Laser-Induced Activation of p-Type GaN with the Second Harmonics of a Nd:YAG Laser

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Magnesium-doped p-type GaN has been activated by irradiation with photons of 532 nm wavelength from the second harmonic of a Q-switched neodymium-doped yttrium aluminum garnet (Nd:YAG) laser. With appropriate laser fluence levels and irradiation pulse numbers, such a laser-induced activation process resulted in a hole concentration about the same as that obtained through the conventional thermal activation technique. Temperature measurement revealed that the laser-induced process is very unlikely to be thermal. It was speculated that the process might involve the photon-induced breaking of the H–Mg bonds.

KEYWORDS: Mg-doped GaN, p-type activation, thermal activation, laser-induced activation

1. Introduction

As-grown magnesium (Mg)-doped GaN prepared by metalorganic chemical vapor deposition (MOCVD) shows an n-type nature. Efficient activation of Mg acceptors in GaN is crucial for realizing high-quality GaN-based light-emitting and electronic devices. With thermal activation at temperatures ranging from 600 to 1000°C for 20 to 30 min, usually a hole concentration of about 10^{17} cm^{-3} in a sample with a Mg doping concentration of 10^{18} to 10^{19} cm^{-3} can be achieved.^{1–3)} According to recent publications, two mechanisms are responsible for Mg deactivation in GaN. One of them is the well-known hydrogen passivation and the other is the self-compensation by a complex of Mg and nitrogen vacancies.^{4–6)} Thermal activation can typically compensate for the effect of shallow hydrogen donors and partially activate the Mg acceptors. However, it cannot activate those Mg acceptors passivated by nitrogen vacancies. Photoluminescence (PL) spectrum measurements have provided strong evidence for these statements.

In this paper, we report the results of Mg acceptor activation in GaN by laser irradiation at a photon energy below the GaN band gap. With such laser irradiation, photons may directly break the bonds in the Mg–H complex, leading to Mg acceptor activation. Measurements of the average temperature showed that the process was very unlikely to be thermal. With appropriate laser irradiation conditions, a hole concentration of the same level as that via thermal activation could be obtained. PL measurements revealed that laser-induced activation could essentially result from the removal of hydrogen donors.

In §2 of this paper, we report the activation procedures, including the thermal and laser-induced method. The results based on these two methods are compared. Then, in §3, we discuss the possible mechanisms of laser-induced activation. Finally, in §4, conclusions are drawn.

2. Activation Procedures and Results

The second-harmonic photons (532 nm in wavelength) of a Q-switched Nd:YAG laser were used to irradiate two Mg-doped GaN samples. The MOCVD-grown samples consisted of a Mg-doped GaN layer of $1.6 \mu\text{m}$ thickness for sample A and of $0.615 \mu\text{m}$ thickness for sample B after the growth of $0.2\text{-}\mu\text{m}$ -thick (sample A) and $1.6\text{-}\mu\text{m}$ -thick (sample B) nucleation layers on sapphire substrates. The growth temperature was 1020°C. The concentrations of Mg doping were $6.3 \times 10^{17} \text{ cm}^{-3}$ (sample A) and $1.2 \times 10^{18} \text{ cm}^{-3}$ (sample B). To obtain uniform laser fluence, the laser output of a 1 mm beam radius was first expanded into a radius size of 2 cm through a defocusing lens. The central portion of the enlarged laser beam, which was believed to be quite uniform in fluence, was then used for laser irradiation onto samples of $5 \text{ mm} \times 5 \text{ mm}$. After laser irradiation, metal contacts were prepared by evaporating nickel and gold layers of 35 and 100 nm, respectively, followed by thermal annealing at 750°C for 20 s in ambient nitrogen. It was confirmed that this short-period thermal annealing process did not activate the GaN samples. The metal contacts were designed in a pattern suitable for Hall measurements. Based on the van der Pauw method, the Hall measurements were used to identify p-type formation and to calibrate hole concentration, resistivity, and mobility.

For comparison, we also conducted thermal activation with the same sample wafers. Thermal activation experiment procedures were the same as those for laser activation except that the laser irradiation was replaced by thermal annealing at various temperatures for 20 (for sample A) or 30 (for sample B) min. Figure 1 shows the variations of hole concentration of the two samples with temperature. One can see that hole concentrations of about $6 \times 10^{16} \text{ cm}^{-3}$ and $2 \times 10^{17} \text{ cm}^{-3}$ for samples A and B, respectively, were achieved with annealing at 800°C. Because of the limited size of sample B, only one data point is available. The corresponding mobility and resistivity of the thermally activated samples range between 10 and $100 \text{ cm}^2/(\text{V}\cdot\text{s})$ and between 4 and $6 \Omega\cdot\text{cm}$, respectively. Both of them are within reasonable ranges based on previously obtained data.^{1–3)}

The effects on hole concentration of laser-induced acti-

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Fig. 1. Hole concentration vs thermally activated temperature for samples A (open circles) and B (solid circle).

