DEGRADATION OF METAMORPHIC InGaAs ESAKI TUNNEL DIODES DUE TO ELECTRODE DIFFUSION AND IMPURITY INTERDIFFUSION

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Abstract

We have investigated degradation of metamorphic $In_{0.53}Ga_{0.47}As$ Esaki tunnel diodes. The degradation due to electrode diffusion and impurity interdiffusion is more prominent than that of lattice-matched $In_{0.53}Ga_{0.47}As$ Esaki tunnel diodes.

I. Introduction

Metamorphic InGaAs devices with high indium contents 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) have been developed[1], and the performance comparable to lattice matched HEMTs grown on InP substrates has been realized[2]. Another important advantage is that the metamorphic devices can be realized with almost any indium content, which is considered as a new device parameter in the device design[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 also being developed[7]. However, device degradation under operation is widely observed in bipolar devices, such as bipolar transistors, Esaki tunnel diodes, light emitting diodes, and laser diodes. Therefore, the problem of the reliability should be serious in the case of bipolar devices using metamorphic materials with the crystalline defects. In the present work, in order to study degradation of the metamorphic materials, we have fabricated and investigated metamorphic $In_{0.53}Ga_{0.47}As$ Esaki tunnel diodes on GaAs substrates. As a result, we have found faster degradation of the diodes than that of lattice-matched $In_{0.53}Ga_{0.47}As$ Esaki tunnel diodes on InP substrates, which is caused by electrode diffusion and impurity interdiffusion.

II. Device Fabrication

The metamorphic InGaAs Esaki tunnel diodes (MTDs) were obtained by molecular beam epitaxy growth on semi-insulating (001)GaAs substrates. On the graded InAlAs buffer layers to relax the lattice mismatch between GaAs and InGaAs, a tunnel junction consisting of 300 nm Si-doped n^+-InGaAs with carrier density of $n = 1 \times 10^{19}$ cm^{-3} and 50 nm C-doped p^+-InGaAs with $p = 4 \times 10^{19}$ cm^{-3} were grown. The lattice matched InGaAs Esaki tunnel diodes (LMTDs) on semi-insulating (001)InP substrates with the same tunnel junction were also obtained. The Indium contents of the InGaAs were confirmed by (004) and (115) X-ray diffraction measurements. By using plain-view transmission electron microscope measurements, the threading dislocation density in the active layer of the MTDs is evaluated to be $\sim 5 \times 10^7$ cm^{-2}, which is larger than that of the LMTDs by three orders of magnitude. Ti/Au or W/Ti/Pt/Au non-alloy Ohmic electrodes were made on the p^+-layer and the n^+-layer. Both the MTDs and the LMTDs show the peak current of ~ 8 kA/cm^2 and the valley current of ~ 1 kA/cm^2 at room temperature.

III. Degradation due to electrode diffusion

For the TDs with the Ti/Au electrodes, the degradation due to the electrode diffusion was observed. Using the TDs with the area of 2.7×10^{-6} cm^2, constant-current stress tests have been carried out in the forward direction. Figure 1 shows the peak and the valley current as a function of time, $I_p(t)$ and $I_v(t)$, under a constant current stress $I_{str} = 20$ kA/cm^2 at the ambient temperature T_a of 200 °C. The increase in I_p and I_v is observed. The lifetime t_{life}, defined by $I_v(t_{life}) = 2I_v(0)$, of the MTDs is shorter than that of the LMTDs by an order of magnitude. From the analysis of the degraded TDs, we found the p-electrode metal penetration into the tunnel junction. Moreover, we confirmed that t_{life} was proportional

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to the square of the p^+-layer thickness. Therefore, we concluded that the degradation was dominated by the Ti/Au p-electrode diffusion into the p^+-layer.

Figure 2 shows T_a dependence of t_{life} with the results of the simple thermal annealing test ($I_{str} = 0$ kA/cm^2). We found that the electrode diffusion in the MTDs is equivalent to that in the LMTDs in the case of the simple thermal annealing. On the other hand, the stress current enhances the electrode diffusion in the MTDs more severely than that in the LMTDs. A possible reason for the faster electrode diffusion in the MTDs is higher device temperature due to higher thermal resistance R_{th} of the MTDs. In order to estimate the device temperature, by employing the conventional transient thermal response method[8], R_{th} and its ambient temperature dependence were measured. Using the measured value of R_{th}, the device junction temperature T_j can be estimated. Figure 3 shows T_j dependence of t_{life}. The electrode diffusion in the MTDs is faster than that in the LMTDs even at the same T_j. This suggests that the faster electrode diffusion in the MTDs is not attributed to their higher device temperature. Figure 4 shows I_{str} dependence of t_{life} at T_j =200 °C. The effect of the current injection in the MTDs is prominent in comparison with that in the LMTDs. The faster electrode diffusion in the MTDs can be attributed to local higher current density or enhancement of the electron-hole recombination near defects. Another possible explanation is that the temperature in the proximity of the p-electrode in the MTDs is higher than that in the LMTDs even at the same T_j.

