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Dilute Nitride Resonant-Cavity Light Emitting Diode

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Abstract— **Resonant cavity LEDs (RCLEDs) are a viable and low-cost alternative light source to lasers for optical communication systems in the 1.3 µm O-band. Most work in this area has been conducted on InP-based material, which is inherently costly, devices often require cooling and the refractive index contrast for constructing mirrors is low. Here, we demonstrate a high-performance GaAs-based RCLED using a dilute nitride GaInNAs active layer emitting in the 1.3 μm wavelength window. While previous 1.3 µm RCLEDs have used metallic mirrors on the back of the device, we exploit the high refractive index contrast of the GaAs/AlAs system to place Distributed Bragg mirrors on both sides of the active layer and achieve superior performance. The external quantum efficiency of the devices is 20% and the full width at half maximum of the emission spectrum is 5.2 nm at room temperature, into a narrow angular cone. The emission power from an 88 μm diameter aperture is 0.5 mW, which, together with the narrow spectral linewidth, makes the device suitable for deployment in a coarse Wavelength Division Multiplexing (WDM) communications system.**

Index Terms— **Dilute Nitride, GaInNAs, Light emitting diodes, Resonant Cavity, RCLED.**

I. Introduction

Resonant cavity optoelectronic devices such as resonant cavity enhanced photodetectors (RCEPDs) [1]–[3], vertical cavity semiconductor optical amplifiers (VCSOAs) [4], vertical cavity surface emitting lasers (VCSELs) [5] and resonant cavity light emitting diodes (RCLEDs) [6], [7]have attracted significant interest both from the research community and from industry in recent years, thanks to their compact size, circular emission profile, wafer scale fabrication compatibility and high coupling efficiency to fibre optic cables. While VCSELs can be an alternative to Fabry–Pérot and distributed feedback lasers in long-distance optical fibre communications, RCLEDs are an alternative to light emitting diodes (LEDs) in short and medium-distance optical fibre communication systems. Compared to conventional LEDs, RCLEDs have the capacity to produce higher spectral purity and increased directionality of the emitted light beam, which is vital for achieving a high fibre coupling efficiency [8], [9].

Here, we demonstrate RCLEDs operating at 1.3 μm using dilute nitride GaInNAs/GaNAs quantum wells as the active layer. Previous works have indicated that the addition of a few percent of Nitrogen into the host III-V group semiconductor, such as GaAs and InGaAs, induces a reduction in the energy bandgap, resulting in a drastic red-shift of the absorption/emission wavelength [10], [11]. Therefore, the operating wavelength of GaInNAs quaternary alloys can be set to 1.3 μm, i.e. into the O-band of fibre optic telecommunications [1], [2]. In addition, the lattice constant of GaInNAs can be tailored to facilitate lattice matched growth on GaAs substrates, which makes it possible to use high refractive index contrast GaAs/AlAs DBR mirrors. As a case in point, high-quality VCSELs based on dilute nitride alloys have been already demonstrated with better performance compared to their InP- based counterparts [11]. The devices based on GaInNAs alloy is not limited to VCSELs or LEDs. Since its discovery, GaInNAs has found place in the applications of photodetectors [13], solar cells [14], site-controlled single photon source[15], [vertical cavity semiconductor optical amplifiers (VCSOAs) [16] and Semiconductor Saturable Absorber Mirrors (SESAMs) [17]etc. There are several studies on GaInNAs-based VCSELs in the literature [18]–[20]; however, there is only a study related to GaInNAs-based RCLEDs in which Montes *et al.*, investigated the temperature dependence of GaInNAs/GaAs quantum well RCLEDs for 1.3 μm applications [21]. The device consists of 7 nm GaInNAs/GaAs single quantum well and 8-pairs of n^+-doped GaAs/AlAs DBR as a bottom mirror and a metal mirror on the back of the device, which has lower reflectivity than the Bragg mirror used here. The spectral FWHM of their devices was 25-40 nm. To the best of our knowledge, there is no other report on GaInNAs based RCLEDs.

II. Experimental Details

The device shown in Fig. 1 was originally designed as a RCEPD [2] and is now characterised as a RCLED, i.e. it can operate as a bi-directional device. The device was grown on an n-type GaAs (100) substrate using Molecular Beam Epitaxy (MBE) equipped with a radio frequency plasma source for nitrogen incorporation. The active emission region consists of nine, 7 nm-thick, $Ga_{0.733}In_{0.267}N_{0.025}As_{0.975}(Sb)/GaN_{0.035}As_{0.965}$ quantum wells. An Sb flux of 1.1×10^{-8} torr was present during growth of GaInNAs and GaNAs layers as a surfactant to mediate better nitrogen incorporation, enabling the shift of the operating wavelength to precisely 1.3 μm and the sharp interface production during growth of the QWs and barriers.

