

## A PROPOSED NARROW-BAND-GAP BASE TRANSISTOR STRUCTURE

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A transistor structure is proposed which alleviates the problem of high base resistance in the narrow quantum-well base region of the Resonant-Tunneling Transistor (RTT). This idea may also be used to improve the performance of the Induced Base Transistor (IBT) and other related structures. Bound states are created in the quantum well by using a base material with lower band gap than the contact layers. Electrons in these bound states form a low-resistance base region for application of bias to the device. Current flow is due to resonant tunneling via the second energy level in the well. Calculated I-V curves and switching transients for the RTT are presented. The issue of undesired tunneling current from base to collector is addressed, and a modified RTT structure is proposed which significantly reduces this problem.

### 1. Introduction

Several three-terminal transistor structures utilizing quasi-bound states in quantum wells have been proposed. In one class of structure, resonant-tunneling double barriers are incorporated in one lead of a more conventional transistor<sup>1-3</sup>. Also, structures where contact is made to the quantum well have been proposed<sup>4</sup>, where the conduction mechanism is parallel transport in the quantum well. A three-terminal resonant-tunneling structure operating in the conventional mode, where conduction is due to injection of electrons through the double barriers, has been analyzed<sup>5</sup>; however in this structure it is believed that significant tunneling of electrons directly from base to collector would occur under applied bias.

A transistor structure has been proposed which bears some resemblance to the device discussed in this paper<sup>6</sup>, however the principal conduction mechanism is thermionic emission over barriers rather than resonant tunneling. Using a lower-band-gap base region, this device was recently fabricated and yielded a dc current gain greater than 10 at room temperature. Another transistor structure that has been proposed is the Induced Base Transistor (IBT)<sup>7</sup>, where a conducting sheet of electrons is induced in the base region under applied bias. It is believed that the scheme proposed

here would also benefit the IBT by lowering the base resistance at low applied bias. Also, it was brought to the authors' attention by one of the reviewers that a resonant tunneling structure similar to the device discussed in this paper has been independently proposed by Schulman<sup>8</sup>.

### 2. Device Structure

We propose a resonant-tunneling transistor where electrons in the base are supplied by filling up bound states in the quantum well. The device considered consists of two 28 Å Al<sub>0.3</sub>Ga<sub>0.7</sub>As barriers surrounding a 67.4 Å In<sub>0.25</sub>Ga<sub>0.75</sub>As well, with n<sup>+</sup> GaAs contact regions doped at 10<sup>18</sup> cm<sup>-3</sup>. The well region is at a lower potential than the conduction band edge in the contacts, due to the lower band gap of InGaAs relative to GaAs<sup>9,10</sup>. For this device, the first energy level in the well lies below the conduction band edge in the contacts. In the calculations it is assumed that the well is 0.11 eV below the GaAs conduction band edge. The barrier height at the GaAs-AlGaAs interface is assumed to be 0.28 eV. Using an effective mass value of .056 m<sub>0</sub> for electrons in the InGaAs region, it is found that the first energy level is 0.0738 eV above the bottom of the well.

The bound electrons in the base allow application of bias to the device. Since these electrons are bound,

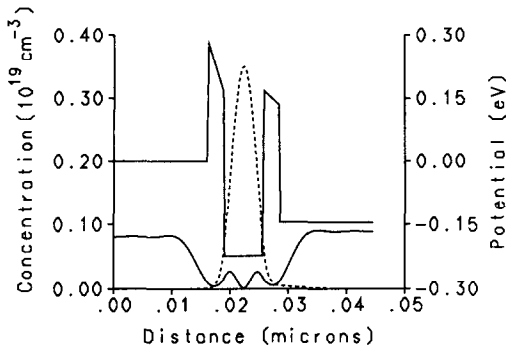


Figure 1: DC Solution for the RTT structure with  $V_{BE} = .1125$  V,  $V_{CE} = .145$  V.

they will not contribute appreciably to base current flow other than for the displacement current accompanying changes of bias. With proper bias applied to the device, the free electrons will tunnel resonantly through the second energy level in the well, which is a quasi-bound state located approximately .094 eV above the Fermi level at zero bias.

