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Thermal stability of GaAs tunnel junctions using carbon as a p-type dopant grown by metal-organic vapor phase epitaxy

Shu Gotoh*, Takashi Ueda, Hiroaki Kakinuma, Masahiro Akiyama

Semiconductor Technology Laboratory, Oki Electric Industry Co., Ltd. 550-5 Higashi-asakawa, Hachioji, Tokyo 193, Japan

Abstract

The annealing characteristics of GaAs tunnel junctions using carbon (C) as a p-type dopant were studied through current–voltage measurement and secondary-ion mass spectroscopy (SIMS). After annealing (750°C, 20 min), diodes fabricated with a C-doped p^+-GaAs/Si-doped n^+-GaAs tunnel junction showed an excellent tunnel peak current density (J_P) of 114 mA/cm^2, which is a larger value than ever reported for structures using Be or Zn as a p-type dopant. Degradation of J_P in diodes after annealing was found to drastically improve when the tunnel junction was sandwiched between p- and n-AlGaAs layers. The inserted n-AlGaAs layer was more effective in suppressing J_P degradation than the p-AlGaAs layer. SIMS results revealed that Si diffusion, which causes J_P degradation, was suppressed at the interfaces of the p^+-GaAs/n^+-GaAs tunnel junction and the GaAs/AlGaAs heterojunction. An excellent J_P value of 1.7 A/cm^2 at 55 mV was obtained after annealing (750°C, 20 min) through structural optimization.

Keywords: Thermal stability; GaAs tunnel junctions; p-type dopant

1. Introduction

Monolithic tandem solar cells are essential to achieving high photovoltaic conversion efficiency. In fabricating such solar cells, it is very important to obtain thermally

* Corresponding author.

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stable tunnel junctions for inter-cell ohmic contact, because tunnel junction performance is limited by inter-diffusion of dopants during the growth of subsequent cell layers. Recently, carbon (C) has been attracting a great deal of interest as a p-type dopant for GaAs/AlGaAs material systems [1–3], due to its high solid solubility [4] and low diffusion coefficient [5] in comparison with commonly used p-type dopants such as Be, Zn, and Mg. Approaches to suppressing dopant diffusion have included the use of AlGaAs layers. Sugiura et al. reported that diodes with a Be-doped p^+-GaAs/Si-doped n^+-GaAs tunnel junction sandwiched between AlGaAs layers exhibited excellent tunnel peak current density (J_P) after annealing, since the AlGaAs layers acted as blocking layers against Be diffusion, which causes J_P degradation [6].

The purpose of this paper is to examine the annealing characteristics of GaAs tunnel junctions using carbon as a p-type dopant grown by metal-organic vapor-phase epitaxy (MOVPE). Diodes fabricated with a C-doped p^+-GaAs/Si-doped n^+-GaAs tunnel junction had excellent values of J_P even after severe annealing. It was also found that J_P degradation in the diodes could be drastically improved by sandwiching the tunnel junction between p- and n-AlGaAs layers. These results are discussed in relation to the behavior of C and Si diffusion as seen by secondary-ion mass spectroscopy (SIMS).

2. Experimental

The growth system used in the present study was a low-pressure MOVPE system with a horizontal reactor. The growth pressure was 100 Torr. The source materials were trimethylgallium, trimethylaluminum and 100% AsH_3. Disilane and CBr_4 were used as the n- and p-type doping sources, respectively. Hydrogen was used as the carrier gas and the total flow rate was 7.0 slm.

In order to investigate the effects of inserting n- and p-AlGaAs layers, samples were fabricated with the structures shown in Table 1. Sample (a), which consisted of a p^+-GaAs/n^+-GaAs tunnel junction sandwiched between 1000 Å thick p- and n-$Al_{0.3}Ga_{0.7}As$ layers, was grown on a (0 0 1) n^+-GaAs substrate. Sample (b) had a standard structure without the n- and p-AlGaAs layers. Meanwhile, the structure of sample (c) had no n-AlGaAs layer, and the structure of sample (d) had no p-AlGaAs layer. The n-GaAs and n-AlGaAs layers were grown at 720°C, while the other layers were grown at 620°C. Annealing was performed in the MOVPE reactor in an AsH_3 ambient atmosphere at 700–750°C for 20 min. For electrical measurements, a Ti/Pt/Au (AuGe/Ni/Au) alloy was evaporated on the p^+-top (n^+-back) GaAs layers, and 180 μm diameter mesas were fabricated by wet chemical etching.

