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An Empirical Direct Tunneling Current Expression for Ultra-Thin Oxide nMOSFETs*

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Abstract: An empirical expression for the direct tunneling (DT) current is obtained. This expression can be used to calculate the DT current for nMOSFETs with ultra-thin oxide when the oxide thickness is considered as an adjustable parameter. The results have good agreement with the experimental data. And the oxide thickness obtained is less than the value acquired from the capacitance-voltage (C-V) method.

Key words: direct tunnel current; nMOSFETs; ultra-thin
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1 Introduction

As dielectric thickness was scaled down, leakage current through the gate dielectric due to direct tunneling became a problem even at a low operating voltage, especially for analog circuit applications. Therefore, a compact expression for gate current due to direct tunneling was required. A number of studies on the direct tunneling gate current had been reported in Refs. [1~9]. The analytic models[1~3,5] had been investigated by Depas, Register, and Hu *et al.*. In these models, the experimental data could not be simulated in the full direct tunneling region. The DT expression given by Hu *et al.*[2] is suit for the oxide thickness less than 4nm. For using the DT expression given by Hu, Choi *et al.* introduced the explicit surface potential model and quantum-mechanical corrections to simulate the 1.3~1.8nm experimental data, the results showed the deviation still existed. The current physical models for simulating the direct tunneling current were focused on the quantum-mechanical models[2,4~7]. In these models, the quantization effect was considered by solving the Poisson and the effective-mass Schrodinger equations self-consistently. Although these models could simulate the experimental data of direct tunneling current measured on the ultra-thin oxides, solving the Poisson and the effective-mass Schrodinger equations self-consistently were complicated and time consuming. In this paper, a modified model for DT current in nMOSFET′s under the condition of inversion is proposed, and an empirical expression is obtained. The results showed the empirical expression could describe the experimental data well while the thickness of ultra-thin oxides varied from 1.9nm to 3.0nm.

2 Results and discussion

The n^+ poly nMOSFETs devices with different oxide thickness were provided by Motorala company. A HP4145B semiconductor parameter an-

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alyzer was utilized to measure the current-voltage characteristics at room temperature. The gate oxide thickness was extracted from the quantum mechanism capacitance voltage (C-V) method[12] as 1.90, 2.08, 2.38 and 3.00nm.

Figure 1 shows direct tunneling of electrons across gate oxide from the p-type Si substrate to

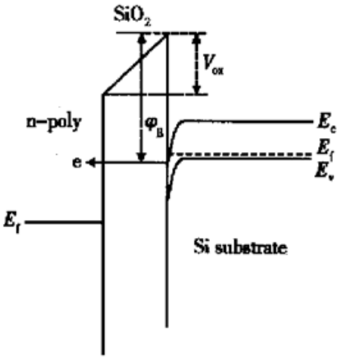

Fig. 1 Schematic diagram of direct tunneling for nMOSFETs inversion

n$^+$ poly Si gate. This direct tunneling current model is expressed as[1]

$$J_{DT} = A\frac{V_{ox}^2}{T_{ox}^2}\exp\left\{-B\left[(q\phi_B)^{3/2}-(q\phi_B-qV_{ox})^{3/2}\right]\right\} \tag{1}$$

$$A = \frac{q^3 m}{16\pi^2\hbar m_{ox}}\frac{1}{\left[(q\phi_B)^{1/2}-(q\phi_B-qV_{ox})^{1/2}\right]^2}$$

$$B = \frac{4}{3}\times\frac{T_{ox}\sqrt{2m_{ox}}}{qV_{ox}\hbar}$$

where ϕ_B is the barrier height of Si/SiO$_2$, 3.15eV[11], m_{ox} is the effective mass of oxide, m_{ox}= 0.5m(m is the free electron mass), V_{ox} is the oxide voltage, T_{ox} is the oxide thickness, $\hbar$ is the reduced Planck constant. In this paper, V_{ox} is obtained using a C-V quantum method[13], the poly Si depletion and quantum effect are considered. Figure 2 shows the relationship between gate voltage(V_G) and V_{ox} for different oxide thickness. Figure 3 shows the relationship between the gate tunneling current and V_{ox} and the results obtained from Eq.(1) with the parameter of T_{ox}. From this figure, we know that using Eq.(1) to simulate the experiment data has good agreement in high voltage region. But in low voltage region, the calculating data have large deviation with the experiment data. So Eq.(1) needs to be modified to simulate the experiment data. We know the electron tunneling current can be calculated by the following formula[12]:

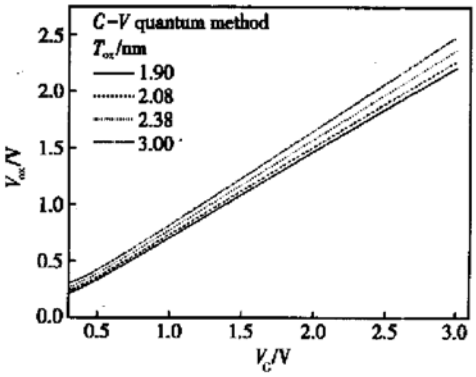

Fig. 2 Relationship between gate voltage and oxide voltage

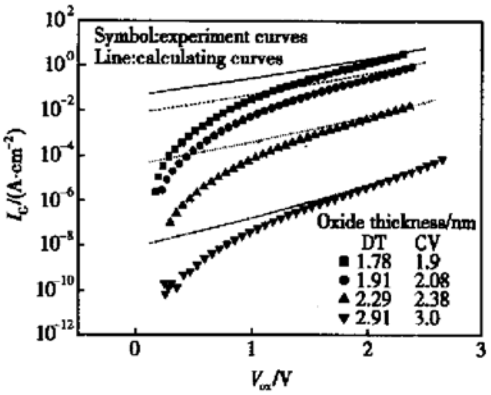

Fig. 3 Comparison between the simulating results by using the DT current of Eq.(1) and the experiment data

$$J = \int_0^\infty J(E_x)\,\mathrm{d}E_x \tag{2}$$

$$J(E_x) = \frac{qm}{2\pi^2\hbar^3}D(E_x)\int_{E_x}^\infty\left[f_r(E)-f_l(E)\right]\mathrm{d}E \tag{3}$$

