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Transformation of a metal-insulator-silicon structure into a resonant-tunneling diode

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A metal-oxide-semiconductor diode, with two tunnel- transparent barriers due to heavily doped silicon and nm-thin insulator, has been shown to exhibit steps or peaks in the current-voltage curves. Both simulations and measurements enable to relate their appearance to resonant tunneling of electrons via the levels of the near-interface quantum well in deep depletion regime.

1. Introduction

Metal – thin Insulator – Silicon (MIS) structures were being so intensively investigated within the last decades that their physics has already become a subject of some textbooks. Nevertheless a possibility of resonant tunneling (RT) between the metal and Si via the discrete levels in the near-interface quantum well (QW) has remained almost unknown so far. It is despite the fact that quantization effect itself was fully understood long ago [1]. In this work, the conditions for RT in MIS structures, modeling and experiments confirming its plausibility [2] are discussed.

2. Conditions for resonant tunneling

For definiteness, the structures on p-Si wafers are focused on. The necessary physical condition for a RT is that at least one of the QW levels must lie below the bulk valence (v-) band edge $E_{v\infty}$. Under the condition of

$$q\varphi_s \geq E_n + E_g \tag{1}$$

n subbands are involved. Here, φ_s is band bending in Si and E_n is the nth subband bottom energy. The nth level gets activated at the voltages V_n^a corresponding to the exact equality in the expression (1). To observe a RT at relatively low (several Volts) biases, the oxide and silicon forbidden-band barriers should be tunnel-transparent. For this purpose aiming also at creating compact and high-speed MIS resonant tunneling diodes (MIS-RTDs) thin insulators (d < 4.0 nm) and high acceptor concentrations (about $N_A \sim 10^{19}$ cm^{-3}), are used.

RT from the Si occurs at a positive gate bias V under a deep depletion condition (Figs. 1a, 2), when electrons are emitted from the broad energy range of the Si v-band. The RT at a negative V (Fig. 1b) occurs into Si, when only a narrow strip of its empty v-band states, below $E_{v\infty}$ serves as a collector.

3. Modeling of current-voltage curves

Calculations relied on the tunneling models [3] have been performed for the Al/SiO$_2$/p$^+$-Si system with its regular barrier parameters.

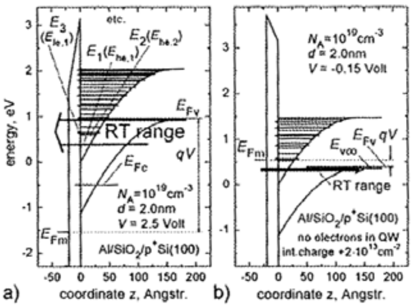

Fig.1: Band diagrams of the MIS structures with RT electron transport component marked: case (a) – positive gate bias, (b) – negative bias.

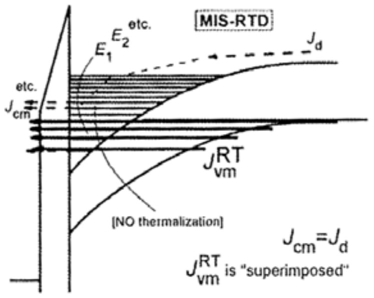

Fig.2: Currents flowing through the QW in the MIS tunnel structure in a RTD regime Additionally there is a non-resonant current from v-band to metal (not marked).

Normally, the condition (1) is satisfied only at positive V. Fig. 3 shows partial contributions of each subband separately. RT activation in the MIS-RTD starts with the energetic alignment of the deepest (1st) subband bottom with the uppermost filled state in the v-band $E_1 \approx E_{v\infty}$. After the subband 1 became active, with increasing bias V, the deeper filled states of the v-band are involved into RT. This shifts the RT origin point, enhancing a band-to-band transport probability $T_s(E_1)$ due to weakening barrier within the tunneling distance. Meanwhile, the 2nd, 3rd etc. subbands get involved. Thus, at $V \geq V_n^a$, all n levels are taking part in RT simultaneously. As a consequence, activation of the higher subbands is not always resolved because it occurs on a background of the excess current and the already acting lower subbands (Fig. 4).

