Efficiency and Forward Voltage of Blue and Green Lateral LEDs with V-defects in Quantum Wells

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For nitride-based blue and green light-emitting diodes (LEDs), the forward voltage $V_{\text{for}}$ is larger than expected, especially for green LEDs. This is mainly due to the large barriers to vertical carrier transport caused by the total polarization discontinuity at multiple quantum well and quantum barrier interfaces. The natural random alloy fluctuation in QWs has proven to be an important factor reducing $V_{\text{for}}$. However, this does not suffice in the case of green LEDs because of their larger polarization-induced barrier. V-defects have been proposed as another key factor in reducing $V_{\text{for}}$ to allow laterally injection into multiple quantum wells (MQWs), thus bypassing the multiple energy barriers incurred by vertical transport. In this paper, to model carrier transport in the whole LED, we consider both random-alloy and V-defect effects. A fully two-dimensional drift-diffusion charge-control solver is used to model both effects. The results indicate that the turn-on voltages for blue and green LEDs are both affected by random alloy fluctuations and V-defect density. For green LEDs, $V_{\text{for}}$ decreases more due to V-defects, where the smaller polarization barrier at the V-defect sidewall is the major path for lateral carrier injection. Finally, we discuss how V-defect density and size affects the results.

I. INTRODUCTION

Blue nitride-based light-emitting diodes (LEDs) with phosphor have become the major white-light source. However, high-efficiency or micro-LED display applications require green- and red-light sources and, for ultimate efficiency, white-light lamps based on RGB color mixing. Currently, the peak internal quantum efficiency (IQE) of blue LEDs is over 90% at a current density of 1–10 A/cm$^2$. However, the IQE of green LEDs remains low, which is likely due to the strong quantum-confined Stark effect induced by the polarization charge and the large defect density. In addition, the forward voltage $V_{\text{for}}$ of green LEDs also exceeds the expected 2.3 V$^3$ which also limits the wall plug efficiency.

III-nitrides in the common (0001) orientation have polarization-induced barriers at the InGaN/GaN quantum well/quantum barrier (QW/QB) interface due to spontaneous and piezoelectric polarization differences between the well and barrier materials.$^3$ The polarization discontinuity at the QW/QB interface results in significant electric fields in the QWs and QBs—often referred to as “piezofields.” For green LEDs, the polarization discontinuity at the QW/QB interface increases due to the increased lattice mismatch between the InGaN and GaN layers.

The influence of polarization-induced barriers has been discussed in many studies.$^{12,17}$ where carriers are easily blocked by the extra potential barrier. Our previous studies of blue LEDs$^{18}$ show that fluctuations in indium composition provide extra paths for carrier injection. Including random indium composition fluctuations in models thus helps to explain the lower $V_{\text{for}}$ in blue LEDs compared with models without fluctuations.$^{18}$

To further reduce $V_{\text{for}}$ in situations with larger barriers, such as in green LEDs, it is important to either reduce the polarization field or find an alternative way to inject carriers. The most significant method is by controlling the V-shaped defect (V-defect) opened at the InGaN/GaN MQW active regions. Most V-defects are the result of dislocation lines that form under certain growth conditions.$^{1,4,5,8,9}$ Unlike the threading dislocation (TD) centers, which are typical nonradiative centers, the inclined sidewalls of V-defects reportedly assist carrier injection into QWs.$^{11,12}$

Given that V-defects play an important role in carrier injection, it is important to understand the role of random alloy fluctuations and of V-defects in carrier injection. The V-defect and random alloy effects may be simulated separately in three-dimensional simulations.$^{13,14}$ On the one hand, V-defects range from a few hundred nanometers in size to the μm scale, allowing for large mesh sizes. On the other hand, random alloy fluctuations occur on a scale of a few nanometers, requiring mesh elements to be as small as possible to account for such small-scale fluctuations. Including both effects in a three-dimensional simulation requires unreasonable computer memory (> a few TB) and computing times. An alternative approach is to work on two-dimensional (2D) simulations that include random alloy fluctuations and V-defects. In this paper, we discuss the influence of V-defects and random alloy fluctuations with such an alternative 2D model.

