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Impurity Diffusion in InGaAs Esaki Tunnel Diodes of Varied Defect Densities

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SUMMARY We have fabricated and investigated InGaAs Esaki tunnel diodes, grown on GaAs or InP substrates, of varied defect densities. The tunnel diodes exhibit the same *I-V* characteristics in spite of the variation of defect density. Under the simple thermal annealing and forward current stress tests, the change in the valley current was not observed, indicating that defects were not increased. On the other hand, the reduction in the peak current due to the carbon diffusion was observed under both tests. The diffusion was enhanced by the stress current owing to the energy dissipation associated with the nonradiative electron-hole recombination. From the reduction rates of the peak current, we obtained the thermal and current-enhanced carbon diffusion constants in InGaAs, which are independent of defect density. Although thermal diffusion of carbon in InGaAs is comparable with that in GaAs, the current-induced enhancement of diffusion in InGaAs is extremely weaker than that in GaAs. The difference between activation energy of thermal and current-enhanced diffusion is 0.8 eV, which is independent of stress current density and close to InGaAs bandgap energy. This indicates that the current-enhanced diffusion is dominated by the energy dissipation associated with nonradiative band-to-band recombination. This enhancement mechanism well explains that the current-induced enhancement is independent of defect density and extremely weak. We also have found that the current-enhanced diffusion constant is approximately proportional to the square of current density, suggesting that the recombination in the depletion layer dominates the current-enhanced diffusion.
key words: *impurity diffusion, current-enhanced diffusion, defects, tunnel diodes, metamorphic devices, InGaAs, carbon*

1. Introduction

Metamorphic InGaAs devices grown on GaAs substrates have received considerable attention because of their performance and cost advantage. In spite of rather high-density crystalline defects, metamorphic high electron mobility transistors (MHEMTs) with comparable performance to lattice matched HEMTs grown on InP substrates have been realized [1], [2]. Another important advantage of the metamorphic devices is that we can choose almost any indium content in InGaAs, which is considered as a new device parameter [3]. The Indium content and temperature dependence of electron transport, saturation velocity and mobility, in the MHEMTs were elucidated [4]–[6]. In addition, metamorphic heterojunction bipolar transistors (MHBTs) are developed [7], [8]. In general, in order to realize reliable HBTs, the stable p^+-base layers are required. Carbon (C) doping for GaAs or InGaAs is considered to be stable for the p^+-base layers, in comparison with Be or Zn doping. In fact, Oh et al. have shown the small thermal and current-enhanced diffusion constants by analyzing reduction rates of the peak current of GaAs Esaki tunnel diodes [9]. They have also pointed out that the current-induced enhancement of the C diffusion is dominated by the energy dissipation associated with the nonradiative electron-hole recombination via energy levels in the bandgap. This enhancement mechanism for C-doped GaAs is same as that for Be-doped GaAs reported by Uematsu et al. [10]. On the other hand, there are no quantitative data of C diffusion in InGaAs. Moreover, InGaAs/InP MHBTs have rather high-density crystalline defects in the active layers, which may affect the current-induced enhancement of the diffusion as nonradiative recombination centers in the bandgap. It is therefore necessary to understand the C diffusion in InGaAs with defects.

The purpose of the present work is to investigate C diffusion in $In_{0.53}Ga_{0.47}As$ quantitatively, focusing on effects of defects and current-induced enhancement. We obtained $In_{0.53}Ga_{0.47}As$ Esaki tunnel diodes (TDs), grown on GaAs or InP substrates, of varied defect densities by employing varied buffer layers. The TDs exhibit the same *I-V* characteristics in spite of the variation of defect density. Simple thermal annealing and forward current stress tests were carried out. Although there was no change in the valley current, suggesting that the defects were not increased by both tests, the reduction in the peak current due to the C diffusion was observed. We obtained the thermal and current-enhanced C diffusion constants in InGaAs from the reduction rates of the peak current, which are independent of the defect density. Comparing the C diffusion behavior in GaAs, we discuss the enhancement mechanism of the diffusion in InGaAs.