Fig. 1a and Fig. 1b show the two types of samples used for SIMS analysis. One had a structure with five GaAs layers; a Si-doped GaAs layer, a Si- and C-doped GaAs layer, and a C-doped GaAs layer sandwiched between undoped GaAs layers (Fig. 1a). The thickness of each layer was 1000 Å, and all layers were grown at a temperature of 620°C. The other sample had the same structure as that shown in Table 1a, with each layer having a thickness of 1000 Å (Fig. 1b). Annealing was performed in the MOVPE reactor in an AsH_3 ambient atmosphere at 750°C for 20 min.

Table 1
Sample structures of the fabricated tunnel diodes

Layer	Carrier concentration (cm^{-3})	(a)	(b) Standard Thickness (Å)	(c)	(d)
p^+-GaAs	8.0×10^{18}	3000	3000	3000	3000
p-AlGaAs	2.0×10^{19}	1000	–	1000	–
p^+-GaAs	1.5×10^{19}	100 or 200	1200	200	1200
n^+-GaAs	7.5×10^{18}	100 or 200	200	200	200
n-AlGaAs	3.0×10^{18}	1000	–	–	1000
n-GaAs	3.0×10^{18}	2000	3000	3000	2000
n^+-GaAs substrate					

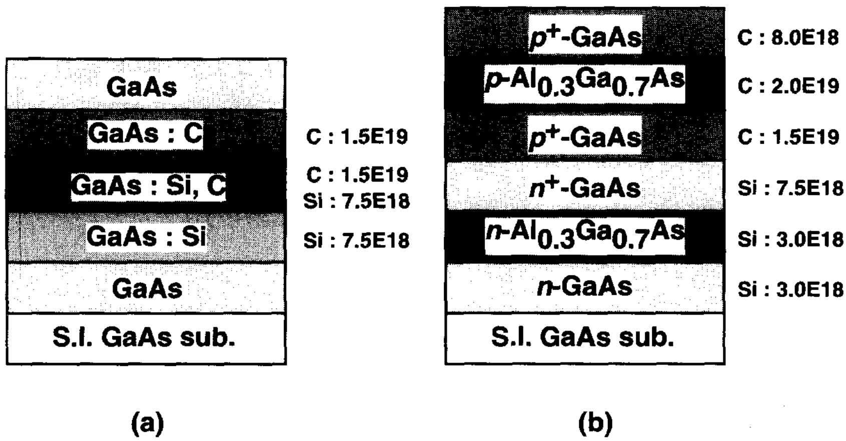


Fig. 1. Sample structures for SIMS analysis. (a) A structure with five GaAs layers. A Si-doped GaAs layer, a Si- and C-doped GaAs layer, and a C-doped GaAs layer are sandwiched between undoped GaAs layers. (b) A structure the same as the tunnel diode fabricated with the p- and n-AlGaAs layers. The thickness of each layer is 1000 Å.

The fabricated samples were characterized by SIMS (Phi 6600) using a 3.0 kV Cs^+ sputtering beam. Calibration standards were used to determine dopant concentrations; depth scales were established by profilometer measurement of the SIMS-produced craters and constant sputter rates were assumed.

3. Results and discussion

3.1. Annealing properties of the fabricated tunnel diodes

Fig. 2 shows the current–voltage characteristics obtained from the diode with a standard structure (Table 1b) before and after annealing (700°C or 750°C, 20 min).

