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Impact of Auger Recombination, Electron Leakage and Hole Injection on Efficiency Droop for DUV LEDs

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Abstract: We reveal the impact of the Auger recombination, electron leakage and hole injection on the efficiency droop for deep-ultraviolet light-emitting diodes(DUV LEDs). According to our results, the minor change of the efficiency droop is caused by the Auger recombination when the Auger recombination coefficients range from 10^{-32} $cm^6 \cdot s^{-1}$ to 10^{-30} $cm^6 \cdot s^{-1}$. The Auger recombination induces notable role on the efficiency droop by defining the Auger recombination coefficient of 10^{-29} $cm^6 \cdot s^{-1}$. However, the large Auger recombination coefficient is not realistic for AlGaN materials. Besides, we find that the efficiency droop becomes significant with the increased electron leakage, even when the adopted Auger recombination coefficient is as small as 10^{-32} $cm^6 \cdot s^{-1}$. Thus, we can prove electron leakage is a major factor causing the severe efficiency droop for DUV LEDs. We then prove that increasing hole injection can suppress efficiency droop because more electrons can recombine with holes instead of escaping from multiple quantum wells(MQWs).

Key words: DUV LED; Auger recombination; electron leakage; hole injection; efficiency droop
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俄歇复合、电子泄漏和空穴注入对深紫外发光二极管效率衰退的影响

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摘要：研究了俄歇复合、电子泄漏和空穴注入对深紫外发光二极管(DUV LED)效率衰退的影响。结果表明，当俄歇复合系数从10^{-32} $cm^6 \cdot s^{-1}$增大到10^{-30} $cm^6 \cdot s^{-1}$时，俄歇复合对效率衰退的影响很小。当俄歇复合系数增大到10^{-29} $cm^6 \cdot s^{-1}$时，俄歇复合对效率衰退有显著的影响。然而，对于AlGaN材料而言，俄歇复合系数很难达到10^{-29} $cm^6 \cdot s^{-1}$。此外，本研究还发现，即使设置的俄歇复合系数等于10^{-32} $cm^6 \cdot s^{-1}$，DUV LED的效率衰退依旧随着电子泄漏的增加而增大。因此，这进一步证明了电子泄漏是导致DUV LED效率衰退的主要因素。此外，本工作还证明了空穴注入效率的提高可以有效地抑制DUV LED的效率衰退问题，这主要是

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由于更多的电子与空穴在量子阱中复合产生了光子,降低了电子从有源区中泄漏的几率。

关 键 词: 深紫外发光二极管; 俄歇复合; 电子泄漏; 空穴注入; 效率衰退

AlGaN-based deep-ultraviolet light-emitting diode(DUV LED) has been recognized a proposing device for gas sensing, water or air purification and light communication[1-2]. However, at the current stage, DUV LEDs are suffering several challenges, such that the low external quantum efficiency (EQE). It has been reported that EQE is about 10% for DUV LEDs[2]. Moreover, the efficiency droop is also observed at high current density, though not as severe as that for Ⅲ-nitride based blue and green LEDs[3]. The origin of the efficiency droop for InGaN/GaN based blue and green LEDs has been investigated by different groups[4-6], and it is concluded that the Auger recombination and electron leakage both have large impact on efficiency droop[7-8]. The unbalanced mobility for electrons and holes causes the electron leakage[6]. Moreover, the low hole concentration for hole injection layers further increases the electron leakage level[9]. The process of Auger recombination is that an electron recombines with a hole and transfers the recombination energy to a third carrier in the quantum wells, which involves three-carrier participation. Therefore, Auger recombination will cause a very remarkable deduction for the internal quantum efficiency (IQE) at the increased carrier injection levels. For InGaN materials, the Auger recombination coefficients range from 10^{-31} $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$ to 10^{-30} $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$[6,10]. However, the bandgap for AlGaN materials is usually larger than that for InGaN materials, and thus the function of the Auger recombination on the EQE is small for AlGaN-based DUV LEDs[11]. Meanwhile, among all factors, it is considered that the electron leakage dominants and influences the efficiency droop[12]. Therefore, significant efforts have been made to reduce the electron leakage for DUV LEDs, *e. g.*, by decreasing the kinetic energy of electrons so that the multiple quantum wells(MQWs) can easily capture electrons for recombining with holes[13]. In addition, the poor hole injection cannot generate sufficient radiative recombination in the active region causing more electrons to escape to p-type region[14]. To promote the hole injection, a variety of p-type electron blocking layer (p-EBL) structures are proposed such as the superlattice p-EBL structure[15-16], the AlGaN p-EBL structure with graded Al mole composition or ultrathin AlGaN/InAlN heterojunction[17-18]. The additional contribution for the proposed p-EBLs is that the reduced efficiency droop can be obtained due to the eliminated electron leakage, and this can be achieved by increasing the effective conduction band barrier height. Chu *et al.* show the influence of the electron leakage and Auger recombination on the efficiency droop by manipulating the electron affinities of the p-EBL[19]. Moreover, they have grown a p^+-GaN/$\mathrm{In}_{0.15}\mathrm{Ga}_{0.85}\mathrm{N}$/$\mathrm{n}^+$-GaN tunnel junction into DUV LED. The results show that the efficiency droop decreases from 29.0% to 8.9% and the parasitic emission is no longer observed due to the decreased electron leakage[19]. According to their results, the electron leakage is a major factor of efficiency droop for DUV LEDs. However, an in-depth discussion is not given yet by Ref. [19]. Meanwhile, Nippert *et al.* indirectly suggest that the magnitude of Auger recombination rate in the quantum wells for AlGaN-based DUV LEDs may be as high as that for InGaN-based LEDs[11]. Hence, it is worth investigating how the Auger recombination and the electron leakage affect the efficiency droop and which can be the correct method to eliminate efficiency droop for DUV LEDs.

