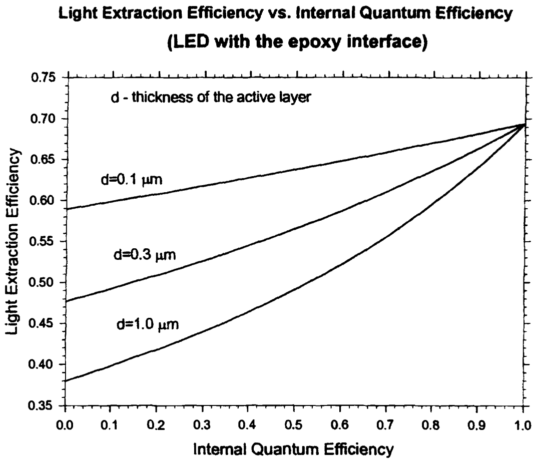

Figure 1: The total efficiency is the product of the internal quantum efficiency times the light extraction efficiency. However the light extraction efficiency is itself dependent on the internal quantum efficiency due to the inevitable re-absorption of some of the light. In thin LED's the re-absorption effect is less severe.

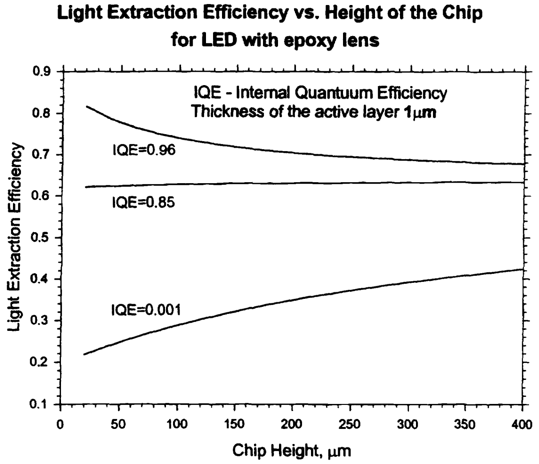

Figure 2: The extraction efficiency versus LED chip height. For the highest internal quantum yield (IQE) material, the LED should be a thin film, but for lower IQE a thick LED is better because the light escapes more readily from the edges.

b) There is a chance that photon traveling in the bulk of the device is absorbed in the cladding layers or in the current spreading window due to free carrier absorption in the volume: .

$$B(\lambda) = L^2 H\alpha(\lambda) I(\lambda) \qquad (3)$$

c) Some of the photons can be reabsorbed in the active region. Some part of them, proportional to internal quantum efficiency, can be re-emitted. The rest produce electron hole-pairs which recombine non-radiatively:

$$C(\lambda) = \frac{L^2}{4\pi} \int d\Omega (1 - e^{-\frac{\alpha d}{\cos\theta}}) \cos\theta (1 - \eta_{int}) \sin\theta \cdot I(\lambda) \qquad (4)$$

where T is average transmission coefficient (within the escape cone), α_{fc} - free carrier absorption coefficient in the bulk $\alpha(\lambda)$ - absorption coefficient of the active layer and η_{int} - internal quantum efficiency.

d. Finally, since contacts are not very good reflectors, there will be losses due to absorption in contacts. The absorption rate due to this process is:

$$D(\lambda) = \frac{A_{contact}}{4\pi} \int d\Omega \cos\theta (1 - R_{contact}) \sin\theta \cdot I(\lambda) \qquad (5)$$

Light extraction efficiency $\eta_{extr}(\lambda)$ is the ratio of the desired rate to the sum of all rates.

$$\eta_{extr}(\lambda) = \frac{A(\lambda)}{A(\lambda) + B(\lambda) + C(\lambda) + D(\lambda)} \qquad (6)$$

In a given device, different wavelengths have different escape probabilities, which means that result must be weighted by spontaneous emission spectrum $R(\lambda)$ which can be derived from the absorption spectrum using the Shockley-van Roesbrueck relation.[3] Thus extraction efficiency is given by

$$\text{Extraction Efficiency} = \frac{\int R(\lambda) E(\lambda) d\lambda}{\int R(\lambda) d\lambda}. \qquad (7)$$

