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Optimum Rapid Thermal Activation for Mg-doped p-type GaN

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1. Introduction

GaN-based semiconductors have attracted extensive interest in applications for optical and electronic devices. Magnesium is known as a common acceptor impurity for p-type doping of GaN. However, since electrical activation of Mg is limited in MOCVD as-grown Mg-doped GaN, additional post-growth thermal annealing is generally used to enhance electrical activation of Mg [1]. Better understanding of thermal activation of Mg is necessary to improve the electrical properties of p-type GaN.

In this work, we have investigated the effects of rapid thermal annealing on electrical activation of Mg-doped p-type GaN. It was found that the electrical activation of Mg was critically determined by the annealing temperature and the resultant optimum annealing temperature was significantly influenced by the doping concentration of Mg.

2. Experimental

GaN samples were grown on a sapphire substrate by MOCVD. The doping concentration of Mg was varied from $1.25\text{x}10^{19}$ to $10\text{x}10^{19}\text{cm}^{-3}$. After growth, the rapid thermal annealing was performed in a flowing nitrogen atmosphere. All samples without encapsulation were placed on a Si wafer with face-up configuration. The temperature was monitored by a thermocouple on the Si wafer. Figure 1 shows the temperature profile used for our rapid thermal annealing. Heating rate was fixed at 100°C/s. Temperature dependence of the hole concentration was measured between 300 and 500K and then curve-fitted using the following equation.

$$\frac{p(p+N_D)}{N_A-N_D-p}=\frac{N_V}{g}\exp\left(-\frac{E_a}{kT}\right)$$

where N_A is the acceptor concentration, N_D is the donor concentration, E_a is the acceptor activation energy, p is the hole concentration, g is the acceptor degeneracy and is assumed to be 4, k is the Boltzmann constant, T is the absolute temperature, and N_V is the valence band effective density of states.

3. Results and Discussion

Figure 2 shows the hole concentration annealed at 700°C as a function of the annealing time. The Mg concentration was $5\text{x}10^{19}\text{cm}^{-3}$. It was found that the Mg activation was less sensitive to the annealing time and the maximum hole concentration achieved was $8\text{x}10^{17}\text{cm}^{-3}$ with an annealing time of 5s. Thus we fixed the annealing time for 5s in the following experiments. Figure 3 shows the hole concentration, estimated at RT, as a function of the annealing temperature. For all samples, significant Mg activation was recognized after annealing at more than 500°C. Results show that there is an optimum annealing temperature that leads to a maximum hole concentration. It is interesting to note that the optimum annealing temperature shifts to a lower temperature by increasing the Mg-doping concentration from $1.25\text{x}10^{19}$ to $10\text{x}10^{19}\text{cm}^{-3}$. The highest hole concentration was around $8\text{x}10^{17}\text{cm}^{-3}$. Figure 4 shows the hole mobility, estimated at RT, as a function of the annealing temperature. Appreciable decrease in the hole mobility observed in the temperature range up to 700°C is due to the increased ionized impurity scattering resulting from Mg thermal activation. At higher temperatures, the hole mobility is primarily determined by the doping concentration of Mg.

Figure 5 shows the hole concentration as a function of the measurement temperature for samples with [Mg] of $5\text{x}10^{19}\text{cm}^{-3}$ annealed at 650°C (optimum) and 850°C. The extracted acceptor activation energy and the donor concentration are summarized in Table 1, together with the related results for samples with different Mg concentrations. The acceptor activation energy estimated lies in the range of 120-135meV regardless of annealing temperature and doping concentration. It should be noted that the generated donor concentration after high temperature annealing at 850°C appreciably increases with increasing Mg doing concentration, strongly suggesting that the generated donor level is closely associated with Mg impurity. Considering nitrogen vacancy (V_N) as a most probable donor-type defect after high-temperature annealing [2], possible candidates for such donor complex involve Mg_i-V_N and Mg_{Ga}-V_N.

4. Conclusions

The electrical properties of Mg-doped p-type GaN treated with rapid thermal annealing have been investigated. It was found that the maximum RT hole concentration achieved after optimized rapid thermal annealing was around $8\text{x}10^{17}\text{cm}^{-3}$. Experimental results showed that the optimum annealing temperature shifted to lower temperature for samples with higher Mg-doping concentration and that high temperature annealing for heavily Mg-doped samples resulted in the generation of Mg-related donor complex defects.

References

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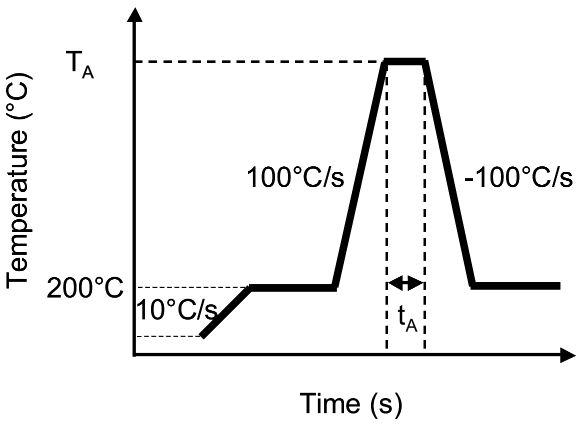

Fig.1 Temperature profile of rapid thermal annealing.

