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Observation of Deep Donor Center Related Tunneling Peak in the $Al_xGa_{1-x}As/AlAs/Al_xGa_{1-x}As/AlAs/Al_xGa_{1-x}As(0.40 \leq x \leq 0.50)$ Resonant Tunneling Diodes

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Deep donor (DX) center related tunneling peak in the $Al_xGa_{1x}As$/ AlAs/ $Al_xGa_{1x}As$/ AlAs/ $Al_xGa_{1x}As$ ($0.4 \leq x \leq 0.5$) resonant tunneling diodes is observed fro the first time. It was found that this DX center related tunneling peak initially appeared at higher voltage when the laser was turned on, and it gradually shifted to lower voltage over several minutes. This peak eventually merged into the lower voltage tunneling peak at temperature below 76 K, but stayed apart at higher temperature. This unusual behavior is attributed to the simultaneous existence of the impurity band formed by the metastable DX states associated with X band (DX(X)) and their isolated double charged states (DX(X)). This tunneling peak is not observed when the AlAs mole fraction x is reduced to 0.35.

1. Introduction

Appreciable interest has been paid in recent years to the origin and behavior of the deep donor (DX) center in $Al_xGa_{1-x}As$.[1)-10)] The structure of the DX center, first proposed as an As vacancy and donor complex,[2),4)] is now considered to be a substitutional donor itself [5)-10)] with different degree of lattice relaxation. In this paper, we report the first observation of DX center related tunneling behavior in the $Al_xGa_{1-x}As$/ AlAs/ $Al_xGa_{1-x}As$/ AlAs/ $Al_xGa_{1-x}As$ resonant tunneling diode (RTD) which uses the $Al_xGa_{1-x}As$ ($0.40 \leq x \leq 0.50$) as the electrodes.

2. Experiment

The samples were grown in a VG MKII Molecular Beam Epitaxy (MBE) system on (100) n^+ GaAs substrate at a growth temperature of 600°C. The device structure of RTDs is shown in Fig. 1. The aluminum compositions of the electrodes are x=0.35 (R428), 0.40 (R287), 0.45 (R288), and 0.50 (R429), respectively. At the measurement temperature of 77 K, the conduction band minimum is Γ band for x=0.35 and 0.40, but switches to X band for x=0.45, and 0.50, respectively. Growth is interrupted for 60 and 30 sec at the AlGaAs on AlAs and AlAs on AlGaAs surfaces, respectively, to create smoother interface. Devices were defined using conventional photolithography and etched with a solution $1H_2SO_4$:$1H_2O_2$:$24H_2O$. The mesas were circular dots with 130 μm in diameter. Ohmic contacts (Au-Ge-Ni) were thermally evaporated on both sides of the sample and then annealed at 390°C for 30 sec. The applied bias is positive on the top contact where the laser is incident and the laser intensity is 0.5 W/cm^2.

3. Results and Discussion

Fig. 2 shows the steady-state peak voltages as a function of temperature for R288 (x=0.45) under laser on at least for 10 minutes, only one peak appears at low temperature (< 76 K) which is probably due to the X band electrons in the $Al_xGa_{1-x}As$ electrodes tunneling through Γ band profile of the central resonant tunneling structure. For temperature beyond 76 K, three peaks are observed. The second one is probably the same as observed at lower temperature. The first one will be explained later. The third higher voltage peak possesses three

100 nm	GaAs:Si	$2 \times 10^{18} cm^{-3}$
200nm	GaAs:Si	$10^{18} cm^{-3}$
50nm grading layer(0→X)		$10^{18} cm^{-3}$
100nm	$Al_xGa_{1-x}As$:Si	$10^{18} cm^{-3}$
5nm	$Al_xGa_{1-x}As$	(u)
5nm	AlAs	(u)
5nm	$Al_xGa_{1-x}As$	(u)
5nm	AlAs	(u)
5nm	$Al_xGa_{1-x}As$	(u)
100nm	$Al_xGa_{1-x}As$:Si	$10^{18} cm^{-3}$
50nm grading layer(0→X)		$10^{18} cm^{-3}$
200nm	GaAs:Si	$10^{18} cm^{-3}$
Si-doped GaAs substrate		

Figure 1: The device structure of the $Al_xGa_{1-x}As$/ AlAs/$Al_xGa_{1-x}As$/ AlAs/ $Al_xGa_{1-x}As$ resonant tunneling diode.

unusual characteristics: first, it takes a few minutes to shift from much higher voltage to the stable one, this time response is a typical characteristic of DX center at this temperature; second, the peak voltage increases with increasing temperature under laser on condition even when the conductivity is still increasing (normal peak voltage should decrease like the low voltage peak). Third, when the peak shifts to lower voltage, its magnitude gradually increases but the total background current remains the same. Similar peaks were observed in R287 (x=0.40)[11] and R429 (x=0.50), but not in R428 (x=0.35).

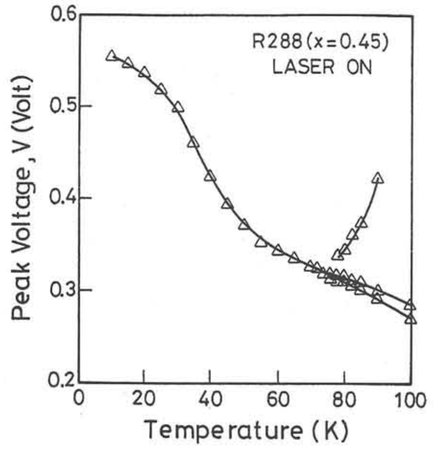

Figure 2: The tunneling peak voltages versus temperature for R288(x=0.45) measured under laser on at least for 10 minutes.

