Resonant tunneling

We have studied experimentally the effect of several electron launcher structures on AlAs/GaAs double barrier resonant diodes (RTD). The experimental results show that a linearly graded AlGaAs launcher structure improves the tunneling current by presumably removing the hump in the conduction band caused by the space charges near the n-i junction in the spacer layer. Peak current densities as high as 170kA/cm² with a peak-to-valley current ration of 3.2 were obtained from these graded launcher RTDs. Compared with the conventional RTD, the graded launcher gives a 50% improvement in the peak current density while reducing the peak-current voltage by 40% and maintaining a similar peak-to-valley current ratio.
Since the first proposal of the resonant tunneling diode (RTD) by Tsu and Esaki\textsuperscript{1}, there has been much interest in RTD because of their potential for high-speed applications\textsuperscript{2-4}. It is generally accepted that the higher the peak current density, the faster the RTD device switches, if a good peak-to-valley (P/V) current ratio is maintained\textsuperscript{5}. Although very high peak current densities were demonstrated in AllInAs/InGaAs/AllInAs and AllSb/InAs/AllSb/InAs material systems, most of the RTD work was done on GaAs substrates due to the maturity of the crystal growth, device process techniques, and the possibility of integration with other high-speed devices such as MODFETs or BJTs.

There has been much work in optimizing the double-barrier structure design for the highest current density while maintaining a reasonable P/V ratio. Our data, consistent with previously published results, show that a double barrier structure of 6ml AlAs/16ml GaAs/6ml AlAs (1ml(monolayer) = 2.83Å) gives a current density as high as 110kA/cm\textsuperscript{2} with a P/V ratio of 3. Moreover, the tunneling current is not only a function of the double barrier structure but also a function of the cathode launcher structure. First, an InGaAs prewell structure\textsuperscript{6} was demonstrated to increase the peak current density in the AlAs/InGaAs/AlAs RTD's. In addition, a thin Al\textsubscript{0.14}Ga\textsubscript{0.86}As, serving as a chair barrier\textsuperscript{7} in the cathode, was found to increase the P/V ratio. However, all these demonstrations were meant to increase the P/V ratio rather than the peak current density. A theoretical self-consistent calculation\textsuperscript{8} was performed to show that the peak current density is higher if the cathode is doped higher. Moreover, for the high doping case, the peak current depended strongly on the thickness of the undoped cathode spacer when the thickness was less than 78 Å. In the normal RTD cathode design, there exists a hump in the conduction band due to the space charge in the n-i junction. The higher the cathode is doped, the higher the hump is. Thus, this undoped spacer layer basically serves as an additional barrier for the electron to tunnel through. Therefore, the theory predicted an improvement in the peak current density by having a thin spacer layer for the high doping cases. Our experimental result did not show
a conclusive improvement (~10%); the change, when the spacer thickness was reduced from 150Å to 50Å, was less than our run-to-run reproducibility. However, the previously mentioned theory did not include the effect of the impurity scattering in the thin spacer cases which was shown by our experiments to result in a significant degradation of the P/V ratio for an RTD with no spacer layer. Therefore, an alternative approach to improve the peak-current density needs to be investigated. In this letter, we present our experimental results showing that a graded AlGaAs launcher structure gives a 50% improvement in the peak current density (170kA/cm²) over the conventional RTD without any degradation of the P/V ratio (~3). This current density is among the highest values ever reported for the RTD's on GaAs substrates.

The RTD samples were grown using a modular Varian GEN II MBE system. Prior to each set of growths, the growth rate was determined by interferometry using an optical pyrometer which was measured through a heated window to prevent As coating during the long calibration run. The growth temperature was maintained at 600 °C during the entire growth. Very high reproducibility (less than 20% variation in the peak current density) for a nominally identical structure was obtained in nearly 15 samples grown over the course of a year. A 20% variation of the peak current corresponds to a 0.3 monolayer variation of the AlAs layer thickness between each growth according to our previous experimental results. This remarkable reproducibility suggests that pyrometric interferometry provides a very high degree of accuracy of the AlAs growth rate.

