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VOLUMETRIC CARRIER INJECTION IN InGaN QUANTUM WELL LIGHT EMITTING DIODES

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InGaN/GaN quantum well (QW) light emitting diodes (LEDs) are essential components of solid-state lighting and displays. However, the efficiency of long wavelength (green to red) devices is inferior to that of blue LEDs. To a large degree, this occurs because the equilibration of injected holes between multiple QWs of the active region is hindered by GaN quantum confinement and polarization barriers. This drawback could be overcome by volumetric hole injection into all QWs through semipolar QWs present on the facets of V-defects that form at threading dislocations in polar GaN-based structures. In this work, we have tested the viability of this injection mechanism and studied its properties by time-resolved and near-field spectroscopy techniques. We have found that indeed the hole injection via the V-defects does take place, the mechanism is fast, and the hole spread from the V-defect is substantial, making this type of injection feasible for efficient long wavelength GaN LEDs.

Keywords: light emitting diodes, InGaN/GaN quantum wells, scanning near-field optical microscopy, carrier transport, V-defect

1. Introduction

The efficiency of multiple quantum well (QW) light emitting diodes (LEDs) to a large degree depends on the uniformity of carrier distribution between QWs. In InGaN/GaN QW LEDs, the electron transport across QWs is fast because of the small electron effective mass [1], and the electron distribution follows that of holes. The nonuniform interwell carrier distribution stems from the inefficient interwell transport of holes, which at room temperature is thermionic [2, 3]. In deep QWs, especially those emitting at long wavelengths (green to red), the thermionic hole transport is hindered by high quantum confinement and polarization barriers [3]. Thus, carrier distribution in multiple QWs of the LED active region is expected to be nonuniform. QWs on the p-side of the device would experience a high carrier concentration and an increased nonradiative Auger–Meitner recombination reducing the overall LED efficiency. In spite of this drawback, an exceptionally high wall plug efficiency of ~30% for yellow LEDs has been reported [4]. It has been suggested that this high efficiency is related to the carrier injection into all QWs of the active region via semipolar QWs located on V-defect facets. The V-defects form in the polar GaN structures at threading dislocations (TDs) under conditions of kinetically limited growth and have shapes of inverted hexagonal pyramids with semipolar $\{10\bar{1}1\}$ sidewall planes [5]. In this work, we have tested the viability of the V-defect injection mechanism and studied its properties by time- and spatially-resolved optical techniques in long wavelength InGaN QW LEDs.

2. Experiment

The studied LED structures were grown by metal-organic chemical vapour deposition on a double-side polished sapphire substrate. A structure contains n-GaN contact layers, a superlattice, an active region, and p-side contact layers. The 20 period GaN/$In_{0.05}Ga_{0.95}N$ superlattice serves to nucleate the V-defects [6]. The active region is formed of three $In_xGa_{1-x}N$ QWs (Fig. 1), two of which with $x = 0.20$ are 2.6 nm thick and emit in the green (~530 nm) spectral range, and one, the detector QW (DQW) with $x = 0.22$ and the thickness of 3.0 nm, emits in the red (~650 nm) range. On the V-defect sidewalls, the QWs become thinner and have a lower indium content (1.7 nm, $x = 0.05$), which shifts their band gap emission to 440 nm. The p-side of the structure contains a 10 nm p-AlGaN electron blocking layer (EBL) and 85 nm thick p and p+ GaN layers. More details on the structure can be found in Ref. [7]. The top metal contact of Pd/Au (50/100 nm) with a honeycomb pattern of open 20-μm diameter circular apertures provides areas for near-field measurements.

Structure parameters were determined by cross-sectional high angle annular dark field scanning transmission electron microscopy (HAADF-STEM) and energy-dispersive X-ray spectroscopy (EDS). Electroluminescence (EL) was studied on a wafer using needle contact probes. EL and photoluminescence (PL) were measured in the far and near field. In the latter case, a room temperature multimode scanning near-field optical microscope (SNOM) [8] with etched multimode silica fibre probes (aperture ~100 nm) was used. EL and PL spectra at each position of a scan were recorded using a spectrometer with a liquid N_2 cooled charge coupled device detector. The maps of surface topography were taken using a feedback signal from the fibre probe tuning fork. The maps of PL decay times were measured with a time-correlated single photon counter after excitation with 2nd harmonic pulses from a Ti:sapphire laser (pulse duration 200 fs, central wavelength 390 nm, pulse repetition frequency 4 MHz). SNOM maps were taken in the collection mode with either electrical carrier injection or optical far-field excitation through the substrate.

