Distinct U-shape efficiency-versus-current curves in AlGaN-based deep-ultraviolet light-emitting diodes

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Abstract: The efficiency of an AlGaN deep-ultraviolet light-emitting diode with peak emission wavelength of 285 nm is investigated as a function of current over a wide range of temperatures (110 K to 300 K). We find that the efficiency-versus-current curve exhibits unique and distinct features over the entire temperature range including three points of inflection. At low temperatures, the change in slope in the efficiency-versus-current curve is particularly pronounced producing a minimum in the efficiency after which the efficiency rises again. Furthermore, at high current density, the low-temperature efficiency exceeds the room-temperature efficiency. The feature-rich efficiency-versus-current curve is consistent with an enhancement in p-type conductivity by field-ionization of acceptors that occurs in the high-injection regime and is particularly pronounced at low temperatures. Differential conductivity measurements show a marked rise in the high-injection regime that is well correlated to the minimum point in the efficiency-versus-current curve.

OCIS codes: (230.0230) Optical devices; (230.3670) Light-emitting diodes.

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1. Introduction

Deep-ultraviolet (DUV) light-emitting diodes (LEDs) emitting at wavelengths < 300 nm are highly attractive for sterilization and sanitation applications, and to enhance the quality of drinking water on a global scale [1–3]. Other applications of DUV light emitters include spectroscopic sensing, environmental monitoring, and food processing [4–6]. Although strong progress has been made in the development of DUV LEDs, they still suffer from a variety of problems, including the efficient extraction of light and the efficient injection of holes into the active region [7–9]. The lack of efficient hole injection into the active region of DUV LEDs is a hallmark of the GaN material system which has a large disparity between electron and heavy-hole effective mass. Consequences of this disparity include a large acceptor ionization energy and a low hole mobility. Taken together, these characteristics lead to a strong asymmetry in electron and hole transport characteristics. The asymmetry is significant for GaN but even more so for $Al_xGa_{1-x}N$ because the heavy hole effective mass in $Al_xGa_{1-x}N$ increases from $0.80m_e$ (free electron mass) to $3.53m_e$ as the Al-mole fraction, x, increases from 0% to 100% [10]. As a result, the Mg acceptor ionization energy increases as the Al mole fraction in $Al_xGa_{1-x}N$ increases so that the attainment of high hole concentrations in p-type AlGaN is particularly challenging.

In the present paper we present efficiency-versus-current curves of DUV LEDs emitting at 285 nm. These curves are rich in features making them too complex to be explained by the well-known *ABC* model [11–13]. In particular, the efficiency-versus-current curves exhibit multiple points of inflection. An advantage of the feature-rich efficiency-versus-current curve is that a model, describing these features, needs to be specific as to the cause of the features thereby making it unlikely that the features can be explained equally well by multiple models. We show that understanding of the efficiency behavior can be attained by assuming an enhancement in p-type conductivity that is particularly pronounced at low temperatures. It is proposed that in the high-injection regime, the electric field in the p-type region leads to an enhancement of the hole concentration by means of field-induced ionization of acceptors [14].

This interpretation is supported by differential conductivity measurements that show a distinct change in the high-injection regime that is well correlated with the minimum point in the efficiency-versus-current curve.

2. Experiments

The AlGaN DUV LEDs investigated here were grown by metal-organic vapor phase epitaxy on a 4-inch sapphire substrate. An AlN nucleation layer is employed to control the transition from the corundum sapphire structure to the wurtzite structure, followed by an AlGaN/AlN superlattice buffer layer, a 2 μm thick Si-doped n-type $Al_{0.55}Ga_{0.45}N$ lower cladding layer, an active region composed of 5 pairs of 3 nm thick undoped $Al_{0.4}Ga_{0.6}N$ QWs and 10 nm thick undoped $Al_{0.55}Ga_{0.45}N$ quantum barriers. The active region is followed by a 20 nm thick Mg-doped (Mg concentration [Mg] = 2×10^{20} cm^{-3}) $Al_{0.7}Ga_{0.3}N$ electron-blocking layer, and a 20 nm thick Mg-doped (Mg concentration [Mg] = 2×10^{20} cm^{-3}) p-type $Al_xGa_{1-x}N$ cladding layer that is composition-graded from x = 65% (near EBL) to x = 0% (near p-type contact), and a 20 nm thick heavily Mg-doped (Mg concentration [Mg] > 2×10^{20} cm^{-3}) GaN p-type contact formation layer.