In this report, we reveal the effect of the Auger recombination on the efficiency droop for DUV LEDs by the band-engineered p-EBL. A well-known common sense is that the carrier injection influences Auger recombination and the electron leakage[10]. Hence, the Auger recombination and the electron leakage will be indirectly controlled by manipulating the p-EBL affinity. The affinity is deemed as the energy of electron escaping from the conduction band energy level to the vacuum energy level. By using advanced simulation tools, we can modify the electron affinity without changing the energy band gap for the p-EBL. We have also adopted different Auger recombination coefficients when changing the electron affinity of the p-EBL. Our results show that for DUV LEDs, the Auger recombination coefficient in the scale of 10^{-29} $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$ causes a significant efficiency droop. However, such a big Auger recombination coefficient is less possible for Al-rich AlGaN materials[6,10,20]. Moreover, when the electron leakage level is tuned to be large, the efficiency droop is less affected by the Auger recombination even when the Auger recombination is large. Details will be given and discussed subsequently.

To reveal the impact of Auger recombination and different electron leakage levels on the efficiency droop. The structural parameters of the Devices A and B are designed as follows: Device A has a 4 μm thick n-type $\mathrm{Al}_{0.59}\mathrm{Ga}_{0.41}\mathrm{N}$ electron injection layer with the electron concentration of 3.0×10^{18} cm^{-3}. Five periods of $\mathrm{Al}_{0.45}\mathrm{Ga}_{0.55}\mathrm{N}/\mathrm{Al}_{0.55}\mathrm{Ga}_{0.45}\mathrm{N}$ MQWs with 3 nm thick quantum wells and 10 nm thick quantum barriers, respectively. Next, we employ a 10 nm thick p-type $\mathrm{Al}_{0.60}\mathrm{Ga}_{0.40}\mathrm{N}$ EBL with the hole concentration of 2.0×10^{17} cm^{-3}. After that, the hole injection layer is composed of a 50 nm thick p-type $\mathrm{Al}_{0.40}\mathrm{Ga}_{0.60}\mathrm{N}$ layer and a 50 nm thick p-type GaN cap layer. The hole concentration is set to 2.0×10^{17} cm^{-3} and 4.0×10^{17} cm^{-3} respectively. Device B possesses the same structure except the $\mathrm{Al}_{0.60}\mathrm{Ga}_{0.40}\mathrm{N}/\mathrm{Al}_{0.50}\mathrm{Ga}_{0.50}\mathrm{N}/\mathrm{Al}_{0.60}\mathrm{Ga}_{0.40}\mathrm{N}$ structured p-EBL. Finally, the mesa size is made by 350 μm × 350 μm.