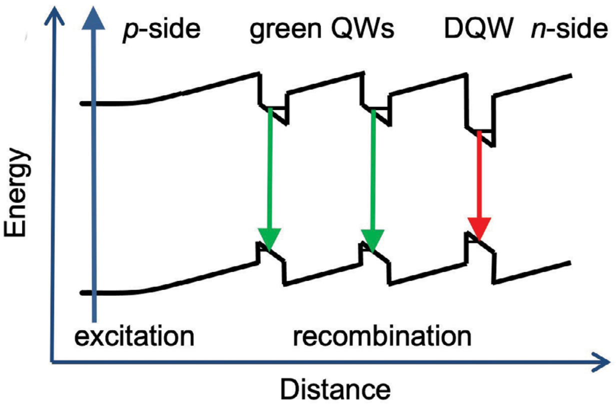

Fig. 1. Schematics of the active region of an LED. The green and red arrows indicate recombination in the green and red QWs.

3. Results and discussion

The far-field room temperature EL spectra at different bias values are displayed in Fig. 2. The spectra contain peaks from both the green (at ~515 nm at higher biases) and red (650 nm) QWs. The sheer presence of the red EL peak confirms that holes do reach the DQW from the p-side.

The hole transport to the DQW can take place either directly across the green QWs (path 1, Fig. 3) or via the V-defect semipolar QWs bypassing the green QWs (path 2). Time-resolved PL dynamics at the DQW band gap wavelength allows distinguishing which of these paths is taken by the holes. PL transients (Fig. 4) experience an ultrafast rise and ~7 ns decay reflecting the recombination of carriers excited directly into the DQW. The absence of a slow rise component, which is an indicator of the thermionic carrier transport from the top GaN layers across the QWs [3], demonstrates that carrier transport to the DQW proceeds via the semipolar QWs located at the V-defect facets and not by the thermionic transport. The measurements of PL dynamics after carrier excitation directly into the semipolar QWs shows that the carrier transport from the semipolar to the polar QWs is fast, a few tens of ps with the room temperature ambipolar diffusion coefficient of ~5.5 cm^2/s [9]. With the diffusion much faster than recombination, the hole transport from the p-side of the structure to the polar QWs should proceed without a substantial recombination loss and not impinging the efficiency of long wavelength GaN LEDs.

The provided far-field data show that the hole transport via the semipolar sidewall QWs is fast and efficient. However, for a complete equilibration of the injected carriers in the active region,

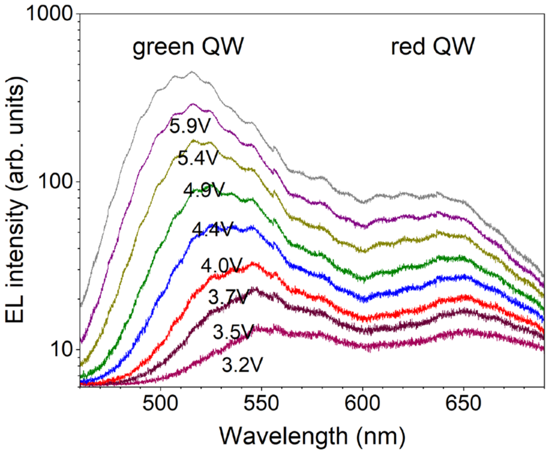

Fig. 2. EL spectra at different bias voltages. Numerical values indicate the applied voltages.

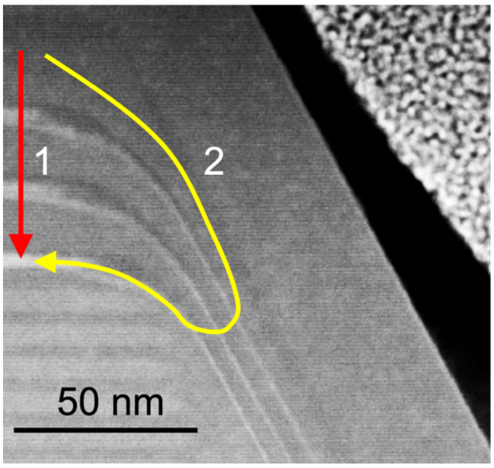

Fig. 3. Cross-sectional HAADF-STEM image of the structure in the vicinity of a large V-defect with hole transport paths towards the red QW directly across the green QWs (1), and via semipolar QWs at the V-defect facets (2).