Overall fabrication processes follow conventional GaN visible LED fabrication methods. First, the LED mesa structures were obtained by photolithographic patterning followed by inductively coupled plasma reactive-ion etching with BCl_3/Cl_2 gas mixture (target etching depth is 1 μm). Then, Ti/Al n-type ohmic contacts were deposited on the exposed n-type AlGaN by electron-beam evaporation and annealed at 900 °C for 1 minute in N_2 ambient. The p-type contact (Ni/Au) is deposited and annealed at 650 °C for 1 minute in air ambient, followed by the deposition of Ti/Au pad metal on the n- and p-type metal contacts. The flip-chip structure is employed for enhancing light-extraction efficiency and heat-dissipation capacity from the AlGaN DUV LED (chip size = 1 mm^2).

Light output–current–voltage (L–I–V) characteristics of the DUV LED were measured by using an Agilent B2902A precision source-measurement unit. The light output power was collected by an ultraviolet-enhanced Si photodiode under pulsed current operation (pulse period = 5 ms and duty cycle = 0.5%) in order to avoid self-heating. The measurements were conducted under vacuum conditions (several mTorr) to avoid the absorption of UV light by air.

3. Results and discussion

The external quantum efficiency (EQE)-versus-current curve for 110 K and room temperature (300 K) is shown in Fig. 1 and a family of these curves for the entire temperature range is shown in Fig. 2. It has been reported that the efficiency droop vanishes if the Shockley-Read-Hall (SRH) recombination rate, A_{SRH}, is excessively large [15]. Therefore, the onset of the efficiency droop at around 1 mA indicates that the inherently problematic AlGaN/AlGaN multiple-quantum wells (MQWs) active region is of high quality and that A_{SRH} is relatively small. Furthermore, the efficiency-versus-current curve has several key characteristics that will be discussed below.

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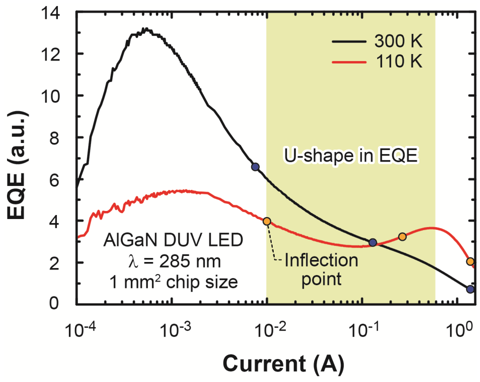

Fig. 1. Efficiency-versus-current curves of the AlGaN DUV LED at room temperature (300 K) and cryogenic temperature (110 K) showing a "U-shape" in EQE and three inflection points in the droop regime.

First, as shown in Fig. 1, the efficiency-versus-current curve is rich in structure in that it contains a "U-shape" and three points of inflection in the high-current regime, as marked in the figure. We note that such feature-rich structure cannot be explained by the well-known *ABC* model since it is mathematically incapable of producing such multiple inflection points. According to the *ABC* model, after the peak efficiency, the efficiency drops upon increasing current - the phenomenon called "efficiency droop" - owing to the increased contribution of higher-order non-radiative recombination mechanisms including Auger recombination and electron leakage, which makes a concave shape IQE curve. However the efficiency should converge into 0 at a very high current density, therefore, there should be an inflection point where the shape of the efficiency curve changes from a concave to a convex one. Here, the presence of two additional inflection points makes the efficiency-versus-current curve highly distinct so that any model explaining the characteristics should provide an explanation for the specific features of the curve.

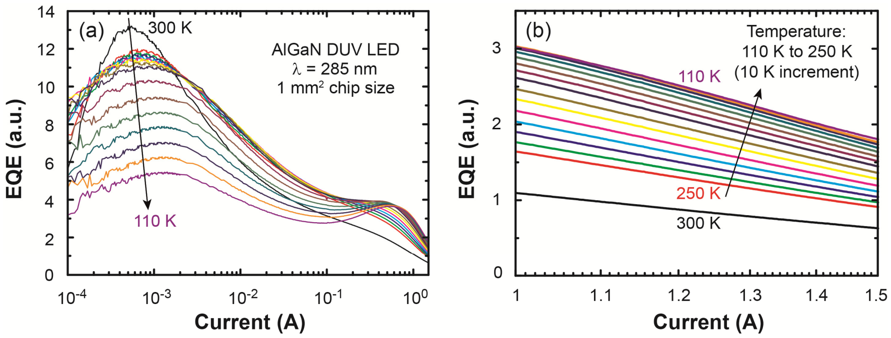

Fig. 2. Efficiency-versus-current curves of the AlGaN DUV LED at various temperatures ranging from 110 K to 300 K for injection currents (a) from 0 to 1.5 A plotted on semi-log current scale and (b) from 1 to 1.5 A plotted on a linear current scale.

