Nanosized-Metal-Grain-Induced Characteristic Fluctuation in Gate-All-Around Si Nanowire Metal-Oxide-Semiconductor Devices

Chun-Ning Lai[1,2], Chien-Yang Chen[1,2], and Yiming Li[1,2,3,*]
[1]Parallel and Scientific Computing Laboratory; [2]Institute of Communications Engineering; [3]Department of Electrical and Computer Engineering, National Chiao Tung University, 1001 Ta-Hsueh Road, Hsinchu 300, Taiwan; [*]e-mail: ymli@faculty.nctu.edu.tw (Y. Li)

INTRODUCTION

Gate-all-around (GAA) nanowire structure is an important role for MOS devices in sub-16-nm technologies. Grain orientation of metals on small gate areas is uncontrollable during fabrication processes. Such random orientation will result in different workfunction for each grain locally. Workfunction fluctuation (WKF) is thus severe and has received significant attention recently [1-3]. Simulation studies on WKF of FinFET and nanowire MOS devices were reported by using different quantum-mechanically corrected models. It will be an interesting study for us to investigate WKF of GAA Si nanowire MOS devices by solving full quantum mechanical model.

In this work, we numerically solve a set of 2D Schrödinger-Poisson (SP) equations [4-5], where the random grains are statistically incorporated into the metal gate area of GAA nanowire MOS devices. The impact of localized WKF on channel quantization is examined with respect to different grain size. The random orientations of metal grains result in different workfunction locally and affect the boundary condition of the 2D SP equations.

STATISTICAL SIMULATION

To study WKF on the GAA Si nanowire MOS devices, 2D SP simulation is performed, as shown in Fig. 1(a), statistically. We directly partition the region of the devices' metal gate into many subregions according to experimentally observed grain sizes: 1, 2, and 4 nm. Then, we randomly generate WKs for each subregion according to the material properties and map them into the devices' gate for the 2D SP simulation. The settings are listed in Fig. 1(b) and the 2D SP equations and solution steps are shown in Fig. 1(c). We generate more than 200 statistically random devices to study random WK-induced fluctuation.

RESULTS AND DISCUSSION

Fig. 2 shows the distribution of electron ground state energy for the GAA nanowire MOS device under thermal equilibrium with respect to different metal grain sizes. The low-frequency peaks increase, as shown in Fig. 2(a), when the grain size is equal to 4 nm because the electron ground state energies are dispersed due to different metal pattern. Figs. 3(a)-(b) show the averaged value and the standard deviation of the electron ground state energy. The averaged ground state energies with 6-nm channel width are higher than other channels and keep relatively small standard deviation. Figs. 4(a)-(c) show the fluctuated electron's ground state wave functions (left plot), the potentials (middle one), and the electron densities (right plot) for the device with respect to different grain sizes and positions. The random grains induce different local potentials on the surface of channel. Then, the electron's wave functions are affected to different extents by local confinement. Such WKF-induced random confinement levels twist the distributions of wave functions and electron density. When the gate voltage increases, the electron density increases and the deviation of electron density due to random nanosized metal grain is suppressed from more than 100% variation to 10%.

CONCLUSIONS

In summary, the impact of WKF on GAA Si nanowire MOS device was studied by solving 2D SP equations statistically. Non-uniform potentials at channel surface affect the distributions of wave functions and electron densities.

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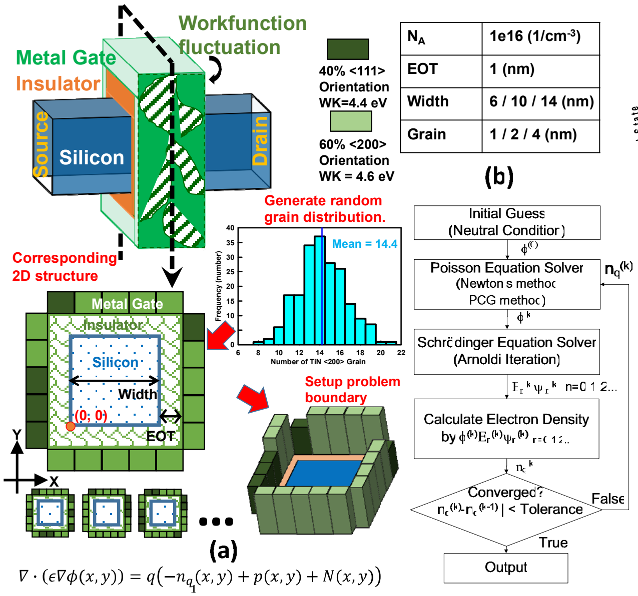


N_A	1e16 (1/cm^{-3})
EOT	1 (nm)
Width	6 / 10 / 14 (nm)
Grain	1 / 2 / 4 (nm)

$$\nabla \cdot (\epsilon \nabla \phi(x,y)) = q\left(-n_q(x,y) + p(x,y) + N(x,y)\right)$$

$$n_q(x,y) = \frac{1}{\pi}\left(\frac{2m_e k_B T}{\hbar^2}\right)^{\frac{1}{2}} \Sigma_n \psi_n^2(x,y) F_{-\frac{1}{2}}\left(\frac{E_F - E_n + e\Delta\phi(x,y)}{k_B T}\right)$$

$$p(x,y) = 2\left(\frac{m_h k_B T}{2\pi h^2}\right)^{\frac{3}{2}} F_{\frac{1}{2}}\left(\frac{V_h(x,y) - e\phi(x,y) - E_F - E_g}{k_B T}\right)$$

$$E_n \Psi_n(x,y) = \left(-\frac{\hbar^2}{2m^*}\nabla^2 + \left(V_h(x,y) - q\phi(x,y)\right)\right)\Psi_n(x,y)\ , n = 0,1,2 \ldots$$

$$\Delta\phi(x,y) = \phi(x,y) - \phi_{old}(x,y)$$

(c)

Fig.1 (a) The GAA Si nanowire MOS device and its channel cross-section. The WKF simulation flow is shown. (b) The settings and the random nanosized grains of TiN metal gate. (c) A set of 2D Poisson and Schrödinger equations solved in this study, where the generated WKF patterns are incorporated in the solution procedure.

