The Transport Mechanisms of Reverse Leakage Current in Ultraviolet Light-Emitting Diodes *

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The transport mechanisms of the reverse leakage current in the UV light-emitting diodes (380 nm) are investigated by the temperature-dependent current-voltage measurement first. Three possible transport mechanisms, the space-limited-charge conduction, the variable-range hopping and the Poole–Frenkel emission, are proposed to explain the transport process of the reverse leakage current above 295 K, respectively. With the in-depth investigation, the former two transport mechanisms are excluded. It is found that the experimental data agree well with the Poole–Frenkel emission model. Furthermore, the activation energies of the traps that cause the reverse leakage current are extracted, which are 0.05 eV, 0.09 eV, and 0.11 eV, respectively. This indicates that at least three types of trap states are located below the bottom of the conduction band in the depletion region of the UV LEDs.

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Due to the advantages of energy conservation, less negative environment impact and selectable wavelength, UV light-emitting diodes (LEDs) started to replace the conventional UV lamps and to play an important role in many special application areas in recent years. However, the leakage current, which is closely associated with the high density of defects inside the band gap of semiconductor materials, such as threading dislocations, is still one of the main obstacles that prevent UV LEDs developing towards higher output power and higher reliability.[1−3] In spite of several suggestions regarding the reduction of defects density that have been proposed,[4] the leakage current is still considerable especially at high temperature. Generally, the generating of the reverse leakage current is considered as a hopping or tunneling conduction process of carriers with the help of these defects. However, the detailed investigation on relationship between the leakage current and defects is still missing and becomes necessary.

It is worth noting that most of the current studies focus on blue (peak wavelength >400 nm) LEDs,[5−8] and the study on UV LEDs (peak wavelength <400 nm) is still lacking and pressingly required. In consideration of such a research status, an investigation on the transport mechanisms of the reverse leakage current in UV LEDs is carried out by utilizing temperature-dependent current–voltage (I–V) measurement in this study. Furthermore, the activation energy of the reverse leakage current is also extracted. The results can help us to provide valuable information for theoretical modeling estimation, processing optimization, and performance improvement.

Utilizing the metal-organic chemical vapor deposition (MOCVD) method, the epitaxial structure grown on (0001) sapphire mainly consists (from bottom to top) of an undoped GaN buffer layer, an n-type GaN layer (doping concentration $N_{\rm D} = 5 \times 10^{18}\,{\rm cm}^{-3}$), an active layer with eight periods of InGaN (1.5-nm-thick)/GaN (10-nm-thick) multiple quantum wells (MQWs) with a peak emission wavelength of 380 nm at 300 K, a Mg-doped AlGaN electron blocking layer, and a Mg-doped p-type GaN layer (doping concentration $N_{\rm A} = 10^{20}\,{\rm cm}^{-3}$). After etching ($1143 \times 1143\,\mu{\rm m}^2$), the semitransparent annealed Ti/Al/Ti/Au and the Ni/Au layers deposited by electron beam evaporation are used for n-Ohmic and p-Ohmic contact metals, respectively.

To study the transport mechanism, the I–V characteristics are measured at variable temperatures in dark vacuum atmosphere. The maximum reverse bias applied is −10 V, which will not induce any additional degradation for the devices under test. Meanwhile, the capacitance–voltage (C–V, with an ac signal level of 15 mV at 1 MHz) is also measured at room temperature, which is used for the evaluation of electric field

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strength in this work. The electric field strength E inside depletion region can be given by[5]

$$E = (V_{\rm bi} - V)/(\varepsilon_0 \varepsilon_{\rm r} A/C), \tag{1}$$

where V is the designedly applied bias, $V_{\rm bi}$ is the built-in voltage in InGaN/GaN LED (assumed to be 3.4 V),[5] ε_0 is the vacuum permittivity, $\varepsilon_{\rm r}$ is the relative permittivity of material, A is the junction area, and C is the measured capacitance.

