Compact modelling for quantum confinement for InGaAs nanowire gate all around MOSFET

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In this Letter, a compact equation for calculating energy sub-bands inside III–V gate all around nanowire MOSFET is developed taking into consideration the penetration of the wave function into the gate oxide and the effective mass discontinuity at the semiconductor–oxide interface. The values of the sub-band energies result from solving Schrodinger's equation in cylindrical coordinates is expressed in Bessel functions. The authors use an approximation for Bessel functions with the introduction of one fitting parameter. The results show very good agreement with self-consistent Schrodinger–Poisson solver data.

Introduction: Innovative solutions regarding MOSFET's structure and material have emerged to continue improvement in performance leading to higher computing ability. Multi-gate structures have been introduced to replace planar devices, also III–V materials such as GaAs or InGaAs have been introduced to replace Si as the conducting channel material [1]. MOSFET's structure has evolved from planar architecture to new and innovative architectures such as FinFET and fully depleted silicon on insulator (SOI) as shown in Fig. 1 [2]. FinFET is now used in the production for 14 nm CMOS node because it offers better electrostatic control in contrast to planar MOSFETs as the gate wraps the channel from three sides [3]. The semiconductor industry is now considering the gate all around (GAA) architecture, where the gate wraps the channel from all sides [4]. Therefore, the GAA structure provides the ultimate electrostatic control over the channel. III–V materials are very good candidates to be used as the conducting channel instead of Si because they provide greater carrier mobility. Therefore, III–V GAA nanowire MOSFET is a promising candidate for future CMOS nodes.

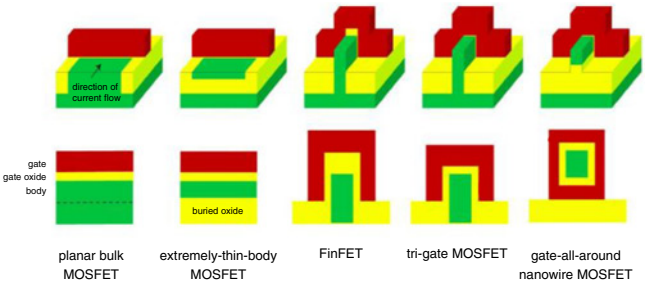

Fig. 1 *Transistor evolution from left, planar bulk MOSFET, SOI, FinFET, tri-gate MOSFET and gate-all-around squared nanowire MOSFET. Note that the simulation is done on gate-all-around cylindrical nanowire MOSFET [2]*

For this new MOSFET structure to be used in integrated circuits design, we need to have compact models, which are sets of analytical equations describing the *I–V* and *C–V* characteristics of the device. Compact models for III–V double gate field effect transistor (DGFET) are available [5], but it takes into consideration the 2D density of states (DOS) as DGFET is confined only in one direction. Unlike the nanowire structure which is confined in two directions, thus we need to take into consideration 1D DOS for charge modelling.

In this work, we present a compact equation for the first energy sub-band inside III–V GAA cylindrical nanowire MOSEFT considering the wave function penetration into the gate oxide, which is important for modelling low-effective-mass materials [6]. This is a necessary step to develop a charge control model of this device. This model is restricted for the isotropic effective mass of Γ valley. We make advantage of this restriction along with the cylindrical symmetry of the device to solve Schrodinger's equation in polar coordinates. The model shows very good agreement with the self-consistent Schrodinger–Poisson solver data.

Model development: First, to obtain the sub-band energies we need to solve the Schrodinger's equation in cylindrical coordinates. A cylindrical well with finite potential barrier is assumed considering different effective masses for semiconductor and oxide. This system is depicted in Fig. 2.

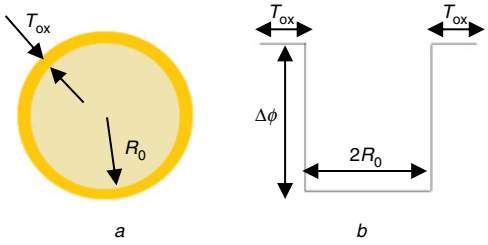

Fig. 2 *Cross sectional view of a nanowire MOSFET and representation for the considered cylindrical potential well*

a Cross-sectional view of the nanowire MOSFET where R_o is the semiconductor radius and T_{ox} is the oxide thickness

b 2D representation for the cylindrical finite potential well, where $\Delta\phi$ is the conduction band difference between the semiconductor and the oxide

Marin *et al.* [7] provide the solution to this system in terms of the Bessel functions in which we can find the values of the energies by solving simultaneously the following set of equations:

$$\frac{\eta}{m_a}\frac{J_{l-1}(\eta)-J_{l+1}(\eta)}{J_l(\eta)} = -\frac{\xi}{m_b}\frac{K_{l-1}(\xi)+K_{l+1}(\xi)}{K_l(\xi)}, \tag{1}$$

$$\eta^2+\frac{m_a}{m_b}\xi^2 = \frac{2m_a\Delta\phi R_0^2}{\hbar^2}, \tag{2}$$

where $J_l(\eta)$ is the Bessel function of the first kind, $K_l(\xi)$ is the modified Bessel function of the second kind, m_a and m_b are the effective masses in the semiconductor and oxide, respectively, R_0 is the radius of the nanowire and $\Delta\phi$ is the potential difference between the semiconductor and the oxide.

