Influence of Guided Mode Absorption on the Effectiveness of GaN-on-Sapphire Photonic Crystal Light-emitting Diodes

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Abstract: Enhanced light extraction from photonic crystal light-emitting diodes etched into the device surface is described. Finite Difference Time Domain modeling indicates that scattering or absorption at the substrate-epilayer interface is the dominant limiting process.

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1. Introduction

The last few years has seen reports of the use of photonic crystals to increase the extraction efficiency of light emitting diodes (LEDs) by coupling the traditionally trapped guided modes in a planar semiconductor structure into radiative modes. The vast majority of InGaN-based LEDs are grown heteroepitaxially on sapphire substrates leading to high dislocation densities at the substrate-epilayer interface. Photonic crystals can be integrated with such structures in several ways: on the top p-GaN surface, the bottom n-GaN surface after substrate removal or buried within the GaN-based epilayer. The approach taken in this paper is to introduce a quasi-periodic structure in the top layer of the high index GaN waveguide. The use of photonic quasicrystals that have higher rotational symmetries rather than regular photonic crystals leads to less azimuthal emission dependency in the light output [1].

2. Experimental details

Standard unroughened GaN-based LED wafers on sapphire substrates were sourced from commercial suppliers. The surface was patterned with electron-beam lithography (EBL) before the resist pattern was transferred via a SiO_2 hard mask to the upper 200nm thick p-GaN layer by Cl_2/Ar plasma etching. The depth of the etched holes was measured to be 110 nm by AFM. The patterned wafer was then processed by conventional lithography into 270x270 micron LED chips using 5:5 nm Ni/Au transparent p-contacts.

The photonic quasicrystal patterns were based on square-triangular tiling [2] with three different pitches: 450, 550 and 750 nm. It was anticipated that the etched holes would have a diameter of half the pitch thus giving a filling factor of ~0.22. In practice, three different beam doses were used in order to achieve three different hole sizes around the design filling factor.

For characterization, an optical fibre mounted on a goniometer was used to measure the far field light distribution of the undiced devices. To estimate the total extraction enhancement through the top surface, the far field profile was integrated over a ± 90° cone, making the assumption that there is no significant azimuthal dependence, which is to be expected for photonic quasicrystals. Control samples with no surface patterning were interspersed between every patterned LED to minimise the influence on the results of growth and fabrication variations across the wafer fragment. These showed Lambertian emission to within ± 2%.

3. Results

Integrating over a ± 90° cone the enhancement ranged between 42-48% for all three pitches. However, integrating over a full ± 90° cone masks a much larger enhancement over cones of smaller angle about the surface normal since the photonic crystal alters the far-field profile from being Lambertian. The enhancement reached a maximum of 58% for a ± 15° cone for the 550 nm pitch PCLED and 62% for a ± 45° cone for the 750 nm pitch PCLED. For each pitch, increasing the hole size caused an increase in the total emission.

The optical properties of the PCLEDs were modeled using a 2D Finite Difference Time Domain (FDTD) technique [3]. Qualitatively the simulations reproduce the key features in the measured enhanced extraction efficiency of the PCLEDs. In general the maximum enhancement is at emission angles corresponding to the peak angles predicted from the simulations. However, quantitatively the simulations strongly overestimate the extraction enhancement that is achieved in experiment.

It was observed from SEM images that the fabricated patterns in the LEDs differ from that intended in the following different ways: the positional accuracy of the element, its size and its circularity. In order to assess the influence of the pattern fidelity on the LED properties, further modeling was carried out using measured parameters deduced from the SEM images. This modeling lead to far-field patterns that differ from the *ideal* and will be referred to as the *real* simulation results.

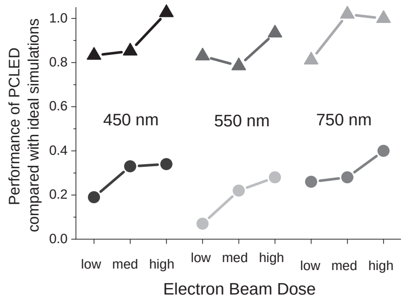

Fig. 1: Performance versus electron beam dose for the simulated 'real' (triangles) and measured PCLEDs (circles). A ratio was taken of the total extraction enhancements for the simulated 'real' and measured PCLEDs with that calculated from the simulations of the 'ideal' structure.

Fig. 1 shows the total extraction enhancement over a ± 90° cone from the *real* simulations, expressed as a percentage of that found from the *ideal* simulations. The experimental results are also shown on the same scale for comparison. The fact that the values for the simulations show almost 100% for each pitch for one of the exposure doses indicates that if the air fraction achieved in practice is about right, the pattern fidelity, specifically the ~5% errors of the hole diameter and position, does not degrade the total extraction enhancement. The more dominant effect is the dependence of performance on fill factor with both the real simulations and the experimental results showing a ~20% degradation for the non-ideal air fractions.

However, the greatest difference between the modeling and experimental results is the size of the extraction enhancement. The experimental extraction enhancement over a ± 90° cone reaches only 40% of the potential enhancement suggested by the simulations. The real simulations suggest that this degradation is not due to the fidelity of the photonic crystal. That the degradation occurs for all three pitches indicates that the physical mechanism does not depend on the properties of the photonic crystal.

One possible reason is a lower than anticipated interaction of the guided modes with the photonic crystal in the real structures. The proportion of such guided light is expected to be as large as 68% from a simple model of a planar structure of GaN on sapphire. A departure from this simple model due to other sources of scattering or absorption within the structure will reduce this percentage leading to less guided light available to interact with the PQC. It has been shown that for InGaN-on-sapphire LEDs the dominant loss mechanism for guided modes is the GaN-sapphire interface where there is a very high density of dislocations [4-5]. Since the defective region is highly localized at the substrate interface the interaction with the light field is highly mode dependent. The modes that interact most strongly with the surface photonic crystal will also be the ones interacting most strongly with the defective region. Also if the loss is caused by scattering, this will cause the experimental control samples to be more efficient in extracting light than the simulations would predict, leading to a harsher normalization and a reduced enhancement factor for the PCLED. The existence of such a defective region and the consequential reduction in the energy in the guided modes would provide the universal mechanism that is observed in the experimental data.

Initial results from a three-dimensional FDTD model that includes absorbing layers has revealed that a thin strongly absorbing layer at the substrate interface significantly degrades the light extraction efficiency of regular surface photonic crystal structures. This work is currently being extended to photonic quasicrystals to find out if a better reconciliation between the experimental and simulated results can be achieved.

4. Conclusion

Results have been presented showing enhanced light extraction from blue-emitting LEDs with photonic quasicrystals etched into the device surface. Detailed 2D-FDTD modeling has been used to assess the influence of pattern fidelity on the extraction. It has been found that the fidelity does not significantly affect the total extraction enhancement. The poor quantitative agreement is ascribed to the limits of the 2D model used that has not included the effects of scattering or absorption, particularly at the substrate-epilayer interface.

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