V-defects may be controlled by tuning the growth conditions. Often, V-defects are formed in the widely used InGaN/GaN short periodic superlattice that is grown before growing active InGaN/GaN QWs.$^{10}$ The general V-defect density is about $1 \times 10^8$ cm$^{-2}$ $\approx 5 \times 10^8$ cm$^{-2}$, and the typical

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diameter is about 30–250 nm for five QWs in blue LEDs. \[54\] V-defects form an inverted hexagonal pyramid with six inclined \{1011\} semipolar sidewalls. \[16\] Studies show that the indium composition in \(c\)-plane QWs is greater than in the inclined QWs in the V-defect region. \[17\] Therefore, the bandgap of QWs in the inclined sidewall of V-defects is larger than the bandgap of QWs in the \(c\) plane. The polarization discontinuity between the \{1011\} InGaN sidewall QW and QB is much smaller than the \(c\)-plane QW and is in the opposite direction. \[18\] Thus, holes can be injected into the QWs in the \(c\) plane through the sidewall V-defect QWs with lower barrier potentials. \[19\] The additional paths provided increased \(V_{\text{for}}\) and increase the carrier-injection efficiency. \[20\] However, V-defects form at TDs, and a high density of nonradiative centers at the center of V-defects could be a drawback. Thus, the density and diameter of the V-defects in the LED should be optimized to minimize this counter-acting effect. \[21\]

In this paper, we use simulations to investigate how random fluctuations and V-defects affect InGaN-based LEDs. As mentioned above, computer-memory limitations oblige us to use 2D simulations with fluctuations instead of three-dimensional simulations. In 2D simulations, the size of the simulated structure may be increased to the micron scale to approach the real device structure of LEDs. In the following, we discuss the 2D structure with different V-defect densities and diameters (lateral size). The forward voltage \(V_{\text{for}}\) and efficiencies (electrical and IQE) are discussed and explained by the interplay between lateral carrier injection through the V-defect sidewalls and subsequent carrier diffusion within the planar QW regions.

**II. METHODOLOGY**

To simulate random alloy fluctuations in devices, we use an in-house-developed 2D drift-diffusion charge control solver to determine the electrical carrier distribution, recombination rates, and other properties. First, to account for the random alloy fluctuations, we construct a device mesh with a V-defect shape. The mesh size at the QW region is 0.5 nm in the \(x\) direction and 0.1 nm in the \(z\) direction. The mesh size is larger in the \(p\) and \(n\) layers to save computer memory. We then use a random number generator to create the random atom distribution in the alloy regions and subsequently use Gaussian averaging to assign the local indium composition in the QWs. \[22\]

Figure \[1\] shows the indium composition fluctuations in the QWs, where the bandgap depends on the indium composition. Note that, in the 2D simulation, we cannot calculate the real strain distribution with a strain solver because we have neglected the third dimension. Thus, fully compressive strain is assumed when calculating the lattice size of the GaN buffer layer based on the local indium composition. We then calculate the local material parameters such as bandgap, conduction- and valence-band energies, polarization according to the local indium composition, and strain state. In addition, we use the localization landscape (LL) model \[23\] instead of the Schrödinger equation solver to obtain the effective quantum potential seen by the carriers. \[24\]

**A. Methodology of analyzing two-dimensional solver**

To simulate the 2D Poisson, drift-diffusion, and LL equations, the following equations were used:

\[
\nabla \cdot (\varepsilon \nabla \varphi) = q \left( n - p + N_A^- - N_D^+ + p_{\text{pol}} \right),
\]

\[
- \frac{\hbar^2}{2 m_e} \nabla \left( \frac{1}{m_{e,h}} \nabla \right) + E_{c,v} \right) u_{e,h} = 1,
\]

\[
n = \int_{1/u_e}^{+\infty} \text{LDOS}(E) \frac{1}{1 + \exp \left( \frac{E - E_{F,n}}{k_BT} \right)} dE,
\]

\[
p = \int_{1/u_h}^{-\infty} \text{LDOS}(E) \frac{1}{1 + \exp \left( \frac{E - E_{F,p}}{k_BT} \right)} dE,
\]

\[
J_{n,p} = \mu_{n,p}(n,p) \nabla E_{F,n,p},
\]

\[
\frac{1}{q} \nabla (J_{n,p}) = R_{n,p} - G_{n,p},
\]

\[
R = R_{\text{SRH}} + B_0 n p + C_0 \left( n^2 p + n p^2 \right),
\]

\[
R_{\text{SRH}} = \frac{np - n_i^2}{\tau_{n_0}(p + n_0) + \tau_{p_0}(n + n_0)}.
\]

In these equations, \(\varphi\) is the electrostatic potential in the structure, \(n\) and \(p\) are the free electron and hole concentrations, and \(N_A^-\) and \(N_D^+\) are the ionized acceptor and donor concentrations determined by the ionization energy (and position in the junction and junction electric field), respectively. \(p_{\text{pol}}\) is the polarization charge that has been computed from the divergence of the total polarization, and \(\frac{1}{m_e}\) and \(\frac{1}{m_h}\) are the effective quantum potentials of electrons and holes calculated by the LL equations, respectively.

