JOURNAL OF APPLIED PHYSICS 119, 023101 (2016)

Variation of the external quantum efficiency with temperature and current density in red, blue, and deep ultraviolet light-emitting diodes

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(Received 26 October 2015; accepted 22 December 2015; published online 8 January 2016)

The temperature-dependent external quantum efficiencies (EQEs) were investigated for a 620 nm AlGaInP red light-emitting diodes (LEDs), a 450 nm GaInN blue LED, and a 285 nm AlGaN deep-ultraviolet (DUV) LED. We observed distinct differences in the variation of the EQE with temperature and current density for the three types of LEDs. Whereas the EQE of the AlGaInP red LED increases as temperature decreases below room temperature, the EQEs of GaInN blue and AlGaN DUV LEDs decrease for the same change in temperature in a low-current density regime. The free carrier concentration, as determined from the dopant ionization energy, shows a strong material-system-specific dependence, leading to different degrees of asymmetry in carrier concentration for the three types of LEDs. We attribute the EQE variation of the red, blue, and DUV LEDs to the different degrees of asymmetry in carrier concentration, which can be exacerbated at cryogenic temperatures. As for the EQE variation with temperature in a high-current density regime, the efficiency droop for the AlGaInP red and GaInN blue LEDs becomes more apparent as temperature decreases, due to the deterioration of the asymmetry in carrier concentration. However, the EQE of the AlGaN DUV LED initially decreases, then reaches an EQE minimum point, and then increases again due to the field-ionization of acceptors by the Poole-Frenkel effect. The results elucidate that carrier transport phenomena allow for the understanding of the droop phenomenon across different material systems, temperatures, and current densities.
[http://dx.doi.org/10.1063/1.4939504]

I. INTRODUCTION

Solid-state light emitters like light-emitting diodes (LEDs) and laser diodes have lots of economic and technical advantages such as high efficiency, small form factor, low voltage operation, and compatibility with modern microelectronic technologies.[1–3] LEDs based on III-phosphides (AlGaInP) are capable of emitting light in the long-wavelength region of the visible spectrum, namely, in the red, orange, amber, and yellow range, whereas III-nitrides (AlGaInN) LEDs can emit light in the short-wavelength region of visible spectrum including the green, blue, violet, and even in the ultraviolet (UV) range. An LED is known as a reliable device that can be operated even under harsh environmental conditions such as high and low temperatures, high humidity, and in environments prone to mechanical and electrical shocks. It is also true that the ambient temperature has always a strong effect on the electrical and optical characteristics of LEDs.[4,5] In other words, temperature is the primary environmental factor that influences most of the material and device parameters in LEDs. The temperature dependence of the LED efficiency is a critical property that should be well understood before LEDs are put to practical use.

It has been generally believed that the efficiency of LEDs becomes better as temperature decreases, a property that has frequently been mentioned as one of the strengths of LED sources when compared to conventional light sources like incandescent and fluorescent lamps. However, in this article, we find that the temperature dependence of the LED efficiency cannot be explained by a single mechanism or a single dependence. When investigating the variation of the external quantum efficiency (EQE) of 620 nm AlGaInP-based red LEDs, 450 nm GaInN-based blue LEDs, and 285 nm AlGaN-based deep-UV (DUV) LEDs for temperatures ranging from room temperature to 110 K, we find that the variation of the EQE with temperature is not the same for all three types of LEDs. On the contrary, the three types of LEDs show substantially different tendencies of the efficiency with temperature and current density. In this paper, we determine the variation of the EQE with temperature for the three types of LEDs, and we study and discuss the underling mechanisms causing the differences in the temperature dependence of the EQE.

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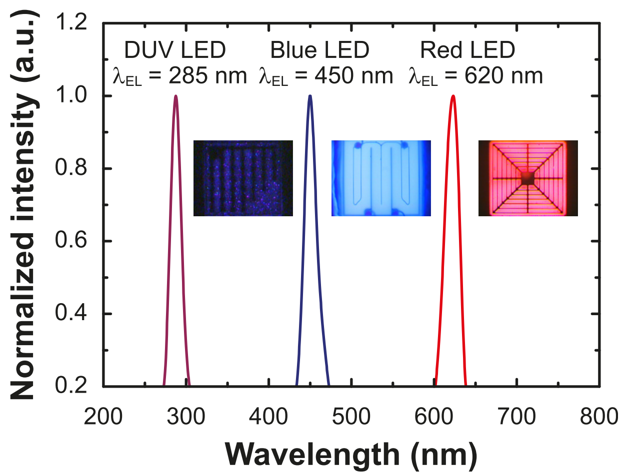

FIG. 1. The normalized electroluminescence spectra measured at 100 mA and optical microscope images under injection current of 10 mA for an AlGaInP red LED, a GaInN blue LED, and an AlGaN DUV LED.