The RTD layer structures are shown in Fig. 1(a). Before growing the RTD structure, a 1.5um n⁺ (N_d=4x10¹⁸ cm⁻³) GaAs buffer layer was grown on S. I. GaAs (100) substrate. This thick buffer layer not only improves the crystal quality but also reduces the series resistance of the fabricated devices. In all four samples, the layer structures are identical except for the electron launchers (at the cathode side). The double barrier structure con-
sists of 6ml AlAs/16ml GaAs/6ml AlAs. The undoped anode spacer is 350Å-thick for all cases. Four launcher structures are studied as shown in Fig. 1. Structure A is our control structure which is just a 150Å-thick undoped GaAs spacer layer. Structure B consists of several layers. The first layer is a heavily doped graded bandgap Al$_x$Ga$_{1-x}$As region to achieve a smooth transition in the conduction band from GaAs to Al$_{0.1}$Ga$_{0.9}$As. Then, above the double barrier structure, a 150Å-thick undoped Al$_{0.1}$Ga$_{0.9}$A is grown as a spacer layer. Structure C is almost identical to Structure B except the undoped Al$_{0.1}$Ga$_{0.9}$As spacer layer is replaced by an undoped GaAs spacer layer. Finally, Structure D modifies the abrupt Al$_{0.1}$Ga$_{0.9}$As/GaAs interface into a graded bandgap structure to completely eliminate any spike in the conduction band. Figure 2 schematically illustrates the corresponding band diagram of each structure under a bias near the peak-current voltage.

To have a high peak-current density, the resonant tunneling energy (~150meV above the GaAs conduction band) should be higher than the fermi-level of the launcher material at zero bias condition. In addition, for our high doping cases, the fermi-level is a few kT’s above the conduction band edge. Therefore, an Al mole fraction of 10%, corresponding to an 88meV conduction offset from GaAs, was chosen in our study.

For reproducibility is concerned, it is not desirable to change the Al flux during the growth even for the grade bandgap materials. Therefore, all the alloy compositions below 30% Al (except GaAs) were grown by short period GaAs/Al$_{0.3}$Ga$_{0.7}$As superlattice with a minimal 5 Å thickness of each layer. Here, Al$_{0.3}$Ga$_{0.7}$As was chosen for being a popular composition used in other devices in this MBE system.

The MBE grown RTD samples were fabricated in a process compatible with our microwave device processing technology. First, a deep proton implantation converted the region
outside the device area into semi-insulating material. This step determines the active device length of 10μm or 20μm. Then, a 0.7μm deep mesa was wet etched, defining a cathode width of 2μm (from a 3μm mask) and leaving a dovetail etching profile to facilitate a subsequent self-aligned ohmic contact metal deposition. The device width was measured under SEM. After standard resist lift-off process for the NiCr/Au/Ge/Au contact metal, the samples were capped by PECVD deposited SiO₂ and were annealed at 420 °C for 10 seconds. The SiO₂ capsulation is essential to prevent the ohmic metal layers (on the top and bottom of the mesa) from short-circuit in the annealing process. Finally, a 1-μm thick interconnect metal was deposited and lifted-off which also realized the 50Ω coplanar waveguide between the device and the scribed edge of the chip. This fabrication process is very similar to that in Ref. 5 except for the self-aligned ohmic process. In addition, the stripe width is as narrow as 2μm to avoid current crowding and reduce the joule heating effect. We observed noticeable degradation in some high current-density devices with a wider (4μm) or longer (20μm) device geometry, presumably caused by thermal effects. The high speed measurement results will be presented elsewhere. In this letter, we will emphasize only the DC I-V characteristics of the devices. It is worthwhile mentioning that the observed peak current density of the RTD devices on the samples exhibits a variation of less than 10% over 2” wafers. The sources of the variation include both the variation of the grown layer thickness and the device processing.

Figure 3(a) and 3(b) shows the typical I-V characteristics of the RTD devices of Structure A and Structure B. All the I-V characteristics were measured using a four-probe technique to exclude the probe resistance. All the devices are 2x10 μm² in size. For the device with a conventional RTD structure (Structure A), the peak current density is about 110kA/cm² with a P/V ratio of 3 and a peak current voltage of 1.4 V. This result is very close to what was obtained in Ref. 5. However, the RTD device with a uniform Al₀.₄Ga₀.₆As launcher has a peak current of only ~30kA/cm² with a P/V ratio of 3 and a peak current voltage of
0.48 V. The drastically reduced peak current density suggests that the hump in the conduction band does limit the tunneling current as illustrated in Fig. 2(a) and 2(b). The formation of the hump is basically due to the space charge in the n-i junction. Under the external bias, the applied electric field will gradually pull down the hump. The larger the electric field, the lower the hump. Compared with Structure A, the bias of Structure B required for resonant tunneling is lower due to the 88meV conduction band offset. The peak-current voltage thus is lowered from 1.4V to 0.48V. Due to a lower applied electric field, the hump in the conduction band is high enough to reduce the tunneling probability. We do not think the alloy scattering in the superlattice launcher is responsible for the reduction of the tunneling current because the P/V ratio is practically the same for both cases. Any scattering effect tends to reduce the P/V ratio.