First, we calculate \(\varphi\) by using the Poisson equation \[1\] and obtain the local band extrema \(E_c\) and \(E_v\) through the local \(\varphi\) and alloy composition. Then, the LL equations \[2\] are solved to yield \(u_e\) and \(u_h\) and the effective quantum potentials \(\frac{1}{m_e}\) and \(\frac{1}{m_h}\). The carrier distributions are calculated by using Eqs. \[3\] and \[4\], the effective quantum potentials \(\frac{1}{m_e}\) and \(\frac{1}{m_h}\), and the quasi-Fermi levels \(E_{F,n}\) and \(E_{F,p}\). Finally, we determine \(E_{F,n}\) and \(E_{F,P}\) from Eqs. \[5\] and \[6\]. The recombination rate is given by Eq. \[7\], and includes radiative recombination (IQE), Auger recombination, and Shockley–Read–Hall (SRH) recombination. \(B_0\) is the radiative recombination rate. Equation \[8\] is the SRH recombination equation, where \(\tau_n\) and \(\tau_p\) are the nonradiative carrier lifetimes of electrons and holes, respectively. \(C_0\) is the Auger recombination rate coefficient, which is the recombination of three particles, either directly or mediated by phonons. \[31\]

Next, we construct the mesh according to the position in the structure; each mesh point has different parameters. To simulate V-defects in the structure, the mesh is readjusted according to the V-defect diameter and density. Finally, these equations are solved self-consistently. Figure \[1\] shows a detailed flowchart of the simulation.
not converge

 converged

FIG. 1. Flow chart of simulation model. The mesh with V-defect shapes is put in the simulation program. The random alloy map is generated by using a random number generator and then put in the solver to realize convergence after the required number of feedback loops. The right panel shows the indium composition map in the MQWs.

B. Device structures and parameters

To discuss the V-defect, we analyze the blue and green LEDs with the structure shown in Fig. 2(a). The chip lateral size is 11 µm and the region of multiple quantum wells (MQWs) is 10 µm wide, which is also defined as the total region. Since our mesh is quite small, we use about 1.1 × 10^7 nodes to simulate the 11 µm chip, which requires 55 GB of memory to run the 2D simulation. The p contact (in common p-side LEDs, this layer is made from indium tin oxide) is about 9 µm wide at the center of the active region, and the n pad is about 1 µm wide.

![Simulated structure of lateral LED](a)

![Definition of parameters](b)

For the blue and green LEDs, we consider a MQW LED with a 0.14 µm top p-GaN layer doped at 3 × 10^19 cm^-3, a p-AlGaN electron blocking layer (EBL) and p-GaN cladding layer both doped at 2 × 10^19 cm^-3. Five QWs and four QBs between the QWs are unintentionally doped n type at 1 × 10^17 cm^-3, one 10 nm n-cladding layer and then a 2.5 µm n-GaN layer doped at 5 × 10^18 cm^-3. The doping density of n-type cladding layer is 1.0 × 10^19 cm^-3. For the green LED, the first two QBs are n doped at 1.0 × 10^18 cm^-3 to partially screen the piezoelectric field for better vertical carrier injection. We also ran a simulated case without doping in the first two QBs (and with no V-defects) for comparison. In addition, \( \tau_n \) and \( \tau_p \) for the blue and green LEDs are 100 and 10 ns, respectively, because the green LED has a higher In content in the InGaN than the blue LED and thus a lower growth temperature, which leads to a higher density of SRH centers in the real device. The detailed parameters of the structures are shown in Table I. For the blue LED, the average indium composition in the QWs is 13% (InGa1.13Ga0.87N). For the green LED, the average indium composition in the QWs is 22% (In0.23Ga0.78N). Additionally, alloy fluctuations in the InGaN layers are included in both the blue and green LEDs.

