Modelling of Extraction Efficiency of GaN-Based Resonant Cavity Light Emitting Diodes Emitting at 510nm.

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The design of GaN resonant cavity light emitting diodes (RCLEDs) emitting at 510nm is optimised for maximum extraction efficiency into numerical apertures of 1.0 and 0.5. The optimisation is performed as functions of Al fraction in the AlGaN/GaN distributed Bragg reflector (DBR) cavity mirror and the InGaN/GaN quantum well (QW) emission linewidth. The calculated enhancement factors of the extraction efficiency compared to a bulk light emitting diode (LED) for emission into a NA of 1.0 (0.5) increase from 3.0 (3.4) for a single metal mirror light emitting diode (LED) structure to 4.2 (5.8) for a metal-AlN/GaN DBR RCLED structure. The dependence of efficiency and optimum number of DBR pairs on Al fraction in DBR, QW emission linewidth, and emission NA are discussed in terms of cavity modal properties.

Introduction Determining the optimum design and performance of GaN resonant cavity light emitting diodes (RCLEDs) is essential to assessing the potential and limitations of these devices in practical applications. In particular the impact of the relatively small refractive index variation of AlGaN with Al fraction compared to AlGaAs on the properties of AlGaN/GaN distributed Bragg reflectors (DBRs) has important implications for GaN RCLEDs incorporating these mirrors.

In RCLEDs the coupling of emission from the active layer to the modes of the cavity produces a modification of the spatial and spectral properties of the spontaneous emission process. This modification of the spontaneous emission process can be used to improve the extraction efficiency compared to convention light emitting diodes (LEDs) by increasing emission at internal angles less than the critical angle for light to escape from the device, as first demonstrated by DeNeve [1]. The capacity of a generic planar cavity structure to enhance the light extraction efficiency through a single surface is extensively discussed in two seminal papers by Benisty [2, 3]. One promising application of RCLEDs is as sources for plastic optical fibre (POF) based local area networks, where red RCLEDs whose emission wavelength is matched to the POF transmission window at 650nm have demonstrated impressive performance [4]. Additional POF transmission windows exist at 510nm and 570nm. These wavelengths are accessible using III-V nitride semiconductors, whose emission properties are less temperature dependent than the AlGaInP materials used for emission in the red. These materials potentially offer a reduced temperature sensitivity of device performance, as is required for POF applications in automotive and avionic environments. In this paper, the optimum design of a GaN RCLED emitting at 510nm for maximum extraction efficiency into air and into a typical POF numerical aperture (NA) of 0.5 is discussed.

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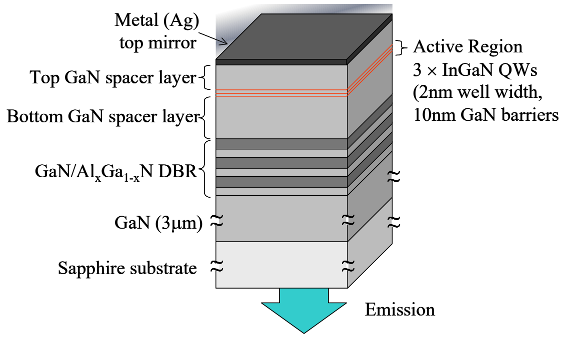

Fig. 1. Schematic diagram of substrate emitting, hybrid metal-DBR GaN RCLED.

