Electroluminescence from the InGaN/GaN Superlattices Interlayer of Yellow LEDs with Large V-Pits Grown on Si (111) *

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A blue emission originated from InGaN/GaN superlattice (SL) interlayer is observed in the yellow LEDs with V-pits embedded in the quantum wells (QWs), revealing that sufficient holes have penetrated through the QWs into SLs far away from the p-type layer. In the V-pits embedded LEDs, hole transport has two paths: via the flat c-plane region or via the sidewalls of V-pits. It is proved that the holes in SLs are injected from the sidewalls of V-pits, and the transportation process is significantly affected by working temperature, current density, and the size of V-pits. Four motion possibilities are discussed when the holes flow via the sidewalls. All these may contribute to a better understanding of hole transport and device design.

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InGaN based LEDs have been widely used commercially. The V-pits are open hexagonal inverted pyramids defined by the six $\{10\bar{1}1\}$ planes, which are common in commercial InGaN-based devices.[1] The V-pits techniques have been developed to enhance performance of devices by promoting hole injection[2–4] and screening the dislocations.[5,6] Our previous work[7] and Li *et al.*[8] reported that a number of holes could inject into multiple quantum wells (MQWs) through the sidewalls of large V-pits in addition to through the *c*-plane region, which is important for GaN LEDs. However, the specific hole transport process in the V-pits embedded LED structures is not very clear, so more in-depth research needs to be carried out. In this Letter, we demonstrate a blue emission from the InGaN/GaN superlattice (SL) interlayer by the electroluminescence (EL) spectra at cryogenic temperatures. For the first time, it is revealed that holes can reach the SL interlayer which is at the bottom of MQWs far from the p-type layer. The specific ways and deep mechanisms of holes injected into SLs were analyzed in detail.

The InGaN-based yellow LEDs studied were grown by a metal organic chemical vapor deposition system on a Si (111) substrate.[9] The growth started with a 110 nm AlN buffer, followed by a 2.4 μm n-GaN with Si doping of 5×10^{18} cm^{-3} and then a 10 nm low temperature GaN (LT-GaN). The active region consists of 5 pairs of 3 nm-$In_{0.3}Ga_{0.7}N$/13 nm-GaN MQWs followed with a p-AlGaN electron barrier layer (EBL) and a p-GaN layer. Here aluminum (Al) was intentionally introduced in the penultimate barrier. In addition, multi-periods of 5 nm-$In_{0.08}Ga_{0.92}N$/1 nm-GaN SLs were inserted between the n-type GaN layer and MQWs as a strain relief layer. V-pits can easily initialize in SLs at the sites of dislocations owing to the external tensile strain originated from the Si substrate. Correspondingly, there is a V-pit recovery layer for filling up the V-pits in the p-type GaN layer. Samples A (with 16 SLs), B (with 24 SLs) and C (with 32 SLs) were prepared with identical structure except for the size of V-pits. In addition, to further identify the SLs' emission, the EL spectra of LEDs with different radiation energies of SLs were investigated. Thus sample D with 5 nm-$In_{0.08}Ga_{0.92}N$/1 nm-GaN SLs and sample E with 3.7 nm-$In_{0.08}Ga_{0.92}N$/1 nm-GaN SLs were prepared. Vertical thin film LED chips with size of 1×1 mm^2 were fabricated with top surface (n-side) roughened and the p-GaN surface coated with Ag-reflector. The detailed chip fabrication process has been reported.[10]

The second ion mass spectra (SIMS) were measured using a CAMECA IMS-7F from the top surface of p-GaN. The variations of In and Al elements with the test depth reveal the structures of MQWs and SLs. The clear oscillation of indium profile implies a fine quality of QWs and SLs, and it can be seen that the p-GaN is highly doped with Mg whose concentration reaches 10^{20}/cm^3 in order in this work. The scanning electron microscope (SEM) images taken by a HITACHI SU8010 SEM show that the V-pits were enlarged by increasing the number of SLs' periods.

Temperature depended electroluminescence was performed with the system described in our previous

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report.[2] As shown in Fig. 2, while at 350 K only the main emission peak (P1) at about 565 nm of the *c*-plane QWs is observed, at 250 K the emission peak (P2)[11] of the sidewall QWs around 475 nm appears. In comparison, P3 appears until 200 K with a shorter wavelength of approximately 437 nm, and the peak wavelength of P3 has a slight blue shift as increasing current (Fig. 6(a)). In addition, from Fig. 2(d), it can be observed that with decreasing the temperature, although P3 appears later than P2, its intensity increases much faster and could exceed P2. The rises of P2 and P3 are accompanied by the shrink of the left side of P1.