We use APSYS to conduct numerical calculation. The software processes various numerical computations, including drift-diffusion equations, Poisson' equations and Schrödinger equations self-consistently[21]. In our calculation model, we choose the polarization level of 40% to calculate interface charge of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}/\mathrm{Al}_y\mathrm{Ga}_{1-y}\mathrm{N}$ heterojunction. This value is reasonable for Ref. [22]. The Auger recombination coefficients range from 10^{-32} $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$ to 10^{-29} $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$[6,23-24]. We set the Shockley-Read-Hall(SRH) recombination lifetime to be 10 ns[25]. The energy band offset ratio is set to 50∶50[26]. The light extraction efficiency (LEE) is assumed to be 8%[27]. Other important parameters can be found in elsewhere[28].

Firstly, the influence of the electron leakage and Auger recombination on the efficiency droop for Device A is investigated. When the injection current density is as high as 170 $\mathrm{A}\cdot\mathrm{cm}^{-2}$, the function of the electron affinity of p-EBL on the electron leakage and the efficiency droop is shown in Figs. 1(a) and (b) when different Auger recombination coefficients are assumed. Inset in Fig. 1(a) depicts the calculated EQE in terms of the injection current density for DUV LEDs with different electron affinities of p-EBL. The electron leakage ratio can be obtained in the way that the integrated p-region horizontal electron current is divided by the integrated n-region horizontal electron current as shown in the inset for Fig. 1(b). It is apparently observed that both the electron leakage current and the efficiency droop increase when we modulate the affinity from 3.22 eV to 3.30 eV. Meanwhile, the increasing trend for the efficiency droop is consistent with that for electron leakage. Moreover, the remarkable impact on the efficiency droop can be found when we define the Auger recombination coefficient to be 10^{-29} $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$. It is noted that the high affinity of the p-EBL will induce decreased hole injection capability, thus causing the increased electron leakage level in Fig. 1(b) and the decreased total Auger recombination rate in MQWs in Fig. 1(c). Besides, Fig. 1(c) also depicts that the total Auger recombination rate is calculated by the integrated value of horizonal Auger recombination rate in the five quantum wells (see the inset in Fig. 1(c)). Here, it is obvious that the Auger recombination in Fig. 1(c) cannot interpret the efficiency droop in Fig. 1(a). Therefore, it can be inferred that the electron leakage has a larger impact on the efficiency droop for DUV LEDs. Our studies also indicate that the Auger recombination coefficient as large as 10^{-29} $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$ can cause a significant efficiency droop. This number is even larger than the