A band anti-crossing model and Vegard's Law were employed to determine the appropriate In and N compositions for emission at 1.3 μm. We used GaAs/AlAs quarter wave layers to form the top and bottom DBR mirrors. The reflectivity and cavity resonance wavelength of the structure were designed using the transfer matrix method (TMM). The bottom mirrors consist of 15-pairs of n-doped GaAs/AlAs (doping density of $7 \times 10^{18}\ cm^{-3}$ and $1.5 \times 10^{18}\ cm^{-3}$ for GaAs and AlAs, respectively), while the top DBRs have 10-pairs of p-doped GaAs/AlAs (doping density of $5 \times 10^{18}\ cm^{-3}$ and $3.1 \times 10^{18}\ cm^{-3}$ for GaAs and AlAs, respectively). The calculated and experimental Q-factor of the cavity mode is about 250 [2].

The fabrication steps were carried out using conventional photolithography techniques. A circular mesa structure with an emission window diameter of 800 μm was patterned and the structure was etched down to the bottom DBR by wet etching, using a $H_2SO_4{:}H_2O_2{:}H_2O = 1{:}8{:}80$ solution. Metal contacts consisting of Au:Ti (120 nm:10 nm) were fabricated *via* thermal evaporation on both the top (p-type) and the bottom (n-type) layers. The device was mounted on a copper heat sink using silver paste in order to dissipate excess heat during characterisation.

Photoluminescence and reflectivity measurements of the devices have been published in our previous studies [2]. Here we focus on Electroluminescence (EL), which was recorded using a micro-EL setup. The emission from the RCLED was collected by a 50x Olympus near-IR objective (LCPLN50XIR, NA = 0.65), and coupled into a spectrometer with an Andor iDus InGaAs detector. The collection area on the sample surface is approximately 88 μm in diameter, which is almost a tenth of the device window. The absolute power and the collection efficiency were calibrated prior to the RCLED characterization, using a 1.3 μm light source (Amonics ASLD130-200-B-FA) and a Ge photodetector (Thorlabs, PDA30B-EC).

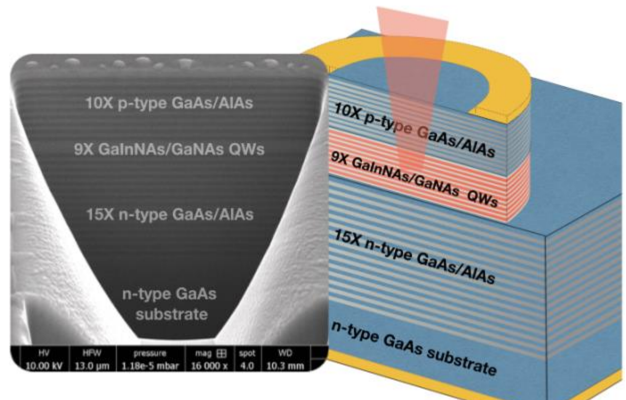

Fig. 1. Schematic structure of the GaInNAs/GaNAs QWs RCLED and its cross-sectional SEM image.

III. Results And Disussion

Fig. 2. shows the spectrum of the device with an applied current density of 10 A/cm^2 at room temperature. The EL peak wavelength is at 1302 nm; the current density is shown in the inset. We note that the spectral FWHM is 5.2 nm for an 88 μm diameter aperture at the centre of the device, which is suitably narrow for communications applications. As shown in the inset,

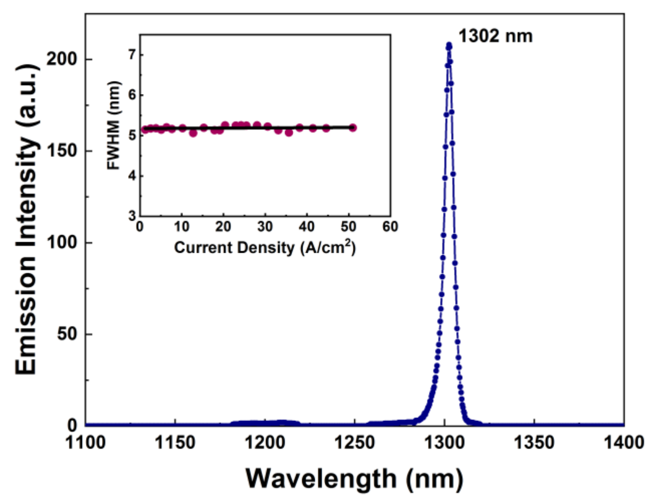

Fig. 2. Electroluminescence spectrum of the GaInNAs/GaNAs QWs RCLED and current density dependence of the FWHM (insert).

the FWHM does not vary with current density, because of the wavelength selectivity of the cavity.