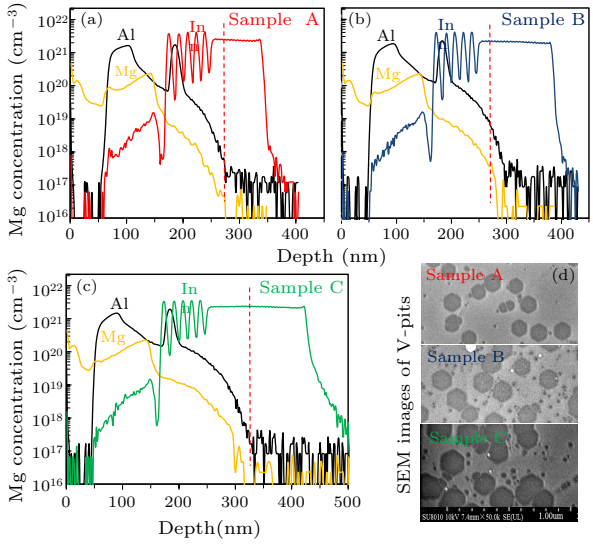

Fig. 1. The SIMS image of yellow LEDs with different numbers of SLs periods: (a) 16 periods, (b) 24 periods, and (c) 32 periods. (d) The SEM images of V-pits of the three samples mentioned above.

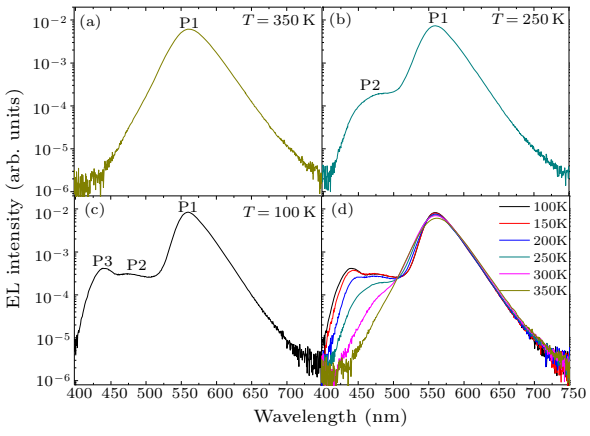

Fig. 2. The EL spectra of sample A with 16 SLs at typical 35 A/cm^2 under different test temperatures: (a) 350 K, (b) 250 K, and (c) 100 K. (d) The evolution of EL spectra with decreasing the temperature.

It is proved that P3 is the emission from the InGaN/GaN SLs below the yellow MQWs. In view of the possible emitting position of LEDs, as P1 is the emission from the *c*-plane QWs and P2 is the emission from the sidewall QWs of V-pits,[11,12] only the Mg-related transition in p-GaN needs to be ruled out to identify the source of P3. As in the previous report, the PL peaks of highly doped p-GaN with a broad line shape are around 3.2 eV, which is much higher than that of P3, and a large continuous blue shift of this Mg peak with increasing the excitation power was observed,[13] which is not consistent with the property of P3. In addition, the phase separation of InGaN wells was also reported to be a possible origin of the blue emission from longer wavelength LEDs. Wang *et al.* observed both blue and yellow emissions from one LED due to In phase separation.[14] However, the InGaN wells in our samples appear to be very uniform (Fig. 3). Moreover, several other reports revealed that the blue emission was observed only in red LEDs,[15] but not in amber and green LEDs.[16] Furthermore, the blue emission in our work did not appear until the temperature drops below 200 K, while the blue emissions caused by In phase separation were all observed at room temperature.[14–16] Hence, the phase separation of InGaN wells could not be the origin of the blue emission in this work. Moreover, Damilano and Gil[17] calculated the fundamental transition of InGaN/GaN QWs as functions of the indium content and the QW thickness. For the SLs with well thickness of 5 nm and In composition of 0.08, the emission of SLs is right in the blue range of about 437 nm. Hence, we believe that P3 belongs to the InGaN/GaN SLs.

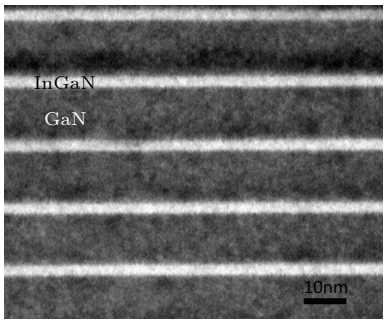

Fig. 3. Cross-sectional TEM image of the InGaN layers of the yellow LED. The uniform InGaN QWs can be seen.

