



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

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ABSTRACT

A metal–oxide–semiconductor diode, with two tunnel-transparent barriers due to heavily doped silicon and nanometer-thin insulator, has been shown to exhibit steps or peaks in the static current–voltage curves. For the positive gate bias, appearance of these features in both simulations and measurements testifies to resonant tunneling of electrons from the silicon valence band via the discrete levels of the near-interface quantum well into the metal in the regime of deep depletion in silicon space charge region.

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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 electron 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.

Beyond an extension of knowledge in the physics of MIS structures, this study has an obvious importance in the applied physics and electronics. It should be noted that the two key branches of the modern electronics, namely, the Si integrated circuit electronics (despite scaling its elements toward nanometer size) and the low dimension functional nanoelectronics with its high speed components featuring non-linear characteristics, are developing rather independently. The materials, technologies and device design of the two branches almost do not overlap which gives rise to compatibility problem. Realization of a RT effect in a MIS diode would therefore become a step towards allying the above-mentioned branches and substantial extension of Si integrated circuit electronics functions.

In this work, for definiteness, the Al/SiO₂/p⁺-Si two-electrode structures are focused on. The samples were fabricated using standard technological processes and measured at 300 K. Calculations

were relied on the tunneling models [3] with the physical barrier parameters.

2. Conditions for a resonant tunneling in MIS nanostructures

In Fig. 1a, the calculated energy band diagram of the investigated nanostructure for the bias conditions enabling electron resonant tunneling from silicon, is presented for a case without any interface charges. There is a QW in the c-band (c = conduction) of the p⁺-Si with an energy depth value equal to the band bending φ_s which exceeds the silicon band-gap value E_g . The QW, being a part of the Si Space Charge Region (SCR), is sandwiched between the two barriers: of the remainder of the SCR from the one side and of the oxide from the other side.

The QW possesses many subbands, clearly distinguished in energy, which is essential for device operation, and level broadening which should be larger at higher temperatures is of no importance. Simulation of the band diagram was performed for the (100) orientation, for which there are overlapping ladders of heavy-electron (he) and light-electron (le) subbands [1]; the le-levels in Fig. 1 are drawn slightly wider to discern them from the he-levels.

The components of the flowing current are marked in Fig. 1b. Under the reverse bias considered the RT current J_{VM}^{RT} is superimposed by the two non-resonant components. One of them arises due to a drift J_d of minority carriers (electrons) in the Si c-band through the SCR, balanced by their tunneling through SiO₂ into the metal (J_{cm}). The other is created by electron tunneling from Si v-band through the oxide to the metal (J_{vm}).

The RT electrons are emitted from a broad energy range of the occupied Si v-band states via the QW subbands into empty states of the metallic Al. The necessary condition for a RT is that at least

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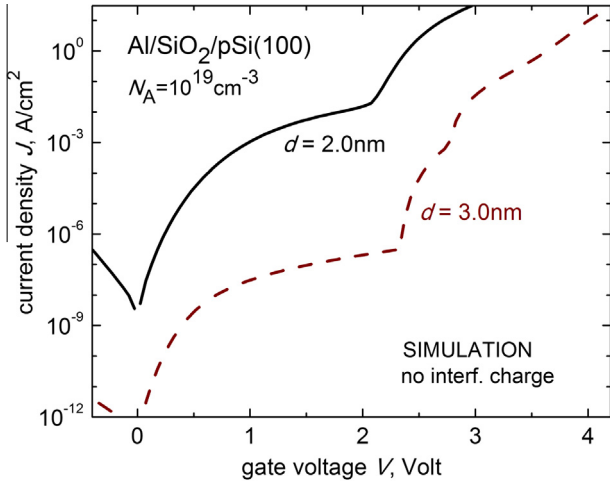


Fig. 3. Calculated current–voltage characteristics of the MIS-RTDs with the same parameters, as in Fig. 2. The total current includes both resonant and non-resonant (excess current) components.

