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# Analysis of impurity diffusion from tunnel diodes and optimization for operation in tandem cells

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**Abstract**

The tunnel diode has been applied as an interconnector in monolithic devices such as tandem solar cells. However, thermal degradation due to impurity diffusion is often observed due to growth at above about 600°C. In this study, the impurity diffusion from highly doped tunnel junctions after annealing has been analyzed, and it has been suggested that carbon has the advantage of a low diffusion coefficient as the p-type impurities. Furthermore, the thermally stable double hetero (DH) structure GaAs tunnel diodes which have been proposed in our previous work have been optimized. The thermal degradation is greatly suppressed by using a DH-structure which consists of a GaAs tunnel diode sandwiched between $Al_xGa_{1-x}As$ layers, and as a result, a higher tunnel peak current density can be achieved by optimizing the impurity concentration and DH composition.

*Keywords:* Tunnel diode; Impurity diffusion; Tandem solar cell

## 1. Introduction

The tunnel diode has been applied as an interconnector in monolithic devices such as tandem solar cells which have a predicted conversion efficiency of about 35%. One of the major problems in achieving high-efficiency and stable tandem solar cells is thermal degradation of the tunnel junction interconnection during fabrication. This degradation is caused by the impurity diffusion from highly doped tunnel junctions

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and results in a decrease in the tunnel peak current. Thus, high doping for obtaining a large peak current density is ineffective for GaAs tunnel diodes when they are annealed above about 600°C. This temperature is too low to grow high-quality AlGaAs layers in an AlGaAs/GaAs tandem solar cell, for instance.

For the interconnection of a tandem solar cell, the thickness of the tunnel junction should be less than 100 nm in order to minimize optical loss; the peak current density after annealing at 700°C should be greater than the short-circuit density (about 20 mA/cm$^2$ at 1-sun for an AlGaAs/GaAs tandem solar cell) in order to minimize electrical loss.

In our previous work, we have found that the decrease in the tunnel peak current due to annealing is greatly suppressed by using a double hetero (DH) structure GaAs tunnel diode [1]. In order to apply this thermally stable tunnel diode to multi-junction solar cells, it is necessary to optimize the diode structure.

The purpose of this study is to analyze the impurity diffusion from highly doped tunnel junctions after annealing at elevated temperatures and to optimize thermally stable tunnel diodes.

## 2. Experimental

The conventional and the DH structure GaAs tunnel diodes were grown on (1 0 0)GaAs substrates by MBE and MOCVD. Si was used as an n-type dopant, and Be, Zn and C were compared as p-type dopants. The doping concentration $N_A$ is $1.9 \times 10^{19}$ cm$^{-3}$ for Be, $2.5 \times 10^{19}$ cm$^{-3}$ for Zn, and $2.5\text{–}4.0 \times 10^{19}$ cm$^{-3}$ for C, respectively, unless otherwise specified. The DH structure tunnel diode consists of a GaAs tunnel junction sandwiched between $Al_xGa_{1-x}As$ layers. The tunnel diodes were annealed in the temperature range 550–750°C for 2 h in the MBE or MOCVD chamber. $I$–$V$ measurements of as-grown and annealed tunnel diodes were carried out.

From the changes in the tunnel peak current densities $J_p$ before and after annealing, the diffusion coefficients of p-type impurities were determined. First, the dependence of the annealing temperature and impurity concentration were investigated with the conventional tunnel diodes. Subsequently, the effect of DH tunnel diodes upon the diffusion coefficient of the dopants was analyzed.

## 3. Results and discussion

$J_p$ is a function of the space-charge region width $W$. Fig. 1 shows the $W$ dependence of $J_p$ for the as-grown tunnel diode. In this figure, $W$ is calculated from the impurity concentrations $N_A$, and $N_D$. $J_p$ is expressed by the following equation in our experiments

$$J_p = 7.26 \times 10^8 \exp(-1 \times 10^7\ W(\mathrm{cm}))(\mathrm{A/cm^2})\,. \qquad (1)$$

From Eq. (1), it is understood that the thermal degradation of $J_p$ is caused by the increase of $W$ as a result of the impurity diffusion. In our previous work, it has been