2. Device Fabrication

The InGaAs Esaki tunnel diodes (TDs) were obtained by molecular beam epitaxy growth on semi-insulating (001)GaAs or (001)InP substrates. Figure 1 shows the layer structures of the four kinds of the TDs, which are (a) lattice-matched to the InP substrate, (b) with the graded InAlAs buffer on the GaAs substrate, (c) with the InP buffer on the GaAs substrate, and (d) with the 10 nm GaP interlayer between the active layer and the InP substrate. The tunnel junction consists of 300 nm Si-doped n^+-InGaAs with carrier density of $n = 1 \times 10^{19}\,\mathrm{cm}^{-3}$ and 50 nm C-doped p^+-InGaAs with $p = 4 \times 10^{19}\,\mathrm{cm}^{-3}$. From plain-view transmis-

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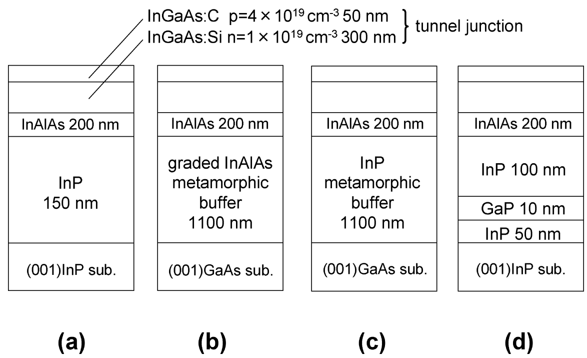

Fig. 1 The layer structures of the Esaki tunnel diodes.

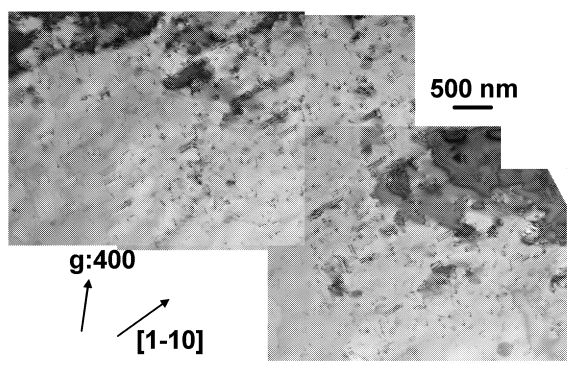

Fig. 2 Plain-view transmission electron microscope image of the active layer of TD(c).

Table 1 Threading dislocation density *D.D.* and number of dislocations N in the active layers of the tunnel diodes. The area of the diodes is 4×10^{-6} cm^2.

sample	(a)	(b)	(c)	(d)
D.D. [cm^{-2}]	$< 10^5$	$5{\times}10^7$	$6{\times}10^8$	$5{\times}10^9$
N	~ none	~ 10^2	~ 10^3	~ 10^4

sion electron microscope (TEM) measurements, the threading dislocation density in the active layer of the TDs was evaluated. As an example, Fig. 2 shows the TEM image of the active layer of the TD(c). Rather high-density defects (threading dislocations and stacking faults) were observed. The threading dislocation density in the active layer of the TDs is summarized in Table 1. The variation of the defect density is from 1×10^5 cm^{-2} to 5×10^9 cm^{-2}. The TDs with the area of $4{\times}10^{-6}$ cm^2 were fabricated by conventional wet etching and lift-off techniques. The number of dislocations in the TDs is also shown in Table 1. In order to suppress the electrode degradation, refractory metal (W/Ti/Pt/Au) nonalloy Ohmic electrodes were made on the p$^+$-layer and the n$^+$-layer [11].

3. Results and Discussions

The TDs show the peak current of ~ 8 kA/cm^2 and the valley current of ~ 1 kA/cm^2 at room temperature as shown in Fig. 3. The effects of the defects were not observed in the *I-V* characteristics. Using the TDs, simple thermal annealing and forward current stress tests have been carried out. The valley current did not change, indicating that the defects were not increased. On the other hand, we have observed the reduction in the peak current I_p, which is attributed to the impurity diffusion as in the case of GaAs Esaki tunnel diodes [9], [10]. Figure 4 shows the normalized peak current $I_p(t)/I_p(0)$ under simple thermal annealing (stress current $I_{str} = 0$ kA/cm^2) and $I_{str} = 25$ kA/cm^2 at ambient temperature $T_a = 275^\circ$C. We consider that, in this case, the reduction in I_p is dominated by the C diffusion into the n$^+$-layer since the doping level in the p$^+$-layer is higher than that in the n$^+$-layer.

