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Analysis of Direct Tunneling for Thin SiO_2 Film

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1. Introduction

Tunnel effect was investigated for metal-insulator-metal(MIM) structure using both the free electron gas model and WKB approximation[1,2]. By this method, direct tunneling (DT) of SiO_2 film has been examined[3]. Although the calculated DT currents fit to the measured data in the intermediate voltage range, they do not fit to the measured data in the low voltage range for thin SiO_2 film. The purposes of this paper are to examine both the characteristics of the DT of thin SiO_2 film on the electrode with a small Fermi energy using the above method and the fitting of the calculated DT currents to the measured data in the low voltage range. The DT currents are calculated by both the conventional formula and new formulas which are discussed in the present paper.

2. Calculation of DT currents

By assuming the conservation of the transverse momentum and the total energy of tunneling electron, the DT current (Jt) of MIM structure is given as follows[1].

$$Jt = \frac{2e}{h}\int D(E,k_\perp)dE\int [f_R(E) - f_L(E+eV)]\frac{d^2k_\perp}{(2\pi)^2} \quad \text{.....(1)}$$

By calculating eq.(1), eqs.(2) and (3) are obtained[2].

$$Jt = \frac{4\pi me}{h^3}\{eV\int_0^{\eta-eV}\exp[-A\sqrt{\eta+\bar{\varphi}-Ex}\,]dEx + \int_{\eta-eV}^{\eta}\exp[-A\sqrt{\eta+\bar{\varphi}-Ex}\,]dEx\} \quad \text{.....(2)}$$

$$Jt = \frac{e}{2\pi h(\beta S)^2}\bar{\varphi}\exp(-A\sqrt{\bar{\varphi}}) - \frac{e}{2\pi h(\beta S)^2}(\bar{\varphi}+eV)\exp(-A\sqrt{\bar{\varphi}+eV}) \quad \text{.....(3)}$$

Since the second term of eq.(3) is negligible for a large applied voltage, eq.(4) has been generally used for the calculation of the DT currents.

$$Jt = \left(\frac{e}{2\pi hS^2}\right)\left(\varphi_0 - \frac{eV}{2}\right)\exp\left[-\frac{4\pi S}{h}\sqrt{2m^*\left(\varphi_0 - \frac{eV}{2}\right)}\right] \quad \text{.....(4)}$$

Although the calculated data by eq.(4) fits to the measured one in the intermediate range, it does not fit to the measured data in the low voltage range. The second term of eq.(3) becomes large as decreasing the applied voltage. Furthermore, for the electrode with a small Fermi energy, the first term of eq.(2) becomes important. Considering these issues, the eqs.(5-1) and (5-2) are given for $eV < \eta$ and $eV > \eta$, respectively. Here, $A=(4\pi\beta S/h)(2m^*)^{1/2}$ and β is a correction factor[2]. $\bar{\varphi}$, φ_0 and S are the average potential of the barrier, the barrier height and the barrier thickness, respectively. η is the Fermi energy of the electrode.

For $eV < \eta$, Jt is given as

$$Jt = \frac{e}{2\pi h(\beta S)^2}\bar{\varphi}\exp(-A\sqrt{\bar{\varphi}}) - \frac{e}{2\pi h(\beta S)^2}(\bar{\varphi}+eV)\exp(-A\sqrt{\bar{\varphi}+eV}) - \frac{e^2V[A\sqrt{\bar{\varphi}+\eta}+1]}{4\pi h(\beta S)^2}\exp(-A\sqrt{\bar{\varphi}+\eta}) \quad \text{.....(5-1)}$$

For $eV > \eta$, Jt is given as

$$Jt = \frac{4\pi me}{h^3}\left[\frac{4}{A^2}\bar{\varphi}\exp\left(-A\sqrt{\bar{\varphi}}\right) - 2\left\{\frac{\eta\sqrt{\eta+\bar{\varphi}}}{A} + \frac{3\eta+2\bar{\varphi}}{A^2}\right\}\exp\left(-A\sqrt{\eta+\bar{\varphi}}\right)\right] \quad \text{.....(5-2)}$$

3. Fabrication and Measurement of SiO_2 Film

Thin oxide films are formed on p-type Si(100) by wet oxidation at 800°C after RCA cleaning. The poly-Si deposition by LPCVD method is followed by $POCl_3$ diffusion with an impurity concentration of $\sim 4\times10^{20}cm^{-3}$. The thicknesses of the SiO_2 films are measured by the ellipsometry or by the TEM. Measured data by ellipsometry or by TEM of the sample 1 is 2.4nm or 2.7nm. That of the sample 2 by ellipsometry or by TEM is 2.7nm or 3.0nm.

4. Results and Discussion

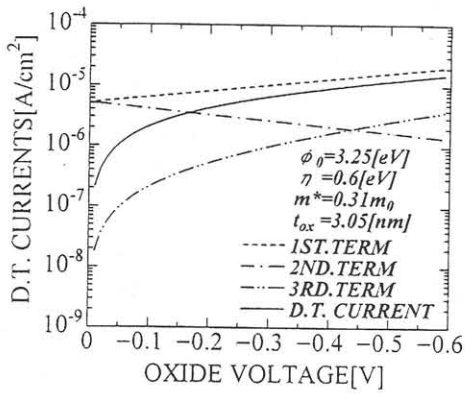

Figure 1. Calculated results of each term of eq.(5-1) for sample 2.