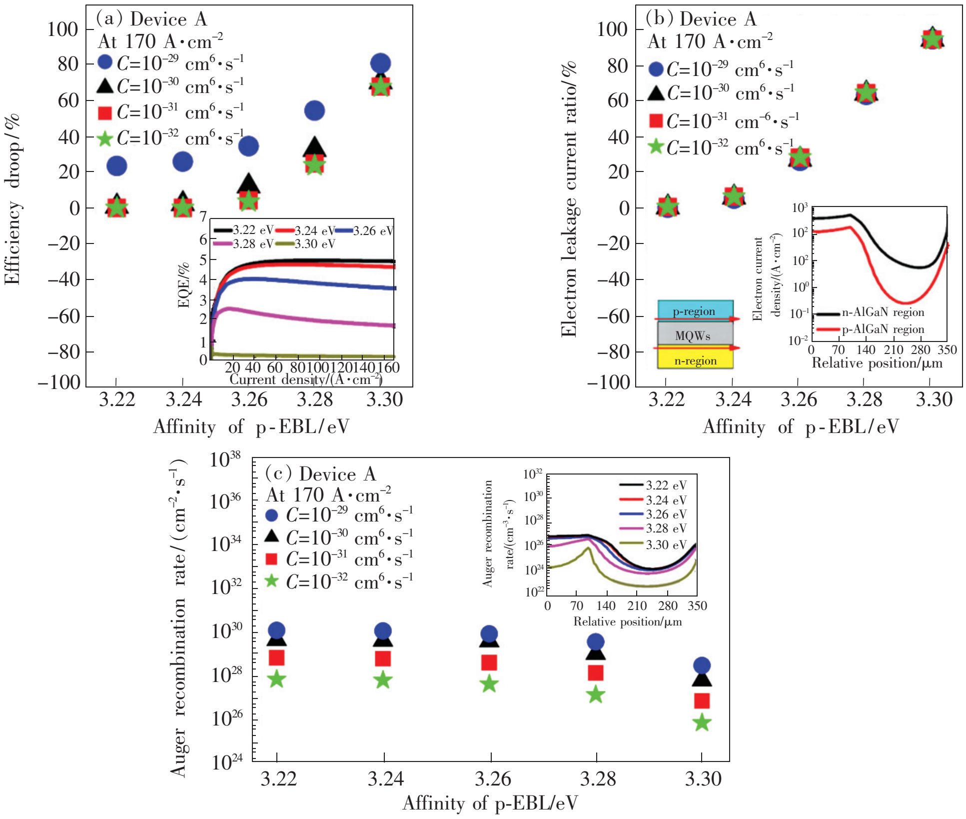

Fig. 1 Numerically computed efficiency droop(a), electron leakage current level(b) and total Auger recombination rate(c) as a function of the different affinities of p-EBL and the various Auger recombination coefficients for Device A at 170 A · cm^{-2}. Inset of Fig. 1(a) depicts the calculated EQE as a function of injection current density for Device A with different electron affinities of p-EBL. Inset of Fig. 1(b) depicts the horizontal electron current density for Device A in the p-region and the n-region, respectively. Inset of Fig. 1(c) depicts the horizonal Auger recombination rate for Device A in the last quantum well closest to the p-EBL.

Auger recombination coefficients of 10^{-31} – 10^{-30} cm^6 · s^{-1} extracted from InGaN material[10]. Nevertheless, the band gap for AlGaN material is larger than that for InGaN material, and therefore, such a large Auger coefficient in the scale of 10^{-29} cm^6 · s^{-1} is generally less possible for Al-rich AlGaN quantum wells[6,10-11]. Hence, the electron leakage is a dominant factor causing the efficiency droop in DUV LEDs.

Fig. 2(a) – (c) present the profiles for holes, electrons and Auger recombination rate, respectively. We selectively choose the DUV LEDs with the electron affinities of 3.22 eV and 3.30 eV for the p-EBLs, and the Auger recombination coefficient set to be 10^{-32} cm^6 · s^{-1}. We then summarize that the Auger recombination is more determined by the hole concentration in the MQWs, such that the increased hole concentration in the MQWs can generate even larger Auger recombination. Nevertheless, Fig. 2(b) shows that the increased hole concentration can make more electrons captured by the quantum wells. Thus, the reduced efficiency droop for DUV LED can be observed with the electron affinity of 3.22 eV due to the decreased leakage electrons. It is worth mentioning that the activation energy for Mg in AlGaN is higher than that in GaN, and thus hole concentration for DUV LEDs is lower than that for GaN based blue LEDs. Therefore, we propose that increasing the hole injection capability can prevent electrons from escaping from MQWs to p-type region, and by doing so, the efficiency droop can be decreased.

However, from the actual point of view, the electron affinity for AlGaN-based p-EBL with specific

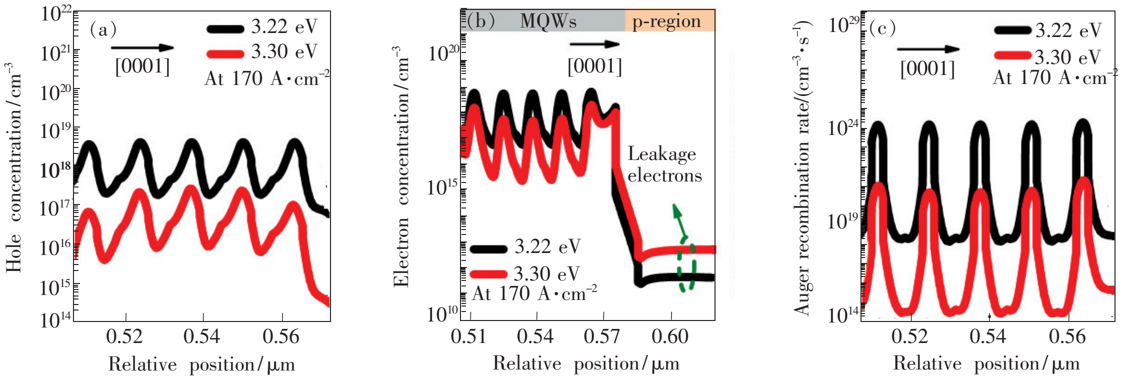

Fig. 2　Numerically computed hole concentration profiles in the MQWs (a), electron concentration profiles in the MQWs and the p-type hole injection layers (b) and Auger recombination rate profiles in the MQWs (c) with the electron affinities of 3.22 eV and 3.30 eV for the p-EBLs at 170 A · cm^{-2}.

