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Mg가 첨가된 GaN 박막에서 캐리어 전이의 열적도움과 전계유도된 터러링 현상

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Thermally Assisted Carrier Transfer and Field-induced Tunneling in a Mg-doped GaN Thin Film

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Abstract The dark current and photocurrent(PC) spectrum of Mg-doped GaN thin film were investigated with various bias voltages and temperatures. At high temperature and small bias, the dark current is dominated by holes thermally activated from an acceptor level A1 located at about 0.16 eV above the valence band maximum (E_v), The PC peak originates from the electron transition from deep level A2 located at about 0.34 eV above the E_v to the conduction band minimum (E_c). However, at a large bias voltage, holes thermally activated from A2 to A1 experience the field-induced tunneling to form one-dimensional defect band at A1, which determines the dark current. The PC peak associated with the transition from A1 to E_c is also observed at large bias voltages owing to the extended recombination lifetime of holes by the tunneling. In the near infrared region, a strong PC peak at 1.20 eV appears due to the hole transition from deep donor/acceptor level to the valence band.

Key words: Mg-doped GaN, Photocurrent, Thermal activation, Field-induced tunneling, Yellow band

1. Introduction

GaN has been considered to be one of the most promising materials for blue-green light-emitting diodes (LED), blue-ultraviolet (UV) lasers, short wavelength radiation detectors and high-temperature electronics.[1] Since deep levels in GaN affect significantly the photoelectric properties of material and devices, they were investigated using a number of techniques in samples grown by different methods and post treatment conditions.[1~17]

For n-type and undoped GaN samples, a shallow donor (SD) at about 30 meV below the conduction band were usually observed by temperature dependent Hall and photoluminescence (PL) measurements[1,5,6], and a double donor (DD) at about 0.7 eV below the minimum of the conduction band E_c as well as a deep level at E_c-2.0 eV were recognized by optically detected magnetic resonance (ODMR) and persistent photoconductivity (PPC) techniques.[5,12] On the other hand, a deep level at 1.4 eV above the top of the valence band E_v was detected using photocurrent (PC) and photoemission capacitance transient spectroscopy methods.[8,13,16] However, one inconsistency seems to appear for the Mg-related deep level; the Hall measurements give an activation energy of 0.16 eV while the PL usually senses a level at 0.34 eV above E_v.[1,4,14] Electro-luminescence (EL) of GaN p-n junction shows one peak at 3.08 eV under small bias voltages while additional peak appears at 3.33 eV under large bias voltages.[21,22]

It seems that there are two Mg-related energy levels, i. e., A1 at E_v+0.16 eV and A2 at E_v+0.34 eV, in GaN and their photo-electric behaviors may be affected by bias and other conditions. In this work, we employed current-voltage (I-V) and PC techniques to study deep levels in Mg-doped GaN thin film. Two acceptor levels, A1 and A2, were detected and holes transferred from A2 to A1 by thermal activation followed by the field-induced tunneling between neighboring Mg-site are responsible for the bias-induced additional peak.

2. Experiment

The Mg-doped GaN sample was grown in a MOCVD system on (0001) oriented sapphire substrate at low

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pressure. A GaN buffer layer with a nominal thickness of 25 nm was grown at 500 ℃ and the 2 ㎛ epitaxial GaN layer was grown at 1010 ℃ with the growth rate of 2 ㎛/h. The sample was annealed in a rapid thermal annealing system at 900 ℃ in a N_2 atmosphere for 5 min. The room temperature Hall concentration and mobility are $2.48\times10^{17}/cm^3$ and 12.3 cm^2/Vs, respectively. Assuming that only 1% of Mg dopant were thermalized, the mean spacing between the Mg-site would be 60 Å.[1,23]

The sample was cut into 3×3 mm^2 and two coplanar electric contacts with 1 mm spacing were formed with Ni/Au solder. The sample was mounted in a liquid nitrogen metal dewar which allows temperature control from 77 to 318 K. The I-V characteristics was measured with a current source of Keithley 236 source measure unit.