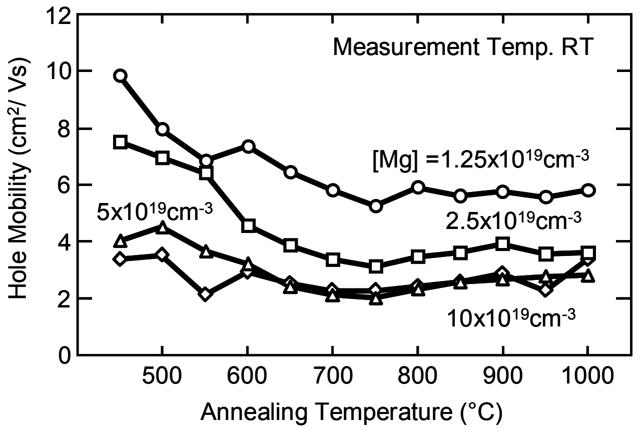

Fig.4 Hole mobility as a function of annealing temperature.

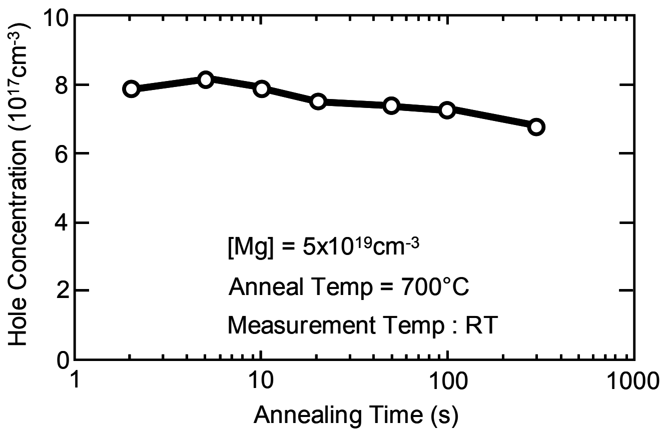

Fig.2 Hole concentration as a function of annealing time.

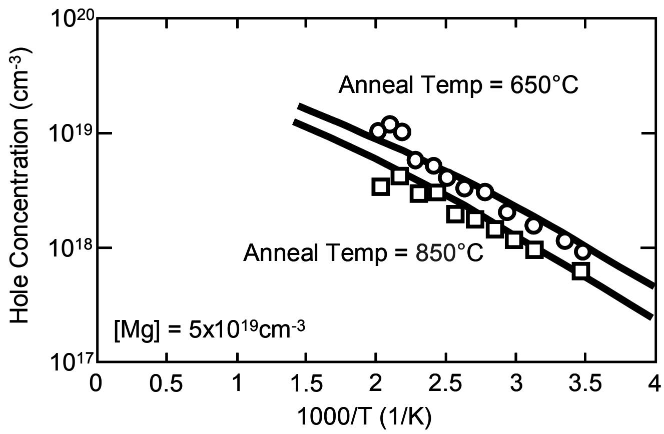

Fig.5 Hole concentration as a function of measurement temperature.

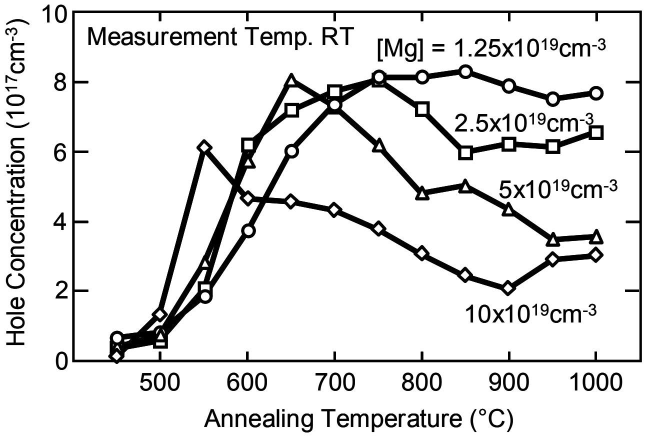

Fig.3 Hole concentration as a function of annealing temperature.

Table 1 Parameters for annealed Mg-doped GaN.

	[Mg] (cm^{-3})	Anneal Temp. (ºC)	N_D (cm^{-3})	N_D/N_A	E_a (meV)
A	$2.5x10^{19}$	750	$4x10^{18}$	0.07	125
B	$2.5x10^{19}$	850	$6x10^{18}$	0.12	125
C	$5x10^{19}$	650	$5x10^{18}$	0.07	130
D	$5x10^{19}$	850	$1x10^{19}$	0.20	120
E	$10x10^{19}$	550	$1.5x10^{19}$	0.15	135
F	$10x10^{19}$	850	$3x10^{19}$	0.33	120