Blue and Violet GaN RCLEDs have already been demonstrated showing clear cavity effects in the emission spectrum and directionality of emission [5, 6]. These structures were designed to achieve high Q cavities suitable for VCSEL devices, but no effort was made to optimise the design for maximum light extraction efficiency. It has been shown that such optimisation often results in a low to moderate reflectivity of the mirror through which light is extracted [3, 7], and hence moderate Q values. Assuming a substrate emitting RCLED structure consisting of a hybrid cavity with a metal top mirror and an AlGaN/GaN DBR bottom mirror (DBR spectral stopband centred on cavity mode wavelength), and with an active region consisting of three InGaN/GaN quantum wells (QWs), we determine the optimum number of DBR mirror pairs for maximum extraction efficiency as functions of the aluminium fraction in the DBR and the QW emission linewidth. The choice of a metal top mirror for our cavity, minimises the effective cavity length and hence the number of cavity modes while still maintaining a high reflectivity of >90%. Since the number of cavity modes plays a determining role in the extraction efficiency of RCLEDs the hybrid metal-DBR cavity structure is deemed optimal for RCLEDs [8]. This structure also has the benefit of the bottom mirror being compatible with epitaxial growth techniques, while the top metal mirror can serve as an electrical contact.

Model The model is based on the method, outlined in reference [9], of exactly calculating the dipole emission in an arbitrary multilayer structure, given the thickness and real and imaginary components of the refractive index of each layer. The model calculates the output power radiated by electric dipoles of arbitrary orientation for both TE and TM polarisations as a function of angle.

The QW active region is modelled by a distribution of noncorrelated isotropic dipoles, located at the centre of the central QW in our structure. This approximation to the physical situation where emission occurs from all three QWs in our structure, only introduces a small correction to our calculated results due to the close spacing of the QWs (the correction factor to the calculated efficiencies is estimated between 0.9-1.0 from Fig.4). The extraction efficiency of the RCLED for a single emission wavelength is determined by calculating the fraction of the total power radiated by the dipole that is emitted into air (or the fraction that is emitted into air at angles less than $\sin^{-1}$(NA) for the extraction efficiency into a reduced NA). To account for a finite QW emission linewidth the total extracted power compared to the total radiated power for a range of wavelengths across the QW emission spectrum is calculated.

The refractive index values for $Al_xGa_{1-x}N$ and InGaN were taken from the literature [10, 11], while refractive index values of the metal top mirror were taken from spectroscopic ellipsometry measurements performed on a silver layer.

Results and Discussion For given mirror structures there are two key considerations in the optimisation of the RCLED design for maximum extraction efficiency. The first involves the choice of the cavity resonance wavelength, which is determined by the effective cavity thickness. It has been shown previously that for maximum extraction efficiency into air (NA=1) the peak QW emission wavelength should be resonant off-axis such that it couples to air at an angle of approx. 45° from the normal. This allows the maximum enhancement of emission at this wavelength within the range of internal angles extracted from the device. The angular dispersion of the cavity mode results in QW emission at wavelengths shorter (longer) than the peak QW emission wavelength being resonantly extracted at larger (smaller) angles. A consequence of the positioning of the cavity to achieve maximum efficiency into air (NA=1) is a two lobed farfield emission pattern, which is undesirable for maximum emission efficiency into a reduced NA. Therefore the optimum position of the cavity resonance wavelength relative to the QW emission spectrum for maximum efficiency is dependent on the NA into which emission is considered. The second key consideration in the optimisation of the RCLED design is the position of the active layer inside the cavity, with the positioning of a localised source layer at the antinode of the electric field of the resonantly extracted mode leading to maximum coupling of emission to this mode. Such optimal positioning of the source layer results in a factor of two increase in extraction efficiency over a distributed source throughout the cavity [2].

The primary focus of this paper is to determine the optimum extraction efficiencies into NAs of 1.0 and 0.5 that can be achieved by hybrid metal-DBR GaN RCLEDs emitting at 510nm, and the corresponding designs of these structures. In order to perform this optimisation for a given Al fraction in the AlGaN/GaN DBR and a given QW emission

