Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 805-807 **PC-1-8**

Emitter Size Effects in the Coupled-Quantum-Well Base Resonant Tunneling Transistor

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A resonant tunneling transistor, which has a base in the well region of the coupled-quantum-well structure, is studied using the quantum distributed model. By investigating the relationship between disappearance of the negative differential resistance and the emitter size, it is found that the large potential drop near the base electrode is crucial in the disappearance of the negative differential resistance.

I. INTRODUCTION

Resonant tunneling transistors look promising for future device applications.[1] To aid analysis of such devices, a two-dimensional device simulator has been developed using the quantum distributed model.[2,3] It is used successfully here to analyze resonant tunneling transistor characteristics, especially the relationship between the negative differential resistance (NDR) and the emitter size. As the emitter size increases, the NDR, which is an important characteristics of resonant devices, is weakened due to a large potential drop near the base electrode. Two-dimensional effects, such as the potential drop in the base region, are shown to be critical to the operation of resonant tunneling transistors, so two-dimensional simulation is indispensable for accurately analyzing these effects.

II. MODEL

The resonant tunneling transistor to be analyzed is shown in Fig. 1. It has an emitter and a collector electrode sandwiching a coupled-quantum-well structure, and also has a base electrode attached in the well region.[1] In the analysis, base current is thought to be the consequence of scatterings, which is one of the important assumptions of the model.

To analyze the time-independent transport in the transistor, we employ an S-matrix method.[3] Using S-matrices, elastic scattering due to the potential barriers and inelastic scattering processes can be treated in a unified way.

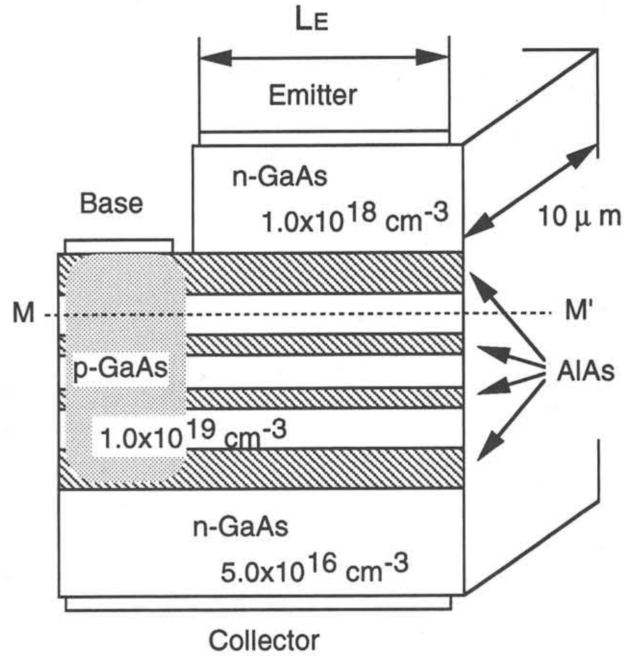

FIG. 1. Coupled-quantum-well base resonant tunneling transistor. The barriers consist of $AlAs$ layers and the other regions consist of $GaAs$.

We use the 4×4 matrix expression for the inelastic scattering:

$$\{S_{ij}\} = \begin{pmatrix} 0 & \sqrt{1-\eta} & \sqrt{\eta} & 0 \\ \sqrt{1-\eta} & 0 & 0 & \sqrt{\eta} \\ \sqrt{\eta} & 0 & 0 & -\sqrt{1-\eta} \\ 0 & \sqrt{\eta} & -\sqrt{1-\eta} & 0 \end{pmatrix}. \tag{1}$$

where coupling coefficient $\sqrt{\eta}$,[3,4] is related to scattering probability p

$$p = \frac{-1}{d}\sqrt{\frac{2E}{m}}\log(1-\eta), \tag{2}$$

where E is kinetic energy and d is the well width.

Channels $i = 1, 2$ are considered as the transport channels between the emitter and the collector. For electrons, the channels $i = 3, 4$ are considered as the states transferring to the base current, and for holes, they are connected to a hole reservoir of thermal equilibrium in the well. Incoherent scattering is also treated by the S-matrix by introducing a virtual reservoir, which is connected to channels 3 and 4.[4] The transport model of our simulation is schematically shown in Fig. 2.