In order to reduce the hump in the conduction band, a simple approach is to have a so-called prewell as shown by Structure C in Fig. 1(c). Although there is still a potential spike at the Al_{0.1}Ga_{0.9}As/GaAs heterointerface as shown in Fig. 2(c), the size of the hump is greatly reduced. However, the charge accumulated in this unoptimized GaAs prewell increases the size of the electric field needed to pull down the resonant tunneling energy close to the fermi-level of the cathode. This results in a higher peak-current voltage (1.82V) of the RTD device as shown in Fig. 3(c). The peak current density is improved to 145kA/cm^2 with a P/V ratio of 3.4. While a higher peak current density is obtained by the GaAs prewell, the increase of the peak-current voltage is undesirable because it increases the power dissipation of the device. In addition, the device performance will be very sensitive to the thickness of the GaAs prewell. One can see that when reducing (or increasing) the thickness of the GaAs prewell, Structure C will become Structure B (or A). There must be an optimal thickness for the prewell approach.
A graded AlGaAs launcher as shown in Structure D in Fig. 1(d) will increase the peak current density while decreasing the peak-current voltage. In a launcher structure, like that shown in Fig. 2(d), the hump in the conduction band is completely eliminated. Since there is no additional barrier for electrons to tunnel through, the highest current density should be obtained in the structure. In addition, due to the increase of the electron energy in the Al$_{0.1}$Ga$_{0.9}$As layer, the peak-current voltage should be somewhere between those of Structures A and C. Indeed, as depicted in Fig. 3(d), the I-V characteristics of the RTD with Structure D exhibits a peak current density of 170kA/cm$^2$ with a P/V ratio of 3.2 and a peak-current voltage of 1.0V. To our knowledge, this current density is among the highest reported for GaAs/AlGaAs RTD's within the experimental error (the uncertainty of the device area, and room temperature). Furthermore, our device has a respectable P/V ratio of 3.2 even at such a high current density at room temperature.

In summary, we report on the effect of the different electron launcher structures of the resonant tunneling diodes. Our results show a factor of 6 difference between various structure. The trend of the experimental results, in general, agrees with the prediction of the existence of the hump in the conduction band due to the space charge formation at the n-i junction in the cathode. A novel graded AlGaAs launcher was proposed and demonstrated to effectively remove this hump. The approach not only improves the peak current density (170kA/cm$^2$) but also reduces the peak-current voltage (1.0V) while maintaining a peak-to-valley current ratio near 3. Such a high peak current density is among the highest values ever reported.

The authors would like to acknowledge R. Twist, J. Norman, and S. Close for the device fabrication, S. Y. Wang for technical discussion, W. Ishak for the project support.
REFERENCES


Figure Captions

Figure 1 (a) The MBE-grown layer structure of the resonant tunneling diode. (b) The detailed layer structure of each launcher.

Figure 2 The band diagram of RTD with various launcher structures in Fig. 1.

Figure 3 The I-V characteristics of the 2x10 μm^2 RTD's with various structures.
**Figure 1**

<table>
<thead>
<tr>
<th>Layer Structure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000Å n⁺ GaAs</td>
<td>Nd = 5 \times 10^{18} \text{cm}^{-3}</td>
</tr>
<tr>
<td>4000Å n⁺ GaAs</td>
<td>Nd = 2 \times 10^{18} \text{cm}^{-3}</td>
</tr>
<tr>
<td><strong>Launcher structure (A-D)</strong></td>
<td></td>
</tr>
<tr>
<td>17Å i AlAs</td>
<td></td>
</tr>
<tr>
<td>65Å i GaAs</td>
<td></td>
</tr>
<tr>
<td>17Å i AlAs</td>
<td></td>
</tr>
<tr>
<td>350Å i GaAs</td>
<td></td>
</tr>
<tr>
<td>2µm n⁺ GaAs</td>
<td>Nd = 5 \times 10^{18} \text{cm}^{-3}</td>
</tr>
<tr>
<td><strong>S.I. GaAs Substrate</strong></td>
<td></td>
</tr>
</tbody>
</table>

(a) (b) (c) (d)

(A) 150Å i GaAs

(B) 500Å n⁺ graded Al\(_x\)Ga\(_{1-x}\)As, x = 0 to 0.1
     200Å n⁺ Al\(_{0.1}\)Ga\(_{0.9}\)As
     150Å i Al\(_{0.1}\)Ga\(_{0.9}\)As

(C) 500Å n⁺ graded Al\(_x\)Ga\(_{1-x}\)As, x = 0 to 0.1
     200Å n⁺ Al\(_{0.1}\)Ga\(_{0.9}\)As
     150Å i GaAs

(D) 500Å n⁺ graded Al\(_x\)Ga\(_{1-x}\)As, x = 0 to 0.1
     200Å n⁺ Al\(_{0.1}\)Ga\(_{0.9}\)As
     55Å n⁺ graded Al\(_x\)Ga\(_{1-x}\)As, x = 0.1 to 0.05
     110Å i graded Al\(_x\)Ga\(_{1-x}\)As, x = 0.05 to 0