II. EXPERIMENT

Commercially available AlGaInP red LEDs with the peak wavelength, λ_{peak}, of 620 nm, GaInN blue LEDs ($\lambda_{peak} = 450$ nm), and AlGaN DUV LEDs ($\lambda_{peak} = 285$ nm) were utilized, all of which were grown by metal-organic chemical vapor deposition. The red LED employed a 38 period AlGaInP/AlInP multiple quantum well (MQW) active region, while the GaInN blue and AlGaN DUV LEDs employed a 5 period GaInN/GaN and AlGaN/AlGaN MQW active regions, respectively. The chip size is $0.7 \times 0.7\,mm^2$ for the AlGaInP red LED, $1.1 \times 1.1\,mm^2$ for the GaInN blue LED, and $1 \times 1\,mm^2$ for the AlGaN DUV LED. The normalized electroluminescence spectra measured at 100 mA at room temperature are shown in Fig. 1 with optical microscope images under an injection current of 10 mA.

Light output–current–voltage (*L–I–V*) characteristics were measured at temperatures ranging from 110 to 300 K using a vacuum chamber probe station equipped with an Agilent B2902A precision source-measurement unit. The light output was collected by a UV-enhanced Si photodiode. All LEDs were operated under pulsed injection currents (pulse period = 5 ms, duty cycle = 0.5%) in order to avoid self-heating effects.

III. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show the representative normalized EQE curves for the three types of LEDs as a function of current density measured at (a) 300 K and (b) 110 K, respectively, which were selected as representatives from a larger group of temperature dependent *L–I* measurements. Substantial differences in the EQE curves measured at 300 K and 110 K are apparent for the three types of LEDs: At room temperature, the AlGaInP LED does not show any efficiency droop at current densities up to 30 A/cm^2, while the GaInN blue LED and AlGaN DUV LED show a moderate and extremely high efficiency droop of 8.6% and 82.1%, respectively, at 30 A/cm^2. At 110 K, the efficiency droop for the AlGaInP red LED at 30 A/cm^2 is 7.1%, while the efficiency droop for the GaInN blue LED is much more pronounced with a value of 48.5%. In the case of the AlGaN DUV LED, interestingly, an unusual efficiency curve is obtained: The magnitude of the efficiency droop at 110 K is reduced compared to the droop measured at room-temperature (38.8% at 110 K versus 82.1% at 300 K and 30 A/cm^2), and also the efficiency has an minimum point, at about 10 A/cm^2, and then, unexpectedly, increases again for injection current densities above 10 A/cm^2, leading to a "U-shaped"-EQE curve.[6,7]

When we investigated the temperature-dependent EQE variation at a very low current density, we found additional distinct differences among the three types of LEDs. Figure 3 shows the temperature-dependent EQE curves measured at a current density of 0.1 A/cm^2 for the three LEDs. Both the AlGaInP red LED and GaInN blue LED show a similar tendency, i.e., the EQE gradually increases with decreasing temperature (T), although the slope of the EQE-versus-T variation for the red LED is larger than that for the blue LED. On the contrary, the AlGaN DUV LED shows an opposite trend; the EQE decreases with decreasing temperature, with the trend accelerating below ~180 K. In order to comprehensively understand the causes of different EQE behaviors with temperature, the factors influencing the EQE are considered. The EQE of an LED can be expressed by the product of internal quantum efficiency (IQE) and light-extraction efficiency (LEE). For simplification, the effect of LEE can be excluded from consideration since the LEE is known to be insensitive to variations in temperature and current density.[8,9] The IQE can be expressed by $\eta_{inj} \cdot Bn^2/(An + Bn^2 + Cn^3)$, where η_{inj} is the carrier injection efficiency defined as the fraction of free carriers that are injected into the active region and recombine inside the active region,[10] n represents carrier concentration in the active region, and A, B, and C are the coefficients of the Shockley–Read–Hall (SRH), radiative, and drift-induced