In general, $I_p(t)$ is expressed by the formula

$$I_p = A \exp(-BW),$$

where A and B are constants, and W is the junction width. Assuming a diffusion constant of impurity D, W is approximately expressed as $W_0 + \sqrt{Dt}$, where W_0 is the initial junction width [12]. Thus, the average diffusion constant D_{ave} during a time interval 0-t is obtained by

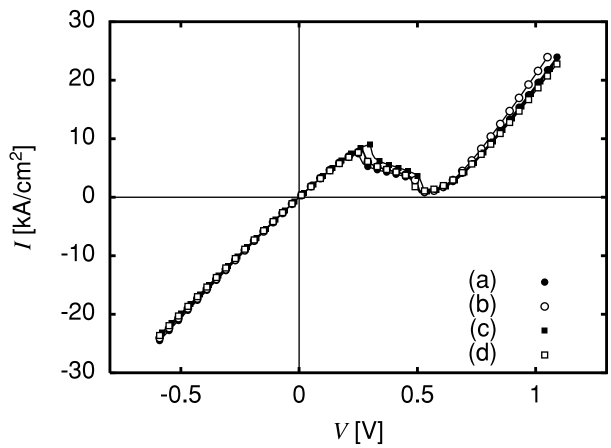

Fig. 3 Current-voltage characteristics of the TDs at room temperature.

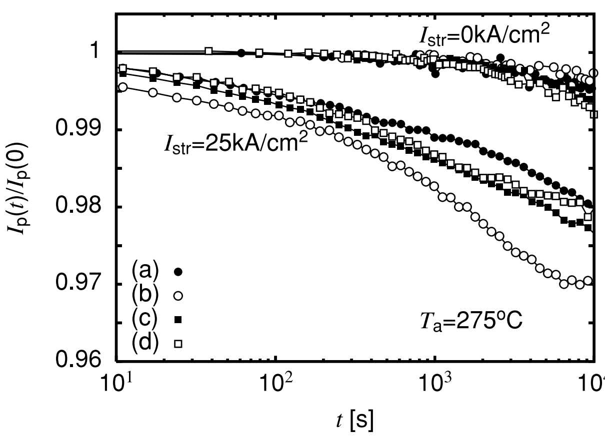

Fig. 4 Normalized peak current $I_p(t)/I_p(0)$ under simple thermal annealing (stress current $I_{str} = 0$ kA/cm^2) and $I_{str} = 25$ kA/cm^2 at ambient temperature $T_a = 275^\circ$C.

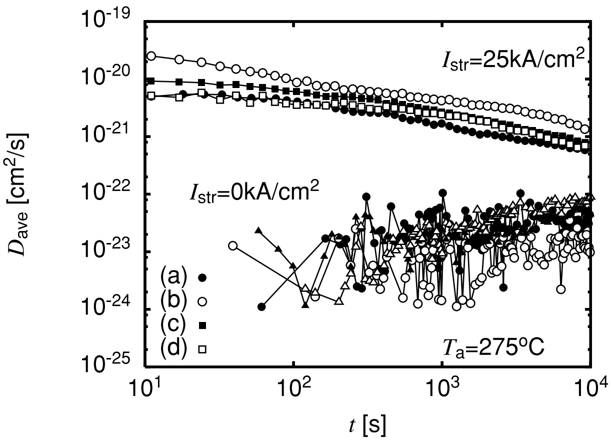

Fig. 5 Average diffusion constant D_{ave} of C in InGaAs obtained from $I_p(t)/I_p(0)$ under simple thermal annealing (stress current $I_{str} = 0\,kA/cm^2$) and $I_{str} = 25\,kA/cm^2$ at ambient temperature $T_a = 275°C$.

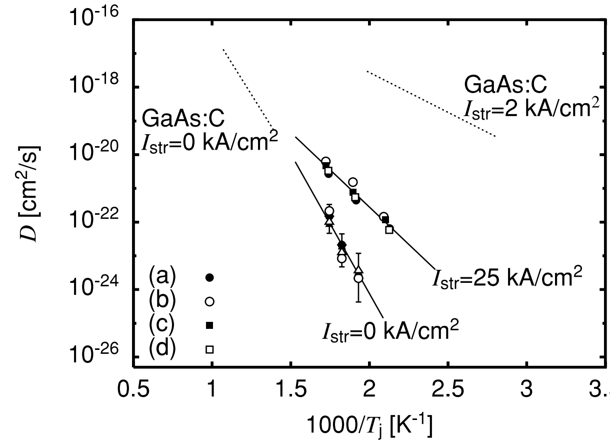

Fig. 7 Junction temperature T_j dependence of C diffusion constant $D = D_{ave}$ ($t = 300\,s$) in InGaAs under simple thermal annealing (stress current $I_{str} = 0\,kA/cm^2$) and $I_{str} = 25\,kA/cm^2$. For comparison, C diffusion constant in GaAs by Oh et al. [9] is also plotted.