To include two-dimensional effects, we use the quantum distributed model. We divide the transistor into slices vertical to the heterostructure interfaces. Each slice is approximated in one dimension and is redivided into regions parallel to the interface. An S-matrix is obtained for each region by solving the Schrödinger equation. Those S-matrices and the S-matrices of inelastic scatterings are combined into one S-matrix within each slice from the emitter to the collector. Similar calculation is also performed for holes. The collector current, I_C, and the base current, I_B, are calculated from the transmission probabilities, which can be obtained from this unified S-matrix. The current flow in the well from the base electrode causes a potential drop because of the internal resistance, which is considered as the potential difference between the nearest neighbor region in the direction parallel to the interface.

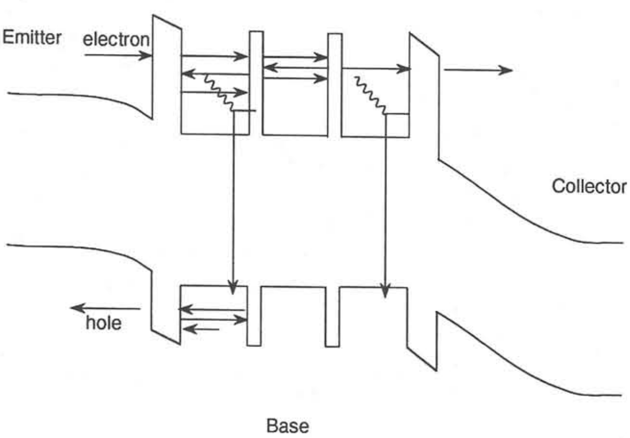

FIG. 2. Transport model of electrons and holes in a slice.

III. RESULTS AND DISCUSSION

The wide outer barriers are 20 Å wide and the inner barriers are 10 Å wide, while each of the three wells is 50 Å wide. The emitter region is $1.0 \times 10^{18}\ cm^{-3}$ donor-doped while the collector is 5.0×10^{16} donor-doped and the base region acceptor-doped, $1.0 \times 10^{19} cm^{-3}$. The emitter area is $L_E \times 10\ \mu m$. Scatterings are considered only in the well regions.

I_C versus base-emitter voltage, V_{BE} characteristics are calculated as shown in Fig. 3 for several L_E conditions. For $L_E = 0.5\ \mu m$, I_C has a clear peak around $V_{BE} = 1.65\ V$. With higher L_E, I_C increases because of the increase in the area where the collector current flows. However, when L_E increases sufficiently, the NDR disappears: For $L_E = 3.0\ \mu m$, I_C increases monotonically with V_{BE}. The reason can be understood when inspecting the potential distribution of the well, which is a related to the distribution of the resonance in I_C.

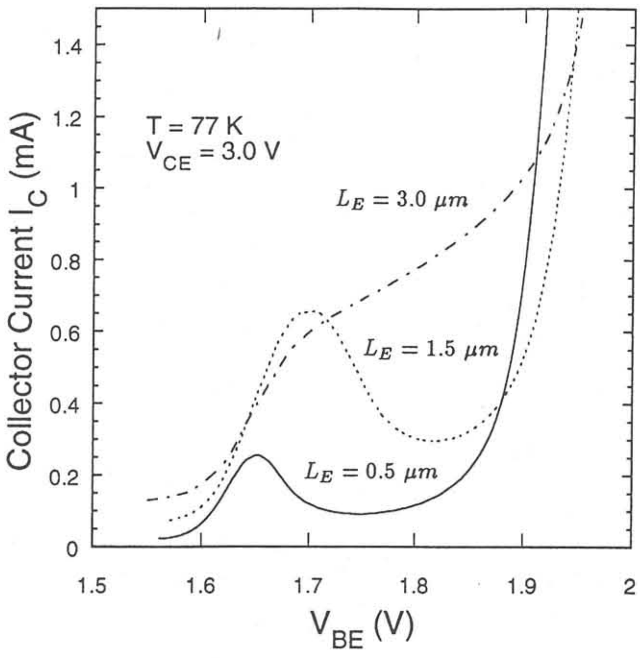

FIG. 3. L_E dependence of I_C-V_{BE} characteristics.

