Activation of p-Type GaN with Irradiation of the Second Harmonics of a Q-Switched Nd:YAG Laser

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Efficient activation of Mg acceptors for obtaining a high hole concentration is a challenging topic. In this paper, we report the results of Mg acceptor activation in GaN with irradiation of the second-harmonic photons (532 nm in wavelength) of a Q-switched Nd:YAG laser. This laser was used to irradiate two Mg-doped GaN samples of different doping concentrations. With doping concentration of $1.2 \times 10^{18} \text{ cm}^{-3}$, a hole concentration of $2.66 \times 10^{17} \text{ cm}^{-3}$ was obtained after laser-induced activation. The average temperature of samples during laser irradiation was around 30 °C. Hence, it was speculated that the irradiation process was very unlikely to be thermal annealing. PL measurements revealed that laser-induced activation could ionize not only the shallow but also the deep donors.

1. Introduction The second harmonic photons (532 nm) of a Q-switched Nd:YAG laser were used to irradiate two Mg-doped GaN samples. The MOCVD grown samples consisted of Mg-doped GaN of 1.6 μm for sample A and 0.615 μm for sample B after the growth of 0.2 μm (sample A) and 1.6 μm (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 1 mm in 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 used for laser irradiation onto samples of $5 \times 5 \text{ mm}^2$ in dimension. After laser irradiation, metal contacts were prepared, followed by thermal annealing at 750 °C for 20 s in ambient nitrogen. It was confirmed that this short-period thermal annealing process could not activate the GaN samples.

2. Experimental Results For comparison, we also conducted thermal activation with the same sample wafers. Thermal activation experiments were conducted with thermal annealing at various temperatures for 20 min (for sample A) or 30 min (for sample B). Figure 1 shows the variations of hole concentrations for samples A and B. One can see that hole concentrations of about 6×10^{16} and $2 \times 10^{17} \text{ cm}^{-3}$ for samples A and B,

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

respectively, were achieved with annealing at 800 °C. Because of the limited size of sample B, only one data point is available. Both of them are within reasonable ranges based on previously obtained data Refs. [1–3].

The hole concentration results of laser-induced activation with various laser fluence levels are shown in Fig. 2. Samples A and B were irradiated with 50000 and 60000 laser pulses, respectively. For sample A, the hole concentration ranges from 4.6×10^{15} to 1.25×10^{16} cm⁻³ when laser fluence increases from 0.094 to 0.3 mJ/cm². Also, for sample B the hole concentration ranges from 1.5×10^{16} to 9.45×10^{16} cm⁻³ when laser fluence increases from 0.154 to 0.46 mJ/cm². The hole concentration results of laser-induced activation with fixed laser fluence but 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 case of 60000 laser pulses generated the highest hole concentration (4.56×10^{16} cm⁻³), which is comparable to the level of thermally activated samples. For sample B, the case of 50000 laser pulses resulted in the highest hole concentration (2.66×10^{17} cm⁻³).

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

Fig. 2. Hole concentration vs. laser fluence in laser-induced activation for samples A (empty circles) and B (filled circles)

Fig. 3. Hole concentration vs. laser pulse number in laser-induced activation for samples A (empty circles) and B (filled circles)

three curves correspond to PL spectra of an as-grown sample (continuous line), a laser-activated sample (dashed line), and a thermally activated sample (dash-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 concentra-

tion 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 Mg–H complexes and their dominance over the deactivation 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.

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 continuous high temperature duration would add up to with at most several seconds in the case of 40000 pulses laser irradiation (assuming 100 µs 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 in-

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

duce 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 [6]. Increasing this value 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 non-thermal. The physical mechanism of this process should be a topic for further investigation.

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