For the PC spectra measurements, the sample was attached to a sample holder and placed inside liquid nitrogen metal dewar. A quartz tungsten-halogen lamp was used as a photoexcitation light source. The light beam from the lamp passed through a chopper and was dispersed by a monochromator before being illuminated on the sample. The PC signal was picked up using lock-in amplifier and then recorded by a computer. A bias voltage was supplied by a current source, and the monochromatic photon flux onto the sample was of the oder of 10^9 photon/s. But, the normalization effect of the incident photon density did not significantly alter the PC spectrum.

3. Result and Discussion

Figure 1 (a) is the dark current of the sample at various temperatures. The I-V curve obtained is almost linear for the sample in the whole range of voltage region. Therefore, for the dark and PC measurements can not be influenced by non-ohmic contacts or injection of photoexcited carriers from the metal into semiconductor upon illumination. Figure 1 (b) is the temperature dependence of the dark current at various bias voltages. The insensitive of dark current to the sample temperature from 77 K up to 120 K is due to the transition from valence band to hopping conduction. At 0.1 V, the dark current almost exponentially increases with the reciprocal temperature with an activation energy of 0.142 eV in the temperature range from 170 K to 250 K. This activation energy is in agreement with results of Mg-related deep level observed from temperature dependent Hall, PL, PPC, photocurrent decay (PCD)[1,4,14,15,18] and current deep-level transient spectroscopy[19] measurements. When the bias voltage is increased to 10 V, the activation energy increases to 0.168 eV. On the other hand, the activation energy decreases to 0.119 eV in the temperature range from 250 K to 318 K, suggesting that the activation depends on both temperature and bias voltage. This observation can be easily explained by invoking the following mechanisms in different temperature ranges: conduction in the valence band as temperature dependence dominated by ionization of acceptors, hopping conduction as temperature dependence dominated by barrier for holes to move from one acceptor level to the next one, and a transition region where both mechanisms contribute to the conduction. The activation energies are real but they have nothing to do with an acceptor level. They may be purely activation energies for hole conduction.

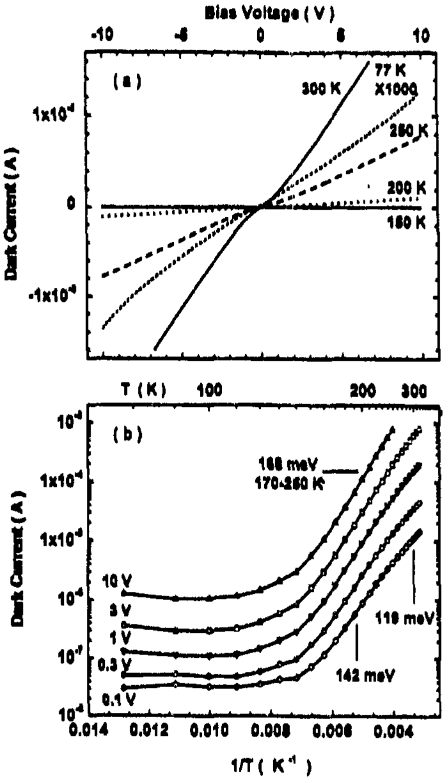

Fig. 1. (a) The I-V curves of dark current from GaN thin film at various temperatures. (b) The temperature dependence of the dark current at various bias voltages.

Figure 2 (a) shows the bias voltage dependence of differential conductance at various temperatures. The differential conductance is insensitive to the bias voltage at low temperature. However, as temperature increases, the differential conductance at small bias is apparently smaller than that at large bias voltage. The bias and temperature dependence of the activation energy is shown in Fig. 2 (b). The activation energy at large bias