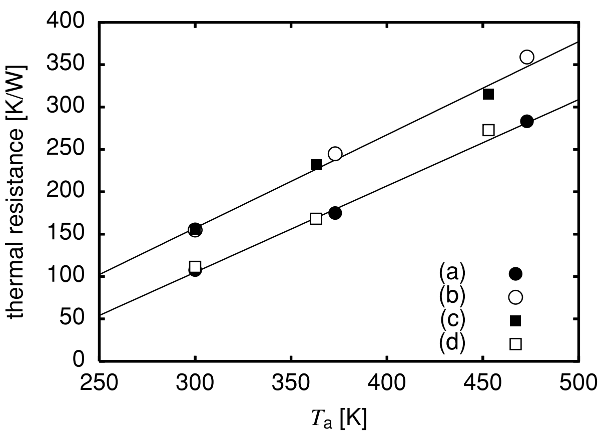

Fig. 6 Thermal resistance of the TDs as a function of ambient temperature T_a.

Table 2 D_0 and E_a which give the carbon diffusion constant $D = D_0 \exp(-E_a/kT)$ in InGaAs for thermal and current-enhanced diffusion. For comparison, the reported values in GaAs obtained by Oh et al. [9] are also shown. I_{str}: stress current. ΔE_a: the difference between activation energy of thermal and current-enhanced diffusion constants.

	I_{str} [kA/cm^2]	D_0 [cm^2/s]	E_a [eV]	ΔE_a [eV]
InGaAs:C	0	3.0×10^{-8}	1.7	0.8
	25	1.7×10^{-13}	0.9	
GaAs:C	0	1.1×10^{-9}	1.5	1.0
	2	1.5×10^{-13}	0.5	

$$D_{ave} = \{\ln(I_p(t)/I_p(0))\}^2 B^{-2} t^{-1}.$$

Figure 5 shows the D_{ave} of C obtained from the $I_p(t)/I_p(0)$ in Fig. 4. The C diffusion was enhanced by the stress current owing to the energy dissipation associated with the nonradiative electron-hole recombination. Although the difference in D_{ave} among the TDs is observed for the current stress test, it is responsible for the difference in substrates rather than the variation in the defect density. The D_{ave} of the TDs on GaAs substrates, TD(b) and (c), is larger than that of the TDs on InP substrates, TD(a) and (d). This observation suggests that the difference in D_{ave} is mainly attributed to the different junction temperature due to the different thermal resistance of the substrates and the buffer layers. Figure 6 shows ambient temperature dependence of thermal resistance of the TDs measured by conventional transit thermal response method [13]. The thermal resistances are mainly dominated by the thermal resistance of the substrates. We can determine junction temperature from the thermal resistance.

In Fig. 7, the C diffusion constant $D = D_{ave}(t = 300\,s)$ is plotted as a function of the inverse of the junction temperature T_j calculated by the measured thermal resistance. In the case of the thermal diffusion, the scatter in D_{ave} is severe. Therefore we plot logarithmic mean of $D_{ave}(100\,s < t < 1000\,s)$ and show the error bars representing standard deviation. We have observed no effects of the defects on both the thermal and current-enhanced diffusion. This indicates that the diffusion is hardly affected by the defects. For comparison, the C diffusion constants in GaAs, obtained by employing GaAs Esaki tunnel diodes [9], are also plotted. Although the thermal diffusion of C in InGaAs is found to be comparable with that in GaAs, the current-induced enhancement of the diffusion in InGaAs is extremely weaker than that in GaAs. At temperature of 275°C, the enhancement is a factor of $\sim 10^6$ in GaAs under the current stress of $2\,kA/cm^2$. On the other hand, the enhancement is a factor of $\sim 10^3$ in InGaAs, even under the strong current stress of $25\,kA/cm^2$. This suggests that the mechanism of the current-enhanced diffusion in InGaAs is different from that in GaAs.