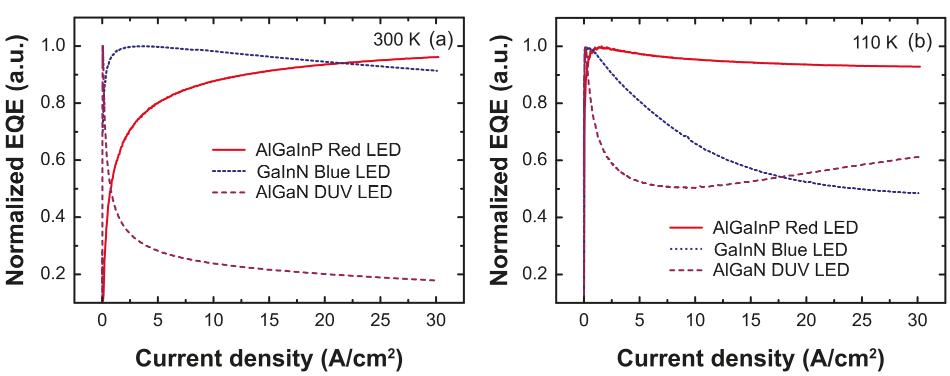

FIG. 2. Normalized EQE curves as a function of current density for an AlGaInP red LED, a GaInN blue LED, and an AlGaN DUV LED measured at (a) 300 K and (b) 110 K.

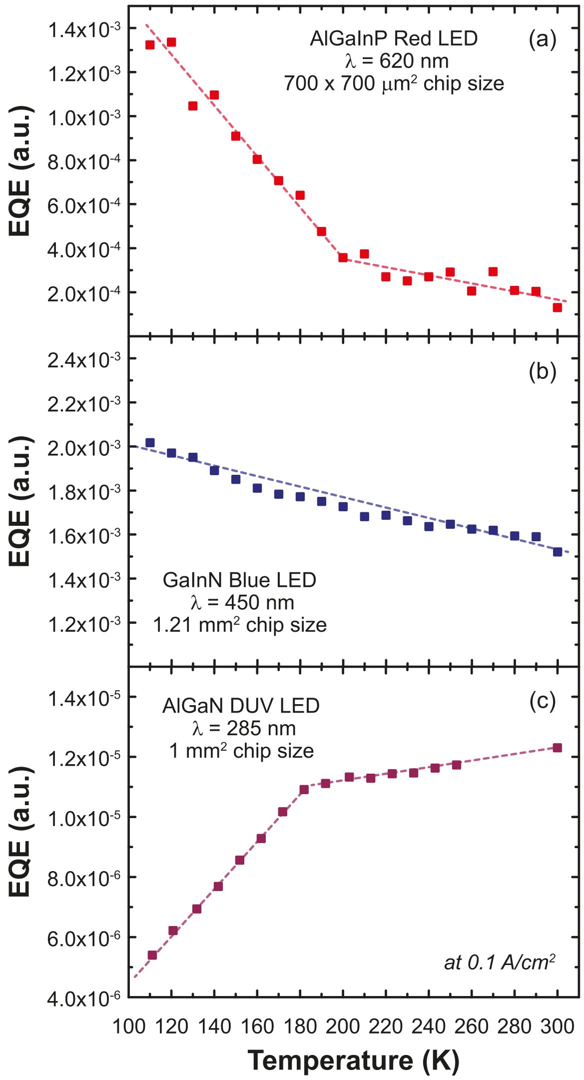

FIG. 3. Temperature-dependent EQE curves for (a) AlGaInP red LED, (b) GaInN/GaN blue LED, and (c) AlGaN DUV LED measured at 0.1 A/cm^2.

