Modeling the Inelastic Scattering Effect on the Resonant Tunneling Current

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INTRODUCTION

Since the double gate $SiO_2/Si/SiO_2$ structure has been proposed as a resonant tunneling diode (RTD) [1] the first experimental observations [2] and theoretical models [3] have been reported. However, theoretical simulation of current flowing through the RTD structure wrestles with difficulties resulting from details of the device's physics and numerical procedure efficiency. This paper describes an implementation of the inelastic scattering into the steady-state model of the RTD.

THEORETICAL MODEL

Fig. 1 shows the carrier flow paths in a biased RTD structure. J_{eCrt} is a current of electrons, which successfully tunnel from the emitter to collector. S_{eE} is the current of electrons tunneling from the emitter to the base and then, on their way of multiply reflections between the barriers, are scattered by inelastic processes. J_{eErt} and S_{eC} denote similar fluxes for electrons tunneling from the collector. In the steady state the total scattering flux $S_{eE} + S_{eC}$ charging the base must be equal to the flux of electrons leaving the quasi-bounded levels in the base E_{ij} by tunneling to the emitter I_{eE} and collector I_{eC} or recombining with holes S_{rg}. Similar fluxes and the steady-state condition can be defined for holes. Thus, the terminal electron and hole currents are:

$$J_e = I_{eRT} + S_{eE} - J_{eE} = J_{eRT} - S_{eC} + J_{eC} \tag{1}$$

$$J_h = J_{hRT} - S_{hE} + J_{hE} = J_{hrt} + S_{hC} - J_{hC} \tag{2}$$

where $I_{eRT} = I_{eCrt} - I_{eErt}$ and $I_{hRT} = I_{hErt} - I_{hCrt}$ are the net electron and hole resonant tunneling currents.

With the use of the transfer matrix method, the scattering matrix elements $[S_E]$, $[S_B]$ and $[S_C]$ are determined, that tie (a_{out}, b_{in}) to (a_{in}, b_{out}) components of the wave functions in the appropriate regions (Fig. 2). It is assumed that due to scattering the t_B and t_B' transition factors through the base are reduced by $(1-P_{sc})^{1/2}$, where $P_{sc} = 1-\exp(-t_T/\tau_{sc})$ is the scattering probability during the time t_T of one transit through the base between the subsequent reflections from the barriers. The resonant tunneling probability P_{eCrt} to the collector is expressed as:

$$P_{eCrt} = \frac{k_C m_{xE}}{k_E m_{xC}} \left| \frac{t_E t_B t_C}{(1 - r_E' r_B)(1 - r_B' r_C) - r_E' t_B t_B' r_C} \right|^2 \tag{3}$$

where the transmission t and reflection coefficients r are complex quantities. The scattering probability of electrons tunneling from the emitter is given by:

$$P_{sE} = P_E P_{sc} \frac{1 + P_B R_C}{1 - P_B{}^2 R_E R_C} \tag{4}$$

The resonant tunneling currents and the scattering fluxes are obtained by integrating products of the appropriate probabilities P_{eErt} or P_{sE} and the ' supply' function $N_E(E)$ in the emitter. The tunnel currents from discrete levels to the gate electrodes are calculated by summing the products of two-dimensional electron concentrations and escape rates to the electrodes.

DISCUSSION

Fig. 3 shows the resonant tunneling probability to the collectoor without (P_{rt0}) and with scattering (P_{rtS}) for a double polysilicon gate ($N_D = 2\mathrm{x}10^{20}\mathrm{cm}^{-3}$) diode with a 3nm thick intrinsic silicon well and two SiO_2 layers of 1nm thickness. The assumed scattering time constant was $t_{sc} = 3\mathrm{x}10^{-14}\mathrm{s}$ as an average of the scattering rates calculated for the obtained quasi-bounded level spectrum according to the perturbation approach. As can be seen, the scattering probability flux for a given energy can be approximated by probability of the sequential tunneling through the first barrier. Scattering damps the tunneling probability peaks. Fig. 4 shows the energy distribution of currents of electrons tunneling from the emitter with the transverse effective mass. The net resonant tunneling current

J_{ert} is compared with the fluxes S_{eC} and I_{eC} affecting the terminal current according to (2). The resultant terminal current with and without scattering is shown in Fig. 5 in dependence on the voltage. Scattering suppresses the resonant current peak for the considered parameters of the DG MOS system and the total current in the plane of collector is dominated by current I_{eC} of non-coherent electrons.

CONCLUSION

Modeling the inelastic scattering effect on the resonant tunneling current may be a key issue for developing a reliable RTD' s simulator.

ACKNOWLEDGEMENT

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REFERENCES

[1] R. M. Wallace, A. C. Seabaugh, *Silicon oxide resonant tunneling diode structure*, U.S. Patent no. 5,606,177, 25 Feb. 1997.

[2] Y. Ishikawa, T. Ishihara, M. Iwasaki, M. Tabe, *Negative differential conductance due to resonant tunneling through SiO₂/single-crystalline-Si double barrier structure*, Electronics Letters, **37**, 1200 (2001).