Simulation, using second method, the Monte-Carlo approach, takes into account details of the LED design, such as the properties of the surfaces of the device, position of the active layer within a device, reflectivity and configuration of

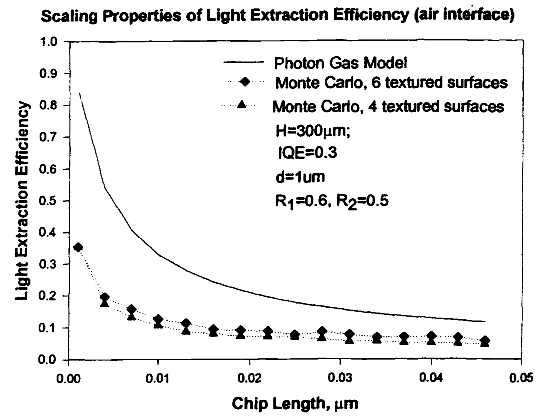

Figure 3:Scaling properties of the light extraction efficiency. When imperfect contacts are introduced into the LED design, photon gas model gives overestimated results for light extraction efficiency.

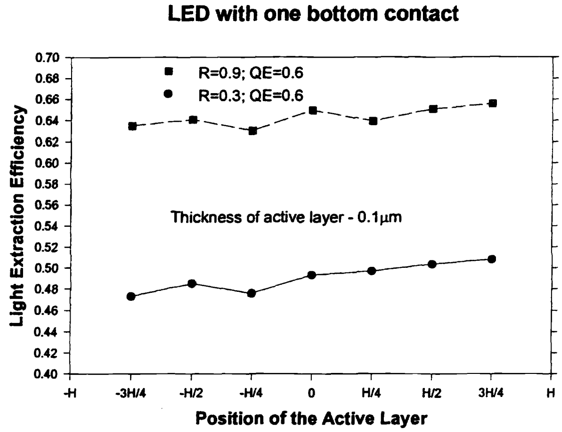

Figure 4: dependence of light extraction efficiency on position of the active layer for a device with a sheet bottom contact and a small circular top cop contact

contacts, etc. Furthermore, the second method allows determination of the light distribution pattern over the facets of the LED.

3.RESULTS OF THE MODELING

Analysis of the results of our modeling leads us to a number of conclusions:
Thinning down the active layer reduces considerably re-absorption losses in the active layer, especially in material with low internal quantum efficiency (see Fig.1). This can also shift the operating point of the device towards the high-level injection regime.

Quality of the active layer material determines whether the preferred device design should be thick or thin. (See Fig. 2). For a high internal quantum efficiency device (>90%), one should minimize bulk absorption by making the device as thin as possible. (This requires that a light randomization mechanism such as nano-texturing be incorporated in the device, or that photon recycling be used for additional randomization of light.). On the other hand, if the active layer has a low (<90%) internal efficiency, it's better to make a thick substrate device which allows the photons to see the device edges where 4 additional escape cones are present. This increases the photon to escape probability from the semiconductor on the very first surface bounce.

The photon gas model is a good approximation when the average photon path consists of many bounces inside the LED. When low quality contacts are introduced on the top and bottom surfaces of the LED, a comparison of the photon gas model with the Monte-Carlo simulation shows a breakdown the former (Fig 3.). Nonetheless the qualitative scaling properties of the LED's light extraction efficiency is calculated correctly. From the point of view of light extraction efficiency, the smaller device area is preferable, since light randomization happens only on the edges of the device.
Even though contacts cover only about 15% of the area of the device under consideration, the dependence of light extraction efficiency on the contact reflectivity is strong (Fig 4). Indeed, for a 50% reflective sheet contact, every probability of contact absorption causes ~7% loss, which is comparable with 6x(1/n^2)~ 12%.