Figure 1 shows the calculated results of each term of

eq.(5-1) for the sample 2. It is found that the second term of eq.(5-1) becomes large as decreasing the applied voltage and that the third term becomes large as increasing the applied voltage. Here, the physical meanings of eqs.(2) and (5) are explained. Figure 2(a) shows the Fermi energy surface when the eV is applied between the electrodes. The electrons which contribute to the DT are shown by the shadow. The first term of the eq.(2) corresponds to the area A and the second term corresponds to the area B. When the applied voltage is small, the electrons of the area A dominate the total DT currents, and when the applied voltage is large, the electrons of the area B dominate the total DT currents as shown in Fig.2(b). The first and second terms of eq.(5-1) is included in the second term of eq.(2), and the third term of eq.(5-1) is in the first term of eq.(2).

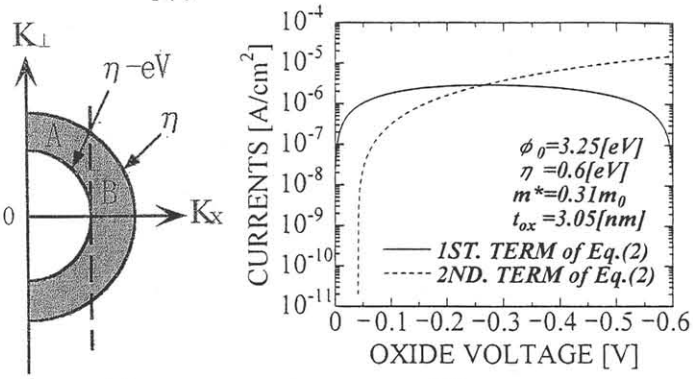

Figure 2.Fermi energy surface(a) and the dominant currents(b).

Figures 3 and 4 show the calculated DT currents by eqs.(3)~(5) and the measured data for samples 1 and 2, respectively. Eq.(4) does not fit to the measured data in the low voltage range. Although eq.(3) reproduces the large increase ratio of the DT currents in the low voltage range, the absolute value of the current is nearly equal to that calculated by eq.(4) for $eV > \eta$. Eq.(5) reproduces the large increase ratio of the currents for $eV < \eta$ and the accurate absolute value of the current for $eV > \eta$.

It is found that the second term of eq.(5-1) or eq.(3), which is defined as the currents from the low potential electrode to the high potential electrode, plays an important role in the low voltage range from 0 to ~-0.5 V, and that the third term of eq.(5-1), which is the current relating to the Fermi energy of the electrode, plays an important role from ~-0.5 to ~-1.0V. By considering these terms, the conservations of the transverse momentum and the total energy of the tunneling electron are satisfied in the range of the low applied voltage.

For the reason why the calculated results becomes large than the measured data from 0 to ~-0.5V, the following are supposed. First, the current due to Fermi distribution at room temperature (RT) is not considered in the present calculation. Although DT is not of cource the thermal activation process, the distribution of electrons affects the increase ratio of the DT currents. In the present calculation, Fermi distribution at 0K was assumed. Secondly, the decrease of the number for the tunneling electrons due to the inelestic scattering is not

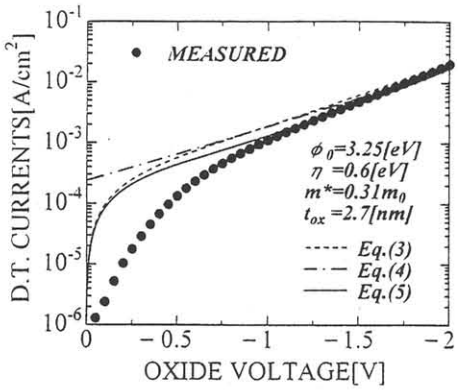

Figure 3. Calculated DT current and the measured data of sample 1.

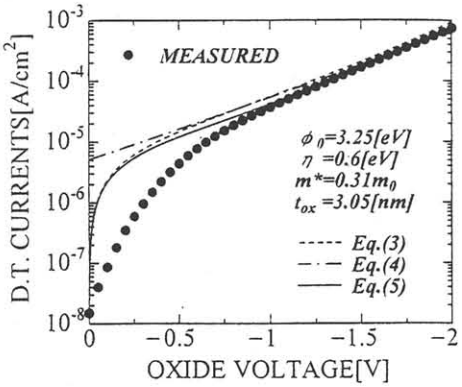

Figure 4. Calculated DT current and the measured data of sample 2.

considered. At RT, the energy of the tunneling electrons which have the large transverse momentum shown by A of Fig.2 could become smaller than (η - eV) due to the scattering, such as at the interface of poly-Si/SiO_2. In this case, the dominant electrons correspond to the second term of eq.(2). By assuming both the effective mass m* of the tunneling electrons in the SiO_2 film and the barrier height of it to $0.31m_0$ and 3.25eV[4], the thicknesses of SiO_2 given by the present fitting agree to the measured data by TEM.

5. Conclusions

The theoretical DT current of thin SiO_2 film on the electrode with small Fermi energy was given by considering the conservation of the transverse momentum and the total energy of the tunneling electrons. Although the conventional calculation of DT current does not fit to the measured data in the low voltage range, the present calculation reproduces the large increase ratio of the currents for $eV < \eta$, and the accurate absolute value of currents for $eV > \eta$.

References

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