Optical quenching behavior related to the deep levels in unintentionally doped n-type GaN epilayers grown on sapphire substrates

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Potential applications of GaN and its related materials in electronic and optoelectronic devices have driven an extensive and successful effort to grow them on various substrates [1–5]. When the GaN epilayers are grown on sapphire substrates, there are inherent problems with obtaining high-quality epitaxial growth due to the existence of the deep levels, which affect the optical properties in the GaN epilayers [6]. Since the deep levels in GaN epitaxial films are very important for achieving high-performance devices [7], they have been systematically studied by using photoluminescence [8, 9], deep-level transient spectroscopy (DLTS) [10], and other measurements [11, 12]. Recently, the broad distribution of impurity states existing in the GaN energy gap was investigated by using photoconductivity (PC) measurements [13–18]. Some of these PC mesurements were performed on n-type GaN epilayers [15–18], and almost all of them addressed the persistent PC and the metastable properties of the yellow luminescence. However, many of the defect levels existing in the energy gap have not been clearly explained by the PC measurements. Furthermore, very few studies concerning the deep levels in nominally undoped GaN epilayers have been performed using the optical quenching effect in photocurrent measurements yet [17, 18]. The typically reported properties of the deep levels, their abilities to undergo transitions from a normal to a metastable atomic configuration under prolonged illumination, are related to the optical quenching effect.

This letter reports data from photoconductivity (PC) measurements which were performed to investigate the optical quenching related to the deep levels in unintentionally doped n-type GaN epitaxial layers grown on sapphire substrates by using plasma-assisted molecular beam epitaxy (PAMBE). A possible model of the optical quenching effect in the GaN epilayers is presented on the basis of the PC results.

The GaN epilayers studied in this work were grown on (0001) sapphire substrates by using a PAMBE system. An inductively coupled radio-frequency (RF) plasma source provided the reactive nitrogen from nitrogen gas with a purity of 99.9999%, and Ga with a purity of 99.9999% was evaporated by using conventional effusion cells. Prior to GaN film growth, the surfaces of the chemically cleaned substrates were exposed to an activated nitrogen beam for 10 min so as to be completely covered with nitridated layers. Two kinds of the GaN epilayers with thicknesses of 600-nm were deposited at a substrate temperature of 700 °C on 300-Å-thick GaN buffer layers which had been grown at 550 °C: one was grown in a gallium-rich atmosphere, and the other was grown in a nitrogen-rich atmosphere. The carrier type, the carrier density, and the resistivity for the unintentionally doped GaN film grown in a gallium-rich atmosphere, as determined from Hall-effect measurements at 300 K, were n-type, 1.8×10^{16} cm^{-3}, and 1.6×10^{6} Ωcm, respectively, and those for the samples grown in a nitrogen-rich atmosphere were n-type, 1.8×10^{17} cm^{-3}, and 1.4×10^{16} Ωcm, respectively.

The extrinsic Pc transient signals were generated by using blue GaN/SiC light-emitting diodes (LEDs) as illumination sources. The optical quenching effects of the PC spectra of the GaN epilayers were measured by using a tungsten lamp as the photoexcitation light source. The light from the tungsten lamp was dispersed using a monochromator. A pulse generator was used to supply a current pulse with a square wave, and the light intensity was controlled by using the change in the current passing through the LED. The value of the light intensity was measured by using a sensitive powermeter. A dc voltage was applied to the sample with a load resistor, whose resistance was small enough to produce a small RC time constant for the circuit. The extrinsic PC signal output from the load resistor was measured with a Tektronix 2430A digitizing oscilloscope, and it was recorded on a computer. The sample temperature was controlled by using a liquid nitrogen flow cryostat.

Fig. 1 shows the PC spectrum of unintentionally doped n-type GaN epilayers grown on sapphire substrates in a gallium-rich atmosphere. The PC spectrum shows a minimum value at 3.245 eV, which might be related to deep localized states in the n-type GaN epilayers. The level of the hole trap determined from the optical quenching effect of the PC spectrum is $E_V + 2.77$ eV.

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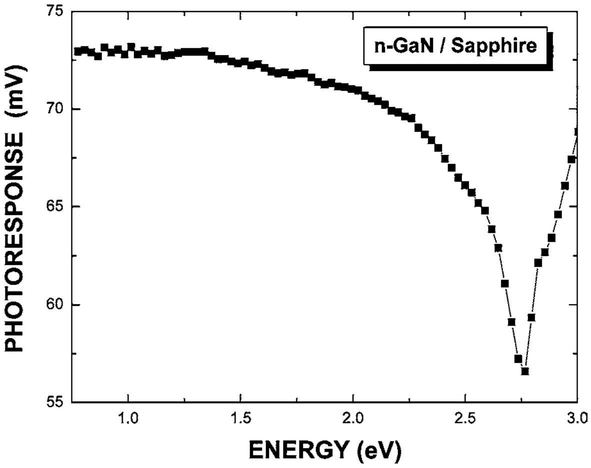

Figure 1 Photoconductivity spectrum of unintentionally doped n-type GaN epilayers grown on sapphire substrates in a gallium-rich atmosphere.