We considered the optimal position of the active layer for the device with sheet contact on the bottom and small circular contact on the top surface. Modeling (Fig 5) show that bringing the active region closer to the smaller contacts results in up to 6% improvement in the extraction efficiency. Of course, we can not make the active layer too close to the top surface, since we use that upper layer for current spreading.
Light output is higher near the edges of the surfaces adjacent to the roughened sides of the device. This is due to the fact that the texturing at the edges scatters some of the light directly into the escape cone. Obviously, better performance

would be achieved if all the surfaces were textured, not only the edge surfaces. Obviously, one should go to great pains to design no optical obstructions anywhere near the edges and corners of the LED's facets because that's where the light is getting out.

4. MEASUREMENTS OF INTERNAL QUANTUM EFFICENCY.

We investigated the quality of InGaAlP wafers with the following structure:

n-GaAs substrate(~200μm)
n-AlInP Lower confining layer (~1μm)
undoped AlGaInP Active layer (~0.75μm)
p-AlInP Upper confining layer (~0.5μm)
p-GaP Window Layer (~50μm)

The samples with an absorbing substrate was optically pumped using the 568nm line of a continuous wave ArKr laser. The absolute external quantum efficiency is measured by referencing the measured photoluminescence (PL) from the sample in against the reading measured from laser off of the perfect white Lambertian reflector. Corrections for transmission through the optical setup and the relative detector efficiency at different wavelengths were made in the calculations. An optical model is used to obtain the internal quantum efficiency of the quantum well (QW) from the measured external quantum efficiency. We used an optical model similar to that used in the modeling of the light extraction efficiency which takes into account Fresnel transmission, absorption at the pump wavelength in cladding layers and in the active region and photon recycling.

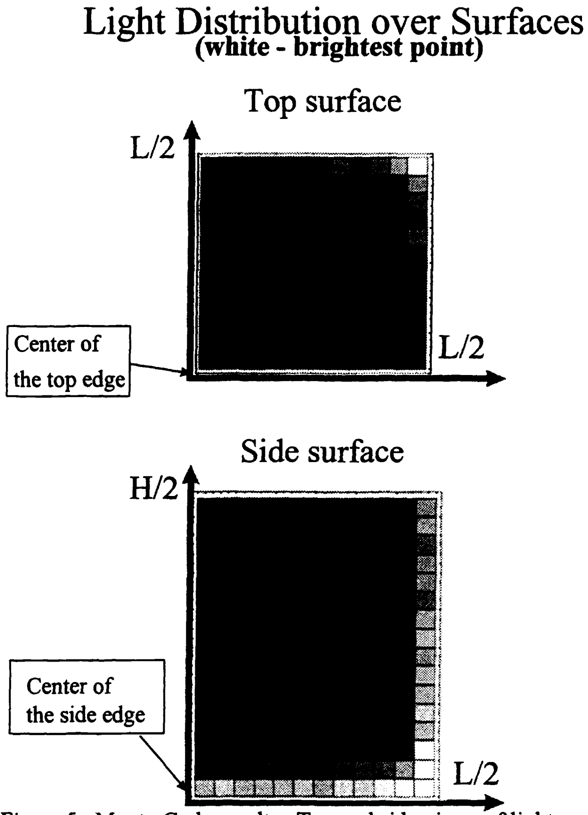

Figure 5: Monte-Carlo results. Top and side views of light escaping from an LED. The white areas have more light emission than the dark ones.

Measurements were performed on samples with active layers emitting at wavelengths 589, 604, 615 and 623 nanometers, yielding internal quantum efficiencies of 15, 23, 45 and 65 percent respectively, after correction for re-absorption.

CONCLUSIONS

We presented results of LED's light extraction efficiency calculated by two methods and the results of PL measurements of internal quantum efficiencies of different InGaAlP-based LED structures.

Recommendations for the design optimization were worked out, based on the results of the modeling.

ACKNOWLEDGMENTS

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