A Compact Model for the Threshold Voltage of Silicon Nanowire MOS Transistors including 2D-Quantum Confinement Effects

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Introduction

- Quantum-mechanical compact model of the threshold voltage ($V_T$) for long channel quantum nanowire MOSFETs.

- Quantum correction based on the perturbation theory has been also introduced to improve the model accuracy.

- Approach based on the decoupled solution of the Poisson and Schrödinger equations in the transverse plane of the structure.

- VT model validated with numerical data obtained with a 2D/3D QM simulation code (BALMOS 3D).
Silicon Nanowire MOSFET

• The multigate architectures: widely recognized as one of the most promising solutions for meeting the roadmap requirements, thanks to their excellent electrostatic control of channel.

• Schematic representation of different architectures envisaged for the Si nanowire MOSFET. The main geometrical key-parameters of the devices are defined.
Definitions and criterion

Threshold voltage definition and criterion

\[ Q_i = Q_{iT} \]

\[ Q_{iT} \approx (V_G - V_T)C_{ox} = \frac{kT}{q} C_{ox} \]

Device electrostatics

Electrostatic potential

\[ \Psi = \Psi_s - \beta t_{Si} \ y + \beta \ y^2 \]

Boundary conditions

\[ V_G - V_{FB} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} t_{ox} E + \Psi_s + \Phi_F \]

Electric field

\[ E = -\frac{d\Psi}{dy}\bigg|_{y=0} = \beta t_{Si} \]
Development of the analytical model

Quantum-mechanical evaluation of the inversion charge

Inversion charge

\[ Q_i(V_G) = q \sum \sum n(E_{kij}) \]

\[ n(E_{kij}) = 2 \times \int_{E_k}^{+\infty} \rho_{ID}(E_{kij}) f(E) \, dE \]

\[ \rho(E_{kij}) = \frac{1}{\pi} \left( \frac{2m_D}{\hbar^2} \right)^{1/2} \frac{1}{\sqrt{E - E_{kij}}} \]

\[ f(E) = \frac{1}{1 + \exp \left( \frac{E - E_F}{kT} \right)} \]

Confinement → Quantization of energy

Energy levels

Infinite rectangular well

\[ E_1(i,j) = \frac{\pi^2 \hbar^2 i^2}{m_I t_{Si}^2} + \frac{\pi^2 \hbar^2 j^2}{m_I W^2} \]

\[ E_2(i,j) = \frac{\pi^2 \hbar^2 i^2}{m_I t_{Si}^2} + \frac{\pi^2 \hbar^2 j^2}{m_I W^2} \]

\[ E_3(i,j) = \frac{\pi^2 \hbar^2 i^2}{m_I t_{Si}^2} + \frac{\pi^2 \hbar^2 j^2}{m_I W^2} \]
Development of the analytical model

Energy levels: perturbation method

First-order perturbation

\[ \tilde{E}_k(i,j) = E_k(i,j) + \Delta E_{ij} \]

\[
\begin{align*}
E_1(i,j) &= \frac{\pi^2 h^2 i^2}{m t_{Si}^2} + \frac{\pi^2 h^2 j^2}{m t_{Si} W^2} \\
E_2(i,j) &= \frac{\pi^2 h^2 i^2}{m t_{Si}^2} + \frac{\pi^2 h^2 j^2}{m t_{Si} W^2} \\
E_3(i,j) &= \frac{\pi^2 h^2 i^2}{m t_{Si}^2} + \frac{\pi^2 h^2 j^2}{m t_{Si} W^2}
\end{align*}
\]

Energy levels
Infinite rectangular well

\[ \Delta E_{ij} = \langle \varphi_{ij} | V | \varphi_{ij} \rangle \]

\[ V(y,z) = \beta_y y(t_{Si} - y) + \beta_z z(W - z) \]

\[ \varphi_{ij}(y,z) = \sqrt{\frac{2}{t_{Si}}} \sin\left(\frac{i\pi y}{t_{Si}}\right) \cdot \sqrt{\frac{2}{W}} \sin\left(\frac{j\pi z}{W}\right) \]

\[ \Delta E_{ij} = \int_{W \times t_{Si}} [\varphi_{ij}(y,z)]^2 V(y,z) dy dz \]

\[ = \frac{\beta_y t_{Si}^2}{6} \left(1 + \frac{3}{i^2 \pi^2}\right) + \frac{\beta_z W^2}{6} \left(1 + \frac{3}{j^2 \pi^2}\right) \]
Model validation

Quantum $V_T$ predicted by the compact model in excellent agreement with QM numerical simulation data
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Abstract

A quantum-mechanical model of the threshold voltage of silicon nanowire MOSFETs has been proposed. The model is based on the calculation of the confinement of electronic states in the nanowire channel. A quantum correction term is included to account for the 2D confinement of the electronic states in the nanowire channel, which is expressed by comparison with deep channel MOSFETs. The model is validated by comparison with test devices with a 2D-Quantum Confinement 2D-Quantum Confinement MOSFET technology.

Silicon Nanowire MOSFET

Model validation

Conclusion

Additional information