The current density-voltage (J-V) characteristic of the device is shown in Fig. 3. The low differential resistance (dV/dI) indicates a low series resistance, which drops to as low as 5 Ohm at the operating voltage of 6 V. This low series resistance is due to the combination of the low band discontinuity of the GaInNAs/GaNAs quantum wells [2] and the highly doped top and bottom DBRs.

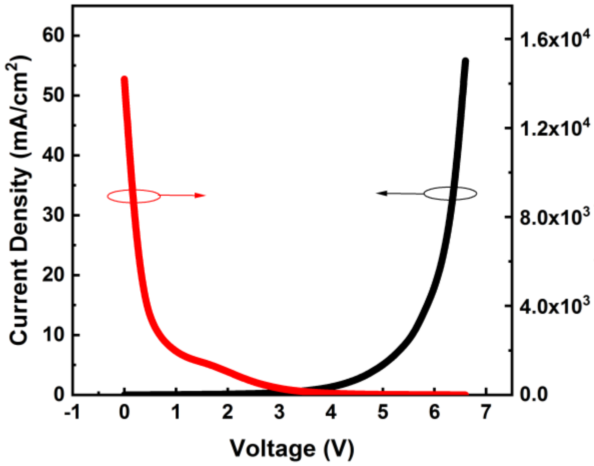

Fig. 3. Current-voltage characteristic of GaInNAs/GaNAs QWs RCLED.

The emission power density of the GaInNAs/GaNAs QWs RCLED as a function of the injected current density is shown in Fig. 4. For an injected current density of 45 A/cm^2, we record an output power of 0.5 mW from an 88 μm diameter aperture at the centre of the 800 μm diameter device. In the beginning of the study, electroluminescence spectrum has been measured on the whole active area of the device by scanning the position of the sample holder. It has been observed that electroluminescence spectrum properties such as intensity, FWHM and peak of the emission wavelength are almost the same. Based on the good homogeneity across the whole active area, we extrapolate the absolute power of 41 mW from the entire 800 μm diameter device.

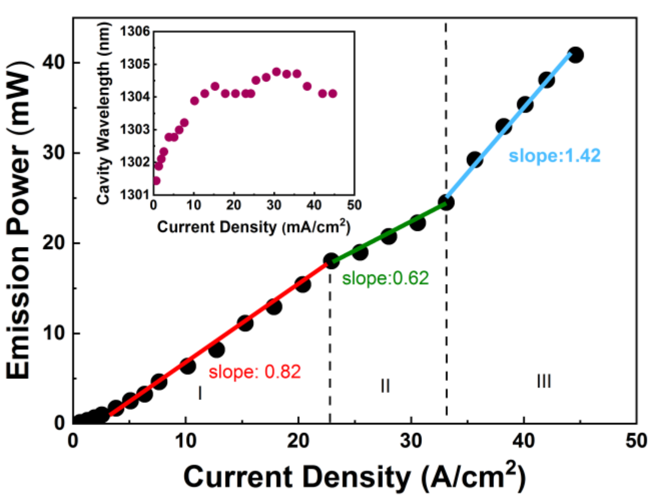

Fig. 4. Extrapolated emission power of GaInNAs/GaNAs QWs RCLED emission as a function of the injection current density.

We note that the relationship between the emission power density and the injected current density of the GaInNAs/GaNAs QWs RCLED exhibits 3 regions of different characteristics (see Fig. 4). A linear characteristic is observed up to 22 A/cm^2 and above 32 A/cm^2 with different slopes. A slight saturation is observed between these two linear regions. The only contribution to the output power in the first linear region comes from the emission of the GaInNAs quantum wells. As the current increases, the quantum wells get flooded with charge carriers and can overflow such that the emission power no longer increases proportionally with current and will fall behind the increase in the current. Above the saturation region, further increasing the current in the device can be an indication of the contribution from the GaNAs barrier layer. The difference in the bandgap values of GaNAs and GaInNAs is about only 50meV, which has been presented in our previous paper [2], therefore barriers in valance and conduction bands are so small to overcome by electrons and holes. Increasing applied current heats up the carriers facilitating them to escape GaInNAs QW towards to GaNAs barrier layer *via* thermionic emission, resulting in recombination not only in GaInNAs QW, but also in GaNAs barrier. Another effect, which can cause an enhancement of the emission power as injection current increases can be related to obtained a better match between emission spectrum and cavity resonance. The more injection current in the device results in more heating, therefore both emission spectrum and cavity resonance shift towards to higher wavelengths. The temperature-induced redshift rate of the effective bandgap of GaInNAs QW layer is 0.6 nm/K, redshift rate of the cavity resonance is about 0.07 nm/K [2]. The optimum operation condition for a resonant cavity device is that peak of emission spectrum and the cavity resonance mode are overlapped. In one of our previous paper, we have shown that, for this device to be operated as a RCEPD, the highest quantum efficiency was observed not at room temperature but higher,