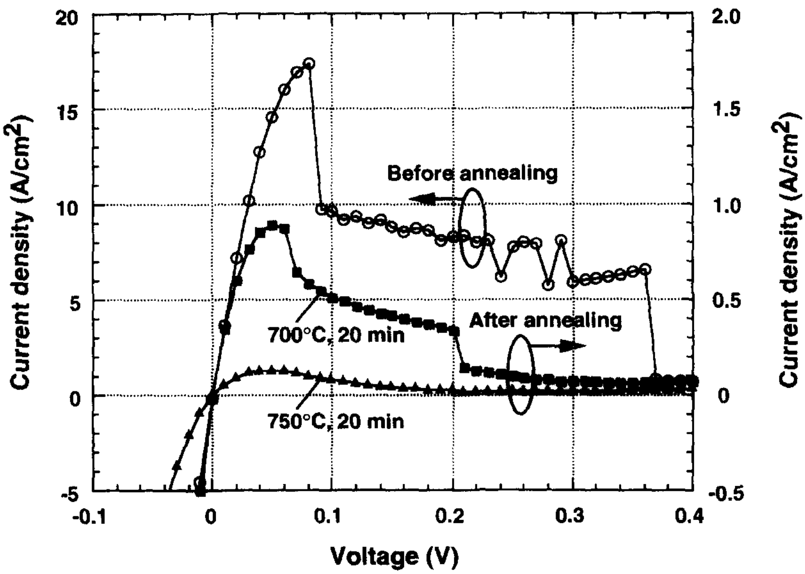


Fig. 2. Current-voltage characteristics obtained from a diode with a standard structure before and after annealing (700°C or 750°C, 20 min).

The diode exhibited a J_P value of 17 A/cm^2 before annealing, while J_P decreased as the annealing temperature increased. However, the value of J_P was 114 mA/cm^2 even after severe annealing at 750 for 20 min, which is a larger value than has ever been reported for structures using Be or Zn as a p-type dopant. This indicates that carbon provides excellent thermal stability in tunnel junctions.

Next, we investigated the effect of n- and p-AlGaAs layer insertion. Fig. 3 shows the dependence of tunnel peak current density on the reciprocal of annealing temperature for the fabricated tunnel diodes. The data for the as-grown samples, which correspond to a temperature of 620°C, are also inserted into Fig. 3. The as-grown samples all had nearly the same value of J_P, about 20 A/cm^2 at 80 mV, indicating that the insertion of p- and n-AlGaAs layers is not effective in improving J_P before annealing.

As Fig. 3 shows, the degradation behavior of J_P for the sample with a p-AlGaAs layer only (Table 1c) was found to be similar to that for the standard structure sample (without the n- and p-AlGaAs layers; Table 1b). In contrast, it should be noted that all samples with a n-AlGaAs layer (Table 1a Table 1d) exhibited excellent tunnel peak current density even after annealing at 750°C for 20 min. These results indicate that the n-AlGaAs layer is more effective than the p-AlGaAs layer in suppressing J_P degradation.

The dependence of tunnel peak current density on the thickness of the p^+- and n^+-GaAs layers for samples with both p- and n-AlGaAs layers was then investigated. An excellent tunnel peak current density of 1.7 A/cm^2 at 55 mV was obtained after