Second, as shown in Fig. 2(a), in the temperature range below 160 K, the positive curvature of the curve in the droop regime is so distinct that a minimum of the efficiency is found. After the minimum, the efficiency increases again. This unusual behavior has hitherto not been found in DUV LEDs. Note that the minimum EQE, and hence the "U-shape" become more prominent as temperature decreases. A key question is as to why the efficiency increases again. Here, we will show that this behavior is consistent with field-ionization of acceptors in the p-type layer of the device. It has been established by multiple research groups that the high-injection point precedes the droop regime [16,17] and that the junction voltage saturates [18]. Consequently, an incremental voltage applied to the LED will drop, in part across the most resistive layer of the device, i.e. the p-type layer. If there is no electric field, the abundance of holes can be determined by the hole trap's (acceptor's) ionization energy ($q\varphi$), which is the energy required for the trapped holes to escape from the trapping center. When an electric field is applied, the ionization energy of the hole trap decreases by the amount of $\Delta\varphi$ [19]. The difference in ionization energy ($\Delta\varphi$) of the hole trap with and without electric field is given by

$$\Delta\varphi = \beta_{PF}\sqrt{E} \tag{1}$$

where E is an electric field and β_{PF} is Poole-Frenkel coefficient: $\beta_{PF} = \sqrt{q^3/\pi\varepsilon\varepsilon_0}$, where q is the elementary charge, ε is the high-frequency relative dielectric constant, and ε_0 is the permittivity of free space. According to the equation above, the trap barrier height can be reduced by the applied electric field, E. As the electric field increases, the potential barrier decreases on the left side of the trap, resulting in field-ionization of Mg acceptors as schematically shown in Fig. 3.

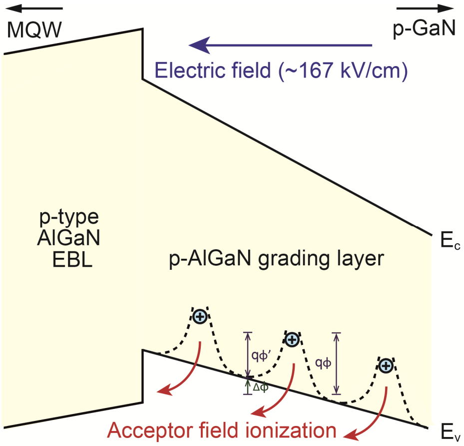

Fig. 3. Schematic band diagram of a DUV LED with acceptor field ionization being indicated. The dotted line around the acceptors represents the energy barrier for ionization.

The threshold for field-ionization of acceptors via the Poole-Frenkel effect has been estimated to be as low as 10 kV/cm [20] and as high as 300 kV/cm [21]. Since the estimated average field is about 167 kV/cm and far exceeds the lower threshold [16], the field-ionization of acceptors should be considered. Based on the *ABCD* model [22], the drift-leakage term is given by $C_{\mathrm{DL}} n_{\mathrm{QW}}^3$ with the drift-leakage coefficient given by $C_{\mathrm{DL}} = \delta\mu_{\mathrm{n}} / (\mu_{\mathrm{p}} p_{\mathrm{p0}})$, where n_{QW} is the carrier concentration in the QW, μ_{n} and μ_{p} are electron and hole mobility, respectively, and p_{p0} is the hole concentration in the p-type layer. Increasing p_{p0} by field-ionization of acceptors will decrease droop and increase efficiency. Therefore, the peculiar minimum in the efficiency is consistent with field-ionization of acceptors in conjunction with the *ABCD* model.

Third, inspection of the efficiency data with respect to the high-current regime, e.g. at 1.0 A, reveals that the low-temperature efficiency is markedly higher than the room-temperature efficiency, as shown in Fig. 2(b). This difference cannot be explained by reduced SRH recombination at low temperatures since the contribution of the $A_{\mathrm{SRH}}\, n$ term is negligible at such high current densities. However, this marked difference is readily explained by the higher hole concentrations attainable by means of field-ionization. That is, by means of field-ionization, all acceptors can be ionized at low temperatures, i.e. $p_{\mathrm{p0}} = N_{\mathrm{A}}^{-} - N_{\mathrm{D}} = N_{\mathrm{A}} - N_{\mathrm{D}}$, where N_{A}^{-}, N_{A}, and N_{D} are ionized acceptor concentration, acceptor concentration, and donor concentration, respectively. At room temperature, i.e. for reduced field-ionization, however, only a fraction of the acceptors are ionized; that is $p_{\mathrm{p0}} = N_{\mathrm{A}}^{-} - N_{\mathrm{D}} < N_{\mathrm{A}} - N_{\mathrm{D}}$. Consequently, in the high-current regime, e.g. at 1.0 A, the higher efficiency can be explained by the difference in the abundance of ionized acceptors and the resulting difference in hole concentration (p_{p0}).