### 3. Calculated Results

Space charge effects and scattering mechanisms have not been included in the calculations presented here. A more thorough analysis should also consider quantum mechanical effects that may alter the device capacitance and affect the ability of the quantum-well base to shield the applied potentials<sup>11,12</sup>. The base current resulting from scattering has not yet been calculated. Also, displacement current is not included in the transient results.

Fig. 1 shows the dc solution with .1125 V applied between base and emitter, and .145 V applied between collector and emitter. This value of  $V_{BE}$  is half the peak voltage in the two-terminal I-V curve for the device and corresponds to peak conduction through the second resonance. The dashed curve of Fig. 1 shows the concentration of bound-state electrons occupying the first level. This concentration is obtained by multiplying the normalized one-dimensional wavefunction by the two-dimensional density of states in the well, integrated over transverse momenta. The Fermi level used in this calculation is 0.036 eV above the conduction band in the contacts, corresponding to a doping of about  $10^{18}\text{cm}^{-3}$  at room temperature. The solid curve shows the density of free electrons incident from particle reservoirs in the contacts. These wave functions were calculated from the time-independent Schrödinger equation using the methods of Ref. 13. The sheet density of bound electrons in the well is about  $1.5 \times 10^{12}\text{cm}^{-2}$ . The first level in the quantum well is still bound at this bias, and the signa-

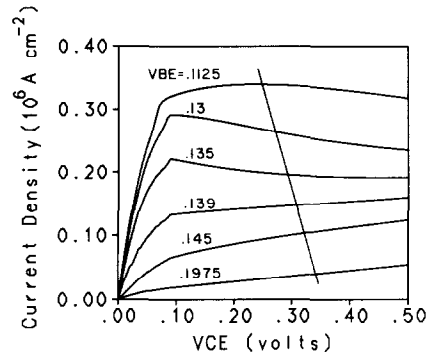


Figure 2: Three-terminal I-V curves at room temperature for the structure of Fig. 1 with  $V_{BE}$  as parameter.

ture of the second resonant wave function is evident for free electrons tunneling across the device.

Fig. 2 shows the three-terminal static I-V characteristics calculated for this device. Each curve is for a constant value of  $V_{BE}$ . The upper curve in Fig. 2 corresponds to peak resonant tunneling through the well, and the lowest curve represents conduction at the valley point. For the one-dimensional analysis without scattering, the first level in the well remains filled along each characteristic until sufficient  $V_{CE}$  is applied to place it above the Fermi level on the collector side, at which point there is no longer a source of electrons for the ground state and it is depleted. The line drawn through the characteristics indicates this point. In reality there would be a source of electrons through the base contact, so that this point represents the onset of tunneling current between the quantum well and collector, which decreases the  $\beta$  of the transistor. A two-dimensional analysis would be required to accurately model this effect, however it can be estimated as is done in Section 4.

Fig. 3 shows switching transients between operating points on the I-V curves of Fig. 2. These transients were calculated by solving the time-dependent Schrödinger equation using the methods of Ref. 13. The solid curve shows the transient starting from the topmost curve in Fig. 2 with  $V_{BE} = .1125$  V and ending on the lowest curve with  $V_{BE} = .1975$  V. In this calculation,  $V_{CE}$  was assumed constant at .145 V. The base-emitter voltage was assumed to switch instantaneously across the device; Fig. 3 shows the resulting electron conduction current density averaged throughout the device. The dashed curve in Fig. 3 shows the transient when the starting and ending operating points are reversed. As can be seen, the intrinsic device is capable of switching in less than 400 fsec. However, the base-emitter capacitance across the 28Å GaAlAs barrier will require a large displacement current component, so that the practical limit on device switching speed will arise from the charg-

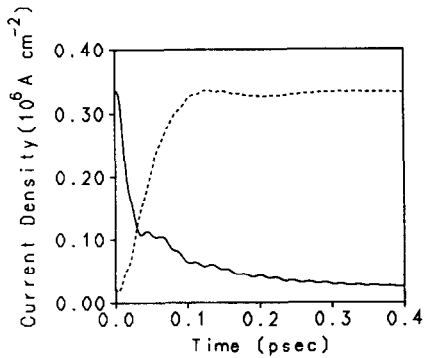


Figure 3: Switching transients between  $V_{BE} = .1125$  V and  $V_{BE} = .1975$  V (solid), and between  $V_{BE} = .1975$  V and  $V_{BE} = .1125$  V (dashed), both with constant  $V_{CE} = .145$  V.

