Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 48-49

B-2-4

Schottky Barrier MOSFETs as Resonant Tunneling Devices

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Abstract- **Double-gate, Schottky barrier MOSFETs in the nanometer regime are numerically studied. The appearance of negative differential resistance due to resonant tunneling effect is confirmed by NEGF simulation.**

1. Introduction

Resonant tunneling (RT) devices can single-handedly exhibit negative differential resistance. They attract us for their application in high frequency signal generation and high-speed signal processing, without increasing circuit area. The leading players in materials for RT devices have been III-V compound semiconductors such as GaAs and InP. Single or multiple quantum wells fabricated by them have produced a large variety of RT devices [1]. In addition, it is theoretically suggested that a tiny carbon nanotube junction device can also exhibit negative differential resistance [2]. However, in terms of easy fabrication and simple integration, silicon-based "monolithic" RT devices are more suitable for existing LSI technology. In this simulation study, we show that scaled Schottky barrier MOSFET (SBT) is a possible candidate for that purpose.

2. Simulation and discussion

Figure 1(a) is the double-gate FET with metal/silicide source and drain structure we used in this study. At the interface between intrinsic Si channel and source/drain, Schottky junctions are formed. Since Schottky barrier height ϕ_B between Si and metal/silicide is relatively high in nature, for example 0.7eV in $NiSi_2$, it causes a large parasitic resistance and limits the on-currents. Therefore, the formation of high ϕ_B has been considered to be a demerit for high performance operation, and much effort to lower ϕ_B has been spent [4]. In contrast, the SBT in RT operation aggressively uses the demerit of high ϕ_B, as a quantum box (Fig. 1(b)). More specifically, Schottky junction barrier replaces a quantum well fabricated by the hetero-junction of compound semiconductors like Fig. 1(c). The electron potential in the channel is pulled by the Schottky barriers at source/drain interfaces, forms a parabolic potential like Fig. 1(b). This parabolic-shaped electron potential plays a role of resonant cavity. In addition, the top and bottom gate modulate the resonance levels.

For the confirmation of RT operation in scaled SBTs, we have developed a device simulator similar to [3], written in C/C++. In the simulator, quantum mechanical phenomena in two directions are treated (Fig. 1(d)). Quantum confinement effect across the channel is taken into consideration by solving Schrödinger equations at each x-mesh slice. Ballistic quantum transport along the channel direction is one-dimensionally calculated by non-equilibrium Green's function (NEGF) method. We assume ideal volume inversion, well homogeneous electron density across the ultra-thin body Si channel. The two-dimensional Poisson equation is self-consistently solved with these two quantum phenomena.

Figure 2 shows calculated the first subband energy of electron in the channel at V_g=0.2V with different V_{ds}. In this case, the gate length L_g, the gate insulator (oxide) thickness T_{ins}, and the thickness of Si channel T_{Si} are 10nm, 1nm, and 3nm, respectively. The effective mass of electron along the confinement direction in the channel m^* is 0.98 m_0. Source and drain are assumed to be the metal or silicide materials forming ϕ_B of 0.75eV. Nevertheless, the calculated barrier height ϕ_{eff} shown in Fig. 2 is about 0.79eV, 40meV higher than ϕ_B. The reason is well discussed in Ref. [3]. In short, for thin body FETs, quantum confinement effect raises the lowest allowed electron energy level in the channel. Since this ϕ_{eff} behaves as actual Schottky barrier height, it should be noted that, regardless of the kind of source/drain materials, both T_{Si} and m^* also determine the shape of resonant cavity.

