Band to Band Tunneling limited Off state Current in Ultra-thin Body Double Gate FETs with High Mobility Materials : III-V, Ge and strained Si/Ge

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Abstract — **We have developed new Band to Band Tunneling (BTBT) model, which captures band structure information, all possible transitions between different valleys, energy quantization and quantized density of states (DOS). Minimum standby off-state currents ($I_{OFF,MIN}$) are investigated in Double Gate (DG) MOSFETs with various high mobility materials, like GaAs, InAs, Ge and strained Si/Ge (s-Si/s-Ge) using the new band to band tunneling model. Our results show that the body thickness & supply voltage strongly affect the BTBT and should be carefully chosen to meet the ITRS specifications of the off state leakage current in these new high mobility/small bandgap materials.**

I. Introduction

High mobility materials are being investigated as channel materials in highly scaled MOSFETs to enhance performance [1]-[4]. The materials such as GaAs, InAs, Ge, strained Si and strained Ge have larger carrier mobility than silicon, but the enhanced band to band tunneling (BTBT) because of their smaller bandgap or direct band gap may limit their scalability [1]-[4]. Although it becomes important to predict the band to band tunneling leakage of devices made with high-mobility materials, the most commonly used BTBT models in commercial TCAD tools [8]-[10] do not capture quantization effects and full band information of nano-scale devices. In this work, we have developed a BTBT model, which captures important quantum mechanical (QM) effects in highly scaled DGFETs. Using the BTBT model, we investigate the operation window for DGFETs with various high mobility/small bandgap (Eg) materials to meet the ITRS High Performance off current requirement for 15nm node.

II. Modeling Band to Band Tunneling (BTBT)

Our BTBT model is able to calculate the leakage current in thin body DGFET simulations where the tunneling occurs dominantly in the x direction and the states are quantized along the z direction (Fig. 1). As shown in Fig. 2, an ultra-thin body has a larger effective band gap and smaller DOS than bulk, due to strong quantization. With larger effective band gap, the wave function decays faster inside the forbidden gap and lowers BTBT rate. To take into account the quantization effect caused by ultra-thin body, the wavefunctions and the energy levels of quantized subband states were obtained by solving 1-D Schrödinger equation along z-direction for both electrons and holes. We evaluated the interband matrix elements between quantized states for both direct and indirect tunneling, following Kane's approach. Fermi's Golden rule is used to determine the band to band transition rate between states. The final BTBT carrier generation rate was calculated by adding up the transition rates for all the possible transitions. Fig. 3 shows the possible transition from valence band to conduction bands such as Γ_V-Γ_C, Γ_V-L and Γ_V-X. While counting, for direct tunneling the momentum conservation selection rule was applied, while for the indirect tunneling, the selection rule was relieved.

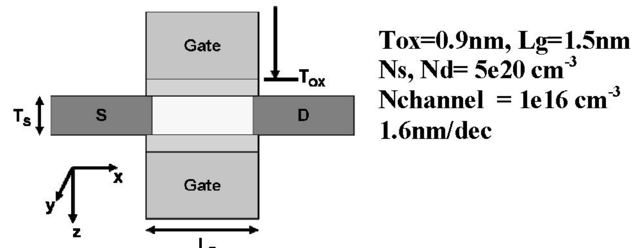

Fig. 1 Schematic of the DGFET structure considered in this work.

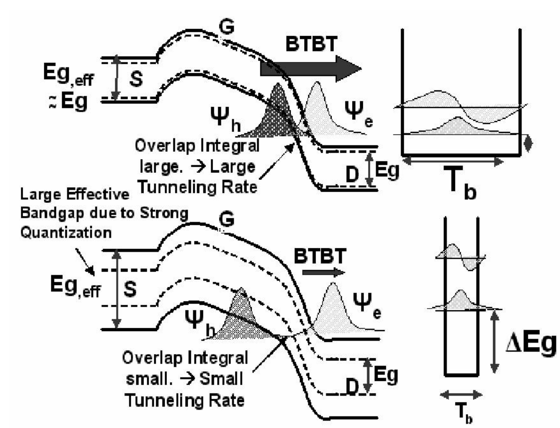

Fig. 2 Ultra-thin body and larger quantization increases the effective bandgap and lowers the tunneling rate.