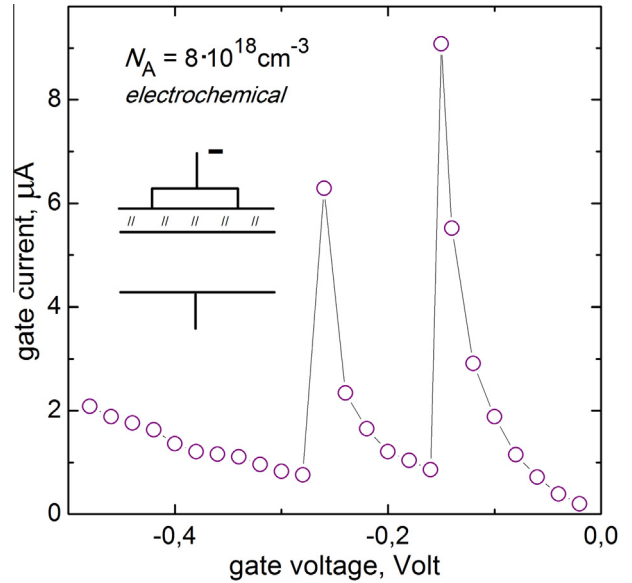


Fig. 5. Measured current–voltage characteristic of a MIS-RTD with an electrochemical oxide for negative gate bias.

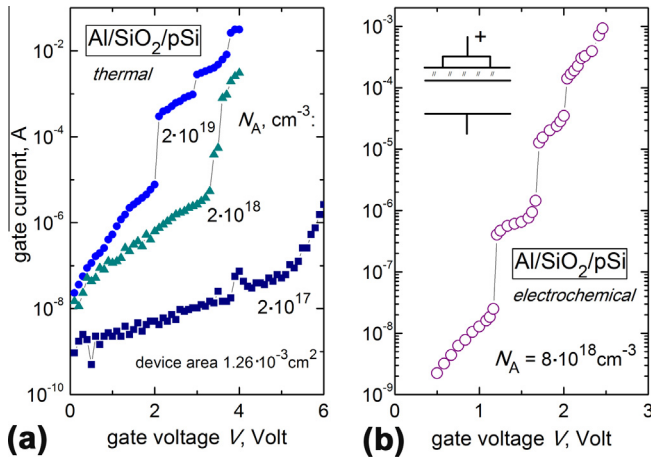


Fig. 4. Measured current–voltage characteristics (gate bias is positive) of MIS-RTDs: (a) with a thermal oxide and different Si doping levels; (b) with an electrochemical oxide.

the deeper filled states of the v -band are involved into RT. The result of this situation is steps (Fig. 3). Moreover, the shifts of the RT origin points enhance a band-to-band transport probability $T_s(E_1)$ due to higher field and weaker SCR barrier within the tunneling distance. Meanwhile, the 2nd, 3rd etc. subbands are getting involved. Thus, at $V \geq V_n^a$, all n levels are taking part in RT simultaneously. Under these conditions, activation of the higher subbands is not always noticeable because they make their appearance on the background of the excess current $J_{cm} + J_{vm}$ and the current J_{vm}^{RT} through already acting lower subbands (Fig. 3). Often, except the ground heavy-electron level $E_1 = E_{he,1}$, the activation of only one more level, which is the first for the light electrons ($E_3 = E_{le,1}$) is pronounced.

It is supposed interesting to estimate the maximal operating frequency of a MIS-RTD:

$$\omega_{crit} = (J_{vm}^{RT})^{-1} \sum_n \tau_{s,n}^{-1} J_{vm}^{RT,n} \quad (4)$$

relying on the times of electron stay $\tau_{s,n}$ in the QW, which are given by the right side of the expression (3) calculated for each n th level. Estimations yield ω_{crit} in the terahertz range for the structures with $d < 2.0$ nm.