[3] B. Majkusiak, *Theoretical modeling of the double gate MOS resonant tunneling diode*, ULIS' 03, Udine, Italy, March 2003, Proceedings.

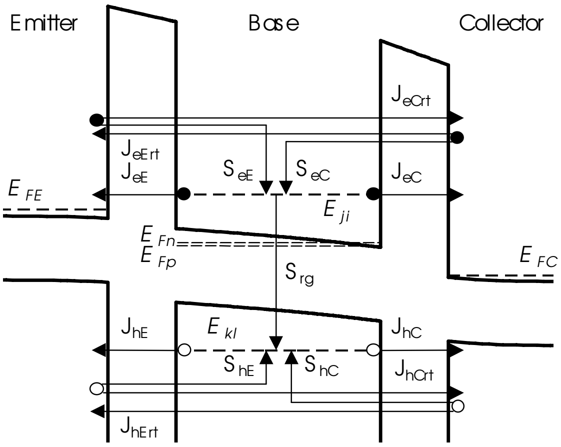

Fig. 1. Current fluxes in the biased DG MOS RTD structure.

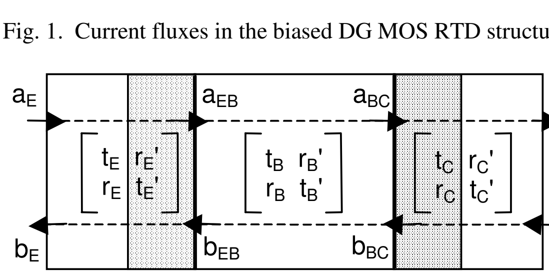

Fig. 2. Scattering matrix representation for considerations of the resonant transition of the wave function.

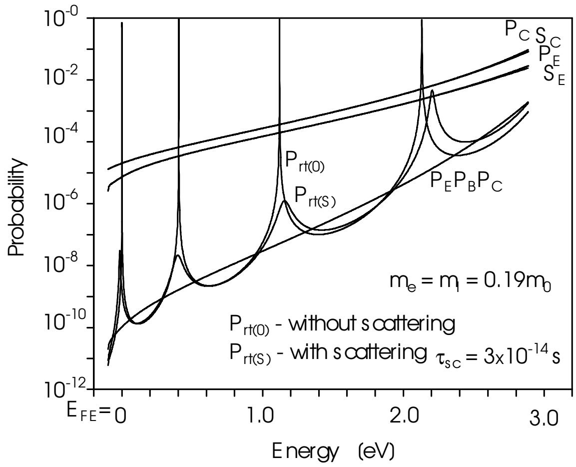

Fig. 3. Energy distribution of probabilities of the resonant tunneling P_{rt}, sequential tunneling P_E and P_C, and scattering P_{sE} and P_{sC} for RTD structure at $V_{CE} = 0.5V$.

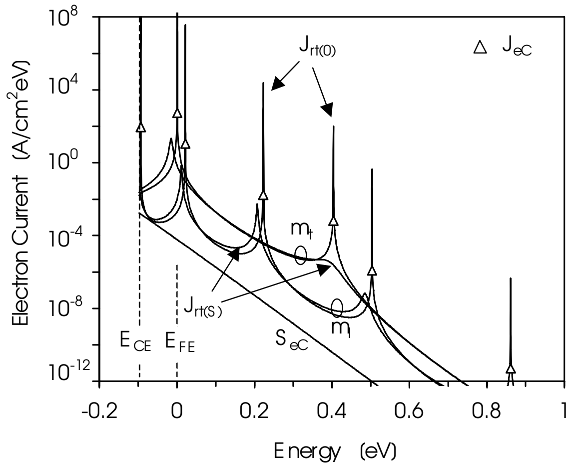

Fig. 4. Energy distribution of the electron resonant tunneling current J_{eCrt} and the scattering current S_{eE} at $V_{CE} = 0.5V$.

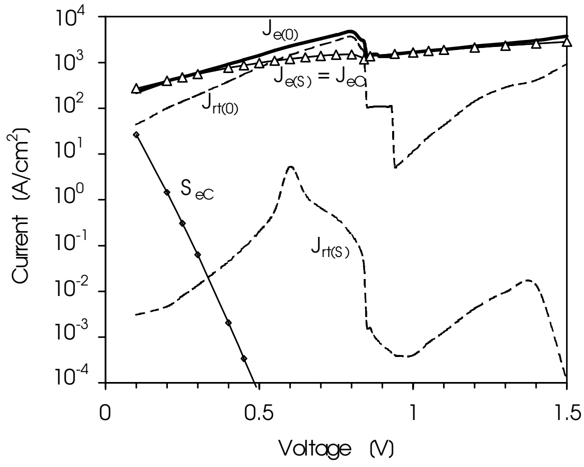

Fig. 5. Comparison of currents flowing through the collector junction and the total currents with and without scattering.