Figures 3(a) to (c) show I_{ds}–V_{ds} characteristics of the simulated device at T = 300 K. It is found that, in all simulated V_g cases, negative differential resistances are certainly exhibited, even though those peak-to-valley ratios are not high. As is schematically depicted in Fig. 1(b), Schottky barrier thickness at both source and drain becomes thinner with increasing V_g. It results in an increase of tunneling probability across the Schottky barrier, thus, at the same V_{ds}, large I_{ds} flows with high V_g. However, compared the peak-to-valley ratio in Fig. 3(a) to that in Fig. 3(b), high V_g does not necessary produce good resonant cavity. The range of applied gate voltage should be of course kept in mind for successful RT operation of SBTs. Local electron density of states shown in figures 4 (a) and (b) explain the appearance of negative differential resistance in Fig. 3(c). Due to the modification in resonance level by V_{ds}, the smooth electron tunneling from source to drain occasionally turns into the localization in the cavity. The localized electrons act as space charges, they no longer contribute to I_{ds} and hence decrease I_{ds}.

3. Conclusion

In summary, Schottky barrier MOSFETs in the nanometer regime are numerically studied. The appearance of the negative differential resistance due to resonant tunneling effect is confirmed by NEGF simulation. Designing the ϕ_B of metal/silicide materials for source/drain, the Si film thickness, and the applied voltage ranges, scaled SBTs could be utilized as resonant tunneling devices compatible with existing LSI technology.

References

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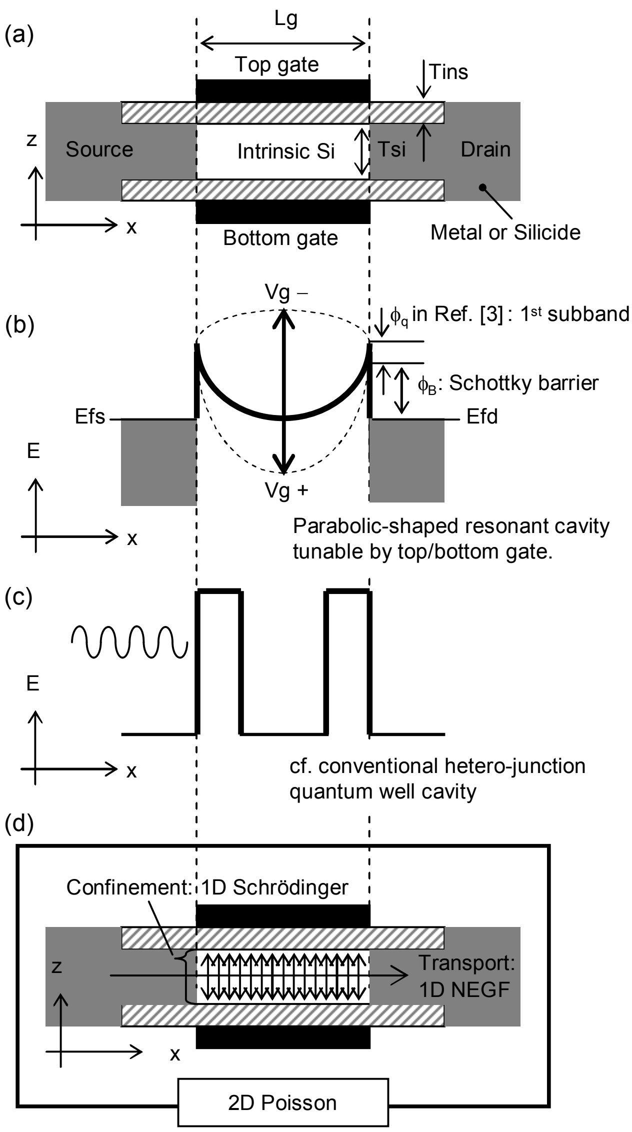

Fig. 1: Schematic view of simulated structures. In this study, the gate length L_g, the gate insulator (oxide) thickness T_{ins}, and the thickness of Si channel T_{Si} are 10nm, 1nm, and 3nm, respectively. The effective mass of electron along the confinement direction is 0.98 m_0. Source and drain are assumed to be the metal or silicide forming ϕ_B of 0.75eV.