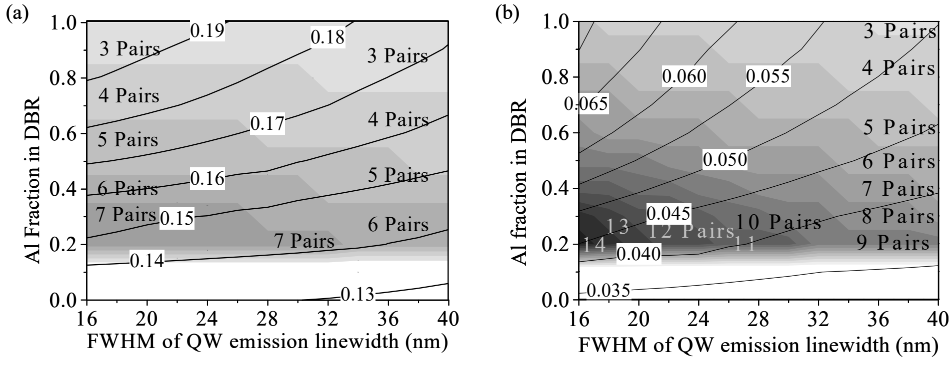

Fig. 2. Contour plots of maximum extraction efficiency and corresponding number of DBR pairs as functions of Al fraction in DBR and QW emission linewidth for emission into (a) NA=1.0 and (b) NA=0.5. (the optimum number of DBR pairs is not shown for Al fractions <0.15 due to the extremely small variation in efficiency with number of DBR pairs)

linewidth the extraction efficiency as functions of both cavity resonance wavelength and number of DBR pairs was calculated. For each number of DBR pairs the cavity resonance wavelength λ_c was varied between ≈460nm and ≈560nm, with a central cavity thickness of $\approx 5\lambda_c/4$ and the QWs positioned at the central antinode of the extracted mode used throughout. From these simulations the optimum number of DBR pairs and corresponding maximum efficiency for each DBR Al fraction (between 0 and 1, step 0.1) and QW emission linewidth (between 16nm and 40nm) pair is determined, with the results for emission into NAs of 1.0 and 0.5 plotted in Fig. 2.

A decrease in extraction efficiency with increasing QW linewidth and decreasing Al fraction is observed for both emission NAs considered. The angular dispersion of the cavity mode wavelength allows the cavity to be designed for maximum extraction efficiency of only a single emission wavelength, resulting in a decrease in the extraction efficiency obtainable as the QW emission linewidth increases. The decrease in extraction efficiency with decreasing Al fraction in the DBR is due to the increased effective cavity length resulting from the increased penetration depth of light into the DBR.

The optimum number of DBR pairs is observed to decrease with increasing QW linewidth and increasing Al fraction. These trends can be understood qualitatively in terms of the role the cavity mode spectral linewidth plays in determining the extraction efficiency. A narrow cavity mode spectral linewidth results in a strong enhancement of a small range of wavelengths, while a wider cavity mode linewidth results in a weaker enhancement of a broader ranger of wavelengths. As the intrinsic QW emission linewidth increases a broader cavity mode linewidth is required to enhance a wider range of source emission wavelengths. A reduction in the number of DBR pairs and hence a decrease in the DBR mirror reflectivity produces such an increase in the cavity linewidth. Correspondingly at a fixed QW emission linewidth an increase in the Al fraction in the DBR requires a reduction in the number of DBR pairs in order to maintain the optimum mirror reflectivity and cavity mode linewidth.

The calculated reflectivity at the centre of the DBR stopband for the optimised DBR mirror structure varies between 0.07 and 0.45. The optimised DBR mirror reflectivity increases with increasing Al fraction in the DBR.

In Fig. 3 the maximum extraction efficiencies and optimum numbers of DBR pairs for emission into NAs of 1.0 and 0.5 assuming a typical InGaN/GaN QW emission linewidth of 30nm [12] are compared. The extraction efficiencies are plotted as multiples of the