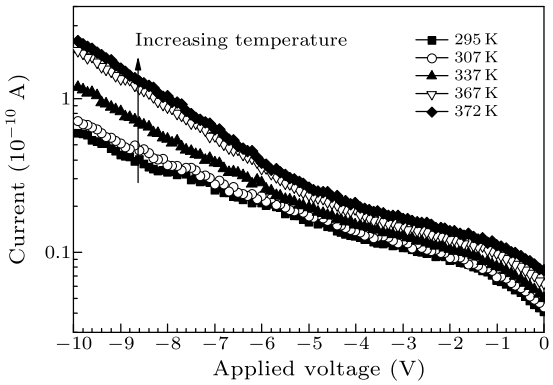


Fig. 1. Curves of reverse I–V characteristics at different temperatures from 295 K to 372 K.

The reverse I–V curves of UV LEDs at temperatures ranging from 295 K to 372 K are measured and plotted. As shown in Fig. 1, it is obviously observed that the reverse leakage current increases significantly with the increasing temperature, which agrees with the results observed in blue LEDs in previous works.[9,10] According to early works, it is known that three main transport mechanisms dominate the reverse leakage current in blue LEDs, which are the space-charge-limited conduction (SCLC), the variable range hopping (VRH) and the Poole–Frenkel (PF) emission (known as field-assisted thermal ionization), respectively.[8] To investigate the transport mechanisms of reverse leakage current in UV LEDs, the experimental data in Fig. 1 are analyzed and compared with the above-mentioned three mechanisms in the following.

Firstly, the SCLC mechanism is studied, which is mainly observed in insulators and high-resistivity materials at high voltage. According to it, the external electric field can lower the Coulomb barrier of traps. The traps will become nearly unoccupied when the field strength is large enough. Thus the depletion region will act as an insulator, and only a few electrons can be stimulated to move along the conduction band. Jaekyun *et al.* also confirmed that in blue LEDs.[6] The induced current can be numerically expressed as[11,12]

$$I = \frac{9}{8}\varepsilon_0 \varepsilon_{\rm r} \mu \frac{V^2}{L^3}, \tag{2}$$

where μ is the electron mobility, and L is the thickness of the insulator. Assuming that the SCLC mechanism works in this study, the reverse leakage current $\ln I$ should have a linear relationship on $\ln V$, and the coefficient is 2. Furthermore, the leakage current should be independent of the measurement temperature.

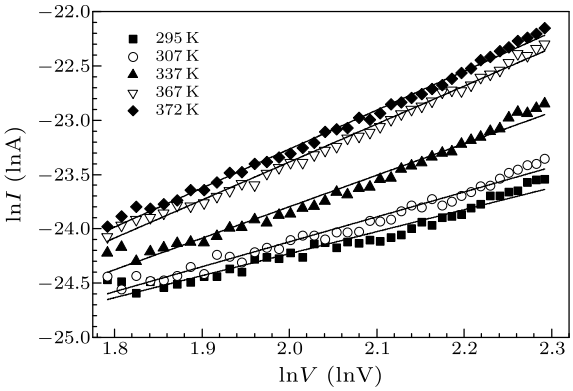


Fig. 2. Plots of $\ln I$ versus $\ln V$ at temperatures ranging from 295 K to 372 K. The solid lines are the linear fitting of the data.

As shown in Fig. 2, the curves of $\ln I$ versus $\ln V$ under different temperatures are plotted. The coefficients are extracted by the linear fitting lines, which increases significantly from 2.03 to 3.59 with the increasing temperature. This indicates that the SCLC mechanism is not the right one to dominate the reverse leakage current in UV LEDs.

The second possible transport mechanism is the VRH mechanism, which describes that the leakage current is generated by the hopping of charged carriers via localized states in the space charge region. Based on Mott's law $\sigma(0) \propto \exp[-(T_0/T)^{1/4}]$, the induced reverse leakage current can be given by[13]

$$I = I_0 \exp\left[C\frac{eaE}{2k_{\rm B}T}\left(\frac{T_0}{T}\right)^{1/4}\right], \tag{3}$$

where $\sigma(0)$ and I_0 are the conductivity and current at zero field, respectively, T_0 is the characteristic temperature, $k_{\rm B}$ is the Boltzmann constant, C and a are constants. To examine whether this mechanism is suitable, Eq. (3) is utilized to fit the experimental data. It is observed that the extracted parameter I_0 with 10^{-14} magnitude has a tremendous deviation in comparison with 10^{-4} that was reported in Refs.[5,14]. Additionally, this equation is valid only in a limited condition that electric field $E \leq 5\times10^5$ V·cm^{-1}.[13,14] However, the electric field calculated by Eq. (1) is about 1.3×10^6 V·cm^{-1} at the bias of -6 V, which is much larger than the environment. Then, we can obtain that the VRH model cannot be used to describe the transport of the reverse leakage current in UV LEDs in this work.