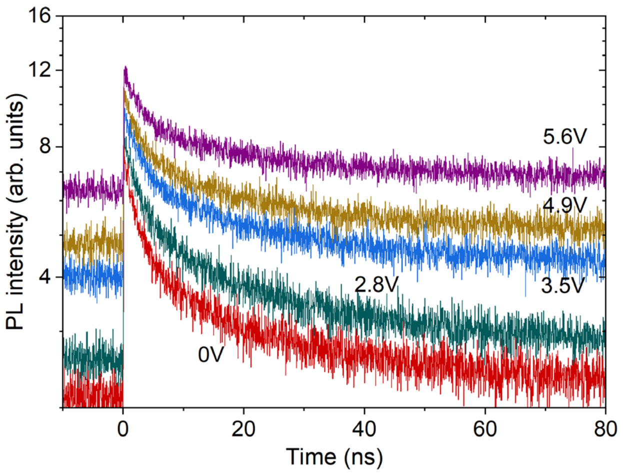

Fig. 4. PL transients for the red QW at different biases.

the hole distribution should be uniform not only in the vertical direction (between QWs) but also in the lateral direction (within individual QWs). To measure the spread of the hole population from the V-defect injectors and to evaluate the injector density required for the laterally uniform distribution, the SNOM measurements of EL were performed.

Figure 5 displays the 4 × 4 μm^2 topography and green QW EL intensity maps at low (~2 A/cm^2) and moderate (20 A/cm^2) average current densities. The EL maps experience large intensity variations, especially at higher currents. The high EL intensity regions correlate with the locations of V-defects. With increased current density, the EL intensity contrast between the V-defect-free and V-defect rich regions increases, showing that at high currents the hole injection takes place preferentially through the V-defects and not directly from the p-GaN to the first green QW. Such an indirect path is probably related to the $Al_{0.20}Ga_{0.80}N$ EBL, which might act as a potential barrier for the direct hole transfer from p-GaN to the first green QW. On the V-defect sidewalls, the EBL is thinner (4 vs 10 nm) with more diffuse interfaces and a slightly lower Al content, 20% vs ~18%, as observed by EDS. Additionally, the AlGaN/GaN interfaces have a large polarization discontinuity and polarization barrier on the *c* plane, but a relatively small discontinuity on the V-defect sidewall $\{10\bar{1}1\}$ plane [10]. Consequently, the hole transfer to the polar QWs from p-GaN should be easier via the semipolar QWs than directly, which would cause the preferential hole flow via the V-defects.

The SNOM study shows that the most efficient hole injection takes place not via individual V-defects but via V-defect clusters. The EL intensity profiles across the high intensity regions allow estimating the hole diffusion length. At moderate to high average carrier densities, the diffusion length is 0.5–1 μm and the hole diffusion coefficient is 0.5–0.8 cm^2/s [11]. These parameters show that for the uniform lateral hole distribution the V-defect injectors should be situated at ~1 μm from each other.

One should bear in mind that the V-defects form at TDs, and the latter have often been

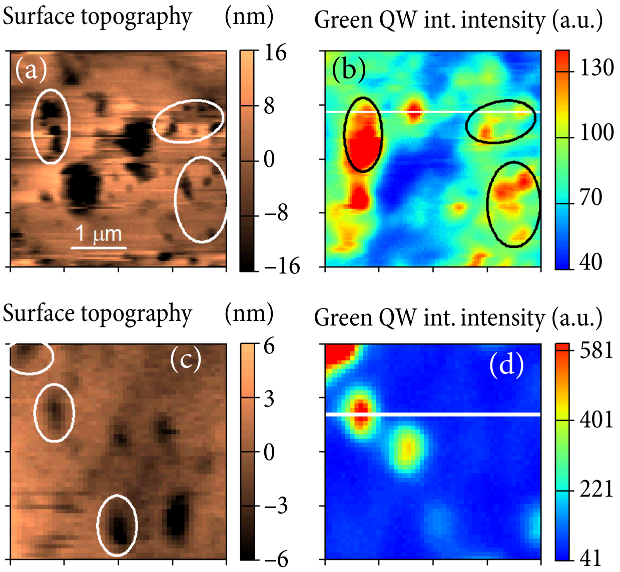

Fig. 5. Maps of the surface topography (a, c) and green QW EL intensity (b, d) at average carrier densities of 2 A/cm^2 (a, b) and 20 A/cm^2 (c, d).

suggested as efficient channels of the nonradiative Shockley–Read–Hall (SRH) recombination [12, 13]. To evaluate the relevance of the SRH recombination at the V-defects and related TDs, time-resolved near-field PL scans were performed. To reveal the effects that are important for device operation, the PL scans were performed on biased devices.