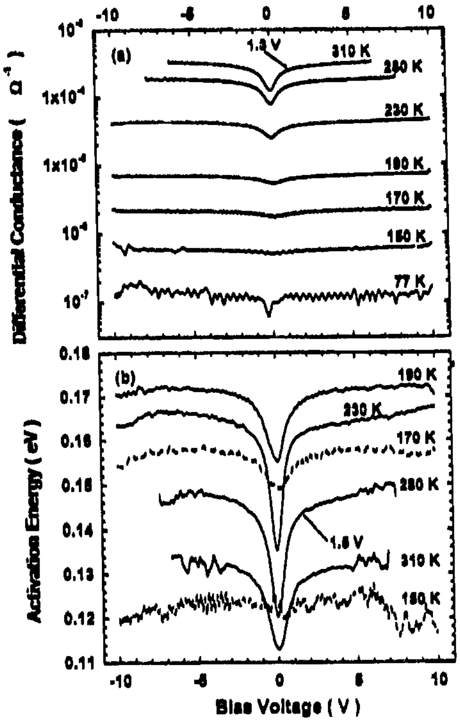

Fig. 2. (a) The bias dependence of differential conductance(R_d) at various temperatures. (b) The bias dependence of activation energy in various temperature ranges calculated using R_d, e.g. using values of R_d at 180 and 200 K for the calculation of the activation energy at 190 K.

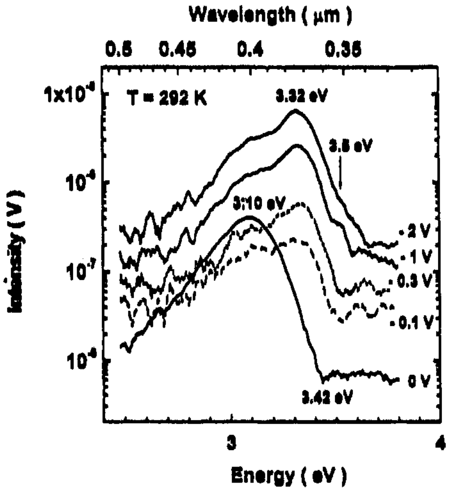

Fig. 3. The bias dependence of photocurrent spectrum at 292 K, measured with a 450 W tungsten-halogen lamp with a chopping frequency of 35 Hz.

increases first from 0.12 eV at 150 K to the maximum 0.17 eV at 190 K, and then decreases down to 0.135 eV at 310 K. The activation energy at small bias is almost the same as that at large bias at low temperature, while it is about 20 meV smaller than that of the bias voltage larger than about 1.5 eV at high temperature, which indicates that two different activation processes prevail at small and large biases, respectively.

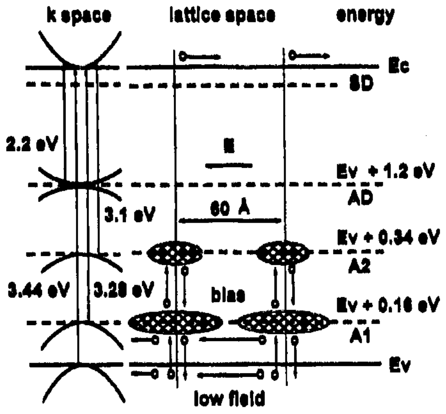

Fig. 4. Schematic diagram of the energy band structure and carrier transfers in Mg-doped GaN. At high temperature and large bias, holes thermally activated from deep level A2 to A1 tunnel to the neighboring Mg-site.

Figure 3 is the bias dependence of the PC at 292 K. At zero bias, the PC is peaked at 3.10 eV with a full width at half maximum (FWHM) of 0.3 eV. The PC response extends to about 2.5 and 3.4 eV at low and high energy sides, respectively. As the bias voltage increases, the PC intensity at 3.32 eV increases and surpasses the peak at 3.10 eV; a weak shoulder due to the near band edge transition is also observed at 3.5 eV.[1,3] The PC peaks at 3.10 and 3.32 eV correspond to transitions from Mg-related deep levels A1 and A2 to the conduction band, respectively.