Finally, the last possible mechanism, the PF emission, is examined for the transport of the reverse leakage current. This model describes the increase of the thermal emission rate of carriers under an external

electric field due to the lowering of trap barrier. The leakage current can be numerically expressed as[15]

$$I = I_0 \exp\left(\frac{\beta_{PF} E^{1/2}}{k_B T}\right), \quad (4)$$

$$\beta_{PF} = [e^3/(\pi\varepsilon_0\varepsilon_r)]^{1/2}, \quad (5)$$

where I_0 is the low-field current, and β_{PF} is the PF coefficient. Assuming that the current follows this model, $\ln I$ should have a linear dependence on $E^{1/2}$. Then $\ln I$ versus $E^{1/2}$ curves under different temperatures in UV LEDs are plotted in Fig. 3. It is clearly observed that $\ln I$ has a linear-like dependence on $E^{1/2}$ under each temperature. Moreover, we fit the experimental data by utilizing Eq. (4), as shown by the solid lines in Fig. 3. According to the fitted lines, the average β_{PF} value is extracted and is about 3.80×10^{-4} eV·V$^{-1/2}$·cm$^{1/2}$, which is very close to the theoretical value 3.28×10^{-4} eV·V$^{-1/2}$·cm$^{1/2}$ that is calculated by Eq. (5), and exhibit slight deviation compared with the listed values in other works.[5,9,12]

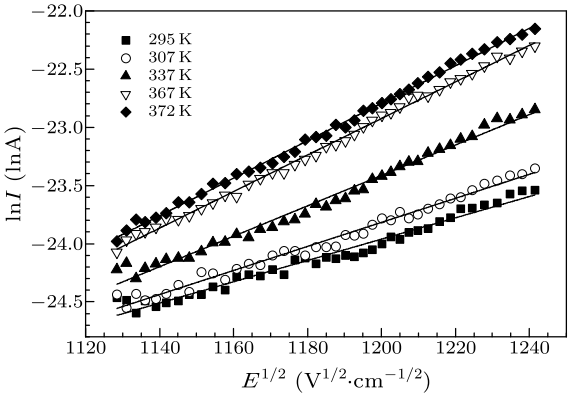


Fig. 3. Curves of $\ln I$ versus $E^{1/2}$ with voltage from -6 V to -10 V at temperatures ranging from 295 K to 372 K. The solid lines are the linear fitting of the data.

Therefore, we obtain that the PF emission mechanism dominates the reverse leakage current above room temperature in UV LEDs. In terms of this model, the trapped electron can get rid of the trap state with the help of electric field and temperature, then it will be captured by another trap and will be stimulated once again later. Through this circulation, the electron finally moves to the conduction band of n-type material and forms the reverse leakage current. The origin of these traps may result from the threading dislocations, the diffused Mg,[16] V-shaped pits at the interface of MQW/p-GaN layer,[17] etc.

To have a better understanding of the traps, the activation energy E_a is extracted in this study. It is known that the temperature dependence of the current emitted by trap states can be expressed as[18]

$$I = AT^2 \exp\left(-\frac{E_a}{k_B T}\right), \quad (6)$$

where A is a proportionality factor, and the activation energy E_a can also reflect the depth of the trap.[14] In Fig. 4, the Arrhenius plots $\ln(I/T^2)$ versus $1000/T$ at different voltages are plotted. It is obvious that the experimental data can be well fitted by a series of straight lines, which have good consistency with Eq. (6).