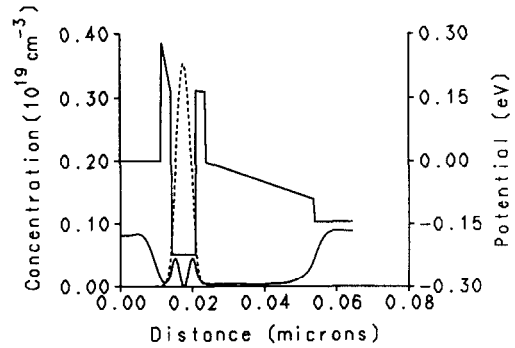


Figure 5: Solution for the structure of Fig. 4 with  $V_{BE} = .1125$  V,  $V_{CE} = .145$  V.

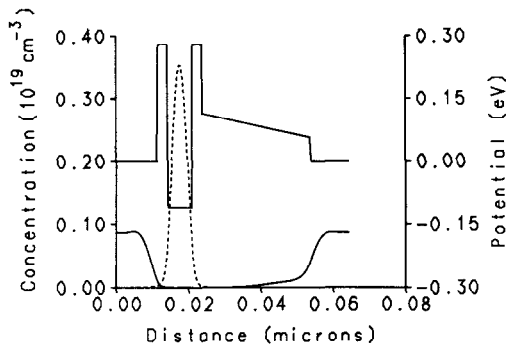


Figure 4: Improved RTT structure at zero bias with 300 Å extension of the base-collector barrier from .1125 eV to .0562 eV.

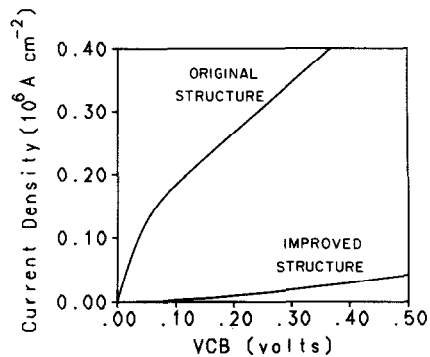


Figure 6: Calculated base-collector tunneling current for both the original structure of Fig. 1 and the improved structure of Fig. 4.

ing time for this capacitance as well as circuit impedance limitations.

#### 4. Improved RTT Structure

A potential problem with this structure, as well as with other RTT structures, arises in the vicinity of the contact made to the quantum-well base region; the base contact is then separated from the collector by a single (in this case 28 Å) barrier and large tunneling currents can flow directly from base to collector. Simply widening the base-collector barrier does not cure the problem, since a wider barrier also significantly reduces the desired resonant tunneling from emitter to collector. In the structure proposed here, it is possible to alleviate this problem by virtue of the fact that electrons from the base lead occupy lower energy states than conduction electrons injected from the emitter.

To improve the RTT structure, it is first noted from Fig. 2 that the peak current for this device occurs for a

base-emitter bias of  $V_{BE} = .1125$  V, slightly less than the distance of the second energy level in the quantum well above the conduction band edge in the GaAs emitter contact at zero bias. It is desired to modify the structure so that electrons injected near this energy will effectively see the same barrier as before in Fig. 1, however lower-energy electrons from the base will see a larger barrier. The structure shown in Fig. 4 accomplishes both these effects. In this structure, the base-collector barrier is extended by 300 Å between the energy values of .1125 eV and .0562 eV. With  $V_{BE} = .1125$  V applied, the knee of the base-collector barrier lines up with the conduction band edge in the emitter, so that injected electrons effectively see the same barrier as before. A solution at this bias point is shown in Fig. 5, where the double-peaked wave function for injected electrons is evident.