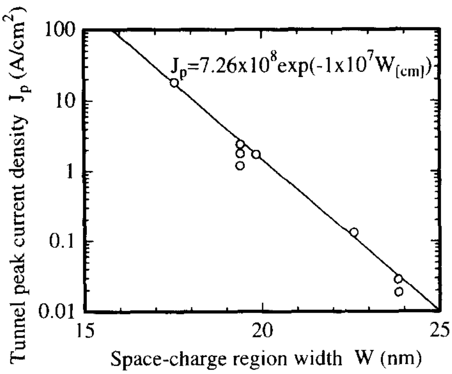


Fig. 1. The space-charge region width dependence of the tunnel current density for the as-grown tunnel diode.

confirmed that the diffusion of n-type impurities can be negligible. Therefore, the equation for the diffusion coefficients $D$ of p-type impurities can be derived from Eq. (1), as follows [2]:

$$D = -\ln\left(\frac{J_p(t)}{J_{p0}}\right)\frac{W}{1\times10^7 t}\left(1+\frac{N_D}{N_A}+\frac{\phi}{kT}\right)^{-1}\ (\mathrm{cm^2/s}), \tag{2}$$

where $J_{p0}$, $J_p(t)$ are $J_p$ values before and after annealing, respectively, and $\phi$ is the barrier potential at the junction.

The annealing temperature dependence of $D$ for Be, Zn and C impurities has been determined from tunnel diode degradation according to Eq. (2), as shown in Fig. 2. The doping concentration $N_A$ is $1.9\times10^{19}$ cm$^{-3}$ for Be, $2.5\times10^{19}$ cm$^{-3}$ for Zn, and 2.5–$4.0\times10^{19}$ cm$^{-3}$ for C, respectively. The obtained values of $D$ for Be show quite good agreement with previous results [3]. The relative magnitude of $D$ for the different dopants is $D_{Be} > D_{Zn} > D_C$. Therefore, C is the most promising candidates for the p-type impurities of thermally stable tunnel diodes. The temperature dependence is expressed by

$$D_{Be} = 1.7\times10^{-8}\exp\left(-\frac{1.44_{(eV)}}{kT}\right)(\mathrm{cm^2/s}), \tag{3}$$

$$D_C = 3.0\times10^{-10}\exp\left(-\frac{1.27_{(eV)}}{kT}\right)(\mathrm{cm^2/s}). \tag{4}$$

Fig. 3 shows the $N_A$ dependence of $D$ for Be impurities at an annealing temperature of 630°C. The diffusion coefficient $D$ increases with impurity concentration, and it is expressed by

$$D_{Be} = 1\times10^{-29}(N_A)^{0.677}\ (\mathrm{cm^2/s}). \tag{5}$$

Double hetero DH structure (Al composition) effects on the lowering of the diffusion coefficient of Be and C have also been determined from degradation of $J_p$ of

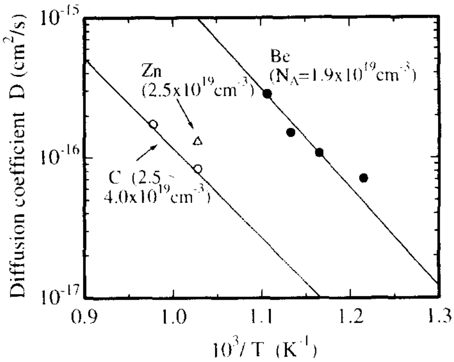


Fig. 2. Annealing temperature dependence of the diffusion coefficients for p-type impurities.

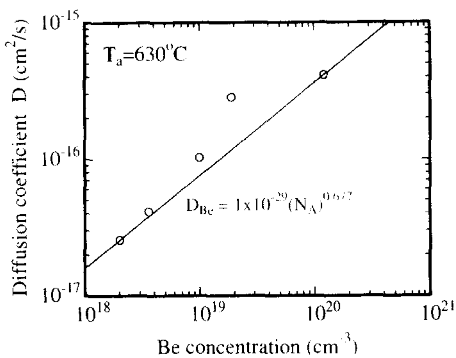


Fig. 3. Impurity concentration $N_A$ dependence of the diffusion coefficients.