Figure 2(b) shows the geometrical definition of V-defects, where H and D are the depth and diameter of the V-defect, respectively. We use these parameters in the following discussion. The region between the vertical black dotted lines correspond to the TD along the direction \{001\} with a 30 nm width at the center of the V-defect, and the V-defect sidewall QWs are inclined about 60° according to both transmission electron microscopy (TEM) and scanning TEM electron microscopy (STEM) which is consistent with early work showing that the sidewalls are \{1011\} planes. In addition, the thickness of the c-plane QWs is 3 nm. The inclined sidewall QW is also 3 nm thick in the z direction, which corresponds to a thickness of 1.73 nm (3 nm × cos 60°) along the normal to the inclined plane.

The indium composition in the inclined QWs depends on the composition in c-plane QWs. For example, for blue LEDs, the indium composition of inclined QWs is 8% [23]. For green LEDs, the indium composition in the inclined QWs is about 16% [24]. In addition, the TDs are defects induced by the lattice and chemical mismatch between the sapphire substrate and GaN [25]. Thus, we include TD-associated trap states in the TD regions, which trap either electron or holes and are shown as the cross-hatched areas in Fig. 2(b). The density of TD-associated trap states is about 1 × 10^16 cm^-3 corresponding to one trap state per c translation along the dislocation line within the 30 nm diameter TD ranges. The trap energy level \( (E_c) \) is 1.14 eV below \( E_c \) for donor-like traps and 2.5 eV below \( E_c \) for acceptor-like traps, as shown in Table I. The trap lifetimes are also given in Table I.

III. RESULTS AND DISCUSSION

A. Influence of random alloy fluctuations, V-defects, and threading dislocations for the current path

Figure 3 shows the calculated \( E_c \) and effective quantum potential \( \frac{1}{2} \nabla^2 \psi \) for the blue and green LEDs, taking into account random alloy fluctuations at a bias voltage \( V = 3 \) V. A cross section with minimum potential barrier was chosen for the full curves. They show the best case for carrier transport across the QWs. The dashed curves for disorder averaged levels show slightly larger barriers. Although Figs. 3(a) and 3(b) show that random alloy fluctuations already change the depth of the QWs for blue LEDs (compare the \( E_c \) curves with and without fluctuations), the potential barrier induced by piezoelectric field between QWs is still about 0.4 eV for the blue LED, whose carriers can overcome the barrier through thermal ex-
For blue LEDs, recombination occurs throughout the structure, from which they diffuse toward the lower-energy c-plane QWs through the inclined plane, as shown in Figs. 5(c) and 5(d). Given the position of the electron-injecting region relative to the c-plane QWs, electrons are first injected into the side-wall QWs, from which they diffuse toward the lower-energy c-plane QWs.

Figures 4(a) and 4(b) show the valence-band potential of blue and green LEDs in a V-defect, respectively. First, in the middle of the V-defect, within ±15 nm of the TD in the p-GaN layer region, holes are trapped in the hole traps associated with the TD, which repels holes from the TD center [the repelling potential is shown in a lighter color in the TD region in Figs. 4(a) and 4(b)]. Next, holes transport toward the c-plane QWs through the inclined plane, as shown in Figs. 5(c) and 5(d). Given the position of the electron-injecting region relative to the c-plane QWs, electrons are first injected into the side-wall QWs, from which they diffuse toward the lower-energy c-plane QWs.

For blue LEDs, recombination occurs throughout the structure as electrons and holes (at least four of the c-plane QWs for holes) are injected vertically [Figs. 5(a) and 5(c)] in the c-plane QWs. For the green LED, while electrons are injected both vertically and through the V-defect [Fig. 5(b)], holes are not injected vertically because of the much larger polarization-induced barrier in the c-plane. Holes are therefore injected through the V-defect sidewall near which recombination occurs and decays laterally within a characteristic diffusion length. In addition, only two to three c-plane QWs receive holes through the V-defect. Both effects limit the effectiveness of V-defects as a solution to excite the whole volume of the c-plane QWs. For the blue LED, the crowding effect of carriers near V-defects is weaker because holes can still be injected vertically into the whole c-plane area due to random alloy fluctuations. The relative importance of vertical injection versus V-defect injection is discussed in more detail below along with how the V-defect size and density affects \( V_{\text{for}} \).

