ELECTRICAL CHARACTERIZATION OF MOVPE-GROWN P-TYPE GaN:Mg AGAINST ANNEALING TEMPERATURE

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ABSTRACT

Hall effect measurements have been applied for the electrical characterization of p-type Mg-doped GaN grown by metalorganic vapor-phase epitaxy on sapphire substrates in terms of annealing temperature for dehydrogenation (N_2 annealing) and hydrogenation (H_2 annealing) of the acceptors. With the N_2 annealing temperature from 600 to 900 °C for dehydrogenation, both hole concentration and mobility increases, showing more activation of acceptors and less incorporation of unfavorable scattering centers probably originating from Mg-H bondings. The N_2 annealing at higher than the growth temperature results in reduced hole concentration, but the mobility gets higher. Some defects compensating acceptors may be induced at high temperature annealing, but they seem to be no scattering centers and be inactivated by successive hydrogenation and re-dehydrogenation at the optimum dehydrogenation temperature 900 °C. The electrical degradation of GaN due to thermal damage is not very destructive and can be well recovered by annealing treatments.

INTRODUCTION

It is now a common understanding that Mg acceptors doped in GaN by metalorganic vapor-phase epitaxy (MOVPE) are severely passivated with hydrogen in as-grown layers and can be activated to achieve p-type conductivity by post-growth thermal annealing in N_2 atmosphere resulting in dehydrogenation. With referring the earliest reports by Nakamura et al. [1], the thermal annealing has been considered to be effective at a temperature sufficiently lower than the growth temperature, e.g., at 600 °C or slightly higher. Although the doped Mg acceptors are expected to be activated almost completely at the present annealing conditions, there have not been a sufficient number of reports investigating the activation processes and the possible defects induced by thermal damage during the annealing.

Youn et al.[2] showed that there was an optimum annealing temperature resulting in the highest hole concentration, dependent on the existing defect structures in Mg-doped GaN (GaN:Mg) layers. The hole concentration decreased at higher annealing temperatures, different from the data in ref.[1] showing the constant hole concentration with annealing temperature above 650 °C, and this phenomenon was interpreted by generation of nitrogen vacancies compensating Mg at higher annealing temperatures. As is demonstrated in this work, the possibility of defect generation or other thermal effects may be an important factor to be taken into account in the discussion of the activation process of Mg acceptors.

In this study, aiming at detailed understanding of activation and degradation mechanism in GaN:Mg layers, characterization of electrical properties has done in terms of wide variety of the annealing temperature, including that higher than the growth temperature, for dehydrogenation in N_2 atmosphere. Effects of successive hydrogenation in H_2 atmosphere and re-dehydrogenation were also investigated.

EXPERIMENTS

Mg-doped GaN layers of 1 µm in thickness were grown on sapphire substrates by MOVPE at around 1000 °C. The post-growth annealing was done either in N_2 or H_2 atmosphere at various temperatures between 600 and 1100 °C, being expected to result in dehydrogenation or (re)hydrogenation, respectively. The electrical characterization was done by temperature-variable Hall effect measurements with Van der Pauw samples, fabricated by evaporating Au/Ni electrodes. The AC-component of Hall voltage was detected under magnetic field modulation typically at 50mHz, which enabled the characterization of highly resistive samples as those with the resistivity of 10^8 Ω·cm. The simple one carrier analysis method has been applied for the calculation of hole concentration and hole Hall mobility from the Hall effect measurement data as a first approximation.

RESULTS AND DISCUSSION

Dehydrogenation

As-grown GaN:Mg samples have been subjected to thermal annealing in N_2 atmosphere for 20 min at different temperatures. The Hall effect measurements were conducted after fabricating the Au/Ni electrodes. Figure 1 shows the temperature dependence of hole concentration and hole Hall mobility with the annealing temperature as a parameter.