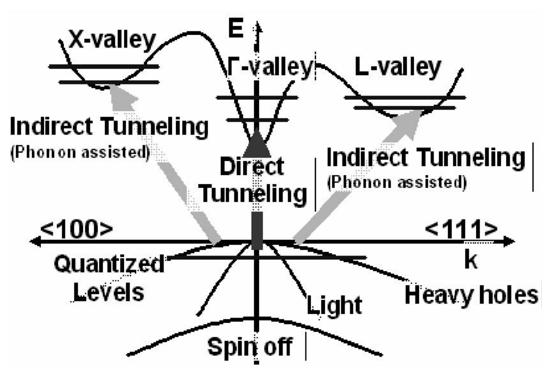

Fig. 3 All Possible (Direct and Indirect) Tunneling Paths, Γ-Γ, Γ-X and Γ-L, are captured by the model.

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III. DGFET Simulations with BTBT Model

The device structure simulated is shown in Fig. 1. Fig. 4 shows typical Id-Vg characteristics of a p-MOSFET. The minimum achievable standby leakage ($I_{OFF,MIN}$) is at the intersection of the BTBT leakage with the subthreshold leakage. TAURUS™ was used to estimate the subthreshold leakage. For all the materials simulated in this paper, channel direction(x) is chosen to be (100), quantization direction(z) to be (001) and width direction (y) to be (010).

Fig. 5 (a) and (b) show the effect of body thickness on the quantization and $I_{OFF,MIN}$ in Ge p-MOSFET. The large quantization in the Γ_C-valley causes > 1000X reduction in $I_{OFF,MIN}$ from 10nm to 3nm. Considering realistic scenario, with finite oxide barrier height (3eV) boundary condition, the quantization in energy levels is lowered leading to a smaller reduction in $I_{OFF,MIN}$. Fig. 5 (c) shows that in Ge the transition of the dominant leakage path from direct tunneling to indirect tunneling occurs due to large quantization in Γ_C-valley compared to L-valley. For 10nm body thickness, direct BTBT through Γ_C-valley is dominant, but with 3nm body thickness, indirect BTBT through L-valley becomes dominant leakage path. Fig. 6 shows $I_{OFF,MIN}$ in both Ge p-MOSFET and n-MOSFET. Here, we find that the $I_{OFF,MIN}$ is not strongly affected by the type of MOS (N or P), which implies that it is also independent of other device parameters, like gate workfunction.

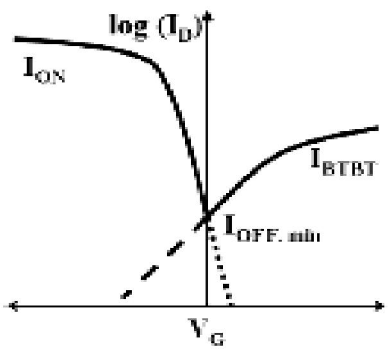

Fig. 4 Typical Id-Vg for a p-MOSFET. $I_{OFF,MIN}$ is the minimum achievable leakage current in a MOSFET.

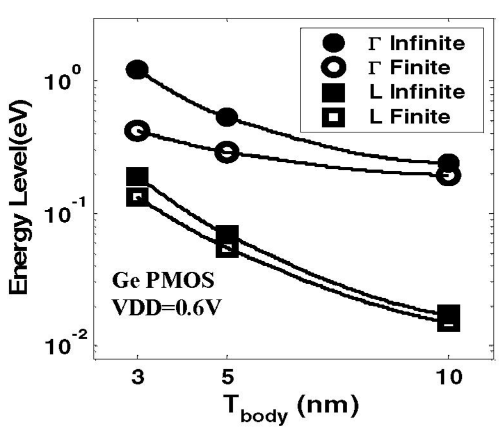

Fig. 5 (a) Effect of Body Thickness on Quantization. Using a realistic (3eV) finite oxide barrier boundary condition reduces the quantization.