TABLE I. Basic parameters of blue and green LEDs.

| Area          | Material          | Thickness | Doping blue, green | \( E_a \) | e, h mobility | \( \tau_n, \tau_p \) |
|---------------|-------------------|-----------|-------------------|-----------|---------------|---------------------|
|               | unit              | (nm)      | \( 10^{18} \) cm\(^{-3} \) | meV       | cm\(^2\)/Vs    | blue, green         |
| p layer       | \( p \)-GaN       | 140       | 30, 30            | 180       | 100, 5        | 100, 10             |
| p EBL         | \( p \)-AlGaN     | 20        | 20, 20            | 264       | 100, 5        | 100, 10             |
| p cladding layer | \( p \)-GaN   | 10        | 20, 20            | 180       | 100, 5        | 100, 10             |
| QB(3,4,5)     | \( n \)-InGaN     | 3         | 0.1, 0.1          | 25        | 150, 10       | 100, 10             |
| QB(3,4)       | \( n \)-GaN       | 10        | 0.1, 0.1          | 25        | 350, 10       | 100, 10             |
| QB(1,2)       | \( n \)-InGaN     | 3         | 0.1, 0.1          | 25        | 150, 10       | 100, 10             |
| QB(1,2)       | \( n \)-GaN       | 10        | 0.1, 1            | 25        | 350, 10       | 100, 10             |
| n cladding layer | \( n \)-GaN     | 10        | 10, 10            | 25        | 200, 10       | 100, 10             |
| n layer       | \( n \)-GaN       | 2500      | 5, 5              | 25        | 200, 10       | 100, 10             |

TABLE II. Trap parameters in the threading dislocation (TD) center.

| Type           | Trap density \( 1/cm^3 \) | \( \times 10^{18} \) | \( \tau_n, \tau_p \) (ns) | \( E_c \) below \( E_e \) (eV) |
|----------------|---------------------------|---------------------|------------------------|-------------------------------|
| Donor-like     |                           |                     |                        |                               |
| Trap density   |                           | \( 1 \times 10^{18} \) | 1.01                   | 1.14                          |
|                |                           |                     |                        |                               |
| Acceptor-like  |                           |                     | 0.38                   | 2.5                           |

Citation. However, for the green LED, the potential barrier is about 0.7 eV, which strongly impedes carrier transport across the MQWs at the bias \( V = 3 \) V. While the current density at that bias is a few A/cm\(^2\) for the blue LED [see Fig. 4(a)], it is negligible in the green LED [Fig. 4(a)]. Thus, even when considering random alloy fluctuations, carriers are hardly injected directly into the c-plane QW for the green LED, despite the large 0.7 V excess voltage. We also observe that the inclusion of the quantum disorder correction through the use of the LL theory (thus yielding the effective potential \( \frac{1}{\hbar^2} \)) only weakly diminishes the potential barriers, in particular for the green LED. Reducing \( V_{\text{for}} \) in these LEDs requires the use of another injection mechanism, namely, injection through V-defects.

We first focus on hole injection through a V-defect. Figures 4(a) and 4(b) show the valence-band potential of blue and green LEDs in a V-defect, respectively. First, in the middle of the V-defect, within ±15 nm of the TD in the p-GaN layer region, holes are trapped in the hole traps associated with the TD, which repels holes from the TD center [the repelling potential is shown in a lighter color in the TD region in Figs. 4(a) and 4(b)]. Next, holes transport toward the c-plane QWs through the inclined plane, as shown in Figs. 5(c) and 5(d). Given the position of the electron-injecting region relative to the c-plane QWs, electrons are first injected into the side-wall QWs, from which they diffuse toward the lower-energy c-plane QWs.

Figures 4(c) and 4(d) show the radiative recombination map for the blue and green LEDs at 20 A/cm\(^2\), respectively. For blue LEDs, recombination occurs throughout the structure as electrons and holes (at least four of the c-plane QWs for holes) are injected vertically [Figs. 5(a) and 5(c)] in the c-plane QWs. For the green LED, while electrons are injected both vertically and through the V-defect [Fig. 5(b)], holes are not injected vertically because of the much larger polarization-induced barrier in the c-plane. Holes are therefore injected through the V-defect sidewall near which recombination occurs and decays laterally within a characteristic diffusion length. In addition, only two to three c-plane QWs receive holes through the V-defect. Both effects limit the effectiveness of V-defects as a solution to excite the whole volume of the c-plane QWs. For the blue LED, the crowding effect of carriers near V-defects is weaker because holes can still be injected vertically into the whole c-plane area due to random alloy fluctuations. The relative importance of vertical injection versus V-defect injection is discussed in more detail below along with how the V-defect size and density affects \( V_{\text{for}} \).