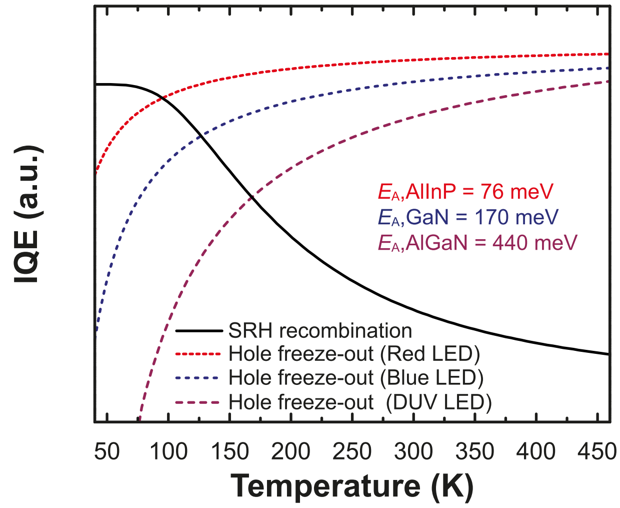

FIG. 4. Calculated factors influencing the temperature-dependence of the EQE curves, including SRH recombination (solid line) and hole freeze-out effects in AlGaInP red LED, GaInN blue LED, and AlGaN DUV LED (dashed lines).

electron leakage as well as Auger recombination, respectively.[11] Note that both, drift-leakage of electrons as well as Auger recombination, have a cubic dependence on the carrier concentration and thus a C coefficient.[12] Among the three recombination mechanisms, while radiative and electron leakage or Auger recombination become relevant at moderate and high current densities, respectively, the SRH recombination is known to be dominant in the low current regime. Figure 4 illustrates the factors influencing the temperature-dependence of the IQE. The solid black line in Fig. 4 illustrates the effect of the SRH recombination rate as a function of temperature. The SRH recombination rate is given by[13]

$$R_{SRH} = \frac{\Delta n}{\tau_{nr}} = \frac{\Delta n}{\tau_{n0}\left[1 + \cosh\left(\frac{E_T - E_{Fi}}{kT}\right)\right]}, \quad (1)$$

where Δn is the excess electron concentration, k is the Boltzmann constant, T is the absolute temperature, τ_{nr} and τ_{n0} are the non-radiative recombination lifetime and minority carrier lifetime, and E_{Fi} and E_T are the intrinsic Fermi level close to the middle of the gap and the trap energy, respectively. Eq. (1) shows the hyperbolic cosine-like dependence of the non-radiative recombination lifetime τ_{nr} on temperature. Furthermore, τ_{nr} is connected to IQE with the equation below[13]

$$IQE = \frac{{\tau_r}^{-1}}{{\tau_r}^{-1} + {\tau_{nr}}^{-1}}, \quad (2)$$

where τ_r is radiative recombination lifetime. According to Eqs. (1) and (2), the effect of the SRH recombination on the IQE can be qualitatively simulated, as shown in Fig. 4. Upon decreasing the temperature, the SRH recombination rate decreases, so that IQE increases.

Next, the freeze-out of free carriers should be considered. The n-type and p-type dopants will not be fully ionized at cryogenic temperatures because dopant ionization requires the dopants' ionization energy to produce mobile carriers in a semiconductor. Insufficient ionization occurring for dopants at low temperature is called free carrier "freeze-out." Some semiconductors, such as p-type GaN, suffer from partial carrier freeze-out even at 300 K. The IQE is directly affected by the freeze-out of carriers because the carrier-injection efficiency depends on the p-type carrier concentration.[14] The free carrier concentration is determined by the dopant ionization energy of the specific material system. Especially for AlGaInN-based materials, hole freeze-out is much more severe than electron freeze-out because the acceptor ionization energy E_A in the p-type region (E_A,AlInP $\sim$ 76 meV, E_A,GaN $\sim$ 170 meV, and E_A,AlN $\sim$ 630 meV) is much higher than the donor ionization energy E_D in the n-type region (E_D,AlInP $\sim$ 80 meV, E_D,GaN $\sim$ 15 meV, and E_D,AlN $\sim$ 62 meV).[15,16] This difference causes a severe asymmetry in the carrier concentration and thus an asymmetry in electron and hole transport, leading to a severe lack in hole injection and, consequently, substantial electron leakage out of the active region at high current densities.[17] Therefore, the freeze-out of holes at cryogenic temperatures could be a serious problem in AlGaInN-based LEDs thereby reducing the IQE and EQE. The hole concentration p which is proportional to the ionized acceptor impurity density N_A^- is expressed by[18]

$$p \approx N_A^- = N_A(1 - f_A) = N_A/(1 + g_A \exp((E_f - E_V - E_A)/kT)), \quad (3)$$