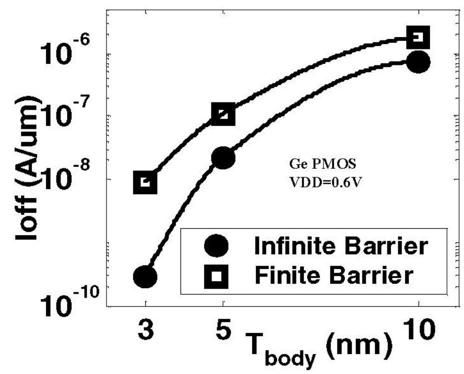

Fig. 5 (b) Effect of Quantization on $I_{OFF,MIN}$. Increase in the Eg,eff and decrease in DOS due to quantization reduces the $I_{off,min}$

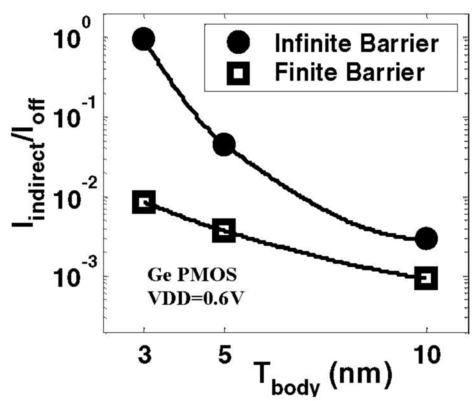

Fig. 5 (c) Ratio of Indirect tunneling as a function of Body thickness. Indirect tunneling becomes significant in ultra-thin body due to the smaller quantization

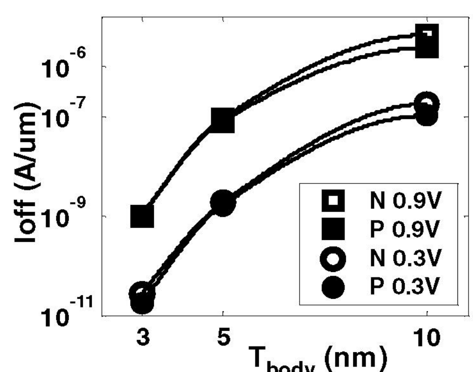

Fig. 6 $I_{OFF,MIN}$ for Ge NMOS and PMOS are identical. The BTBT is not a strong function of device parameters, like gate workfunction.

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IV. Leakage Current in High Mobility/ Small Bandgap Materials

GaAs, InAs, Ge and Si are strong candidates for channel material in n-MOS. In the case of p-MOS, 100% biaxially tensile-strained Si (s-Si), 100% biaxially compressive-strained Ge (s-Ge), relaxed Ge and relaxed Si are considered. 100% biaxially tensile-strained Si (s-Si) has same strain as the silicon epitaxially grown on germanium substrate (001). 100 % biaxially compressive-strained Ge (s-Ge) has same strain as the germanium epitaxially grown on silicon substrate (001). The material parameters are taken from [6][7].