With the annealing from 600 to 900 °C the hole concentration slightly increases from 1 to 6×10^{17} cm^{-3} at room temperature (RT). The increase of hole concentration values at lower temperatures may be attributed to occurrence of impurity band conduction [3] which makes invalid to use the one carrier analysis method for calculating the actual hole concentrations. The Hall mobility at RT also increases with the annealing temperature. It is worth noticing that the mobility of 600 °C-annealed sample exhibits a plateau characteristics near RT, suggesting that

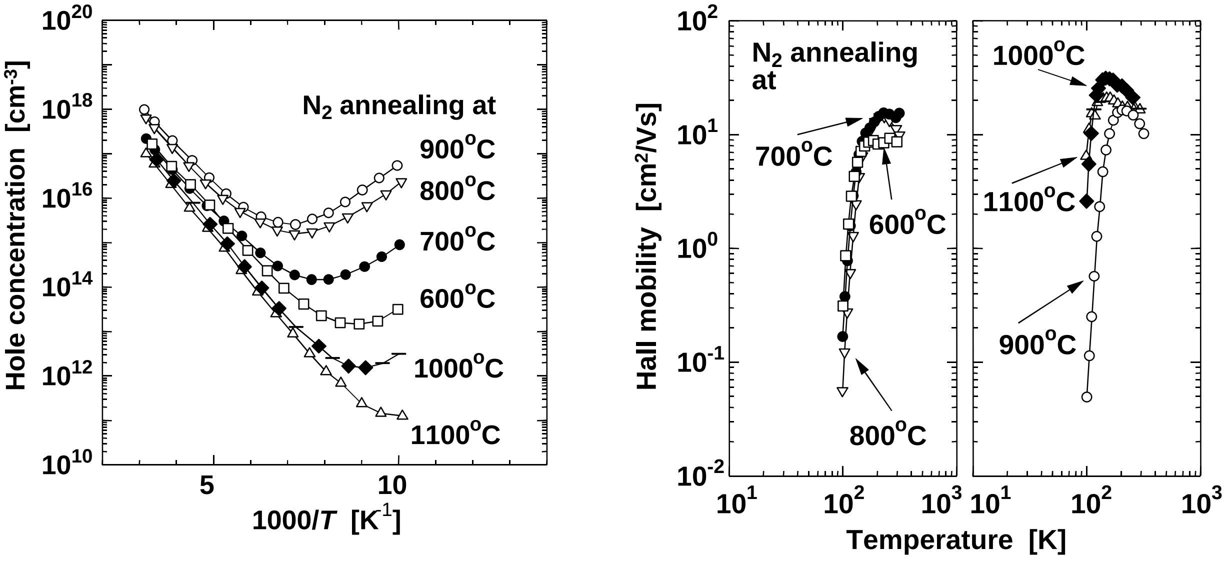

Fig. 1 Temperature dependence of hole concentration and hole Hall mobility of GaN:Mg samples subjected to different dehydrogenation (N_2 annealing) temperature.

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the hole transport is severely suppressed by neutral impurity scattering. From these mobility data, it is speculated that the samples of insufficient acceptor activation (i.e., those annealed at lower temperatures) contain unfavorable scattering centers probably originating from Mg-H bondings.

On the other hand, for the samples annealed at 1000 or 1100 °C, which are higher than the growth temperature, the hole concentration decreases to mid-10^{16} cm^{-3}. However, one of the noticeable results is that the mobility becomes higher than those annealed at 700-900 °C and exhibits the more well-defined lattice scattering characteristics in Hall mobility data, i.e., that is proportional to $T^{-1.5}$ from 130 K to RT. The maximum mobility of the 1000 °C-annealed sample is 32 cm^2/Vs at 130K, which is the highest value among those observed in all samples examined here. If the decrease in hole concentration of those high-temperature annealed samples is due to generation of defects such as nitrogen vacancies, as has been suggested in ref.[2], the increased mobility and its lattice scattering characteristics cannot be explained.

From these investigations, it may be concluded that (i) with the higher annealing temperature up to the growth temperature more activation of acceptors proceeds and unfavorable scattering centers originating from Mg-H bondings decrease, and (ii) the annealing at the temperature higher than the growth temperature results in compensation but does not enhance the generation of scattering centers. In additions to those, it is seen that the mobility-temperature characteristics, where the mobility rapidly decreases below 200 K for all samples, are not different significantly irrespecive of different contribution of the impurity band conduction. This is probably because that the conduction at low temperatures is dominated by native crystallographic characteristics such as grain boundaries.