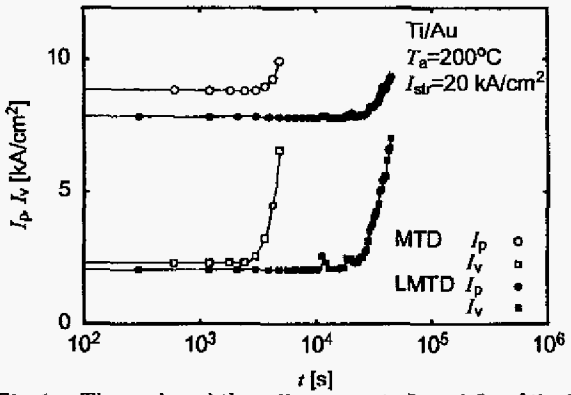

Fig. 1. The peak and the valley current, I_p and I_v, of the TDs with Ti/Au electrodes under a constant current stress I_{str} of 20 kA/cm^2 at ambient temperature T_a of 200 °C.

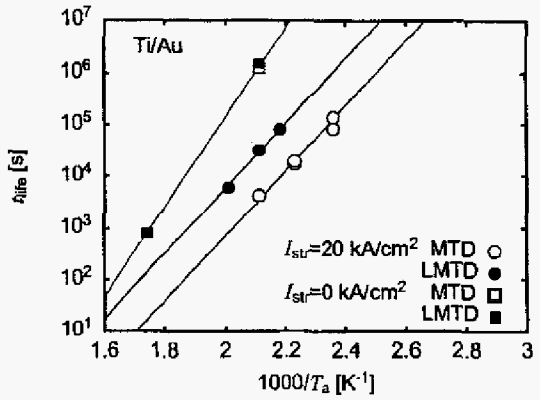

Fig. 2. Ambient temperature T_a dependence of lifetime t_{life} for the TDs with Ti/Au electrodes.

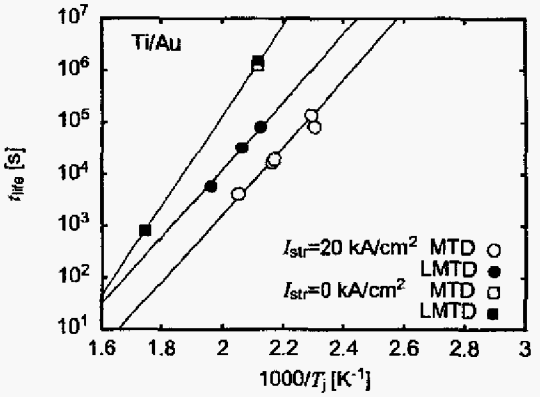

Fig. 3. Junction temperature T_j dependence of lifetime t_{life} for the TDs with Ti/Au electrodes.

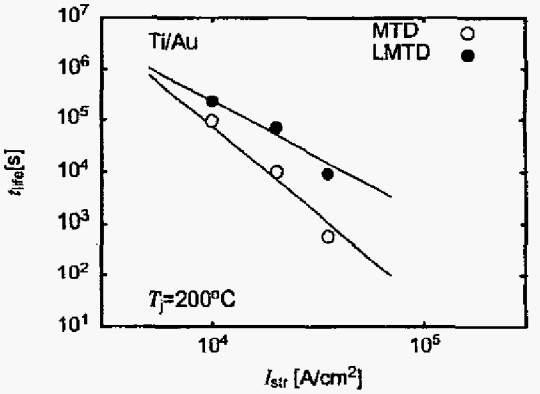

Fig. 4. Stress current I_{str} dependence of lifetime t_{life} for the TDs with Ti/Au electrodes at junction temperature T_j of 200 °C.

IV. Degradation due to impurity interdiffusion

The degradation caused by the electrode diffusion can be suppressed by employing a refractory metal. Using the TDs with W/Ti/Pt/Au electrodes, constant-current stress tests also have been carried out. Figure 5 demonstrates the normalized peak current $I_p(t)/I_p(0)$. The t_{life} of the LMTDs with Ti/Au electrode are estimated to be 1400s under the same stress condition. This indicates that the electrode diffusion is successfully suppressed by employing the refractory metal. As a result of suppressing the electrode diffusion, we have observed another degradation behavior, the reduction in I_p. This behavior is attributed to the impurity interdiffusion as observed in GaAs Esaki tunnel diodes[9,10]. The reduction in I_p of the MTDs is faster than that in the LMTDs.