As is evident from Fig. 2(a), the distinctiveness of the minimum in efficiency and the modulation of the efficiency-versus-current curve become increasingly stronger as temperature decreases. This can be explained as follows: Firstly, as temperature decreases, the concentration of neutral acceptors becomes larger. As a result, opportunity for field-ionization of acceptors increases as temperature decreases. Secondly, as temperature decreases, the voltage applied to the DUV LED for a given injection current becomes larger, resulting in increase of the accompanying electric field in the p-type region. Thirdly, as temperature decreases the hole concentration decreases, causing a large electric field in the p-type region for field-ionization of acceptors [23].

Next, we investigate the differential conductance, dI/dV of the DUV LED as a function of current and correlate the increase in conductance with the efficiency-versus-current curve. The results are shown in Fig. 4. Inspection of the figure reveals that in the low-current regime, e.g. in the range 1 mA to 0.1 A, the low-temperature (110 K) conductivity of the DUV LED is smaller than the high-temperature (300 K) conductivity. However, this comparison reverses at a high current density where the low-temperature conductivity is higher than the high-temperature conductivity. The trend is consistent with the enhancement of p-type conductivity at low temperatures by means of field-ionization of acceptors.

Here, we note that the increase in hole concentration by means of the field-ionization is limited by the concentration of neutral acceptors in the p-type region. Thus, above a certain high current density, non-radiative recombination mechanisms such as Auger recombination and electron leakage become predominant over the increase in radiative recombination by the field-induced ionization, leading to a second peak efficiency followed by a decrease in efficiency.

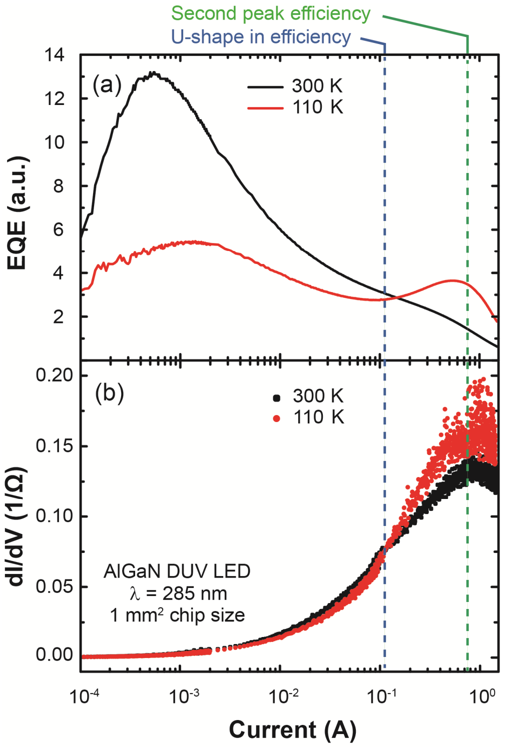

Fig. 4. (a) Efficiency-versus-current curves of the AlGaN DUV LEDs at 110 K and 300 K. (b) Differential DUV LED conductance as a function of current for the same two temperatures.

4. Conclusion

We investigated the temperature-dependent efficiency characteristics of DUV LEDs emitting at 285 nm, and found that the efficiency-versus-current curve exhibits distinct features over the entire temperatures ranging from 110 K to 300 K. First, the efficiency-versus-current curve contains three inflection points. The presence of the three inflection points makes the efficiency-versus-current curve highly distinct so that any model explaining the characteristics should provide an explanation for the specific features of the curve. Second, we have found a U-shape phenomenon in the efficiency-versus-current curves in AlGaN-based DUV LEDs for temperatures ranging from 110 K to 160 K. At typical operating current densities (10–100 A/cm^2), conventional LEDs are strongly affected by the efficiency droop. For AlGaN based DUV LEDs, however, the positive curvature of the curve in the droop regime is so distinct that a minimum of the efficiency is found at cryogenic temperatures below 160 K. After the minimum, the efficiency increases again. Third, the low-temperature efficiency exceeds the room-temperature efficiency at high current density. The feature-rich efficiency-versus-current curve is consistent with an enhancement in p-type conductivity by field-ionization of acceptors via the Poole-Frenkel effect that occurs in the high-injection regime and is particularly pronounced at low temperatures. Differential conductivity measurements show a distinct rise in the high-injection regime that is well correlated to the minimum point in the efficiency-versus-current curve.

Acknowledgments

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