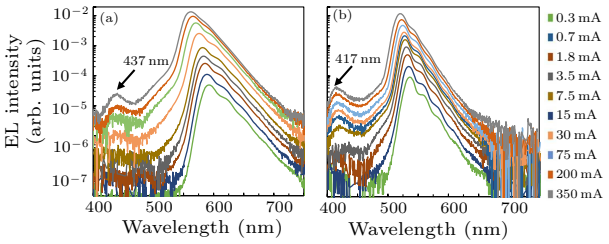

Fig. 4. Comparison of the peak positions of the emission from the SL interlayer, the EL spectra of (a) sample D with 5 nm-$In_{0.08}Ga_{0.92}N$/1 nm-GaN SLs, and (b) sample E with 3.7 nm-$In_{0.08}Ga_{0.92}N$/3.3 nm-GaN SLs. The wavelengths of SLs emission blue shift obviously due to the decrease of the thickness of InGaN layer of SLs.

The blue emission from SLs was further confirmed by EL spectra of LEDs with different InGaN thicknesses of SLs. It is well known that the wavelength

of QWs is determined by thickness and In content, and will increase with the well thickness. As shown in Fig. 4, the emission from SLs blue shifts obviously due to reducing the thickness of InGaN layer of SLs, which further identifies that the blue emission is originated from SLs. Although it is generally assumed that the emission in LEDs occurs mainly in the QWs close to p-GaN,[18] the observed emission from SLs is consistent with several recent reports, which demonstrated that holes could penetrate through the upper active region into the structure at the bottom.[19–21]

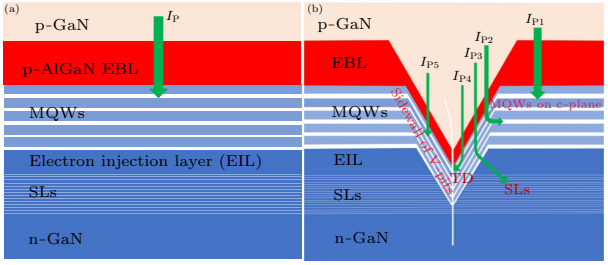

Fig. 5. Schematic hole-flow paths in LEDs (a) without V-pits and with V-pits, and I_p is the hole current. In the LEDs with V-pits, I_{p1} is the hole current via the flat c-plane region. In addition, the holes could also transport via the sidewalls of V-pits. If via the sidewalls, there are four directions for the further motion of holes: flowing into the MQWs on the c-plane (I_{p2}); transporting farther to SLs (I_{p3}); leakage to TDs or other defects (I_{p4}); or taking part in radiative recombination (I_{p5}), which results in the emission of P2; $I_p = I_{p1} + I_{p2} + I_{p3} + I_{p4} + I_{p5}$.

As mentioned in the introduction, V-pits have changed the hole transport in GaN-based LED structures. If there are no V-pits, hole injection is only through the flat c-plane region (path 1) of the LED structure. In contrast, it is well known that holes could also inject via the sidewalls of V-pits (path 2) in the V-pit-embedded LEDs,[7,8] as shown in Fig. 5. If holes transport via the sidewalls of V-pits, there are four directions of holes motion: (1) injecting into the c-plane QWs,[7] which is contributed to the emission of P1; (2) taking part in radiative recombination,[11] in the sidewall QWs, leading to the emission of P2; (3) leakage to defects, such as the threading dislocations (TDs) in the core of V-pits,[22] or (4) transporting to farther SLs. Among them, the first three have been proved by previous research. In this work the last is proved by the observed emission of P3. The photon energies of P1, P2, and P3 are all less than the energy gap of GaN. In addition, there should also be some other holes that are consumed in the layer where the energy gaps are close to or larger than those of GaN, such as EBL and EIL. However, there are no emissions from these layers in this study, which may be caused by strong self-absorption of GaN and weak intensity.