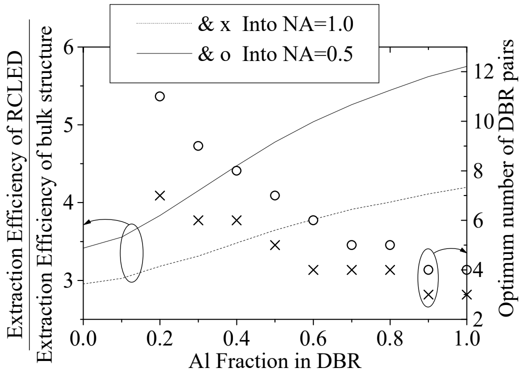

Fig. 3 Comparison of efficiency enhancement factors and optimum numbers of DBR pairs for emission into NA=1.0 and NA=0.5, assuming a QW emission linewidth of 30nm.

corresponding extraction efficiencies of a conventional bulk LED structure emitting through a single facet (same structure as shown in Fig. 1 but with the mirrors removed and thick cavity spacer layers). Even for the single mirror structure (i.e. silver mirror only, Al fraction in DBR = 0) enhancement factors of 3.0 and 3.4 of the extraction efficiencies are predicted over the bulk LED structure. These single mirror efficiency enhancement factors are greater than the factor of two expected from a simple geometrical mirror effect due to the exploitation of constructive interference effects that come when the source is localised near a single mirror [2]. The efficiency enhancement factors increase with increasing Al fraction in the DBR up to values of 4.2 and 5.8 for emission into NAs of 1 and 0.5 respectively for a metal-AlN/GaN DBR cavity structure. The enhancement of efficiency is more pronounced for the NA=0.5 case due to the RCLEDs ability to enhance emission into a limited range of angles by reducing the angular width of the cavity mode resonance. The angular width of the cavity mode resonance for a single wavelength can be reduced by increasing the DBR mirror reflectivity, explaining the greater number of DBR pairs in the optimum RCLED design for maximum extraction efficiency into a NA of 0.5 compared to a NA of 1.

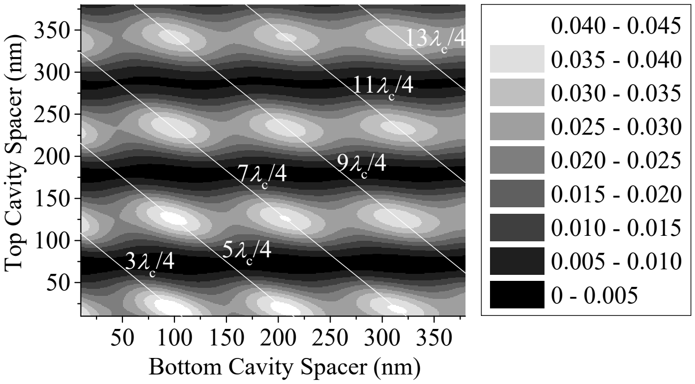

Fig. 4. Contour plot of modelled extraction efficiency into NA=0.5 of metal-$Al_{0.3}Ga_{0.7}N$/GaN DBR RCLED as functions of top and bottom cavity spacer layers, assuming a QW emission linewidth of 30nm. The diagonal white lines mark cavity structures with near optimum cavity resonance wavelength, labelled with the optical thickness of the central cavity region.

While AlN/GaN DBRs have been reported [13], epitaxial growth considerations usually limit the Al fraction to between 0.25 and 0.4 [14, 15]. In light of this limitation the performance of a RCLED structure incorporating a 9 period $Al_{0.3}Ga_{0.7}N$/GaN DBR was further investigated. In Fig. 4 we see that the extraction efficiency of such a structure into a NA of 0.5 exhibits a periodic dependence on the thickness of both cavity spacer layers, with a greater variation in efficiency observed with top spacer layer thickness than bottom spacer layer thickness. The diagonal lines in Fig. 4 represent structures with constant cavity thickness and hence resonant wavelength, with variations along a single diagonal caused by changes in the position of the active region in the cavity. Clearly the correct positioning of the QWs relative to the metal mirror in this structure is more important than either the correct positioning of the cavity resonance wavelength or the cavity order ($3\lambda_c/4$, $5\lambda_c/4$ etc.) in determining the efficiency of the device. This is because the small refractive index contrast in the $Al_{0.3}Ga_{0.7}N$/GaN DBR results in a large penetration depth of the cavity mode into the DBR mirror. This makes for a large effective cavity length irrespective of the central cavity thickness and limits the ability of the cavity to enhance the extraction efficiency. Therefore the constructive interference effects from the highly reflective non-distributed metal mirror are more important than the cavity effects, although cavity effects are still significant as shown by the variation of efficiency with bottom cavity spacer layer thickness. At increased Al fractions in the DBR the penetration depth of the field into the DBR is reduced, increasing the ability of the cavity to enhance efficiency, and hence the dependence of extraction efficiency on cavity resonant wavelength and cavity order.