Figure 2 shows the low temperature (24 K) photoluminescence (PL) spectra of the annealed samples. The PL intensity decreases with the annealing temperature from 600 to 900 °C but in tern increases for 1000 °C, showing also no heavy degradation with generation of optical defects for the high temperature annealing. The change in the spectral shape may involve useful

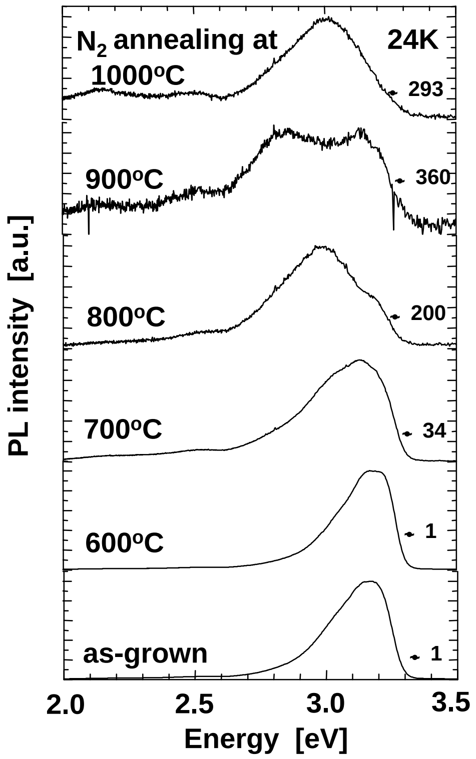

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Fig. 2 24 K PL spectra of GaN:Mg samples subjected to different dehydrogenation (N_2 annealing temperature.

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information on the phenomena occurred by the annealing, but the analysis has not been performed at present.

Rehydrogenation

Hydrogenation of active Mg acceptors in low resistive p-type GaN has been known to result in passivation of the acceptors and high resistivity [4-6]. In order to investigate the hydrogenation processes in more detail, which is also helpful for understanding the dehydrogenation processes, in this work the GaN:Mg samples subjected to dehydrogenation by annealing in N_2 atmosphere have been then annealed in H_2 atmosphere. The hydrogenation for each sample was done at 700 °C for 20 min.

Figure 3 summarizes the variation of hole concentration at RT against the dehydrogenation (previous N_2 annealing) temperature. The hydrogenation results in reduction of hole concentrations due to hydrogen passivation of acceptors. For the samples experienced the dehydrogenation by the N_2 annealing at 700-900 °C, as the N_2 annealing temperature is higher, more incomplete hydrogenation or passivation seems to result by the H_2 annealing. This phenomenon can easily be attributed to that more dehydrogenation has been proceeded in the sample subjected to N_2 annealing at higher temperatures. However, for the sample subjected to dehydrogenation at 1000 °C, only incomplete hydrogenation results compared to what we can expect from the behavior of those dehydrogenated at 700-900°C. The hole concentration of this sample was about 1×10^{17} cm^{-3}, which was similar to that dehydrogenated at 700 °C. After the hydrogenation, the hole concentration is still 4×10^{15} cm^{-3}, which is much higher that that of the latter, 3×10^{12} cm^{-3}. One of the possible interpretations for this phenomenon is that the hydrogen dominantly passivated the defects which had been generated by the thermal damage during the N_2 annealing at 1100 °C and compensated the Mg acceptors.

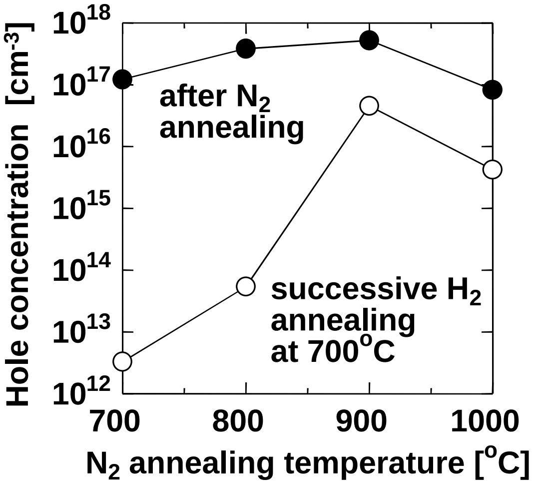

Fig. 3 Variation of hole concentration at RT after dehydrogenation (N_2 annealing) and successive hydrogenation (H_2 annealing) against the dehydrogenation temperature. The hydrogenation was done at the same condition, 700 °C and 20 min.