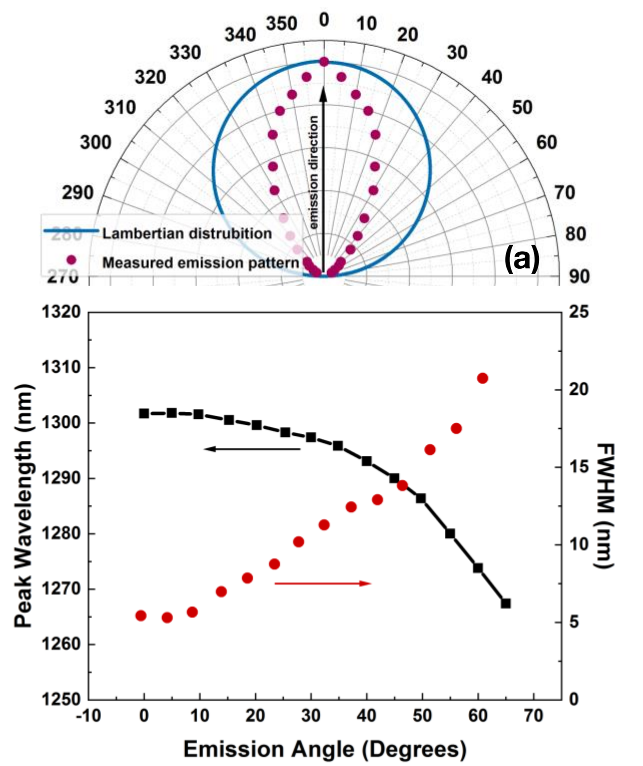

Fig. 5. a) Angular emission characteristics of the GaInNAs/GaNAs QWs RCLED at angles ranging from 0 to 65 degrees with respect to the cavity axis. The Lambertian pattern is plotted for comparison. b) Emission peak wavelength and FWHM with injected current of 5 mA/cm^2 as a function of angles.

which is related to better match between cavity resonance and emission spectrum of the active layer. Consequently, the observed higher emission power in the third region of the emission power *versus* injection power can be attributed to both contributions: i. better overlap between emission spectrum from the active region of the device and the cavity resonance peak and ii. recombination of the injected carriers in barrier layer GaNAs.

Finally, we examine the directionality of the emission. The output was measured at angles ranging from - 65 to 65 degrees (0 degree is defined as the optical axis) and the results are shown in Fig. 5 (a) together with a Lambertian emission pattern for comparison. The output is highly directional, exhibiting a significantly smaller divergence compared to the Lambertian emission pattern typical of an LED. Fig. 5 (b) shows the dependence of the peak wavelength and its FWHM on emission angle for an injected current density of 5 mA/cm^2. Within the acceptance angle of 19° of a single mode fibre operating at 1310 nm, the emission peak wavelength and the FWHM of the spectrum change very little.

IV. Conclusions

We have demonstrated the operation of an RCLED based on dilute nitride GaInNAs emitting at 1.3 μm wavelength and have characterised its electroluminescence properties. The emission linewidth is 5.2 nm at room temperature, from an 88 µm diameter aperture on the device, and the external quantum efficiency is approximately 20 %. The emission power is 0.5 mW from an aperture diameter of 88 μm, which corresponds to extrapolated absolute power of 41 mW from an 800 µm diameter device. Our results indicate that, with its narrow emission line, low divergence, finesse of the cavity selectivity, and high emission power, the proposed device is a promising candidate for a low-cost communication system in the 1.3 µm wavelength window. Together with our previous results highlighting the use of the same device as a detector, this device design offers the opportunity of bi-directional operation, without the need for cooling. Bi-directionality is exciting for the realization of low-cost fibre-to-the-home systems as the same device can be used for transmission and reception of data. Furthermore, the growth process of the device is simpler than that of comparable InP-based devices, which adds further to the cost advantage.

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