Figure 6 shows a comparison of the base-collector tunneling current calculated for both structures. Note

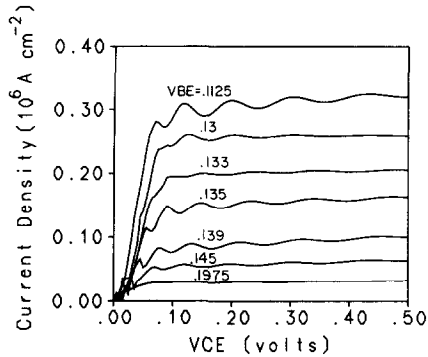


Figure 7: Static I-V curves at room temperature for the improved structure of Fig. 4 with  $V_{BE}$  as parameter.

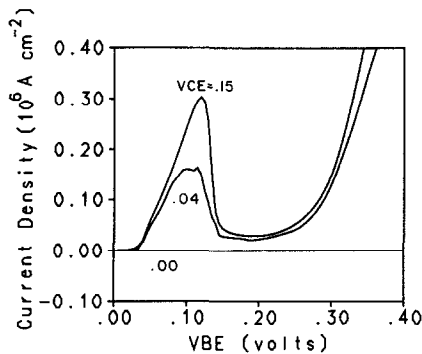


Figure 8: Static I-V curves at room temperature for the improved structure of Fig. 4 with  $V_{CE}$  as parameter.

that the current scale is the same as for the emitter-collector current curves of Fig. 2. The curves of Fig. 6 were obtained by removing the first barrier between the emitter and base. If the improved structure is biased at the peak emitter-collector current point and if  $V_{CB} = 0.1$  volt, the leakage current in Fig. 6 is down by a factor of 100 from the desired emitter-collector current.

Static I-V curves were calculated for the improved structure of Fig. 4 and are shown in Fig. 7. Comparison with Fig. 2 shows that the resonant-tunneling current magnitude is nearly the same for both structures. Differences in the characteristics are caused by additional reflections from the base-collector barrier extension in Fig. 4, which show up as ringing in the I-V characteristics of Fig. 7. The characteristics of Fig. 7 represent operation in the negative-transconductance region, since increasing  $V_{BE}$  results in decreased current. The negative transconductance is more clearly displayed in the characteristics of Fig. 8, where the current is plotted vs.  $V_{BE}$  with  $V_{CE}$  as parameter. It is also shown how the current may be quenched by suitably biasing  $V_{CE}$ .

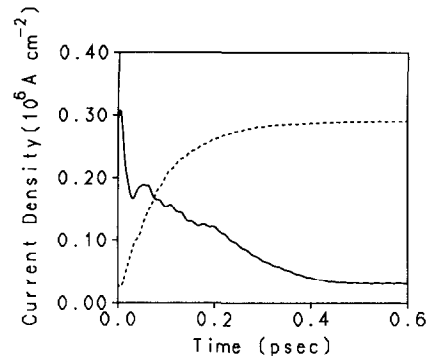


Figure 9: Switching transients for the improved structure of Fig. 4 between  $V_{BE} = .1125$  V and  $V_{BE} = .1975$  V (solid), and between  $V_{BE} = .1975$  V and  $V_{BE} = .1125$  V (dashed), both with constant  $V_{CE} = .145$  V.

Since the modified structure of Fig. 4 is significantly longer than the original device, it is of interest to compare the switching transients for the two structures. Figure 9 shows the calculated transients, between the same bias points as in Fig. 3. Comparison shows that inclusion of the base-collector barrier extension increases the turn-on transient from approximately 0.15 ps to 0.3 ps, while the turn-off transient is increased from about 0.3 ps to 0.5 ps.

The wider base-collector barrier affords additional advantages besides reducing the leakage current. The base-to-collector capacitance is significantly reduced, so that displacement currents accompanying bias changes across this junction are reduced. Also, the base contact is easier to accomplish for the modified structure, since punch-through to the collector is less likely.

## 5. Conclusions

In summary, a resonant-tunneling transistor structure has been proposed with a novel mechanism for supplying low-energy electrons to the base region. The problem of tunneling current directly from base to collector has been addressed, and an extended-barrier structure has been proposed which significantly reduces this effect. The idea of introducing bound states into the base region can also be used to lower the base resistance in other transistor structures such as the IBT. Sub-picosecond switching times have been calculated for the intrinsic RTT device.

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