Figure 6 shows the maps of surface topography, EL and PL spectrally-integrated intensity, and the PL decay time of the red QW. One can notice that the V-defect rich regions have a higher EL intensity, which agrees with the data of Fig. 5. The EL intensity variations stem from the lateral nonuniformity of the hole injection, as discussed above. For PL, the carrier excitation is spatially uniform, and its intensity variations reflect variations of the internal quantum efficiency, which, in our case, is primarily determined by the nonradiative recombination. The PL intensity and decay time in the V-defect-rich regions are lower but not by much, some 20–40%. This demonstrates that under forward bias the V-defects and related TDs do not act as efficient recombination channels, since the majority of SRH recombination centres are filled. This is different from the situation experienced in the unbiased QW structures, in which emission intensity variations of several to several tens of times have been observed [12, 13]. The moderate PL intensity and lifetime variations between the V-defect-rich and V-defect-free regions show that the V-defects do not considerably enhance the nonradiative recombination [14, 15], which is advantageous for their usage as volumetric hole injectors.

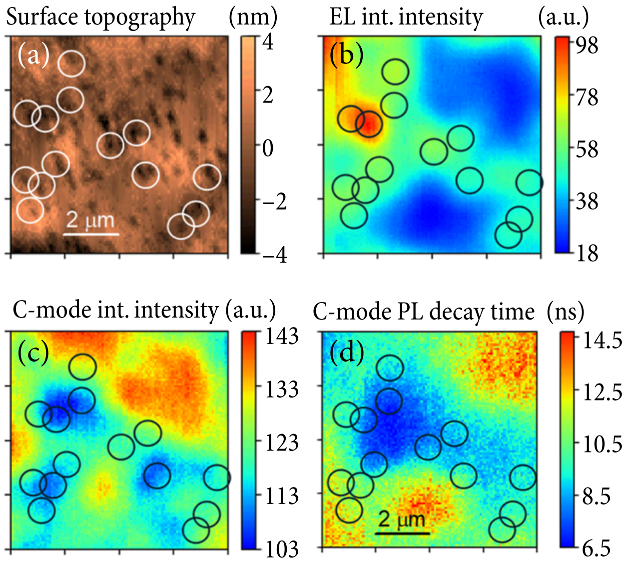

Fig. 6. SNOM maps of the surface topography (a), EL (b) and PL (c) intensity, and the PL decay time (d) of red QW.

4. Summary

The properties of hole injection via volumetric V-defect injectors have been studied in dual colour (green/red) InGaN QW LEDs with time- and spatially-integrated and resolved EL and PL. The experiments have shown that the hole injection via the semipolar QWs located on the facets of V-defects indeed takes place, and this process is fast, a few tens of ps. It has been found that in the devices with V-defects, the hole injection is spatially nonuniform and takes place preferentially via the V-defect injectors. The hole diffusion length in the polar QWs is close to 1 μm, which provides guidance for the design of the long wavelength V-defect-based InGaN QW LEDs. The nonradiative SRH recombination at threading dislocations and V-defects was found to be moderate and should not significantly reduce the efficiency of the V-defect LEDs. Overall, the studied effects and revealed transport parameters show that the volumetric hole injection via the V-defects is a viable path pursuing highly efficient GaN-based LEDs for the green and red spectral regions.

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TŪRINĖ KRŪVININKŲ INJEKCIJA InGaN KVANTINIŲ DUOBIŲ ŠVIESOS DIODUOSE

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Santrauka

InGaN/GaN kvantinių duobių šviesos diodai yra esminiai kietojo kūno apšvietimo ir ekranų komponentai. Tačiau ilgojo matomos šviesos diapazono (nuo žalios iki raudonos) prietaisų efektyvumas yra prastesnis nei mėlynų šviesos diodų. Iš dalies tai atsitinka todėl, kad skylės nevienodai pasiskirsto tarp šviesos diodų aktyviosios srities kvantinių duobių. Šį netolygų pasiskirstymą lemia didelis kvantinių duobių gylis bei poliarizacijos barjerai tarp kvantinės duobės ir barjero sluoksnių. Šį trūkumą galbūt būtų galima apeiti naudojant tūrinę skylių injekciją per pusiau polines kvantines duobes, kurios formuojasi ant vadinamųjų V defektų, susidarančių ant dislokacijų polinėse GaN struktūrose. Šiame darbe ištyrėme, ar toks tūrinis skylių injekcijos mechanizmas yra iš principo galimas, ir išnagrinėjome jo savybes laikinės skyros ir artimojo lauko spektroskopijos metodais. Nustatėme, kad skylių injekcija per V defektus iš tiesų vyksta, šis mechanizmas yra greitas, o skylių difuzijos ilgis yra nemažas. Visa tai parodo, kad tūrinė skylių injekcija per V defektus turi didelių perspektyvų konstruojant efektyvius ilgų bangų GaN šviesos diodus.