Numerical simulation for direct tunneling current in poly-Si-gate MOS capacitors

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To provide adequate control of short channel effects, gate-oxide thickness of MOSFETs is reduced nearly in proportional to channel length. For sub-100nm channel lengths, an oxide thickness, $t_{\rm ox}$, of less than a few nm is needed. In such a device, gate current is significant even for low gate bias region due to direct tunneling of electrons through the oxide. To simulate direct tunneling current, quantum effects, such as (1) tunneling transition rate and (2) standoff distance due to the quantum confinement of electrons in the channel region, should be properly taken into account. For poly-Si-gate devices, (3) a depletion-layer in the gate region should also be taken into account. Recently, Price demonstrated that the Gamow formulation can be applied to analysis of the escape of electrons from the channel region into the gate [1]. In the present study, we have numerically simulated direct tunneling current in poly-Si-gate MOS capacitors by integrating the Gamow method into a Schrödinger-Poisson solver. We especially focus on the boundary condition for the confined states that gives natural results.

In the Gamow method [1] for MOS capacitors, the system is divided into two parts at a certain point, $z = z_0$ (we define the z-direction as the direction perpendicular to the gate plane); a quasi-confined state for $z > z_0$ and an outgoing state for $z < z_0$. The quasi-confined wavefunction, $\Psi(z)$, is then connected to the the outgoing state at $z = z_0$ using a complex energy, $E - i\Gamma/2$. The imaginary part of the complex energy gives tunneling rate, and we do not have to introduce a quasi-classical concept of attempt frequency [2].

For metal-gate MOS capacitors, it is natural to set z_0 to the position of the interface between the gate and the oxide, $z_{\rm I}$ (see Fig. 1(a)). This gives a simple plain-wave, e^{-ikz}, as the outgoing state, and the tunneling transition rate, λ, is given by [1]

$$\frac{1}{\lambda} = \frac{m}{\hbar k}\frac{1}{\Psi^2(z_0)}\int_{z_0}^{\infty}\Psi(z)^2 dz.$$

For poly-Si-gate MOS capacitors, the electric field penetrates into the gate to $z = z_{\rm D}$ (see Fig. 1(b)), and we may have a choice of $z_0 = z_{\rm D}$ or $z_0 = z_{\rm I}$. For $z_0 = z_{\rm D}$, we find a resonant structure appearing in $I_{\rm G}$-$V_{\rm G}$ characteristics when the outgoing wavelength commensurates with $z_{\rm I} - z_{\rm D}$. This resonant structure seems to be rather artificial. On the other hand, setting $z_0 = z_{\rm I}$ gives more natural $I_{\rm G}$-$V_{\rm G}$ characteristics as shown in Fig. 2, where the calculated gate current density is plotted together with the experimental results [3]. Note that we numerically evaluate the outgoing state for $z_0 = z_{\rm I}$, because it is not a simple plain-wave due to the field penetration.

[1] P.J. Price, Appl. Phys. Lett. **82**, 2080 (2003); P.J. Price, Semocond. Sci. Technol. **19**, S241 (2004).
[2] P.J. Price, Am. J. Phys. **66**, 1119 (1998).
[3] N. Yang, W.K. Henson, J.R. Hauser, and S.K. Banerjee, IEEE Trans. Electron Devices **46**, 1464 (1999).

A full journal publication of this work will be published in the Journal of Computational Electronics.

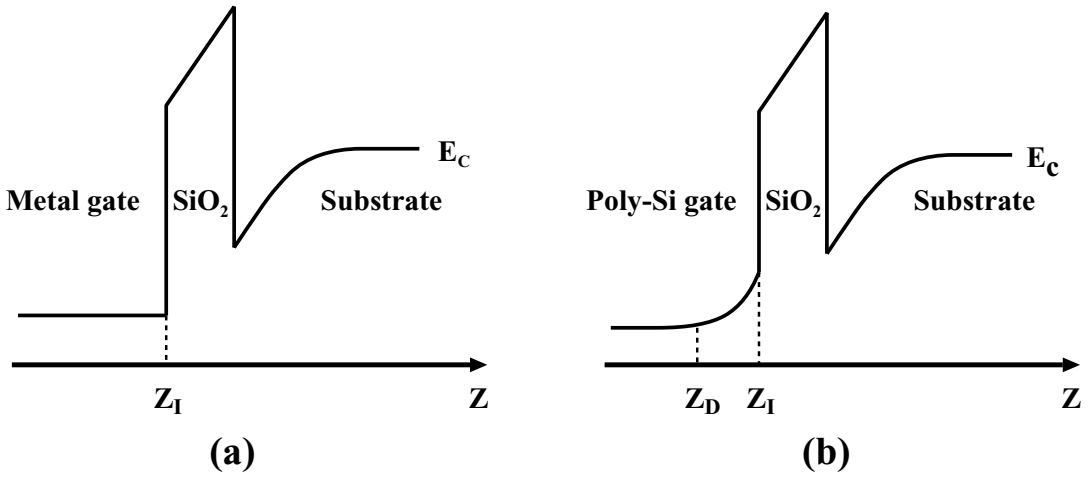

Figure 1: Schematic potential profile for a metal-gate (a) and a poly-Si-gate MOS capacitor (b).

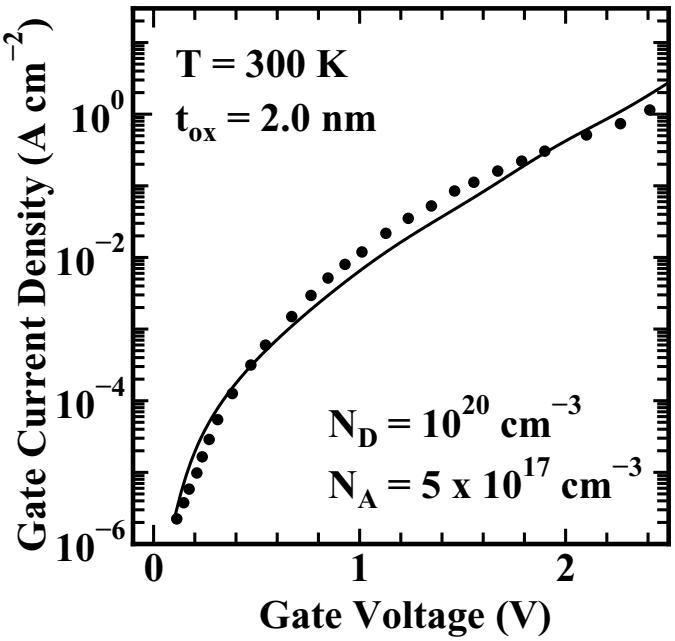

Figure 2: Calculated tunneling current density as a function of gate voltage in a poly-Si-gate capacitor (solid line). Closed circles show the experimental results reported in Ref. [3].

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