Continuum versus Quasi-Bound State Tunneling in Novel Device Architectures

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INTRODUCTION

For down scaling to the sub-30nm channel length, novel device structures such as silicon-on-insulator (SOI), ultra-thin body (UTB), and double gate (DG) MOSFETs are expected to be introduced to suppress short-channel effects [1]. Accurate modeling of gate leakage currents remains an important issue.

CONTINUUM BASED TUNNELING MODELS

Calculation of tunneling currents is frequently based on the assumption of a three-dimensional continuum of states at both sides of the gate dielectric and the conservation of parallel momentum (see Fig. 1). Then, the tunneling current can be described by the Tsu-Esaki formula,

$$J_{\mathrm{TSU}} = \mathrm{q} \int_{\mathcal{E}_{\min}}^{\mathcal{E}_{\max}} TC(\mathcal{E}_x, m_{\mathrm{diel}}) N(\mathcal{E}_x, m_{\mathrm{D}}) \,\mathrm{d}\mathcal{E}_x \ ,$$

where $TC(\mathcal{E}_x, m_{\mathrm{diel}})$ is the transmission coefficient and $N(\mathcal{E}_x, m_{\mathrm{D}})$ the supply function [2]. The density of states mass and the mass of the dielectric is denoted by m_{D} and m_{diel}, respectively. The model has been successfully applied to reproduce the leakage behavior of bulk devices with moderate doping [3].

QBS TUNNELING MODELS

In contrast to bulk MOSFETs, in UTB devices using SOI substrates, also the geometrical confinement yields quantization. This strongly affects the local density of states, and gives rise to quasi-bound states (QBS), hence the assumption of a continuum of states is no longer valid. Each QBS gives rise to a tunneling current which follows from the number of electrons occupying the state over the corresponding lifetimes (see Fig. 2). Following [4], a summation over all contributing valleys and states gives the total leakage current by

$$J_{\mathrm{QBS}} = \frac{\mathrm{k_B}T\mathrm{q}}{\pi\hbar^2} \sum_{i,\nu} \frac{g_\nu m_\parallel}{\tau_{\nu,i}} \ln\left(1 + \exp\left(\frac{\mathcal{E}_{\mathrm{F}} - \mathcal{E}_{\nu,i}}{\mathrm{k_B}T}\right)\right) .$$

Here, $\mathcal{E}_{\nu,i}$ and $\tau_{\nu,i}$ denote the energy level and the lifetime of the i^{th} QBS of the ν^{th} valley respectively, which have been estimated form a numerical solution of the Schrödinger equation with open boundary conditions [5].

RESULTS

Both, the Tsu-Esaki and the QBS tunneling model has been implemented in a general purpose Schrödinger Poisson (SP) solver. Double Gate device structures with 5 nm and 20 nm Si film thickness have been investigated. For the Tsu-Esaki model, the transmission coefficient of the barrier and the current distribution over the energy is shown in Fig. 3. It has to be evaluated at both gate dielectrics. For QBS tunneling, the energy levels, the lifetimes, and the contribution to the total current of some QBS is depicted in Tab. I. It directly gives the total current density. Fig. 4 shows the lifetimes of the first three QBS as a function of the applied gate bias. A comparison of the leakage current using continuum based Tsu-Esaki and the QBS tunneling model is carried out in Fig. 5. It clearly shows that the continuum model, neglecting the effect of quantization, overestimates the current about two orders of magnitude for quite arbitrary geometries.

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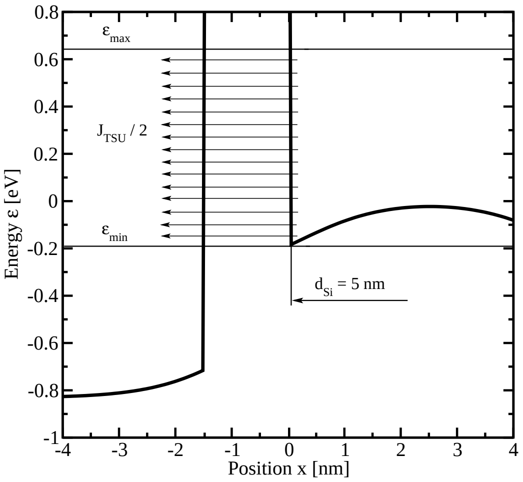

Fig. 1. For the Tsu-Esaki tunneling model, a continuum of states at both sides of the dielectric layer is assumed.