Conclusion Maximum extraction efficiency from hybrid metal-DBR GaN RCLEDs emitting at 510nm is achieved for between 3 and 15 DBR pairs in the AlGaN/GaN mirror through which light is extracted, depending on the Al fraction in the DBR and the QW emission linewidth. Assuming a QW emission linewidth of 30nm the optimised extraction efficiency from the RCLED structure increases with Al fraction in the DBR from 0.13 (0.03) for a single metal mirror device to 0.18 (0.055) for a metal-AlN/GaN DBR RCLED for emission into a NA of 1.0 (0.5). While the maximum efficiency enhancement factors for our GaN RCLED compared to a bulk LED structure are less than the order of magnitude values measured for infra-red RCLEDs in the GaAs/AlAs material, they still represent significant improvements in device performance especially for emission into a reduced NA.

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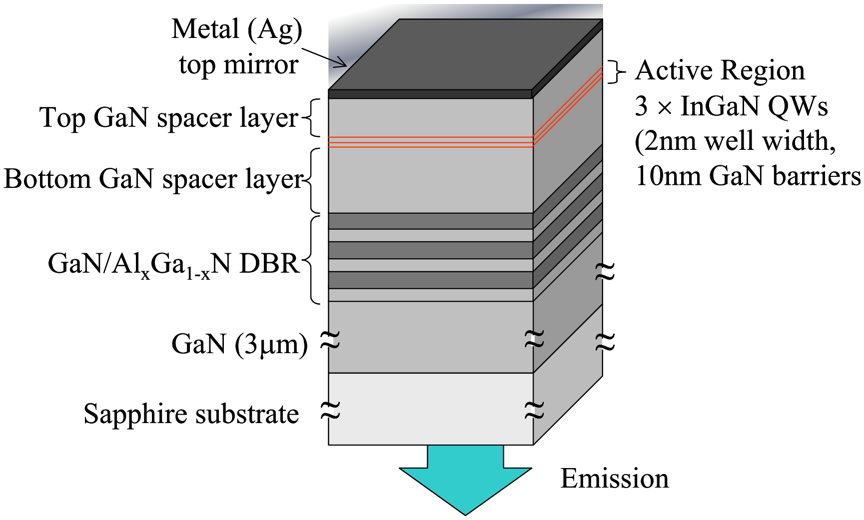

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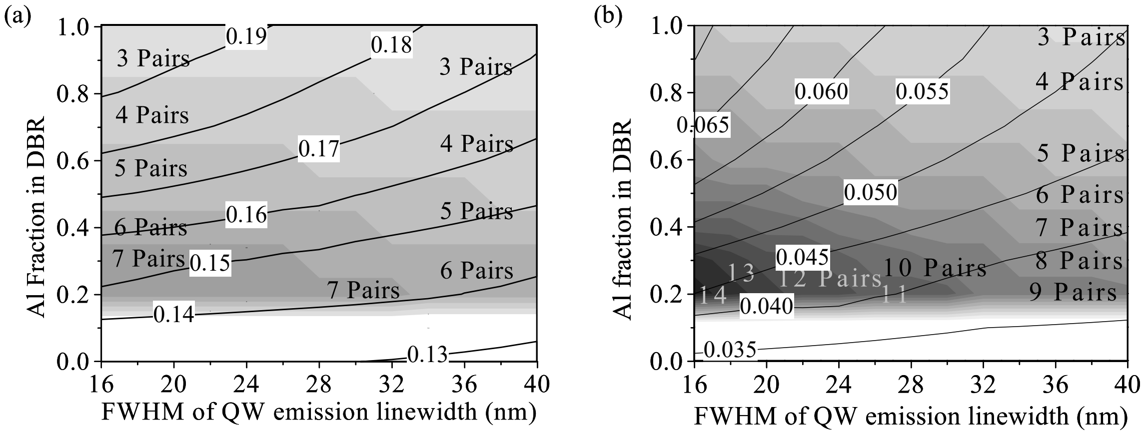