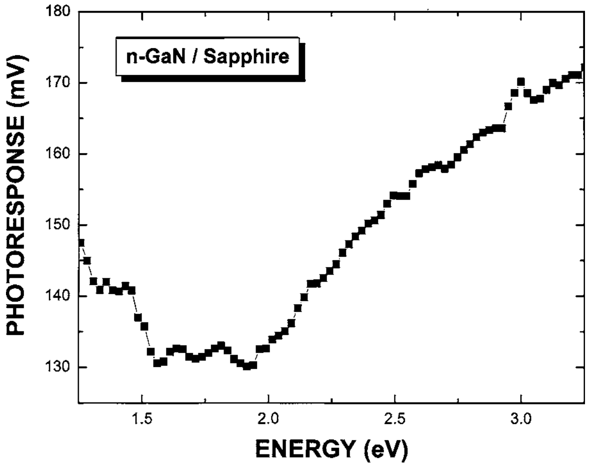

Figure 2 Photoconductivity spectrum of unintentionally doped n-type GaN epilayers grown on sapphire substrates in a nitrogen-rich atmosphere.

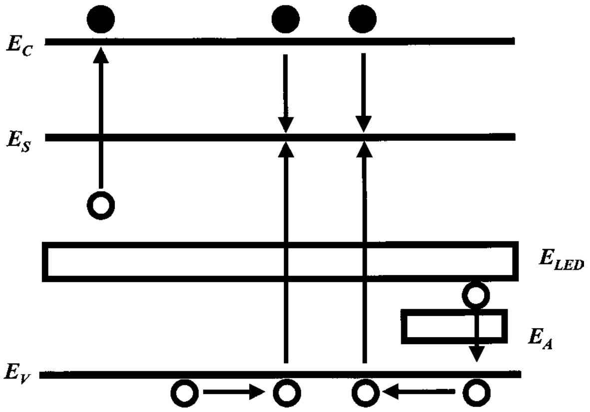

Figure 3 Schematic model of the optical quenching effect in the n-type GaN epilayer. The solid circles and the empty circles represent the electrons and the holes, respectively.

Fig. 2 shows the PC spectrum of unintentionally doped n-type GaN epilayers grown on sapphire substrates in a nitrogen-rich atmosphere. The energy level of the deep level, determined from Fig. 2, is between $E_V + 1.55$ eV and $E_V + 2.0$ eV, and is distributed broadly. Since the energy range between $E_V +$ 1.55 eV and $E_V + 2.0$ eV cannot be measured by using DLTS and thermally stimulated current measurements on n-type GaN epilayers, the optical quenching method is an effective way to determine the deep level that traps minority carriers.

When the blue LED is illuminated, the magnitude of the PC increases and then becomes saturated after a certain period of time. When the saturated GaN epilayer is continuously illuminated by the LED, the photoinduced free electrons and holes recombine. If there is a metastable state in the energy gap of the GaN epilayer, the photoexcited electrons can occupy this state and induce an optical quenching behavior after the saturation, as shown in Figs 1 and 2. The optical quenching of the photocurrent in the n-type GaN epilayer is attributed to the presence of hole traps and the existence of the metastable state reuslting from the presence of the hole traps is in reasonable agreement with the observation by the Haung *et al.* [16].

A possible schematic model of the optical quenching effect in n-type GaN epilayers grown in gallium-rich and nitrogen-rich atmospheres is described on the basis of the PC results as shown in Fig. 3. The ($E_V + 2.77$ eV) level shown in Fig. 1 is represented by E_{A1}, and the levels between $E_V + 1.55$ eV and $E_V + 2.0$ eV shown in Fig. 2 are indicated by E_{A2}. E_C and E_V represent the conduction band minimum and the valence band maximum, respectively. E_{LED} is the energy of the level generated the conduction electrons induced by the LED, and E_S is the recombination center. Even though many hole traps in undoped n-type GaN epilayers exist at definite locations, as reported in other literatures [19–21], the trap levels studied in this work were distributed broadly in the energy range between 1.55 and 2.0 eV. When the sample is illuminated with the light with a above energy band gap, E_S and E_{A1} or E_{A2} are in the equilibrium state when the capture and the emission are balanced. With the addition of a subband gap energy light, the photons excite valence band electrons to hole trap level E_{A2}, and recombine with holes trapped in centers E_{A2}, then resultant excess free holes are captured by E_S, or recombine with electrons in the conduction band. Therefore, optical quenching of PC occurs. The decrease in the PC intensity, which is related to the optical quenching due to hole traps, as shown in Figs 1 and 2, plays an important role in the deterioration of the efficiencies for optoelectronic detector devices fabricated using GaN thin films. The behavior of the distribution of the deep level in the GaN epilayer is affected significantly by the growth conditions. The details of studies on the optical quenching mechanism and the physical origin of the metastable state in the n-type GaN epilayer will be investigated in the future.

In summary, the results of the PC measurements on n-type GaN epilayers grown on sapphire substrates by using PAMBE in gallium-rich and nitrogen-rich atmospheres showed optical quenching effects related to the existence of deep levels. The positions of the deep levels in the n-type GaN epilayers were significantly affected by the growth conditions. Although some details of the optical quenching mechanism in n-type GaN epilayers remain to be clarified, these observations can help improve the understanding of GaN epilayers and lead to their applications in optoelectronic devices, such as solar ultraviolet detectors.

Acknowledgment

This work was supported by the Korea Science and Engineering Foundation through the Quantum-Functional Semiconductor Research Center at Dongguk University.

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Received 30 April
and accepted 18 May 2004