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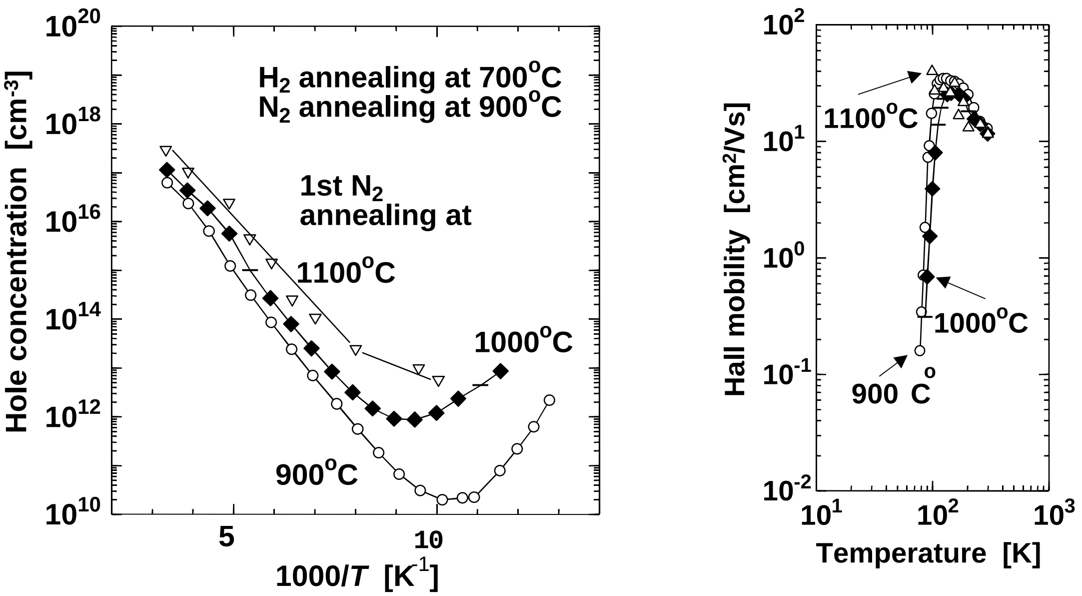

Fig. 4 Temperature dependence of hole concentration and hole Hall mobility of GaN:Mg samples experienced dehydrogenation, hydrogenation, and re-dehydrogenation, successively. The 1st dehydrogenation temperatures are shown as a parameter and the succesive hydrogenation and re-dehydrogenation were done at 700 °C and 900 °C, respectively.

Re-Dehydrogenation

For three samples which had been subjected to dehydrogenation at 900, 1000, and 1100 °C and then hydrogenation at 700 °C, the annealing was again done in N_2 atmosphere for re-dehydrogenation. In this experiment, the annealing temperature and time was fixed at 900 °C and 20 min, respectively, where from Fig. 1 the maximum dehydrogenation was expected.

The temperature dependence of the hole concentration and hole Hall mobility is shown in Fig. 4. This re-dehydrogenation process again activates Mg acceptors in GaN and results in p-type conductivity. It should be noted that the sample experienced the previous dehydrogenation (1st N_2 annealing) at 1100 °C showed the higher hole concentration and the higher Hall mobility compared to those at 900 or 1000 °C. The maximum mobility seems to be about 40 cm^2/Vs at 100K, which is even higher than all samples shown in Fig. 1. This again evidenced that any compensation centers generated in GaN:Mg with annealing in N_2 at 1100 °C do not seriously act as scattering or trapping centers and are almost inactivated by the successive thermal annealing treatments.

CONCLUSIONS

Successive dehydrogenation and hydrogenation of Mg acceptors in GaN have been done by N_2 and H_2 annealing, respectively, at different temperatures. For the dehydrogenation of as-grown GaN:Mg samples, the N_2 annealing at higher temperatures in the region below the growth temperature results in increase of both hole concentration and mobility, showing more activation of acceptors and reduction in unfavorable scattering centers associated with Mg-H bondings. When the N_2 annealing is higher than the growth temperature, the hole concentration reduces. However, the remarkable result is that the mobility gets higher. The GaN:Mg layer may be subjected to thermal damage which induces some defects and these defects compensate the acceptors, showing reduction in the hole concentration. But these defects cannot be severe scattering centers and inactivated by successive hydrogenation. Even if the GaN experiences thermal damage by high temperature annealing, it is not destructive and can be well recovered by appropriate hydrogenation/dehydrogenation treatments afterwards. The phenomena that thermally-induced defects do not severely affect the electrical properties is an another "stable nature of defects" in GaN crystals, similarly to the optical properties against dislocations.

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