where N_A and f_A are the total acceptor density and the distribution function of holes, g_A is the degeneracy factors for an acceptor (the degeneracy factor is assumed to be 4 for acceptor), and E_f, E_V, and E_A are the Fermi level, the top level of the valence-band energy, and the acceptor ionization energy, respectively. According to Eq. (3), the hole concentration is proportional to an exponential function of $-E_A/kT$, so we can estimate the effect of the carrier's freeze-out at different temperatures on the IQE.[11,13,18] As illustrated in Fig. 4 (dotted line), when the temperature decreases, the IQE tends to increase due to the reduced SRH recombination but also tends to decrease due to the increased hole freeze-out. Note that a higher acceptor ionization energy (e.g., for DUV LEDs) leads to larger carrier asymmetry, making the freeze-out of holes the dominant effect. As the result, the different behaviors of the temperature-dependent EQEs of the LEDs at low current densities shown in Fig. 3 can be explained by which effect (the temperature dependence of either SRH recombination or freeze-out of holes) is dominant (or more relevant) at a particular temperature. In this respect, the experimental data indicate that, for the AlGaInP red LEDs, the effect of SRH recombination on EQE is stronger compared to the effect of hole freeze-out. That is, the effect of asymmetry in carrier concentration is relatively smaller for the AlGaInP red LED. On the contrary, in the AlGaN DUV LEDs, the effect of hole freeze-out is stronger than that of SRH recombination due to the larger acceptor activation energy and the resulting larger carrier asymmetry.

In order to support the findings stated above with additional evidence, we investigated the temperature-dependent current–voltage (I–V–T) characteristics. Figure 5(a) shows the I–V characteristics of the three types of LEDs measured at temperatures ranging from 110 K to 300 K, showing variations of energy-bandgap-dependent turn-on voltage and temperature-dependent series resistance. Furthermore, as shown in Fig. 5(b), the diode ideality factors as a function of temperature were extracted from the data of Fig. 5(a) by using the equation of $q/kT \cdot dV/dln(I)$, where q is the elementary charge.[13] The ideality factor of a diode has typical values between 1 and 2; however, it can be higher than 2 when the carrier transport is largely affected by trap-assisted tunneling,[19] carrier leakage,[20] and carrier's freeze-out.[21] At 300 K, the AlGaInP red and GaInN blue LEDs show ideality factors smaller than 2, while the AlGaN DUV LED shows a much higher value, 10.3. Such a high ideality factor for the AlGaN DUV LED even at room temperature can be understood when the p-n rectifying junctions and non-ohmic metal semiconductor junctions in the AlGaN LED are considered.[22] As temperature decreases from 300 to 110 K, the ideality factor increases for all three LEDs. As for the AlGaInP red LED and GaInN blue LED, there is no remarkable change in the ideality factor within the temperatures from 300 to 180 K; however, at cryogenic temperatures below 180 K, the ideality factor increases. Note that the ideality factor of the AlGaInP red LED is still lower than 2, even at 110 K. However, a significant increase in the ideality factor with decreasing temperature was found in the GaInN blue LED, suggesting that an additional effect, e.g., hole freeze-out, starts to contribute to carrier transport in the GaInN blue LED, more so than for the AlGaInP red LED. In the case of the AlGaN DUV LED, having the largest asymmetric carrier concentration in its p- and n-type sides, it is worthwhile noting that the increase in the ideality factor with decreasing temperature starts from a temperature of 300 K, which is different from the other two LEDs. In addition, the ideality factor in the DUV LED increases significantly even at temperatures below 180 K and reaches values as high as about 25. This result is consistent with hole freeze-out (shown in Fig. 4) causing the IQE trend in the AlGaN DUV LED. Furthermore, when we compare this result with the temperature-dependent EQE of the AlGaN DUV LED shown in Fig. 3, we find that the EQE starts to decrease significantly for temperatures below 180 K as shown in Fig. 3(c) while simultaneously the ideality factor significantly increases at the temperatures below 180 K (see Fig. 5(b)). Such a coincidence elucidates that the hole freeze-out effect should be considered as the main reason for the AlGaN DUV LED's decrease in EQE with decreasing temperatures, which is the complete opposite of the case of the AlGaInP red LED. That is, in the low current density regime, the EQE variation with temperatures is strongly affected by both SRH recombination and hole freeze-out; which one will be dominant is determined by the degree of the asymmetry in carrier concentration of the devices.