The transient behavior of the dI/dV versus V curves of RTD R288 (x=0.45) are shown in Figs. 3(a) and (b) as a function of the laser illumination time at (a) 60 and (b) 80 K, respectively. It is clear that the higher voltage peak takes 30 seconds to appear and gradually shifts down in voltage. It eventually merges with the lower voltage peak at 60 K, but stays apart at 80 K even after illumination time for 10 minutes. In addition, when the higher voltage peak shifts to lower voltage, its magnitude gradually increases but the total background current remains the same. Similar peaks were observed in x=0.40 and 0.50 samples, but not in x=0.35 sample.

This unusual tunneling peak can be explained by using the metastable DX state model.[7),9),12)] This metastable state is associated with X band minimum, designated as DX(X) and shallower than the DX state associated with L band (DX(L)). Electrons in the X band minimum can communicate directly with DX(X) state, but encounter a barrier when communicate with DX(L). Due to the high doping in the electrodes (10^{18} cm^{-3}), it is possible that after a prolong time illumination at low temperature, the electrons excited from DX(L) center but fell into the DX(X) state exceeds a critical value that the metastable DX(X) states form the impurity band.[13)] This explains why it takes 30 sec to observe the higher voltage peak at 60 K. With the higher and higher metastable state concentration, the impurity band is formed and its width widens which causes the peak to grow and shift to the lower voltage. Finally, the impurity band width widens so much that it merges with the conduction band and two voltage peaks merge into one. At temperature beyond 76 K, the conduction band (X band) electrons begin to communicate with the DX(L) centers so that part of the electrons are captured by DX(L) centers which reduces the metastable state DX(X) concentration and the impurity band no longer merges into the X band which results in two separate voltage peaks.

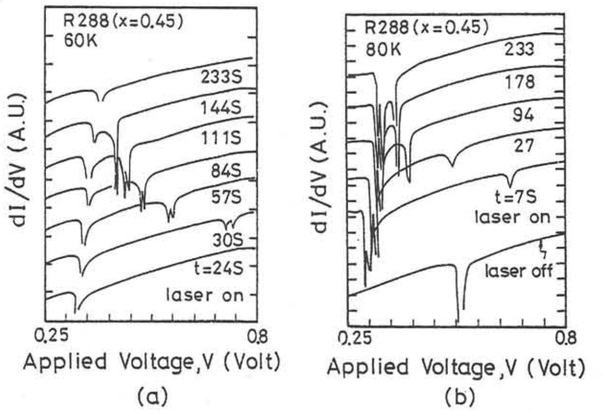

Figure 3: The dI/dV versus V curves of R288 (x=0.45) measured at (a) 60 and (b) 80 K, respectively, at different time after the laser was turned on.

Fig. 4 shows the I-V curves of R288 (x=0.45) at different temperature. The sample is illuminated by the laser at 8 K until two peaks appear and then the laser is turned off and the temperature is raised. It is found that the current level increases significantly with increasing temperature, and the two peaks merge together at 70 K. It is rather a peculiar behavior since at higher temperature, more electrons in the metastable DX(X) impurity band are ionized to the conduction band, the impurity band width should decrease and two tunneling peaks should separate farther apart which is contrary to what we observed. Furthermore, the total current increases appreciably indicating a large increase of conduction band electrons from certain impurity level which must be much shallower than DX(X) state. This level is attributed to the isolated doubly charged states ($DX^-(X)$).[12),14),15)] When the temperature increases, the $DX^-(X)$ state sends one electron to conduction band and the remaining center becomes the DX(X) metastable state so that the impurity band width increases and electron concentration in the X band also increases. Eventually, the two peaks are merged together.

Now the first tunneling peak shown in Fig. 2 may be explained. As shown in Fig. 4, the current increases quickly as temperature rises. This indicates that the carrier concentration in the conduction band also increases. Due to the biaxial compression stress of AlGaAs grown on GaAs, the X band of the electrode may split into lower energy X_t (parallel to interface) and higher energy X_ℓ (normal to interface) valleys. Therefore, at temperature above 76 K, the electrons start to populate the higher X_ℓ band. The first and second lower voltage peaks may be due to the X_ℓ and X_t band electrons tunneling through the Γ band profile.

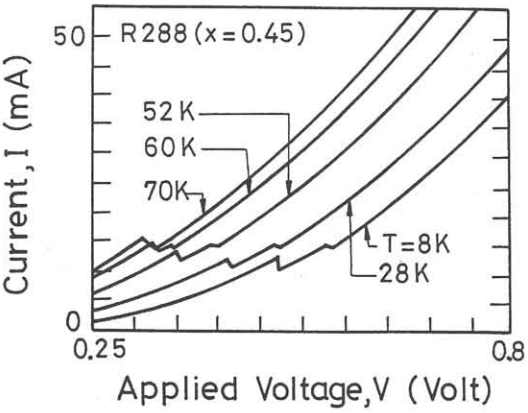

Figure 4: The I-V curves of R288 (x=0.45) at different temperature. The sample was illuminated by laser at 8 K until two peaks appeared and then the laser was turned off, the I-V curves were measured at 8, 28, 52, 60, and 70 K, respectively.

4. Conclusion

In summary, an unusual tunneling peak associated with metastable DX(X) centers was observed for the first time in $Al_xGa_{1-x}As$/ AlAs/ $Al_xGa_{1-x}As$/ AlAs/ $Al_xGa_{1-x}As$ RTDs for $x \geq 0.4$, but not for x=0.35. This behavior is attributed to the simultaneous existence of the metastable DX state associated with X band and its isolated double charged state ($DX^-(X)$).

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