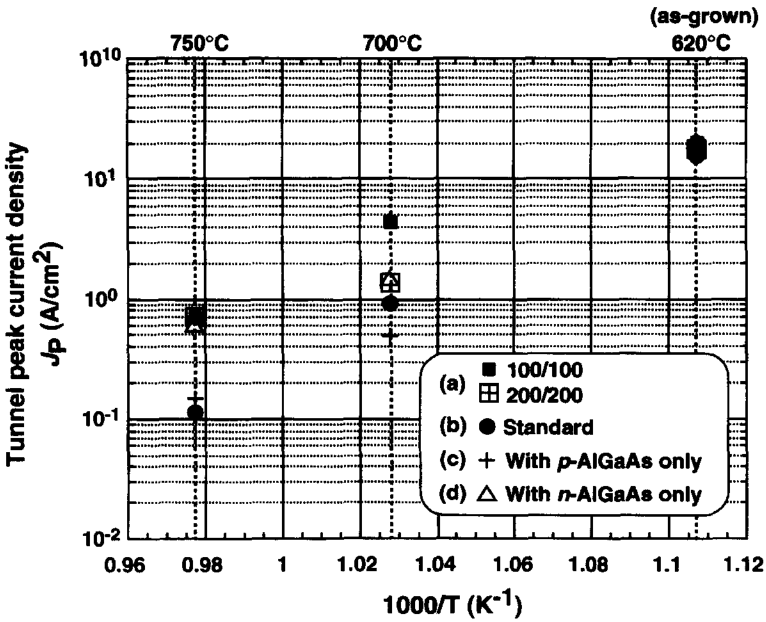


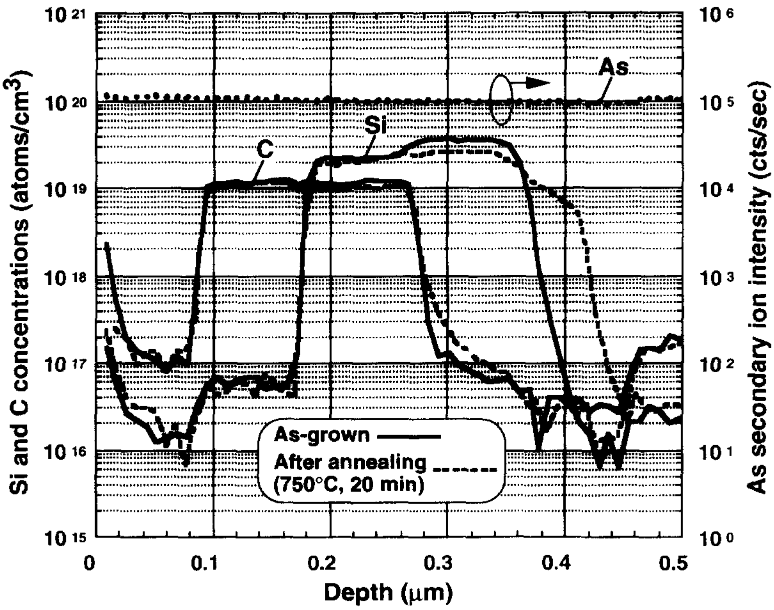
Fig. 3. Dependence of the tunnel peak current density on the reciprocal of annealing temperature for the fabricated tunnel diodes.

annealing (750°C, 20 min) when the thickness of the p^+-GaAs layer was selected at 100 Å and that of the n^+-GaAs layer at 200 Å.

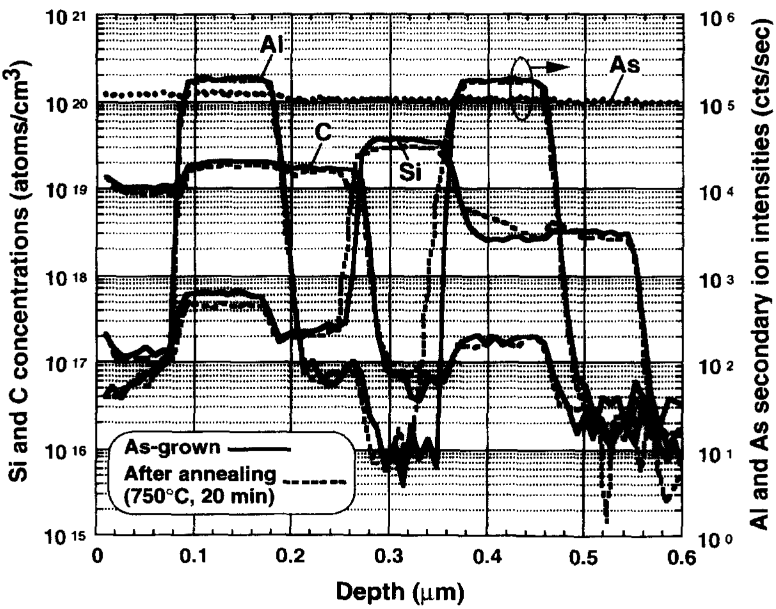
3.2. SIMS analysis

Fig. 4a shows SIMS depth profiles of the carbon and silicon in the GaAs for the sample in Fig. 1a. The solid lines are for an as-grown sample, while the dashed lines are for a sample after annealing (750°C, 20 min). As Fig. 4(a) shows, the silicon diffused into the undoped region to approximately 500 Å. The carbon profile, however, is almost the same before and after annealing, indicating that there is very little carbon diffusion into GaAs even at high doping levels of 1.5×10^{19} cm^{-3}.