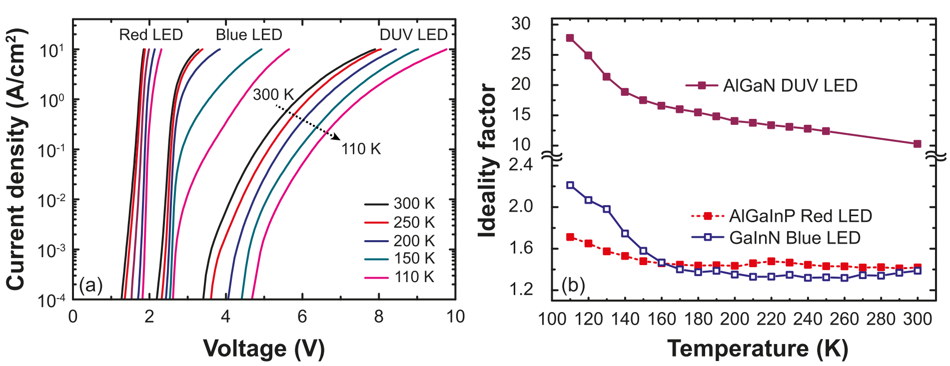

FIG. 5. (a) Current-voltage characteristics of AlGaInP red LED, GaInN/GaN blue LED, AlGaN DUV LED measured at temperatures ranging from 110 K to 300 K. (b) Variation of the diode ideality factor n for temperatures ranging from 300 K to 110 K.

Finally, we investigated the three diodes' differential conductance, the first derivative of the injection current with respect to the voltage, in order to clarify the temperature-dependent EQE variation at high injection currents, including the "U-shape" found for the DUV LED. The differential conductance as a function of current density is shown in Fig. 6 for the three types of LEDs. Note that, as shown in Fig. 2, while the AlGaInP red LED exhibits efficiency droop only at cryogenic temperatures which resulted from relatively high symmetry in its carrier concentrations and mobilities at room temperature, the GaInN blue LED and AlGaN DUV LED show a deterioration and an improvement of the efficiency droop at cryogenic temperature, respectively. The diode differential conductance of the AlGaInP red LED is higher for all current densities than the differential conductance of both types of AlGaInN-based LEDs due to the higher carrier concentrations and mobilities in AlGaInP, and its lower acceptor ionization energy. Also, we found that the diode conductance measured at 110 K is slightly smaller than those measured at 300 K due to the increased bulk resistance in the AlGaInP red LED; the other two LEDs have the same behavior of the conductance for current densities below around 10 A/cm^2. In the case of the AlGaInN-based LEDs, however, an unusual conductivity behavior is observed at high current densities as shown in Figures 6(b) and 6(c). The diode conductance at 110 K is higher than that measured at 300 K in the high current density regime of above ∼20 A/cm^2 for the GaInN blue LED and ∼10 A/cm^2 for the AlGaN DUV LED. These increases in the diode conductance at 110 K compared to the room-temperature conductance can be attributed to enhancement in p-type conductivity by means of field-ionization of acceptors,[6,7] which is also known as the Poole-Frenkel effect.[23] As shown in Fig. 4, as temperature decreases, more neutral acceptors are expected in the AlGaN DUV LED than for the GaInN blue LED due to the higher acceptor ionization energy in p-type AlGaN (DUV LED), resulting in field-ionization of more acceptors in the AlGaN DUV LED. Note that in the AlGaN DUV LED, the increase in diode conductance with increasing current density (at 110 K) has a steep slope even at 30 A/cm^2, while it is nearly saturated at the same current density for the GaInN blue LED, as shown in Fig. 6. For the AlGaN DUV LED, therefore, the asymmetry in carrier concentration can be reduced by increasing injection current density, thereby increasing field-ionization of acceptors, and resulting in the "U-shape" in efficiency at cryogenic temperatures. The minimum of the "U-shape" is found at the current density of 10 A/cm^2 (at 110 K), as shown in Fig. 2(b). This demonstrates that the asymmetry between electron and hole carrier concentrations plays an important role in the EQE variation with temperature and can explain, even for LEDs based on different material systems, the occurrence and detailed characteristics of the efficiency droop.