Note that $\eta=\gamma R_0$ and $\xi=\alpha R_0$ are related to the energy eigenvalues through the following set of equations:

$$\gamma^2=\frac{2m_a}{\hbar^2}\hat{E}, \quad \alpha^2=\frac{2m_b}{\hbar^2}(\Delta\phi-\hat{E}). \tag{3}$$

Various solutions are possible depending on the value of l in (1), $l=0$ will provide the value of the first energy sub-band and $l=\pm 1$ will give the second and third degenerate sub-bands. The number of solutions depends also on the magnitude of the right-hand side in (2).

In order to solve the above set of equations, we need to find the values of the Bessel functions, which are given by a tabular form. This is not recommended from the compact modelling prospective.

To develop a compact model, we need to make approximations for the Bessel functions. Similar work was done in [8], where they used trigonometric function as an approximation for $J_l(\eta)$ and an exponential function for $K_l(\xi)$.

In this work, we use the same approximation for $K_l(\xi)$, but we use different approximation to express $J_l(\eta)$. This leads to a much simpler equation for the energy eigenvalues.

The Bessel function of the first kind can be expressed as the following series [9]:

$$J_l(\eta)=\sum_{m=0}^{\infty}\frac{(-1)^m}{m!\,\Gamma(m+l+1)}\left(\frac{\eta}{2}\right)^{2m+l}. \tag{4}$$

Taking only the first term from the series, $J_l(\eta)$ can be approximated as

$$J_l(\eta)\simeq\frac{1}{\Gamma(l+1)}\left(\frac{\eta}{2}\right)^{l}. \tag{5}$$

For the modified Bessel function of the second kind $K_l(\xi)$, we used the approximation presented in [8] as given in the following equation:

$$K_l(\xi)\simeq\left(\frac{\pi}{2\xi}\right)^{1/2}\mathrm{e}^{-\xi}\left[1+\frac{4l^2-1}{8\xi}\right]. \tag{6}$$

By substituting (5) and (6) in (1) and after doing some algebra we obtain:

$$\frac{2l}{m_a}-\frac{\eta^2}{2(l+1)m_a}=-\frac{2\xi}{m_b}\left[1+\frac{1}{2\xi}\right] \tag{7}$$

After rearranging the terms, we obtain

$$\eta^2 = 4l(l+1) + [4(l+1)\xi + 1]\frac{m_a}{m_b}. \quad (8)$$

Solving (8) and (2) simultaneously and after doing some algebra we obtain the following quadratic equation:

$$\xi^2 + 4(l+1)\xi + 4l(l+1)\frac{m_b}{m_a} + 1 - \Omega = 0, \quad (9)$$

where $\Omega = \left((2m_b\Delta\phi R_0^2)/\hbar^2\right)$, by substituting $l = 0$ to find the value of the first energy sub-band, solving (9) will result in two roots for ξ, taking the positive root we can then find the eigenvalue of the first sub-band as given by the following equation:

$$\hat{E} = \Delta\phi - \frac{\hbar^2}{2R_0^2}\frac{\xi^2}{m_b}. \quad (10)$$

There is an error between the simulation data and the data resulted from our model, so we have introduced a fitting parameter to compensate that error. Consequently, the above energy equation is given by

$$\hat{E} = \Delta\phi - \frac{y\hbar^2}{2R_0^2}\frac{\xi^2}{m_b}, \quad (11)$$

where $y = \left(1/(A + BR_0)\right)$ is the equation for the fitting parameter, A and B are constants.

Model validation: The nanowire used in this simulation is $In_xGa_{1-x}As$, where ($x = 0.53$) and the gate oxide is Al_2O_3 with 1 nm thickness. The semiconductor parameters are taken from [10]. The subthreshold gate voltage is used to keep the validity of the flat approximation of the potential well, but this is not true for higher gate voltages. Our model has been validated with the self-consistent Schrodinger–Poisson solver data given in [7] and shows a very good agreement with them as shown in Fig. 3.

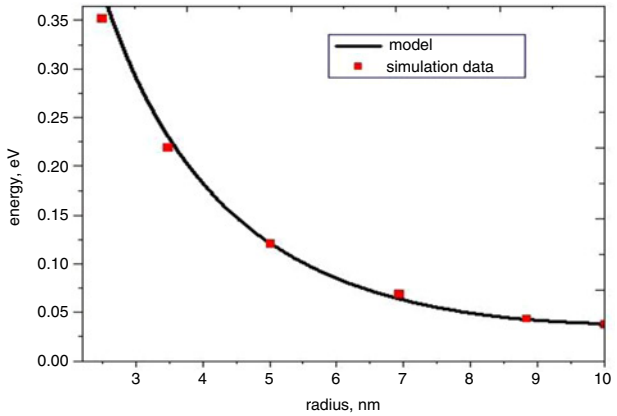

Fig. 3 *Energy eigenvalues of the first sub-band for InGaAs nanowire resulted from our model (line) in comparison with numerical data (symbols)*

Conclusion: We have developed a compact equation for calculating energy sub-bands inside III–V nanowire MOSFET considering wavefunction penetration into the gate oxide and the effective mass discontinuity at the semiconductor–oxide interface. The model shows very good agreement with the self-consistent Schrodinger–Poisson solver data.

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One or more of the Figures in this Letter are available in colour online.

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