By comparing Fig. 1(b), 2(b) and 3, a field-induced carrier tunneling model can be proposed as shown in Fig. 4. At small bias voltage and high temperature, holes thermally activated from deep level A1 to the valence band E_v are drifted by electric field within the lifetime and contribute to the dark current, while holes thermally activated from deep level A2 to E_v can be neglected due to the large activation energy. On the other* hand, when consider the difference of kind of recombination lifetime due to the emission intensity dependence on the ratio of radiative recombination to non-recombination lifetime, holes generated by the photo-excitation of electrons at A2 may be have longer recombination lifetime with electrons in E_c in comparison with holes in A1, resulting in the PC peak at 3.10 eV. However, at large bias, holes at A2 are thermally activated to A1, and then field-induced tunneling to the neighboring Mg-site occurs to form one-dimensional defect band. Consequently, the activation of holes from A2 to the defect band A1 with a larger activation energy than that associated with the activation from A1 to E_v dominates the dark current; the increase of the

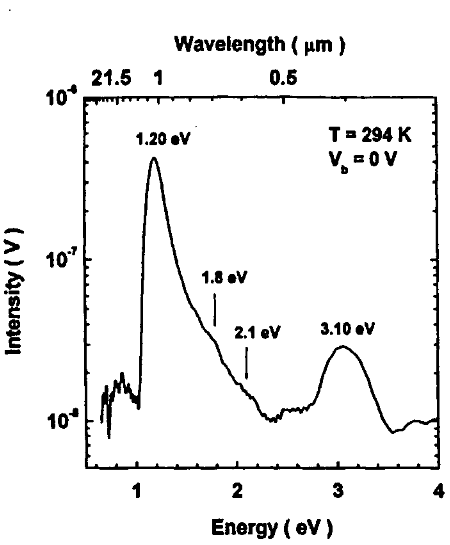

Fig. 5. The photocurrent spectrum at zero bias and 294 K, measured with a 100 W tungsten-halogen lamp with a chopping frequency of 35 Hz.

activation energy by about 20 meV at large bias shown in Fig. 2(b) reflects that the carrier activated from A2 to A1 dominates the dark current through the impurity band conduction. On the other hand, after electrons are photo-excited from A1 to E_c, the holes left in A1 face the tunneling to the next Mg-site because of the deformed wave function by the strong electric field. The tunneling of the hole prolongs the recombination life time due to the separation of electron- and hole- wave function in the lattice space. As a result the intense PC peak at 3.32 eV is observed. The activation energy shown in Fig. 2(b) increases with temperature up to 190 K as the thermal activation of holes from A2 to A1 starts to contribute to the dark current, in addition to those activated from A1 to E_v. However, the activation energy decreases with further increase of the temperature because holes are thermally distributed at the high energy states in A2 and A1 reducing the effective thermal activation energies.

Finally, Fig. 5 shows the PC signal at zero bias and 294 K recorded in a wide spectral range; the PC spectrum shows two main peaks at 3.10 and 1.20 eV, respectively. The peak at 3.10 eV is related to the transition from A2 to E_c as assigned in Fig. 3, and the strong peak at 1.20 eV is associated with the absorption from the valence band edge to the deep donor/acceptor state (DA)[24,25], which might cause the yellow band emission in GaN. The deep trap state might be originated from the dislocation which should be investigated further. Two shoulders located at around 1.8 and 2.1 eV can be attributed to the electron transitions from deep states to the conduction band which have been proposed by the theoretical investigation.[1,16,17]

4. Conclusions

The current-voltage(I-V) and PC techniques have been employed to investigate deep levels of Mg-doped p-type GaN thin film grown by MOCVD. At high temperature and small bias, holes thermally activated from deep level A1 to E_v dominate the dark current while electrons excited from A2 to E_c control the PC. However, with a large bias, holes thermally activated from A2 to A1 experience the field-induced tunneling to form one-dimensional defect band which controls the dark current. The field-induced tunneling of holes at A1 prolongs the recombination lifetime of holes which leads to the main PC process associated with transition from A1 to E_c. We have also observed a strong PC peak at 1.20 eV due to the electron transition from valence band to a deep donor/acceptor state which might be responsible for the yellow band emission in GaN.

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