Fig. 2. Hole concentration vs laser fluence for laser-induced activation of samples A (open circles) and B (solid circles). The laser pulse number for sample A (B) is 50000 (60000).

vation at various laser fluence levels are shown in Fig. 2. Samples A and B were irradiated with 50000 and 60000 laser pulses (100 Hz pulse repetition rate), respectively. From Fig. 2, it is evident that for sample A, the hole concentration ranges from 4.6×10^{15} to $1.25 \times 10^{16} \text{ cm}^{-3}$ when laser fluence increases from 0.094 to 0.3 mJ/cm². For sample B, the hole concentration ranges from 1.5×10^{16} to $9.45 \times 10^{16} \text{ cm}^{-3}$ when laser fluence increases from 0.154 to 0.46 mJ/cm². The corresponding mobility values are in the same range as those of thermal activation. In terms of resistivity, although laser-induced activation of sample A led to relatively high values compared with those of thermal activation, laser-induced activation of sample B resulted in quite low values, comparable to those of thermal activation.

The effects on hole concentration of laser-induced activa-

Fig. 3. Hole concentration vs laser pulse number for laser-induced activation of samples A (open circles) and B (solid circles). The pulse fluence for sample A (B) is 0.25 (0.23) mJ/cm².

tion at fixed laser fluence but with different laser pulse numbers are shown in Fig. 3. The laser fluence levels were fixed at 0.25 mJ/cm² for sample A and at 0.23 mJ/cm² for sample B. For sample A, the condition of 60000 laser pulses (100 Hz for 10 min) generated the highest hole concentration ($4.56 \times 10^{16} \text{ cm}^{-3}$), lowest mobility [$10.7 \text{ cm}^2/(\text{V}\cdot\text{s})$], and lowest resistivity ($12.46 \Omega\cdot\text{cm}$). Note that this hole concentration is comparable to the level of thermally activated samples (see Fig. 1). For sample B, the condition of 50000 laser pulses (100 Hz for 8.3 min) resulted in the highest hole concentration ($2.66 \times 10^{17} \text{ cm}^{-3}$), which was again about the same as that with thermal activation.

3. Discussion of Activation Mechanisms

As mentioned previously, the thermal process is believed to induce the dissociation of Mg–H bonds in MOCVD-grown samples. In other words, the thermal energy ionizes shallow H donors and activates Mg acceptors. The shallow H donors and Mg acceptors correspond to the fluorescence peak near 3.2 eV.^{4,5} The deep donors formed by a complex of H and nitrogen vacancies lead to the fluorescence peak near 2.8 eV. This PL feature has been observed in the thermally activated samples. To identify the mechanisms of laser-induced activation, we conducted PL measurements of sample A under different conditions, and the results are shown in Fig. 4. Here, the three curves correspond to PL spectra of an as-grown sample (continuous line), a laser-activated sample (dashed line), and a thermally activated sample (dashed-dotted line). The laser-activated sample was prepared under the conditions of 60000 pulses at 0.25 mJ/cm² fluence. The thermally activated sample was prepared by annealing at 800°C for 20 min. The hole concentration of the former is only slightly lower than that of the latter. Although the peaks around both 2.8 and 3.2 eV are not prominent, the redshift trend of these spectra is consistent with findings previously reported.^{4,5} The as-grown sample has a peak near 3.2 eV, indicating the existence of the Mg–H complexes and their dominance over the deactivation

Fig. 4. PL spectra of an as-grown sample (continuous line), a laser-activated sample (dashed line), and a thermally activated sample (dashed-dotted line).

mechanism. The PL peak of the thermally activated sample shifts to around 2.9 eV, revealing that the Mg–H complexes have essentially been eliminated and the dominating deactivation mechanism is the effect of nitrogen vacancies. In the case of laser-induced activation, the PL spectrum lies in between. Such a spectral distribution may indicate that the used photons (with an energy of 2.33 eV) may partially ionize not only the shallow but also the deep donors. However, this hypothesis requires further investigation.

To understand whether the laser-induced process was thermal, we measured the temperature of the sample during laser irradiation. The measured temperature was around 30°C, only a few degrees above room temperature. This temperature was an average value calculated from repeated pulse irradiation. A question may be raised about the possibility that high temperatures existed for a short duration (in the microsecond range) after the irradiation of one pulse. If this is true, the continual high temperature duration would add up to with at most several seconds in the case of 40000 pulses laser irradiation (assuming 100- μ s-duration high temperature for one laser pulse irradiation). Even if the transient temperature was as high as 800°C, there was no evidence of thermal activation for such

a short time period. It should be noted that the laser photon energy expended was 2.33 eV, which is lower than the absorption band of the samples, except possibly that caused by defects. Also, it is almost impossible for such photons to induce efficient phonon generation. Hence, the process involved in laser-induced activation is very unlikely to be thermal. Note that the required energy for ionizing the shallow donors, i.e., breaking the Mg–H bonds, is only around 1.5 eV.⁷⁾ By increasing this by 0.4 eV, the incident photons can possibly ionize the deep donors. Therefore, it is reasonable to speculate that photon-induced ionization of shallow and possibly deep donors is the mechanism of the laser-induced activation process. In other words, the relevant bonds are directly broken by the incident photons. However, such speculation requires further investigation.

4. Conclusions

In summary, we have successfully activated Mg acceptors in p-type GaN samples with laser irradiation at a photon energy lower than the major absorption band. With appropriate laser fluence levels and exposure periods, the hole concentration reached the level obtained with thermal activation. Temperature measurements indicated that the laser-induced process was nonthermal. The physical mechanism of this process should be a topic for further investigation.

Acknowledgments

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