The observation of P3 reveals that sufficient holes have injected into SLs far from the p-GaN. We deduce that the holes in SLs are injected via the sidewall of V-pits but not the c-plane, as the EBL and MQWs on the c-plane are much thicker than those on the sidewall of V-pits.[5] When the temperature dropped below 200 K, the holes number would decrease dramatically due to the high active energy of Mg doping in p-GaN.[23] Hence, it is more likely that the limited holes have been consumed in the process of moving across the MQWs region on the c-plane. However, the thicknesses of EBL and MQWs on the sidewalls of V-pits were only 1/4 and 1/5 times than those on the c-plane, thus the sidewall of V-pits is easier for holes to pass through.[7] In addition, a higher proportion of holes would flow through path 2 with decreasing the temperature.[11] This may be caused by the more difficult hole tunneling through the c-plane region due to its much thicker EBL. With decreasing the temperature, the hole concentration reduces severely, thereby the barrier difference between paths 1 and 2 may be amplified, leading to more holes flowing through the V-pits. Both of them can help holes inject into the SLs layer via the sidewalls of V-pits.

In addition, the increased kinetic energy of holes may be necessary to the rise of P3. According to the microscopic expression of current, $I = nqvs$, where I is the current, n is the carrier concentration, q is the charge of the carrier, v is the rate of carrier orientation movement, and s is the cross-sectional area of a conductor. The values of q and s are constant for one chip of LEDs, and the number of holes would reduce with decreasing the temperature. Hence, the hole must be sped up for compensation and thus be entitled to higher kinetic energy to achieve a certain current. Then, the increased kinetic energy of holes could reduce the opportunity of them being captured by QWs and could drive more holes to transport further,[24,25] helping the emission of P3. This also explains why the intensity of P3 rises faster and can exceed P2 with decreasing temperature or increasing current. Another factor that might contribute to the increasing intensity of P3 at cryogenic temperature is the frozen defects, which could suppress the Shockley–Read–Hall recombination effectively.

It is also worth contemplating that the rises of P2 and P3 are accompanied by the shrinking of the left side of P1, as shown in Fig. 2(d). This gives us a chance to explore the further hole transport after they flow into the sidewall QWs of V-pits. Our previous report has proved that the holes injected into the c-plane QWs from the sidewall QWs have a significant contribution to the left side of P1.[2] Hence, this phenomenon reveals that with decreasing the temperature, some holes going to be injected into the c-plane QWs changed their flow direction. Considering the 'frozen defects' at the cryogenic temperature, more holes were likely to be transported further or took part in radiative recombination, resulting in the rises of P2 and P3 accompanied with the shrink of the left side of P1. This also supports our inference that the holes injected into SLs are via the sidewalls of V-pits.

The effects of size of the V-pits on hole transport

in yellow InGaN-based LEDs are investigated by EL spectra of the three samples at 100 K. As shown in Fig. 6, larger V-pits lead P2 and P3 to appear later and weaker. A lower forward voltage is also obtained with larger V-pits, which can be regarded as the improved hole injection via the side-wall of V-pits.[7] The behaviors of P2 and P3 can be explained by the decreased kinetic energy of holes owing to the lower forward voltage. This phenomenon means that larger V-pits would help to suppress the hole being transported to SLs, which is beneficial to the efficiency of LED. In addition, by other experiments, it is found that the suppression of holes transported into SLs could also be achieved by increasing the number of QWs and adjusting the Si doping concentration. These will be reported in the future.

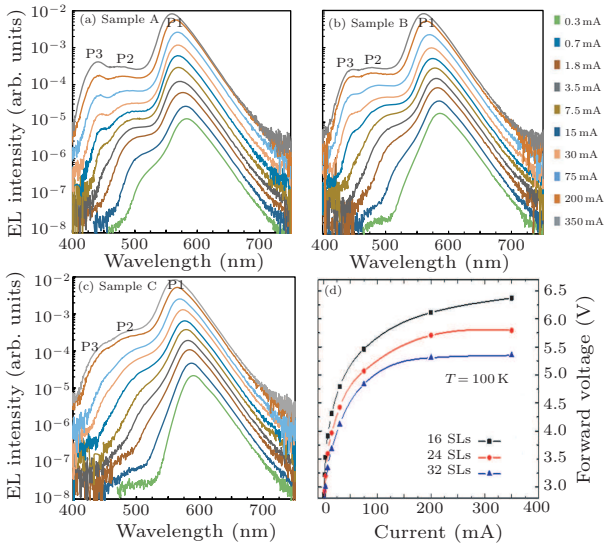

Fig. 6. The EL spectra for (a) sample A, (b) sample B, and (c) sample C at 100 K. (d) The comparison of the forward voltage among these three samples.

In summary, we have found a blue EL emission from the InGaN/GaN SL interlayer at the bottom of yellow MQWs at cryogenic temperatures. It implies that sufficient holes have penetrated through MQWs into SLs far from the p-GaN. The V-pits have an important influence on the hole transport in LEDs, which has been studied in detail.

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