

Influence of Carrier Confinement on the Subthreshold Swing of Multigate SOI MOSFETs

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1. Abstract

The minimum energy of the first conduction subband varies with gate voltage in trigate SOI MOSFETs in subthreshold operation. In an inversion-mode device, the energy level of the lowest subband increases when the electron concentration increases, while it decreases under the same conditions in some accumulation-mode devices. As a result of this quantum effect, the subthreshold swing of accumulation-mode trigate FETs is smaller than predicted by classical theory, while that of inversion-mode devices is higher. This effect is not observed in FinFETs and GAA MOSFETs and can be amplified by modifying the device cross section.

2. Introduction

It has been previously shown that the minimum of the energy subbands increases in trigate FETs when the section of the device is reduced. Furthermore, in inversion-mode devices, the minimum energy of the energy subbands increases when the electron concentration is increased, which dynamically increases the threshold voltage as the inversion charge builds up. This effect reduces the current drive of the device and is not predicted by classical simulators. It also increases the value of the subthreshold swing, expressed in millivolts per decade, as the energy of the first subband increases with carrier concentration in subthreshold operation.[1] In this paper, we analyze this phenomenon in different type of multigate devices operating either in inversion or accumulation mode.

3. Device simulation

Two-dimensional simulations of FinFETs, trigate and GAA FETs have been carried out by solving the Poisson equation and the Schrödinger equation self-consistently.[1] Both inversion-mode and accumulation-mode N-channel devices were simulated. The gate oxide thickness, t_{ox} , is 2 nm and the buried oxide thickness, t_{BOX} , is 10 nm. The fin height, or silicon film thickness, t_{si} , is equal to the device width, W_{si} , in the trigate and GAA devices, and it is equal to $3 \times W_{si}$ in the FinFET. There is no hard mask at the top of the FinFET, which is basically a trigate FET with a 3:1 height to width aspect ratio. The inversion-mode (IM) devices have a P-type doping concentration of $5 \times 10^{18} \text{cm}^{-3}$ and the

accumulation-mode (AM) devices an N-type doping concentration of $2 \times 10^{19} \text{cm}^{-3}$. Devices with a larger section ($10 \text{nm} \times 10 \text{nm}$ for GAA and trigate devices and $10 \text{nm} \times 30 \text{nm}$ for the FinFET) were simulated as well and present the same characteristics as the $5 \text{nm} \times 5 \text{nm}$ and $5 \text{nm} \times 15 \text{nm}$ devices. The subthreshold curve, defined as $dV_G/d(\log(I_D))$ plotted vs. V_G is shown in Figure 1 for the different devices, as a function of the average electron concentration.

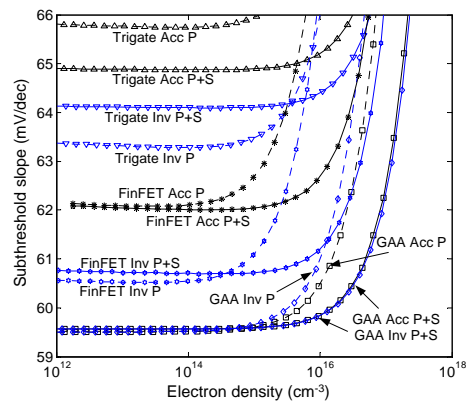


Fig.1: Subthreshold swing in inversion-mode (Inv.) and accumulation-mode (Acc.) trigate FETs calculated using the Poisson equation (P) or a Poisson/Schrödinger solver (P+S).

The subthreshold swing is defined as the value of S when the curves plateau, typically for electron concentrations below 10^{14}cm^{-3} . In the GAA device, the subthreshold swing reaches the theoretical limit of 59.6 mV/decade at $T=300\text{K}$. This is because there is no body effect in this device. In the FinFET, similar classical (P) and quantum (P+S) subthreshold swings are obtained. The subthreshold swing value is a little bit higher than in the GAA device because there is a non-zero body effect. The swing in the accumulation-mode device is larger than that in the inversion-mode device because the charge centroid of the AM device is in the centre of the devices (at a distance $W_{si}/2$ from the lateral Si/SiO₂ interfaces), while the charge centroids in the IM device are located at a smaller distance from the interfaces.[2] In the trigate device, the subthreshold swing is larger than in the two other devices because of a larger body effect.[3,4] More remarkably, the classical simulation overestimates the subthreshold swing in the accumulation-mode device, while it underestimates it in the inversion-mode device.

4. Discussion

Figure 2 helps understanding the discrepancy between the classical and quantum calculations in trigate devices. In the GAA device, where there is no back gate and, therefore, no body effect, the shape of the potential distribution within the silicon remains unchanged as long as the device is in subthreshold operation, *i.e.* when the electron concentration is low. As a result, the minimum of the first energy subband stays constant as long as the electron concentration is below 10^{17} cm^{-3} .