FIG. 3. Cross section plot for the three top QWs of \( E_c \) without fluctuations \( (E_c \text{ w/o fluc}) \), \( E_c \) with fluctuations \( (E_c \text{ w/ fluc}) \), and effective potential \( \frac{1}{\hbar^2} \), \( E_{\text{Fluc}} \), along z-direction with random alloy fluctuations but without V-defects. (a) is for the blue LED, and (b) is for the green LED. The full curves w/ fluc are for the cross section with minimum barrier and the dashed lines are for the fluctuation-averaged potential \( E_{\text{Fluc}} \).
and the IQE for blue and green LEDs.

Fig. 4. Valence-band energy and radiative recombination for blue LED and green LED at V-defect density $2.5 \times 10^7$ cm$^{-2}$ and $D = 100$ nm at a current density of 20 A/cm$^2$. (a) Valence band for the blue LED, (b) valence band for the green LED, (c) radiative recombination for the blue LED at 20 A/cm$^2$, and (d) radiative recombination for the green LED at 20 A/cm$^2$. White dashed lines show the location of V-defects on the x axis. Insets in panels (a) and (b) at different color scale emphasize the higher potential energy for holes at the center due to trap charging.

Since carriers are mainly going through V-defects for the green LED, the density of V-defects play an important role in the LED current-voltage characteristics. Using a high V-defect density to obtain more injection sites, the active c-plane QW area becomes smaller and the carrier density in the plane increases for the same current. This adversely affects the IQE and droop behavior. Therefore, it is important to discuss in detail how the V-defect density and size affect the LED structure.

B. Influence of V-defects and random alloy fluctuations on l-V and IQE

The influence of V-defects for the specific lateral LED of Fig. 2 is now discussed for green and blue LEDs. The effects on IQE and $V_{for}$ of both random alloy fluctuations and V-defects are simulated for different V-defect densities and diameters. We use V-defect densities of $1 \times 10^8$, $2.5 \times 10^7$, $1 \times 10^6$, $2.25 \times 10^6$, and $6.25 \times 10^6$ cm$^{-2}$ and V-defect diameters of 50, 100, 220, 280, and 340 nm.

1. Performance of blue V-defect LED

We first discuss the dependence of $V_{for}$ on the V-defect density. Here we define the forward voltage $V_{for}$ as the voltage needed for a current density of 1 A/cm$^2$. Figure 6(a) shows the results for the blue LED structures without and with the V-defects. The V-defect diameter is 100 nm. $V_{for}$ is about 2.88 V for the case without V-defects. The maximum density of V-defects is $6.25 \times 10^6$ cm$^{-2}$, and $V_{for}$ for this case is about 2.74 V at 1 A/cm$^2$, which equates to about zero excess voltage.

For a V-defect density of $1 \times 10^8$ cm$^{-2}$, Fig. 6(b) shows the dependence on V-defect size. The results show that the voltage decreases as the V-defect diameter increases from 50 to 100 nm, but $V_{for}$ remains constant for the larger V-defect diameters, with all the decrease in $V_{for}$ already realized at the lateral V-defect size of 50 nm. One factor contributing to this result is that the voltage is already close to $\frac{hv}{e}$, leaving little possibility for further reduction of $V_{for}$.

Figure 6(c) shows the IQE of blue LEDs with different V-defect densities; the IQE peak slightly decreases as the V-defect density increases. For high V-defect densities, the IQE peak appears at higher current density. In the low-current-density region ($10^{-3}$ to 1.0 A/cm$^2$), holes are injected mainly through V-defects and electrons are injected vertically through the random alloy fluctuating potential, whereas for higher current density, the higher $V_{for}$ means that both carriers start to be injected directly from the c-plane QW through the fluctuating potential barriers. Since the V-defect center contains strong nonradiative recombination (NR) centers, carriers are injected through V-defects experience more NR.