In Fig. 7, $I_{OFF,MIN}$ is plotted as a function of band gap (Eg) and thickness (Tbody) for different materials. Generally, the wider bandgap materials show smaller BTBT current. In Fig. 7, Ge deviates from the trend due to its large direct tunneling component. Compared to other candidate materials for PMOS, direct tunneling is dominant in Ge due to the proximity of the Γ-valley to the L-valley. In Fig 8, Si deviates from the trend, exhibiting lower $I_{OFF,MIN}$, due to its indirect bandgap. Since s-Si has a large conduction band effective mass in the z-direction, its quantization is very weak and shows a small reduction in $I_{OFF,MIN}$ even at 3nm body thickness. With 3nm body thickness InAs exhibits smaller BTBT current than Ge. Although InAs has smaller bandgap than Ge, smaller Γ-valley mass of InAs leads larger quantization and larger reduction in leakage current as body becomes thinner. Fig. 9 and Fig. 10 show the relationship between $I_{OFF,MIN}$ and VDD. Large drain voltage increases electric field in the device, which worsens the BTBT current.

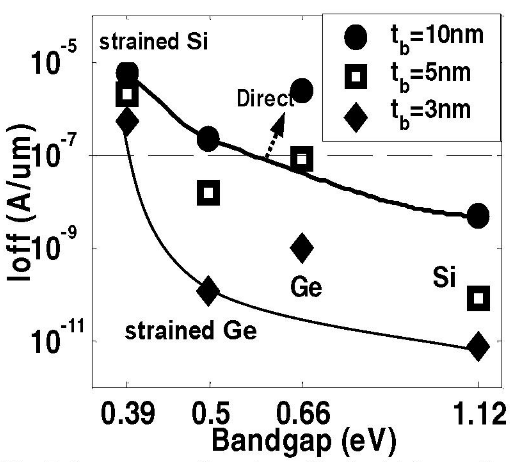

Fig 7. $I_{OFF,MIN}$ as a function of body thickness for p-MOS channel materials. Ge has a large direct bandgap leakage component

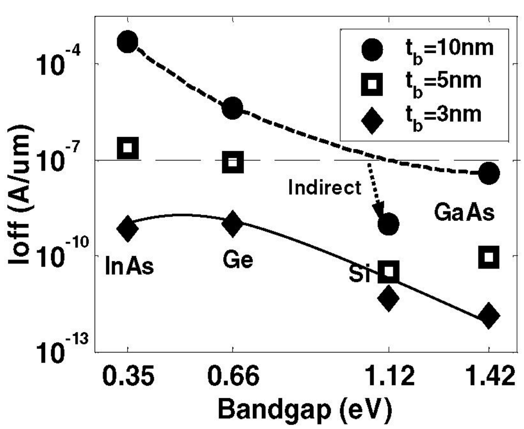

Fig. 8 $I_{OFF,MIN}$ as a function of body thickness for n-MOS channel materials. Si is indirect bandgap and leaks less.

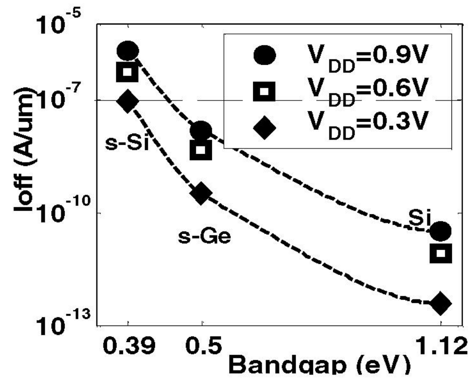

Fig. 9 $I_{OFF,MIN}$ as a function of V_{DD} for indirect bandgap materials. Bandgap varies depending on strain and material (strained Si /Ge and relaxed Si).

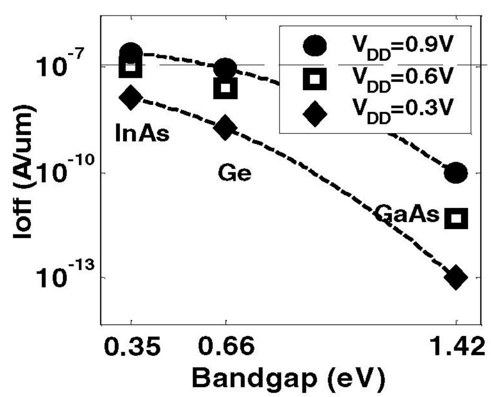

Fig. 10 $I_{OFF,MIN}$ as a function of V_{DD} for direct bandgap materials. Bandgap varies depending on material.