For verifying a concept of RT in MIS tunnel structures, the samples with thermal and electrochemical silicon dioxide were fabricated and measured. The static current–voltage curves for the MIS nanostructures with a thermal oxide for several substrate doping levels are shown in Fig. 4a and a curve for the structure with an electrochemical oxide in Fig. 4b. In both cases the current–voltage characteristics exhibit step-like features. Although the form of the current jump segments is not exactly the same as in simulations, the features are difficult to attribute to anything else but to RT of electrons from the v -band of Si. For large N_A , such a behavior was typical for all examined diodes. A suspect that the jumps might be due to a peculiar oxide breakdown is removed by the fact of a complete repeatability of the features in several sequential J - V recordings for the same MIS sample (not shown). Note that the capacitance–voltage measurements on the “electrochemical” structures indicate a presence of some amount of a positive Si/SiO₂ interface charge, which may lower the activation voltages V_n^a (i.e. shift them to the left).

These features, in their appearance, differ from the peaks observed in the J - V curves of the known RTDs [4]. This distinction between the RTDs and MIS-RTDs mainly results from a difference between the energy ranges of the electron emission in the compared devices. In the former case, when the peaks are observed, electrons are emitted only from a narrow energetic stripe, so that within a voltage range just after the resonance condition (i.e. an alignment of some QW level and this stripe) has been passed, current reduction takes place. In the latter case, the occupied Si v -band states over a broad energy range are getting involved in electron RT transport which occurs within the correspondingly broad voltage range.

Note that the resonance peaks can also appear if the electron-collecting energy range, instead of the electron-emitting one, is narrow enough. In principle, in MIS-RTDs, there is such a situation with an energetically narrow electron collector at negative gate biases ($V < 0$). Then it can be imagined that the electrons from the metal are tunneling via the QW levels into the empty v -band states. A reasonable amount of such states is available only slightly below the bulk valence band edge $E_{v\infty}$. Thereby, when $E_n \approx E_{v\infty}$ the RT peaks may appear. Electron tunneling into the much lower, filled states is improbable in accordance with Fermi statistics.

Theoretically, for the Al/SiO₂/p⁺-Si system with its regular band-offset parameters, it is not possible to fulfill the basic requirement

(1) for $V < 0$; consequently the above hypothetical RT-process seems to be excluded. However, some samples with electrochemical oxide demonstrate peaks (Fig. 5), which can be explained if some QW subbands may lie under $E_{v\infty}$ even at a negative gate bias. It should be noted that these features are making their appearance for relatively thick SiO_2 possessing positive Si/SiO_2 interface charges, and only after exposure of a MIS-RTD at $V > 0$ by the passage of some steps. Besides, the number of the discussed peaks under the polarity $V < 0$ is about the same as the number of the steps passed during a preliminary application of $V > 0$. In this case a form of the current–voltage curve depends on the program of voltage variation. These details may be related to the charging effects thanks to carrier localization in the QW in the course of electron RT from the silicon and their delocalization during electron RT from the metal. This phenomenon requires further study.

4. Conclusion

By presentation of the results of modeling and experimental investigations, the possibility for transformation of a metal–insulator–silicon capacitor into a resonant-tunneling diode has been shown. The energy band diagrams and the J – V characteristics of the $\text{Al}/\text{SiO}_2/\text{p}^+\text{-Si}(100)$ structures with Si doping level N_A of about 10^{19} cm^{-3} and SiO_2 thickness within 0.4–4.0 nm were discussed.

Novel MIS-RTDs are supposed to become a promising alternative to the traditional RTDs [4], based on the more complex materials and technologies not easily compatible with the MIS technologies. As compared to the previously reported Silicon-RTDs relying on the $\text{Al}/\text{SiO}_2/\text{Si}/\text{SiO}_2/\text{Si}/\text{Al}$ [5] and $\text{CaF}_2/\text{CdF}_2/\text{CaF}_2/\text{Si}$ [6] multilayer structures, or using the Si/SiGe systems (e.g. [7]), the proposed MIS-RTD is unambiguously simpler, that is one of its obvious advantages.

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