GaAs tunnel diodes, as shown in Fig. 4. The larger Al composition is found to be more effective in suppressing the impurity diffusion. It is speculated that the reduction in $D$ is attributed to the strain induced by the difference of lattice constants between the GaAs and the AlGaAs layers. However, the exact explanation is not clear. The average rate of change of $D$ with Al composition, $x$, is expressed by

$$D \propto \exp(-x),\ 0 \leqslant x < 0.6\,, \tag{6}$$

$$D \propto \exp(-5x),\ 0.6 \leqslant x \leqslant 1.0\,. \tag{7}$$

On the basis of the above analysis, the $N_A$ dependence of $J_p$ after 2 h of annealing for the DH tunnel diodes was calculated by using Eqs. (1)–(7). $N_D$ was fixed at $1 \times 10^{19}\ cm^{-3}$. Fig. 5 shows the calculated results of $J_p$ for Be doped GaAs tunnel diodes, when the annealing temperature $T_a$ was fixed at 700°C and the Al composition $x$ of the DH layer was varied. From this figure, it is seen that the annealing characteristics are improved by using a DH structure tunnel diode, and as a result a higher tunnel peak current density can be achieved.

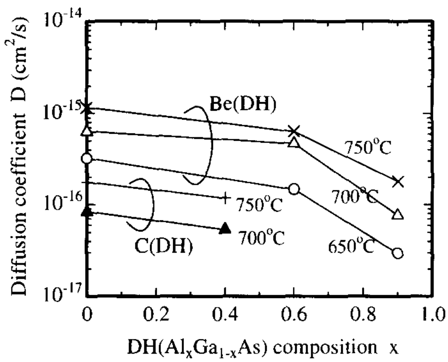


Fig. 4. DH structure (Al composition) effects on suppressing impurity diffusion.

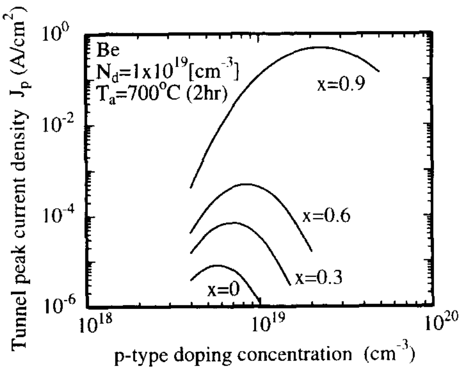


Fig. 5. Optimization of thermal-resistance of Be-doped GaAs tunnel diodes. (The Al composition $x$ of the DH layer is varied.)

Next, $x$ was fixed at 0.9, and $T_a$ was varied. The calculated results of $J_p$ are shown in Fig. 6. At this stage, the upper limit of growth temperature is about 700°C in the case of using Be as p-type impurities.

From this calculation, the basis for the design of thermally stable tunnel diodes has been acquired. Thermally stable GaAs tunnel junction with higher $J_p$ for use in multi-junction solar cells will be realized by selecting the impurity species and optimizing $N_A$, $N_D$ and DH composition.

## 4. Conclusions

The impurity diffusion from highly doped tunnel junctions after annealing was analyzed, and it was suggested that carbon had the advantage of a low-diffusion coefficient as the p-type impurities. Furthermore, the thermally stable double hetero DH structure GaAs tunnel diodes which were proposed in our previous work were

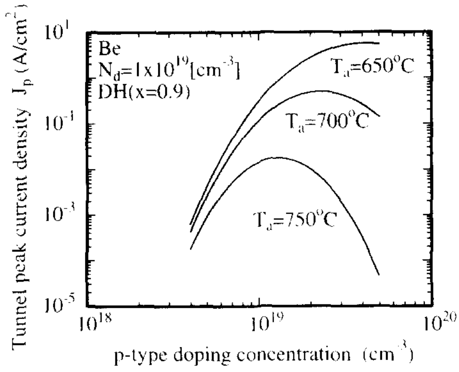


Fig. 6. Optimization of thermal-resistance of Be-doped GaAs tunnel diodes. (Annealing temperature $T_a$ is varied.)

optimized. The thermal degradation is greatly suppressed by using a DH structure, and as a result the higher tunnel peak current density can be achieved by optimizing impurity concentration and DH composition.

## References

[1] H. Sugiura, C. Amano, A. Yamamoto, M. Yamaguchi, Jpn. J. Appl. Phys. 27 (1988) 269.
[2] J.H. Buckingham, K.F. Hulme, J.R. Morgan, Solid-State Electron. 6 (1963) 233.
[3] E.F. Schubert, J.M. Kuo, R.F. Kopf, H.S. Luftman, L.C. Hopkins, N.J. Sauer, J. Appl. Phys. 67 (1990) 1969.