V. Maximum allowable V_{DD} – T_{BODY} Tradeoff

Reducing body thickness is very effective in reducing the BTBT current. However it is not easy to manufacture thin body DGFETs because of process variations, technological complexity and increased cost. Larger V_{DD} increases the drive current but results in a worse $I_{OFF,MIN}$. To evaluate the practicability of various materials based on BTBT leakage current at the 15nm technology node, we plot the maximum V_{DD} versus T_{body} curve (Fig. 11). The figure shows the maximum allowable V_{DD} at a given T_{body} for a constant $I_{OFF,MIN}$ of 0.1uA/um (iso-leakage contours). The combination of V_{DD} and T_{body} below the curve satisfies the ITRS HP requirement for the 15nm node Off-current specification. The result shows that 100% s-Si cannot be used unless it is operated under 0.5V, while Ge and InAs can be operated at 0.9V as long as body is thinner than 5nm. Si and GaAs can be operated over 1.5V due to their large bandgap. Although s-Ge has a smaller bandgap than Ge, s-Ge shows a much lower BTBT leakage current than Ge due to its large quantization and indirect bandgap.

VI. Conclusion

We have developed a Band to Band Tunneling model which captures band structure information, all possible transitions between bands (Full Band), energy quantization and quantized density of states. This new model is implemented to study 15nm DGFETs with various futuristic high-mobility channel materials, like GaAs, InAs, Ge and strained Si/Ge. The possibility of adopting these new materials, in terms of BTBT leakage current, is examined. We suggest a new design rule, which constrains the maximum allowable V_{DD} at a given body thickness, to meet the Off-state specifications in DGFET with various high-mobility / small bandgap channel materials.

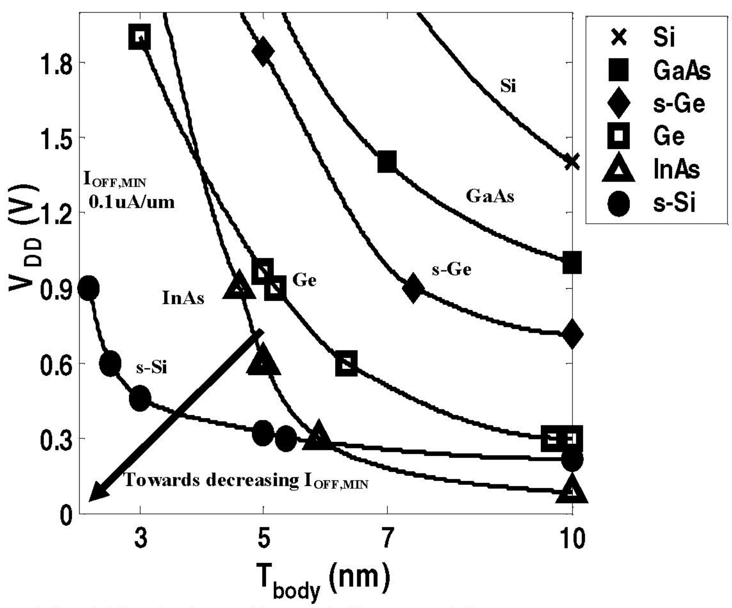

Fig. 11 Iso-leakage ($I_{OFF,MIN}$) Contours. These curves determine the maximum allowable V_{DD} to meet the ITRS off current requirement for a 15nm gate length, at a given body thickness (constrained by technology).
s-Si cannot be used for >0.5V operation. Ge and InAs can be used for 0.9 operation when Tbody<5nm. For Tbody<7nm s-Ge can be used for >1V operation. Si and GaAs comfortably meet the off-current specification because of their large bandgap.

VII. References

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