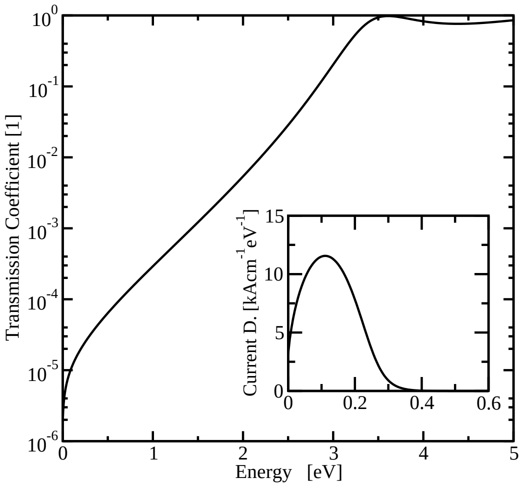

Fig. 3. The transmission coefficient of the barrier and the current density as a function of the energy at a gate bias of 1.2 V.

QBS	$\mathcal{E}_\mathrm{r}$ [eV]	τ [ns]	J_G [A cm^{-2}]
1	0.11	2.74	5.7×10^2
2	0.23	1.79	4.6×10^2
3	0.28	1.38	9.2×10^1
4	0.42	0.62	4.9×10^0
5	0.52	0.30	6.0×10^{-2}

Tab. I. The QBS in a DG MOS structure, energy levels, lifetimes, and their contribution to the gate current density for a gate bias of 1.2 V.

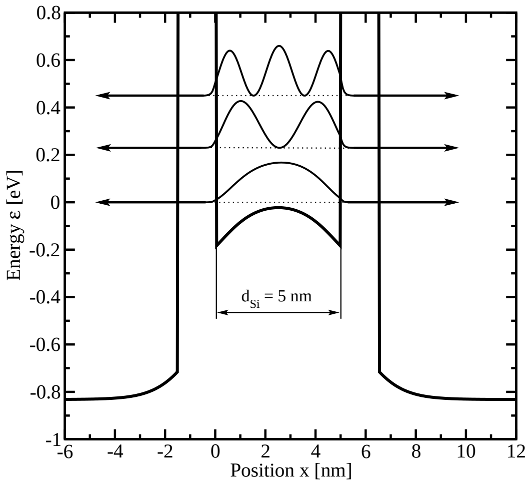

Fig. 2. The wave functions and the energy levels of the three lowest quasi-bound states are shown.

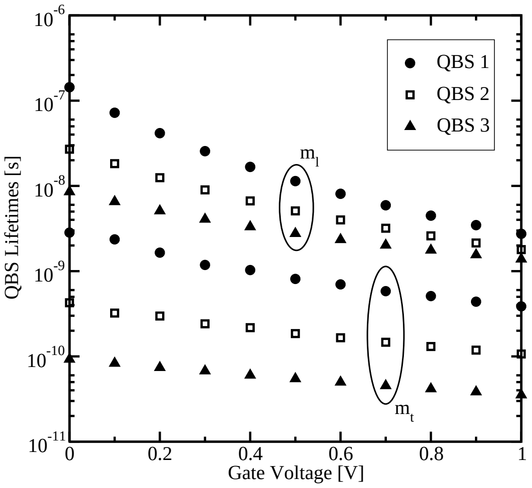

Fig. 4. The QBS lifetimes as a function of the gate bias using lateral and transversal mass as quantization masses.

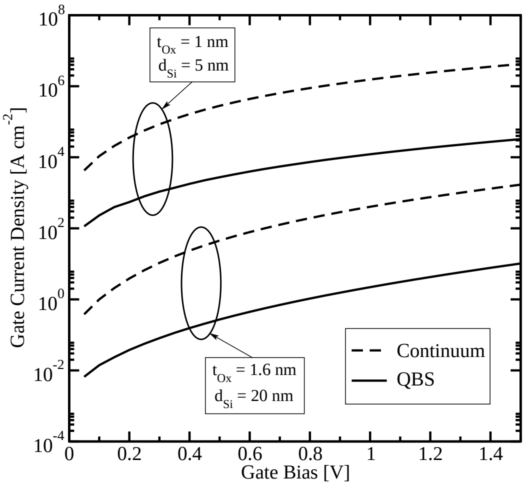

Fig. 6. The leakage current of different devices using continuum based and QBS tunneling model. The continuum based model clearly overestimates the current.