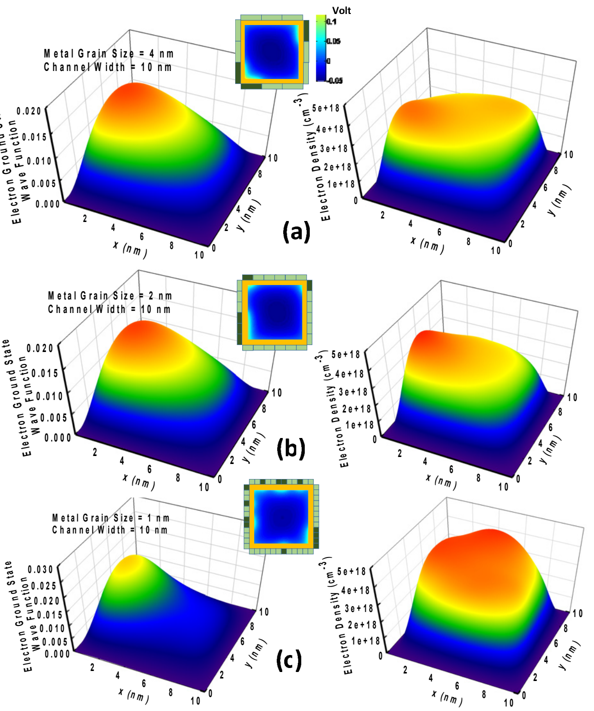


Fig. 4. (a)-(c) The WKF fluctuated electron ground state wave function (left plot), the potential (middle one), and the electron density (right plot) for the device with respect to different grain sizes: 4, 2, 1 nm, randomly. The electron density is affected by random grains owing to fluctuated electron wave functions which are governed by the random size and position of metal grains.

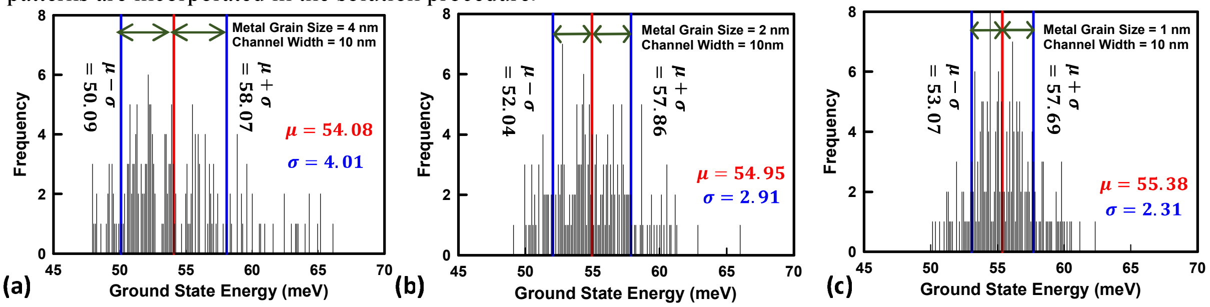
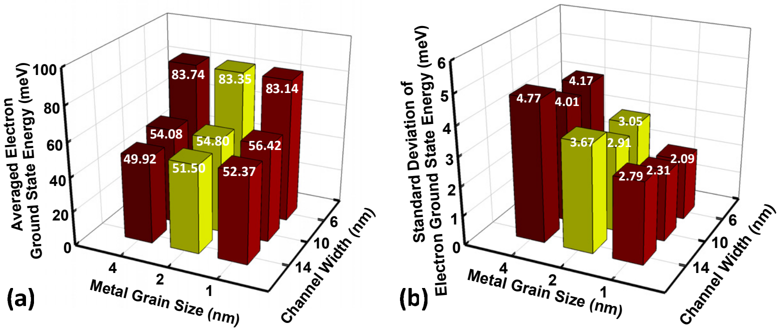


Fig. 2. The distribution of electron ground state energy for the device with respect to different metal grain size: (a) 4 nm (b) 2 nm, and, (c) 1 nm, respectively, where the channel width = 10 nm at zero gate voltage.



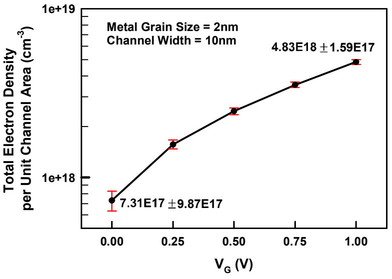


Fig. 3. (a) The averaged value and (b) the standard deviation of electron ground state energy for the device under zero gate voltage. The averaged ground state energy depends on the channel width. The size of random grains dominates its deviation.

Fig. 5. The electron density increases when the gate bias increases. However, the deviation of electron density due to random nanosized metal grains appearing for all gate biases simultaneously.