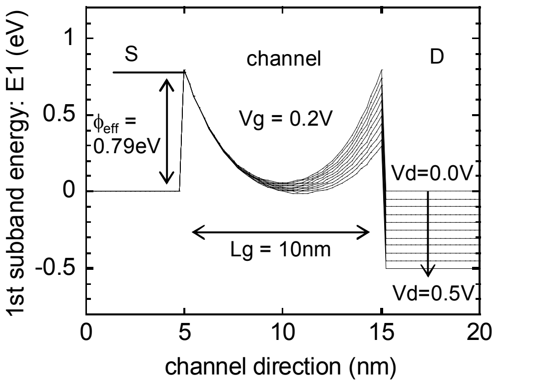

Fig. 2: Self-consistent calculation of 1st subband energy along the channel direction as a function of V_d.

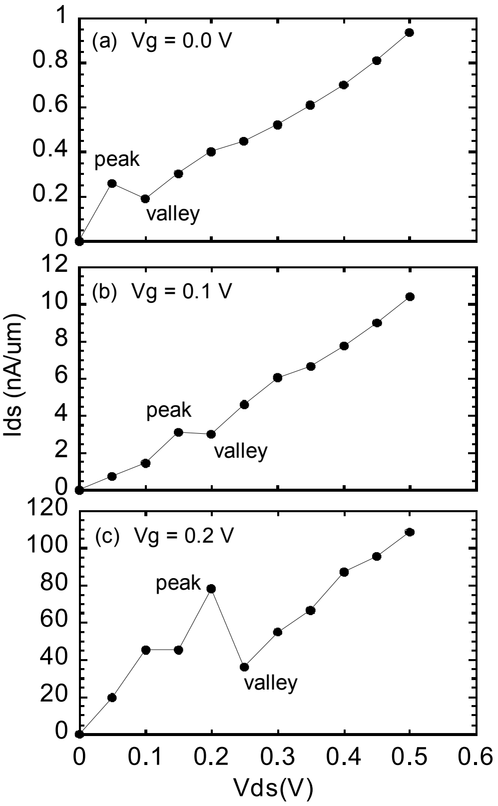

Fig. 3: I_d–V_d characteristics of SBTs. For all simulated V_g, negative differential resistances are observed.

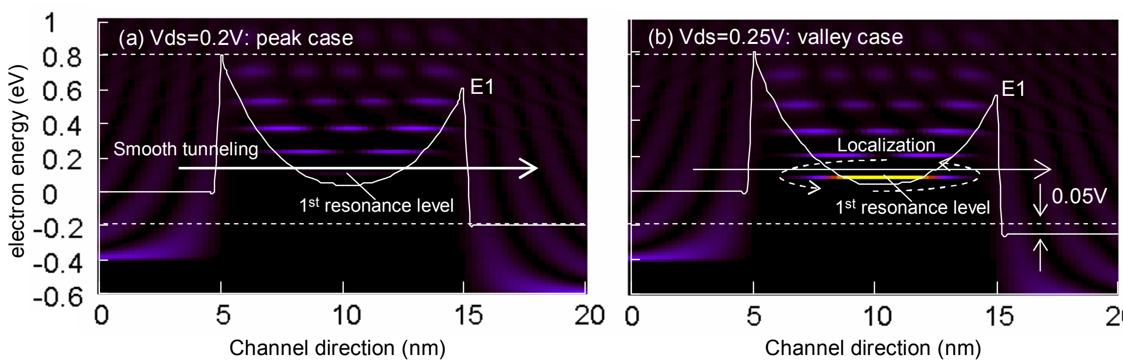

Fig. 4: Local electron density of states at V_g = 0.2 V for (a) V_{ds} = 0.2 V and (b) V_{ds} = 0.25 V. Bright regions mean higher density, whereas dark regions mean lower density. Despite the increase in V_{ds}, the smooth electron tunneling from source to drain seen in (a) occasionally turns into the localization seen in (b). The localized electrons act as space charges, they no longer contribute to I_{ds}.