Figures 5(a) and 5(b) show the radiative recombination for current densities of $10^{-2}$ and 20 A/cm$^2$, respectively, for blue LEDs at a V-defect density of $2.5 \times 10^7$ cm$^{-2}$. At low current, the top QW shows weak radiative recombination, which means that holes are injected from V-defects. At high current,
the top QW also emits light because holes are also injected vertically. Thus, at higher current density, the IQE and $V_{\text{for}}$ are less influenced by V-defects and the dislocation region. More QWs emit light, and the impact of NR diminishes, so all curves regroup.

Figures 6(b)–6(d) show the recombination distribution for different V-defect densities at $J = 20\, \text{A/cm}^2$. The crowding effect is limited because of vertical injection through random alloy fluctuations but is significant at low V-defect density. Increasing the V-defect density diminished the crowding effect and thus moves the peak IQE to a higher current density, although the peak IQE diminished somewhat because of the increased density of NR centers [Fig. 6(c)]. Figure 6(d) shows the IQE for different V-defect diameters at a V-defect density of $1.0 \times 10^8\, \text{cm}^{-2}$. When the diameter increases, the V-defect area increases and the active c-plane area decreases. Thus, the IQE decreases with increasing V-defect diameter because of the increased Auger effect, which is consistent with earlier work.\[13\]

![FIG. 6. (a) Voltage versus current for blue LED at different V-defect diameters and a constant V-defect density of $1.0 \times 10^8\, \text{cm}^{-2}$. (b) Voltage versus current for blue LED at different V-defect diameters and a V-defect density of $1 \times 10^8\, \text{cm}^{-2}$. (c) IQE versus current for blue LED at different V-defect densities and a V-defect density of $10^9\, \text{cm}^{-2}$. (d) IQE versus current for blue LED at different V-defect diameters and a V-defect density of $1 \times 10^8\, \text{cm}^{-2}$.](image)

To further discuss the joint influence of V-defect density and diameter on the IQE, we consider the ratio of the V-defect area to the total chip area. Figure 7(a) shows $V_{\text{for}}$ as a function of the V-defect area ratio, where points on a given V-defect density curve correspond to the different V-defect diameters (50, 100, 220, 280, and 340 nm), which change the V-defect area ratio. At low V-defect area ratio, $V_{\text{for}}$ is affected by both the V-defect area ratio and the V-defect density. This result is attributed to the density being too low, even for large V-defects, so the carriers injected from V-defects need to travel through a long lateral region to inject into the entire QW. In addition, the natural alloy potential fluctuations in the QW limit the lateral transport distance of electrons and holes. As a result, carriers become crowded near the V-defect at low V-defect density, so the device performance is strongly limited by the lateral transport distance from the V-defect within the QW.\[13\]

This result is again verified by Figs. 7(b)–7(d). The recombination becomes less crowded when the V-defect density increases. Once the V-defect area ratio grows larger, $V_{\text{for}}$ decreases and then saturates at the expected value near 2.7 V. Another contribution comes from the modified vertical injection due to the presence of V-defects: the fluctuations in the vertical energy barriers induced by the random alloy fluctuations cause some carriers to be directly injected from the c plane in regions with lower barriers. With V-defects, electrons and holes can flow laterally into all quantum wells.\[13\] Once carriers flow into QWs, they screen the polarization-related electric fields so that vertical current injection directly into c-plane QWs increases at lower bias voltage compared with the case without V-defects.

The diameter and density of V-defects also affect the efficiency of the blue LED. We simulated how the IQE at a fixed $20\, \text{A/cm}^2$ current density depends on the V-defect area ratio, which corresponds to different diameters and densities of V-defects. The results are shown in Fig. 8(b). Interestingly, the low V-defect density of $1.0 \times 10^8$ and $2.5 \times 10^7\, \text{cm}^{-2}$ have a much lower IQE than the others because the current paths from V-defects to the whole chip are too long so the constant injected current of $20\, \text{A/cm}^2$ becomes crowded near the V-defect region. When the V-defect density exceeds $1.0 \times 10^8\, \text{cm}^{-2}$, which is within the lateral diffusion length, the carriers are easily injected into the whole active region and further cancel the quantum-confined Stark effect. This is also
seen in Figs. 7(b)–7(d).