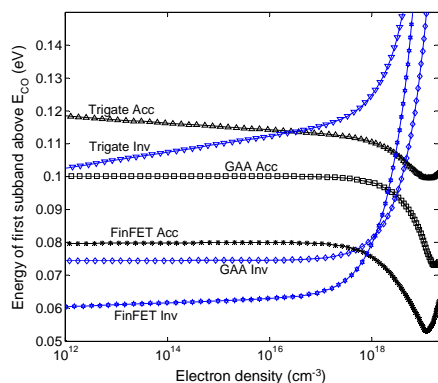


Fig.2: Minimum energy of first subband vs. average electron concentration in inversion-mode (Inv.) and accumulation-mode (Acc.) trigate FETs calculated using the Poisson equation (P) or a Poisson/Schrödinger solver (P+S).

The increase or decrease of the energy level is related to the "compression" or "decompression" of the electron gas, represented by the $-\frac{\hbar^2}{2m}\nabla^2\psi$ term in Schrödinger's equation. To illustrate this we simulate a special structure with an electron "reservoir" below the silicon fin (Figure 3).

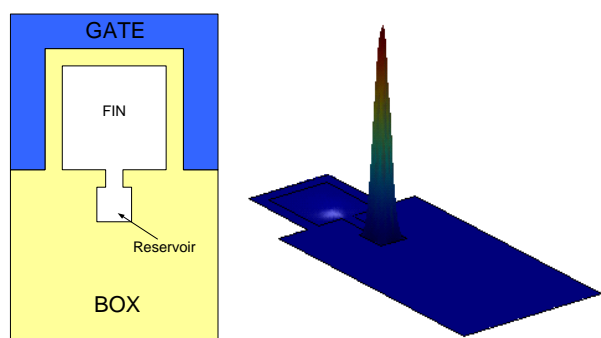


Fig.3: Accumulation-mode MuGFET with an electron "reservoir" below the Fin (right). Electron concentration at $V_G = -0.5V$ (left).

At low gate voltage the electron wavefunctions are compressed in the small volume of the reservoir, which creates relatively high subband energy levels. As the gate voltage is increased, the wavefunction "move" towards the fin, where they are "decompressed", and the energy values decrease (Figure 4). At very high gate voltage, the wavefunctions are again "compressed" in two peaks near the top of the fin, and the energy increases again.

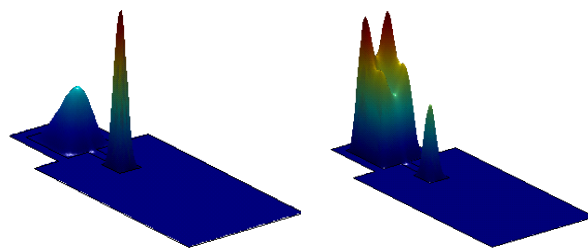


Fig.4: Electron concentration at $V_G = 0.0V$ (left) and $+0.9V$ (right).

The energy of the first subband is shown in Figure 5 in the accumulation-mode device with a "reservoir", as a function of electron density. It decreases when the electron gas is "decompressed" and increases when it is "compressed". The effect on this energy reduction on the subthreshold slope curve can be seen in Figure 6, where the classical and quantum simulations are compared.

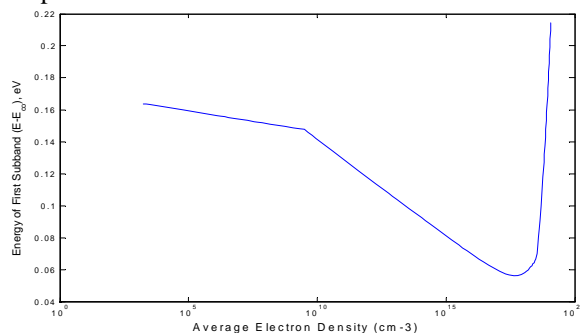


Fig.5: Energy of first subband vs. electron concentration.

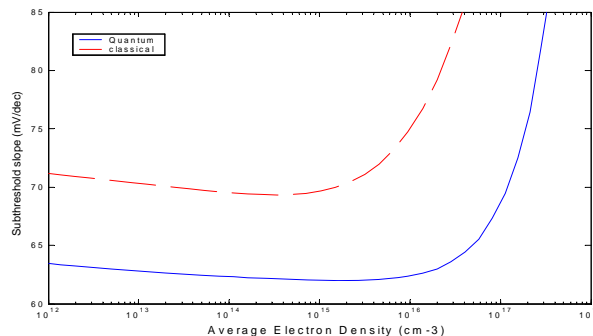


Fig.6: Subthreshold curve vs. electron concentration.

5. Conclusions

Electron wavefunction "compression/decompression" is shown to worsen/improve the subthreshold slope of MuGFETs, respectively.

Acknowledgements

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References

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