Table 2 summarizes D_0 and E_a which give the C diffusion constant in InGaAs and GaAs $D = D_0 \exp(-E_a/kT)$

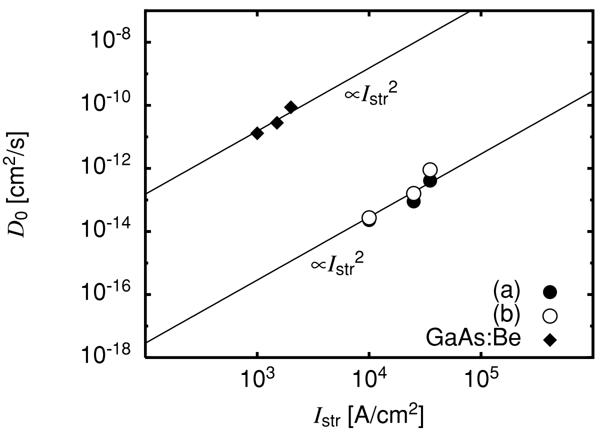

Fig. 8 Current stress I_{str} dependence of prefactor D_0 of C diffusion constant in InGaAs. For comparison, D_0 of Be diffusion constant in GaAs by Uematsu et al. [10] is also plotted.

for thermal and current-enhanced diffusion. We also show ΔE_a, the difference between the activation energy of thermal and current-enhanced diffusion constants, which is independent of stress current density and corresponds to the energy associated with the nonradiative electron-hole recombination. For the C diffusion in GaAs, the energy difference is 1.0 eV, which is smaller than the bandgap energy of GaAs, indicating that the recombination via energy level in the bandgap dominates the enhancement of diffusion. On the other hand, for the C diffusion in InGaAs, the energy difference is 0.8 eV, which is close to the bandgap energy of InGaAs. This indicates that the current-induced enhancement of diffusion is dominated by nonradiative band-to-band recombination. The recombination via energy level in the bandgap, with small energy dissipation, hardly affects the diffusion. As a consequence, the current-induced enhancement of the diffusion is independent of the defect density and extremely weak for InGaAs even with the high-density defects, which may act as recombination center.

We investigated I_{str} dependence of the diffusion constant. Although the activation energy E_a is independent of I_{str}, the prefactor D_0 depends on I_{str} as shown in Fig. 8 for the TD(a) and (b). In spite of the high-density defects, the D_0 of the TD(b) exhibits similar I_{str} dependence of TD(a). It seems that both diffusion constants are approximately proportional to $I_{str}{}^2$, suggesting that current-enhanced diffusion is dominated by the recombination in the depletion layer. Although data concerning I_{str} dependence of diffusion constant for C-doped GaAs have not been reported, the data for Be-doped GaAs have been given by Uematsu et al. In Fig. 8, we show the same I_{str} dependence for Be-doped GaAs, which has not been pointed out in [10].

4. Conclusion

We have fabricated and investigated InGaAs Esaki tunnel diodes of varied defect densities. Under the simple thermal annealing and forward current stress tests, we have observed the reduction in the peak current due to the C diffusion. The thermal and current-enhanced C diffusion constants in InGaAs were obtained from the reduction rates of the peak current, which are independent of the defect density. Although the thermal diffusion in InGaAs is comparable with that in GaAs, the current-induced enhancement of the diffusion in InGaAs is extremely weaker than that in GaAs. The difference between the activation energy of thermal and current-enhanced diffusion constants is close to the bandgap energy of InGaAs. This indicates that the current-enhanced diffusion is dominated by the energy dissipation associated with the nonradiative band-to-band recombination. This enhancement mechanism well explains that the current-induced enhancement is independent of defect density and extremely weak. Therefore, C-doped p$^+$-InGaAs layer is expected to be stable even for metamorphic HBTs with high-density defects.

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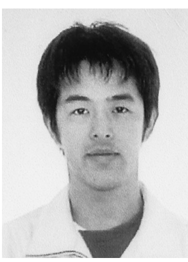

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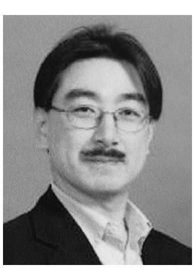

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