This effect helps to increase electron-hole overlap and increase the efficiency. However, the IQE gradually decreases as the V-defect area ratio further increases because the active volume decreases, and the droop effect starts to dominate at lower current density for larger V-defect area ratio. The conclusion is obvious: it is advantageous (i) to have a high V-defect density so that the V-defect separation is about the lateral carrier transport distance (often referred to as a diffusion length), to inject carriers homogeneously, and (ii) to have small V-defects to minimize nonmitting, unproductive V-defects.

2. Performance of green V-defect LED

For the green LED without V-defects, \( V_{\text{for}} = 3.83 \text{ V} \) at 1 A/cm\(^2\) current density is greater than for the blue LED [Fig. 8(a)]. If we further remove the barrier doping, as indicated by the black dotted line, \( V_{\text{for}} \) increases. Despite doping the QB barriers between the MQWs, the polarization barrier induced by the high indium composition is not completely offset. Therefore, V-defects are much more helpful to decrease the turn-on voltage for green LEDs than for blue LEDs. The lowest V-defect density of \( 1 \times 10^8 \text{ cm}^{-2} \) decreases the turn-on voltage to 2.81 V, as shown in Fig. 9(a).

We also simulated different V-defect densities and find that \( V_{\text{for}} \) decreases as the V-defect density increases. The different diameters of V-defects are also simulated at a density \( 1 \times 10^8 \text{ cm}^{-2} \), as shown in Fig. 8(b). The results are similar to the blue LED shown in Fig. 8(b). The voltage decreases as the diameter increases and then saturates.

We also calculate IQE versus V-defect density for \( D = 100 \text{ nm} \) [see Fig. 9(c)]. The results show that different V-defect densities produce different performances. Unlike the blue LED where some carriers are injected from the \( c \)-plane, in the green LED, most carriers are injected into the planar QWs through the V-defect sidewall, as shown in Figs. 8 and 9. For the lower V-defect density, the IQE peaks slightly higher due to a lower TD density. However, due to greater current crowding, where carriers are crowded in the \( c \)-plane QW near V-defects, the droop effect appears at lower current densities, as shown in Fig. 9(c). When the current density increases, additional carriers flow into the whole active QW region for all V-defect densities. Therefore, the IQEs reach a similar value for all V-defect densities, as shown in Fig. 8(c).

Figure 9(d) shows the IQE for different V-defect diameters and for a V-defect diameter of \( 100 \text{ nm} \). For the larger diameters, the V-defect area increases and the active \( c \)-plane area decreases. Thus, the IQE decreases as the V-defect diameter increases. To further discuss this, we consider how the performance depends on the V-defect area ratio.

Figure 10 shows the recombination distribution for different current densities and different V-defect densities. Unlike for blue LEDs, a strong crowding effect occurs until the V-defect density exceeds \( 1 \times 10^8 \text{ cm}^{-2} \), independent of the current density. This again shows that the V-defect density is the dominant factor for carrier injection.

Figure 11(a) shows \( V_{\text{for}} \) versus the V-defect area ratio and for different V-defect densities. Figure 11(a) shows that the turn-on voltage for green LEDs decreases as the V-defect area ratio increases. In addition, green LEDs have a higher indium composition and a higher polarization-related electric field, so only holes flow into the \( c \)-plane from V-defects and become crowded at the last QWs, as do electrons [see Fig. 8(b)]. Therefore, the turn-on voltage decreases as the V-defect area ratio increases. This effect influences the efficiency of the green LED.

Figure 11(b) shows how the V-defect area ratio affects the IQE at 20 A/cm\(^2\). At the same V-defect area ratio, a greater V-defect density corresponds to a greater IQE. Because carriers are injected into the QW from V-defects and the diffusion length in the fluctuating QWs is short, the IQE depends much more on the V-defect density than on the V-defect diameter. As a results, the IQE decreases as the V-defect area ratio increases and reduces the active region.
When carriers are injected into the c-plane QWs at high bias and current density, they can screen the polarization field and thereby allow more carriers to be injected either through V-defects or vertically through the c-plane stack of barriers and wells, thus providing a welcome synergy between V-defects and vertical carrier injection. However, optimization will require further work. Although the increase of V-defect density decreases $V_{\text{for}}$, it also reduces the IQE due to a higher possibility to be trapped and recombine nonradiatively in TDs around the center of V-defects. Detailed measurements of these nonradiative parameters are required for precise selection of V-defect density and size.

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