Al mole composition is a fixed value. Therefore, besides the reference Device A that has the $Al_{0.60}Ga_{0.40}N$ p-EBL, we also design Device B that possesses the $Al_{0.60}Ga_{0.40}N/Al_{0.50}Ga_{0.50}N/Al_{0.60}Ga_{0.40}N$ structured p-EBL, which can promote the hole tunneling probability and favor thermionic emission process to increase the hole injection ability[29]. Our results are also further proven by our calculated hole concentration in the active region in Fig. 3(a) such that Device B has the even larger hole concentration in the quantum wells than Device A. The enhanced hole concentration then provides more radiative recombination channel with electrons, which is beneficial to alleviate the electron leakage current as shown in Fig. 3(b).

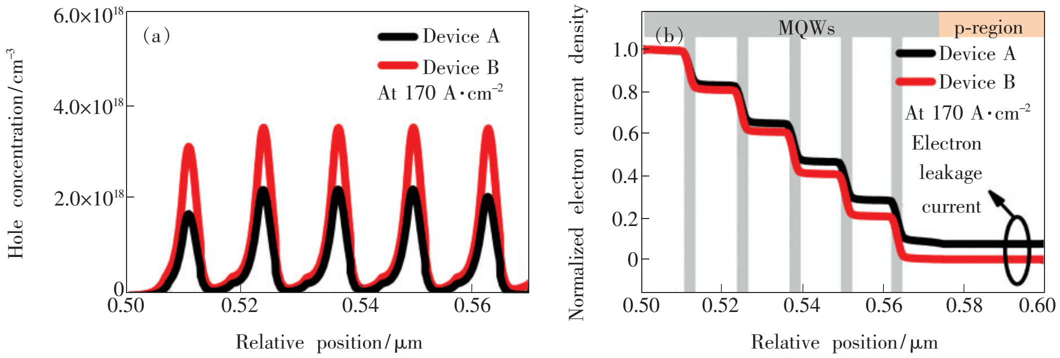

Fig. 3　(a) Hole concentration profiles in the MQWs. (b) Normalized electron current density for Devices A and B at 170 A · cm^{-2}.

We then compare the optical performance of two devices in Fig. 4. It is apparently observed from Fig. 4 that the performance of Device B is improved compared with Device A in the probed current density. The efficiency droops of 12.0% for Device A and 4.7% for Device B can been obtained at 170 A · cm^{-2}. In addition, it is shown in Fig. 4 that the optical power for Device B is increased by 32.79% when compared with Device A at 170 A · cm^{-2}. The maximum value of EQE for Device B is numerically increased by 22.83%. The increased EQE and optical power are due to the alleviated electron leakage.

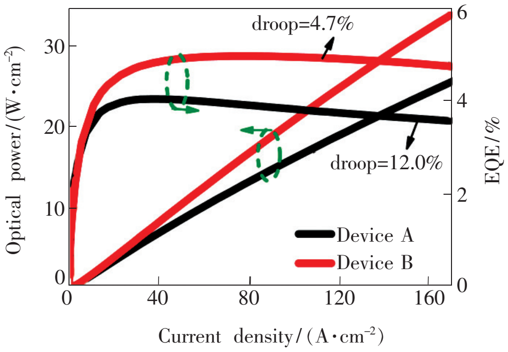

Fig. 4　EQE and optical power for Devices A and B as the function of injection current density

In summary, in this report, we modulate the affinity of p-EBL and also use different Auger recombination coefficients to explore the influence of electron leakage and Auger recombination on the efficiency droop for AlGaN-based DUV LEDs. According to the results, the Auger recombination has an obvious impact on the efficiency droop only when the Auger recombination coefficient is larger than 10^{-29} $cm^6 \cdot s^{-1}$, which number is unrealistic for Al-rich AlGaN layer. Therefore, for DUV LEDs, the Auger recombination rate has negligible impact on the efficiency droop. Instead, the efficiency droop is strongly influenced by the electron leakage. Fortunately, the electron leakage can be decreased as long as more electrons can get involved into radiative recombination. For that purpose, we strongly suggest increasing the hole injection efficiency for DUV LEDs. We believe that the report is useful for the community to study the physical mechanism regarding the efficiency droop, and the findings are helpful to increase the external quantum efficiency for DUV LEDs.

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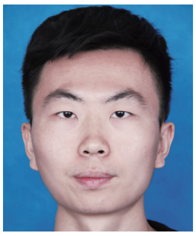

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