In general, I_p is expressed by the formula

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

where A and B are constants, and W is the junction width[11]. Assuming a diffusion constant of impurity D, W is approximately expressed as $W_0 + \sqrt{Dt}$, where W_0 is the initial junction width. Thus, the average diffusion constant D_{ave} during a time interval 0-t is obtained as

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

Figure 6 shows the T_a dependence of the D_{ave} during 0-300 s with the result of the simple thermal annealing test. We found that the impurity interdiffusion with a stress current in the MTDs is more prominent than that in the LMTDs. In order to clarify the effect of the difference in R_{th} between the MTDs and the LMTDs, T_j dependence of the D_{ave} is plotted as shown in Fig. 7. Although the impurity diffusion in the MTDs is slightly faster than that in the LMTDs, the impurity interdiffusion in the MTDs and that in the LMTDs are almost comparable at same T_j. This indicates that the faster impurity diffusion in the MTDs is mainly attributed to their higher junction temperature. Figure 8 shows the I_{str} dependence of the D_{ave} at $T_j = 200$ °C. The effect of the current injection in the MTDs seems to be slightly more prominent than that in the LMTDs. However, the difference in D_{ave} between the MTDs and the LMTDs is within an order of magnitude even for the I_{str} of 35kA/cm^2.

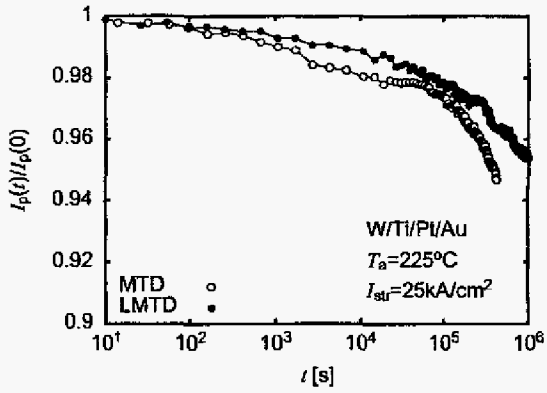

Fig. 5. The normalized peak current $I_p(t)/I_p(0)$, under a constant stress current I_{str} at ambient temperature T_a of 225 °C for the TDs with W/Ti/Pt/Au electrodes.

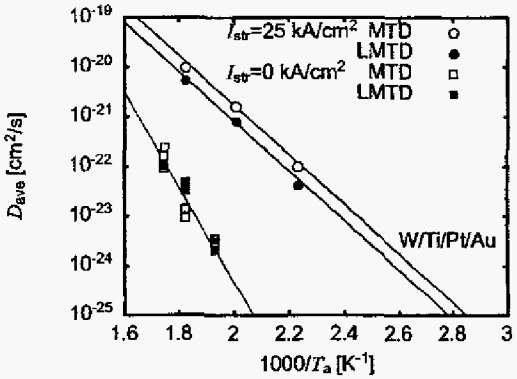

Fig. 6. Ambient temperature T_a dependence of the average diffusion constant D_{ave} for the TDs with W/Pt/Ti/Au electrodes.

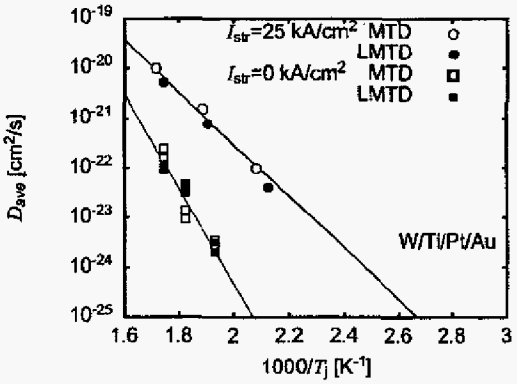

Fig. 7. Junction temperature T_j dependence of the average diffusion constant D_{ave} for the TDs with W/Ti/Pt/Au electrodes.

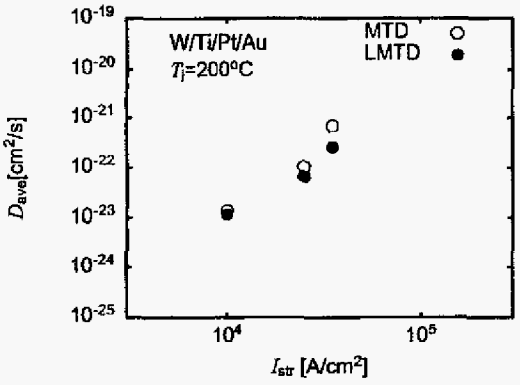

Fig. 8. Stress current I_{str} dependence of the average diffusion constant D_{ave} for the TDs with W/Ti/Pt/Au electrodes at junction temperature T_j of 200 °C.

V. Conclusion

We have fabricated and investigated metamorphic $In_{0.53}Ga_{0.47}As$ Esaki tunnel diodes on GaAs substrates. As a result, we have observed degradation of the diodes due to the current induced electrode diffusion and impurity interdiffusion, which are faster than that of the lattice-matched $In_{0.53}Ga_{0.47}As$ Esaki tunnel diodes on InP substrates. The faster electrode diffusion can not be explained by their higher junction temperature. On the other hand, the faster impurity interdiffusion can almost be explained by their higher junction temperature. The reduction in thermal resistance will be important issue for the devices using the metamorphic materials. Furthermore, the defects with the density of $5 \times 10^7 cm^{-2}$ will not be so serious for the impurity interdiffusion in the metamorphic materials.

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