Fig. 4b shows a SIMS depth profile for the sample in Fig. 1b. The solid lines are for an as-grown sample, while the dashed lines are for a sample after annealing (750°C, 20 min). Fig. 4b shows that the behavior of Si diffusion differed from that seen in Fig. 4a in two respects: (1) Si diffusion into the C-doped p^+-GaAs is estimated to have been less than 100 Å at the interface of the p^+-GaAs/n^+-GaAs tunnel junction, which is one-fifth of that into the undoped GaAs seen in Fig. 4a. This indicates that the C-doped GaAs acted as a blocking layer against Si diffusion. (2) The Si profile remains abrupt before and after annealing at the interface of the n^+-GaAs/n-AlGaAs heterojunction; that is, there was less Si diffusion into the n-AlGaAs than into the undoped


Si and C concentrations (atoms/cm3)
As secondary ion intensity (cts/sec)
Depth (μm)
As
Si
C
As-grown
After annealing
(750°C, 20 min)

(a)


Si and C concentrations (atoms/cm3)
Al and As secondary ion intensities (cts/sec)
Depth (μm)
Al
As
C
Si
As-grown
After annealing
(750°C, 20 min)

(b)

GaAs seen in Fig. 4a. Satsuta et al. have reported that the diffusion coefficient of Si in GaAs is less than half of that in AlGaAs [7]. Thus, the GaAs/AlGaAs interface can be said to block the diffusion of Si from GaAs into AlGaAs. On the other hand the carbon profile is almost the same in both GaAs and AlGaAs before and after annealing.

From the SIMS results, the annealing behavior of J_P can be interpreted as follows. The fabricated tunnel diode exhibited excellent tunnel peak current density after severe annealing (750°C, 20 min), even without the AlGaAs layers. This is because (1) there is very little carbon diffusion in GaAs even at high doping levels of $1.5 \times 10^{19}\ cm^{-3}$ and (2) the C-doped GaAs acts as a blocking layer against Si diffusion, which causes J_P degradation. It was also found that the degradation of J_P in diodes after annealing could be drastically improved by sandwiching the tunnel junction between p- and n-AlGaAs layers. The inserted n-AlGaAs layer was more effective in suppressing J_P degradation than the p-AlGaAs layer. These results can be explained by a third reason in addition to reasons (1) and (2); the GaAs/AlGaAs interface blocks the diffusion of Si from GaAs to AlGaAs.

4. Conclusions

The annealing characteristics of GaAs tunnel junctions using carbon as a p-type dopant were studied. Diodes fabricated with a C-doped p^+-GaAs/Si-doped n^+-GaAs tunnel junction showed an excellent tunnel peak current density of 114 mA/cm^2 after annealing (750°C, 20 min), which is a larger value than ever reported for structures using Be or Zn as a p-type dopant. It was also found that J_P degradation in the diodes after annealing drastically improved when the tunnel junction was sandwiched between p- and n-AlGaAs layers. The inserted n-AlGaAs layer was more effective in suppressing J_P degradation than the p-AlGaAs layer. SIMS results revealed that Si diffusion, which causes the J_P degradation, was suppressed at the interfaces of the p^+-GaAs/n^+-GaAs tunnel junction and the GaAs/AlGaAs heterojunction. Through structural optimization, an excellent J_P value of 1.7 A/cm^2 at 55 mV was obtained after annealing (750°C, 20 min).

Acknowledgements

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Fig. 4. SIMS depth profiles of carbon and silicon for (a) the sample in Fig. 1a and (b) the sample in Fig. 1b. The solid lines are for as-grown samples, while the dashed lines are for samples after annealing at 750°C for 20 min.

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