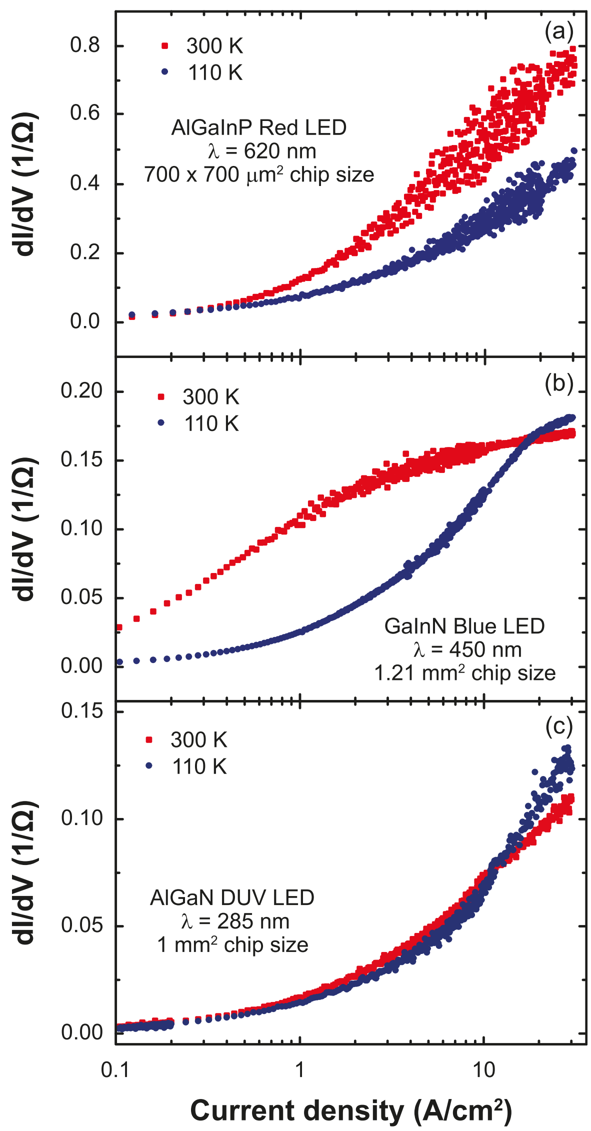

FIG. 6. Diode differential conductance at 110 K and 300 K as a function of the injection current density for (a) AlGaInP red LED, (b) GaInN blue LED, and (c) AlGaN DUV LED.

IV. CONCLUSIONS

The variation of the EQE with temperature and current density was investigated for three different types of LEDs. The EQE variations were markedly different for AlGaInP red, GaInN blue, and AlGaN DUV LEDs. We found that the asymmetry between electron and hole concentrations plays an important role in the EQE variations with temperature and current density. In the low-current density regime of 0.1 A/cm^2, the EQE variations on temperature are strongly affected by both (i) SRH recombination and (ii) hole freeze-out effects with the latter effect determining the degree of asymmetry in carrier concentrations. The specific behavior of the EQE depends on the relative strength and dominance of these two effects. As for the EQE variation with temperature in the high-current density regime, the efficiency droop for the AlGaInP red and GaInN blue LEDs becomes more apparent as temperature decreases, due to the exacerbation of the asymmetry in carrier concentration. The AlGaN DUV LED has an intrinsically large asymmetry in carrier concentration at cryogenic temperatures, so that the EQE initially decreases (droop), then reaches an EQE minimum point (minimum of "U-shape"), and then increases again due to the field-ionization of acceptors by the Poole-Frenkel effect.

These results suggest that the field-ionization Poole-Frenkel effect has to be considered in the high-current density regime for GaN-based LEDs when considering the EQE variation with temperature and current density. The results, which exhibit specific phenomena and distinct dependences, elucidate that carrier transport phenomena allow for the understanding of the droop phenomenon across different material systems, temperatures, and current densities.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the supports by the International Collaborative R&D Program of Korea Institute for Advancement of Technology (KIAT) (M0000078, Development of Deep UV LED Technology for Industry and Medical Application), the Brain Korea 21 PLUS project for Center for Creative Industrial Materials (F14SN02D1707), and the Basic Science Research Program through the National Research Foundation (NRF) of Korea funded by the Ministry of Education (2014R1A1A2054092 and 2015R1A6A1A04020421).

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