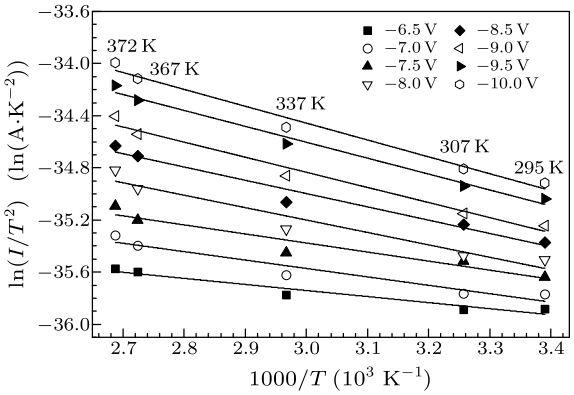


Fig. 4. Arrhenius plots of $\ln(I/T^2)$ versus $1000/T$ at temperature ranging from 295 K to 372 K. The bias voltage is ranging from -10.0 V to -6.5 V.

From the fitting lines, three slopes are obtained, corresponding to three activation energies: $E_a \approx 0.05$ eV for the bias between -6.5 V and -7.5 V, $E_a \approx 0.09$ eV for the bias being -8.0 V and -8.5 V, and $E_a \approx 0.11$ eV for the bias larger than -9.0 V. This indicates that at least three types of trap states are located below the bottom of the conduction band in the depletion region of the UV LEDs. In previous work in InGaN/GaN LEDs, Giulia *et al.* detected the electron traps with 0.04 eV and 0.12 eV in the p-type GaN layer, which are attributed to the threading dislocation.[19] In our work, we use a similar structure as that in Ref. [19], and the extracted activation energy values are very close. It is indicated that the traps in our work may also originate from the threading dislocations in the p-type GaN layer. It is also noted that the activation energy increases with the increasing bias, and this phenomenon has also been observed in nanowire blue LEDs by Musolino *et al.*[14] To explain it, for simplicity, two trap states (trap states 1 and 2) with different activation energies are assumed to be located below the bottom of the conduction band, as shown in Fig. 5. According to the PF emission model, the trapped electrons in the shallower trap state 1 will firstly escape with the help of a lower electric field E_1, in which the activation energy needed is E_{a1}, as shown in Fig. 5(a). Under this case, the trapped electrons located in the deeper trap state 2 cannot escape due to the higher barrier. When the electric field increases to a higher electric field E_2, the trapped electrons within the deeper trap state 2 can be stimulated, and the corresponding activation energy is E_{a2}, as shown in Fig. 5(b). It is evident that E_{a2} is larger than E_{a1},

which is consistent with the phenomenon observed in Fig. 4.

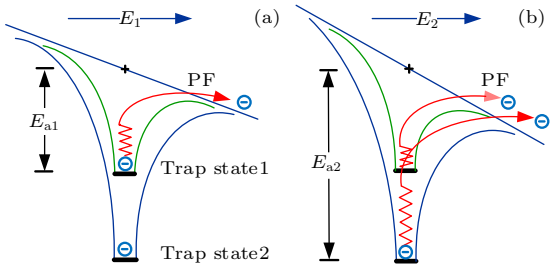


Fig. 5. The process of electron escaping from different trap states with the help of an applied external electric field, where E_2 is larger than E_1.

In summary, the transport mechanisms of the reverse leakage current in the 380-nm UV LEDs have been investigated by utilizing the temperature-dependent I–V measurement ranging from 295 K to 372 K. Three possible transport mechanisms have been proposed to clarify the reverse leakage of the device. The mechanisms of the SCLC and the VRH cannot explain the leakage current well. However, the experimental data of $\ln I$ versus $E^{1/2}$ is nicely consistent with the PF emission model. The PF coefficient is extracted and is about $3.80 \times 10^{-4}\,\mathrm{eV{\cdot}V^{-1/2}{\cdot}cm^{1/2}}$, which is close to the theoretical value. Therefore, we conclude that the mechanism that dominates the reverse leakage current in the UV LEDs is the Poole–Frenkel (PF) emission. Lastly, the activation energy under different bias are extracted, which are 0.05 eV, 0.09 eV, and 0.11 eV, respectively. It is indicated that at least three types of trap states are located in the depletion region of UV LEDs.

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