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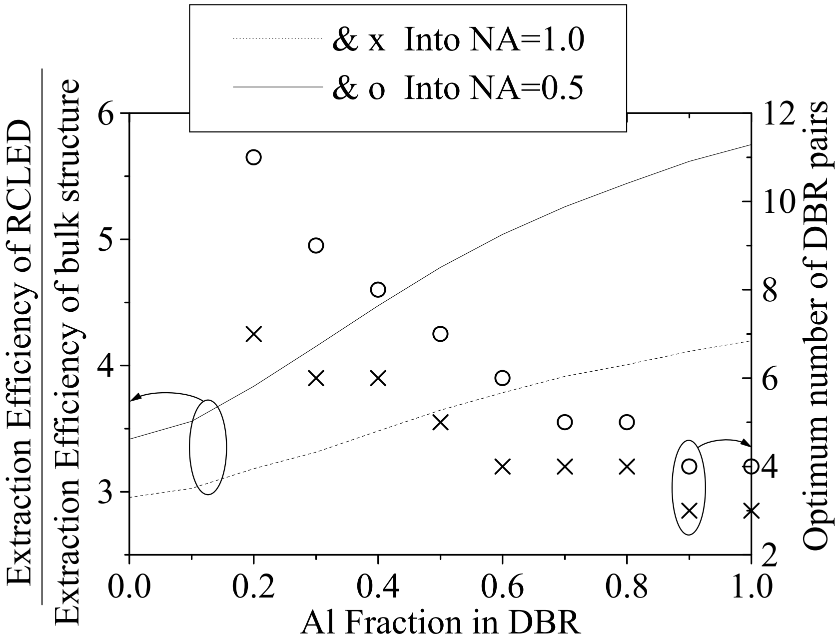

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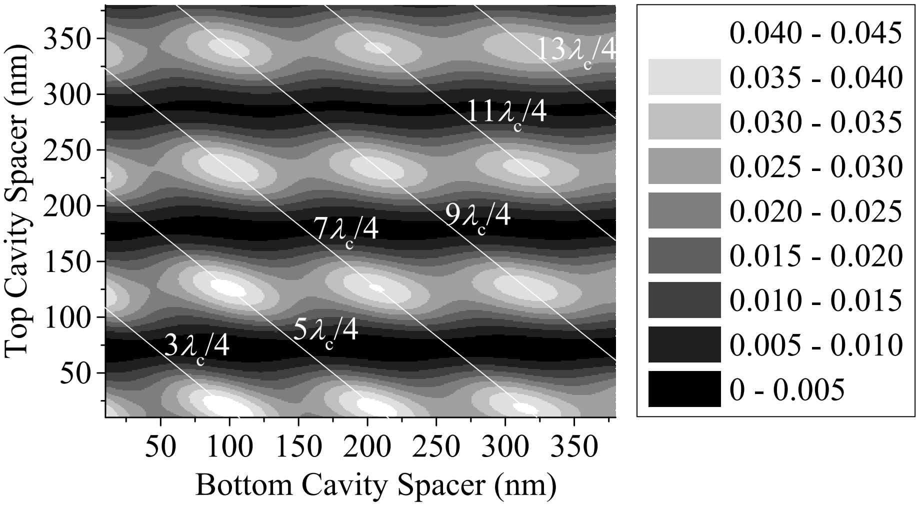

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