Unlike for $V > 0$, only one, if any, level can contribute to the RT current at a fixed $V < 0$. This should result in the current peaks like those for the casual RTDs [4]. But in order to generate the curves with peaks, either presence of some pos-

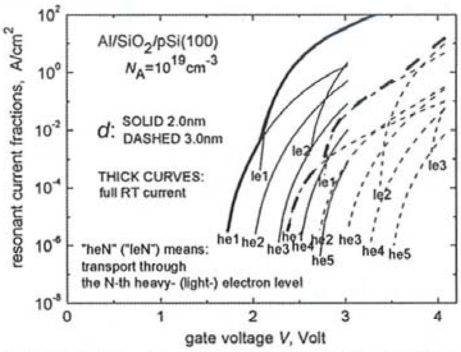

Fig.3: Calculated partial RT currents flowing from the v-band of the silicon into the metal through the individual QW sub-bands in a MIS structure.

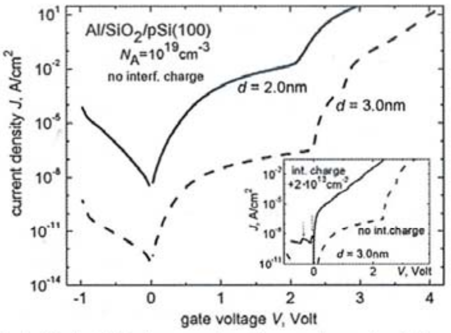

Fig.4: Calculated current-voltage characteristics of an Al/ SiO$_2$/pSi MIS-RTD. Inset: the characteristics for the same system with large positive interface charge.

itive interface charge (inset to Fig. 4), or a reduction of the metal barrier, have to be assumed.

4. Experimental verifications

For verifying a concept of RT in MIS structures, the samples with thermal and electrochemical silicon dioxide were fabricated and measured. These samples exhibit features of the current-voltage curves (Figs. 5-6) which are difficult to attribute to anything else but to the RT of electrons. So, at $V > 0$, the steps are observed (Figs. 5, 6a). For large N_A, such a behavior was typical for all the structures.

For some MIS structures with an electrochemical SiO$_2$ possessing a positive charge, several QW levels may lie below $E_{v\infty}$ even at $V < 0$. In this case the RT-related features are peaks (Fig. 6b). Experience shows that preliminary application of high $V > 0$ provokes an appearance of larger positive charge and therefore of more peaks at $V < 0$.

Effects of electron storage in the QW were also revealed in MIS-RTD structures.

5. Conclusion

In this work, a possibility of realization of electron resonant tunneling in MIS structures, as a promising alternative to the traditional RTDs, based on the more complex materials, not easy compatible with the MIS technologies [4], has been demonstrated with a corresponding theoretical support.

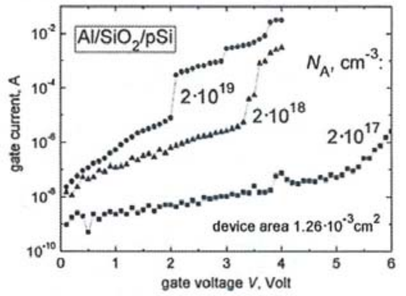

Fig.5: Current-voltage characteristics of the MIS structures with a thermal oxide of ~2.5 nm thick for three different acceptor concentrations N_A in substrate.

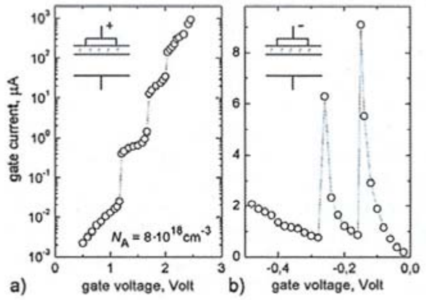

Fig.6: Current-voltage characteristics of the MIS structure with an electrochemical oxide: (a) – for positive gate bias, (b) – for negative bias.

The phenomenon needs further detailed study in both basic and applied aspects.

References

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