$D(E_x)$ is the transmission probability when the longitudinal electron energy is E_x. f_r and f_l are the distribution functions in the right and the left of the electron. For direct tunneling electrons, we assumed that the energy range of tunneling electrons is less than qV_{ox}. Then the direct tunneling current is

$$J_{DT} = \int_0^{qV_{ox}} J(E_x)\,\mathrm{d}E_x \tag{4}$$

So the expression of direct tunnel current is as:

$$J_{\mathrm{DT}} = \frac{V_{\mathrm{ox}}^2}{T_{\mathrm{ox}}^2}\exp\{-B[(q\varphi_{\mathrm{B}})^{3/2} - (q\varphi_{\mathrm{B}} - qV_{\mathrm{ox}})^{3/2}]\}J_{\mathrm{Mod}} \quad (5)$$

$$J_{\mathrm{Mod}} = (1 - \exp(-qV_{\mathrm{ox}}BC)qV_{\mathrm{ox}}BC - \exp(-qV_{\mathrm{ox}}BC)) \quad (6)$$

$$C = \frac{3}{2}[(q\phi)^{1/2} - (q\phi - qV_{\mathrm{ox}})^{1/2}]$$

Figure 4 shows the comparison between the calculating results by Eq. (5) and the experimental data. From Fig. 4, we know that the calculating results still agree well with experiment data at high voltage region. The deviation between the calculating results and experiment data in low voltage region is still large. So the DT current expression needs to make a further correction. Considering the energy range of direct tunneling electrons are different when oxide voltage is different, we introduce two parameters m and n. Equation (6) changes as

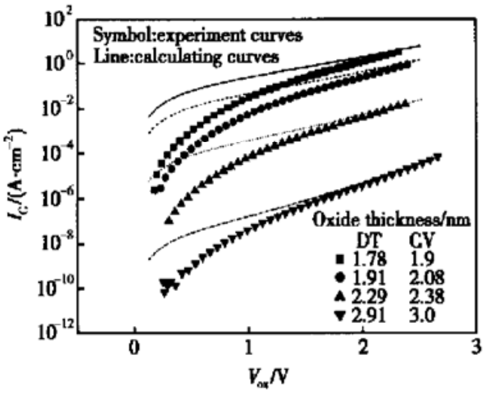

Fig. 4 Comparison between the simulating results by using the DT current of Eq. (5) and the experiment data

$$J_{\mathrm{Mod}} = \left|1 - \exp\left(-q\frac{V_{\mathrm{ox}}}{m}BC\right)q\frac{V_{\mathrm{ox}}}{m}BC - \exp\left(-q\frac{V_{\mathrm{ox}}}{m}BC\right)\right|^n \quad (7)$$

Figure 5 shows the comparison between the calculating results and the experimental data after introducing the m and n. This figure shows that the results simulated after introducing m and n have good agreement with the experiment data. The oxide thickness obtained from DT simulation is less than the value obtained from C-V method. This is due to the quantum effect makes the C-V electrics oxide thickness larger than the true oxide thickness. In our results, for different oxide thickness, m has same value, $m = 3.0$, but n is different. Figure 6 shows the curve n with oxide thickness.

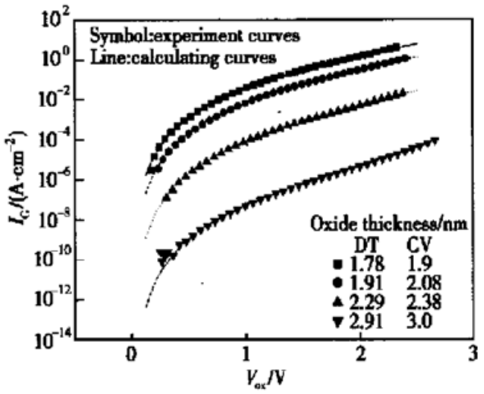

Fig. 5 Comparison between the simulating results by using the DT current and the experiment data after introducing m and n

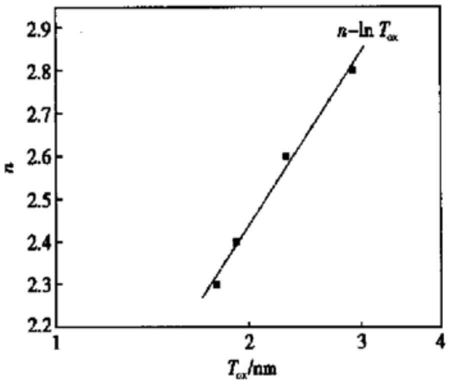

Fig. 6 n changing with oxide thickness

3 Conclusion

In this paper, we introduce m and n to modify the DT current and obtain the empirical DT current expression. The simulating results show the experiment data can be simulated well using the empirical DT current expression.

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一个超薄氧化物nMOSFET器件的直接隧穿电流经验公式*

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摘要: 建立了一个直接隧穿电流的经验公式.将氧化层厚度作为可调参数,用这个经验公式可以很好地拟合超薄氧化物nMOSFET器件的直接隧穿电流.在拟合中所得到的氧化层厚度比用量子力学电压-电容方法模拟得到的氧化层厚度小,其偏差在0.3nm范围内.

关键词: 直接隧穿电流; nMOSFET; 超薄

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