The potential and I_C distribution are shown in Fig. 4 for (a) $L_E = 0.5\ \mu m$ and (b) $L_E = 3.0\ \mu m$. For the smaller L_E, the well potential drops gradually and the resonance occurs over the entire region of the transistor. This can be understood by the fact that no peak is shown in I_C. When L_E increases, I_C also increases because of wider I_C resonance in space. When L_E is increased further the potential drop near the base electrode becomes greater, as shown in Fig. 4, due to the increase in I_B. The resonance in I_C occurs locally, as shown by a small peak in the I_C current density. By increasing V_{BE}, this resonant region moves to the right-hand side of the figure and the new resonant region of I_C appears near the base electrode while the earlier resonant region remains spatially in the transistor. In this situation, collector current flows through more than two resonant levels. As a result, I_C increases monotonically and the NDR does not occur. The size of L_E, where the NDR disappears, is dependent on the resistance in the well region and also on the scattering probability. Furthermore, for smaller well resistance, the size of L_E at which the NDR disappears becomes large.

IV. CONCLUSION

Detailed analysis of the coupled-quantum-well base resonant tunneling transistor is performed, taking into account two-dimensional effects and inelastic scattering. Through this analysis, it is found that increasing L_E causes a large potential drop near the base electrode, which leads to the localization of I_C and disappearance of the NDR. The simulation results indicate that the present simulator is a useful tool for analyzing device operation.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Mizutani for his encouragement and Dr. Waho for his discussions.

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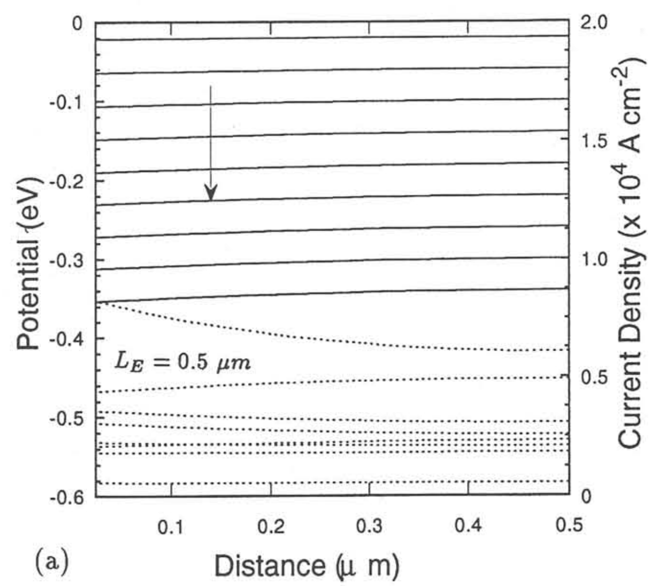
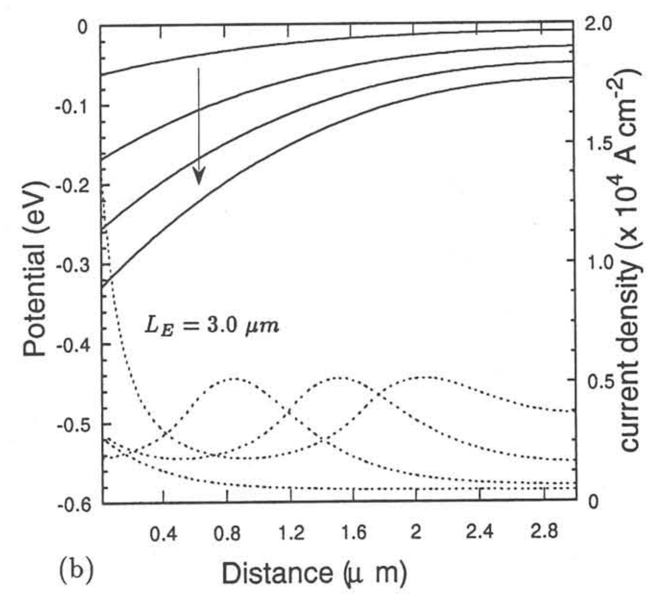


(a)



(b)

FIG. 4. Potential and current distribution of the intersection through M-M' under the emitter for (a) $L_E = 0.5\ \mu m$ and (b) $L_E = 3.0\ \mu m$. Solid lines are the potential measured from the conduction band edge of the emitter and broken lines I_C densities. The arrow corresponds to the direction of V_{BE} increase.