MODELLING OF TUNNELLING CURRENTS IN METAL-INSULATOR-METAL JUNCTION

Ajay Manwani[1], Rajesh Junghare[2] and Abhishek Vaidya[3]
Visvesvarya National Institute of Technology, Nagpur, India

ABSTRACT

A numerical model to determine tunnelling currents in metal-insulator-metal (MIM) capacitor is presented is this paper. This model is based on Wentzel-Kramers-Brillouin (WKB) approximation and Tsu-Esaki model. Analytical expressions based on physical parameters have been given in detail. Simulations have been performed for Al-Al_2O_3-Al system.

KEYWORDS

Tsu-Esaki model, WKB approximation, MIM structure

1. INTRODUCTION

Metal-Insulator-Metal (MIM) capacitors have become a vital part in the design of integrated circuits. As a component in RF integrated circuits, passive MIM capacitors with high capacitance density are required for future technology generations. MIM capacitors are also being used for solar cell applications [6]. Effect of MIM capacitance is also seen in interconnects as the distance between interconnects has been decreasing with each technology node [4]. Hence a detailed study of MIM capacitance is required to determine their leakage currents and other parameters such as capacitance between the interconnect layers and interference among the interconnect lines. In this paper, we discuss about the modelling of leakage currents in MIM structures which could be useful in determining the distance between interconnects. In section 2 of this paper, we discuss about MIM device structure and energy band-profile under different bias conditions. In section 3, the Tsu-Esaki formulation [3] and Wentzel-Kramers-Brillouin (WKB) approximation [1,2] have been described which are used to model leakage currents. Section 4 presents results obtained for Al-Al_2O_3-Al system and shows the variation of Transmission coefficient with incoming electron energy as well as leakage current variation with the applied bias and insulator thickness.

2. DEVICE STRUCTURE & ENERGY-BAND PROFILE

Figure 1 shows the MIM structure which is Aluminium-Aluminium oxide-Aluminium (Al-Al_2O_3-Al) structure. External voltage *(Vs)* is applied across the two contacts due to which band bending

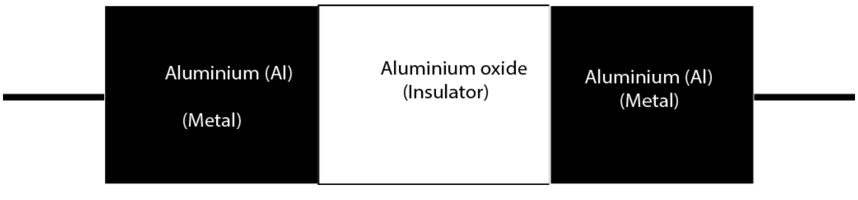

Figure 1. Metal-Insulator-Metal device schematic

Occurs. Since the insulator (Al_2O_3) layer is very thin, direct and Fowler-Nordheim currents flows through depending on the magnitude of applied external bias. Band profiles and currents at different $V_{applied}$ are considered as follows:

2.1. Band profile at zero bias $V_{applied} = 0$

Al –Al_2O_3 have conduction band-gap difference of qΦ = 3.9eV [1] under no applied bias as shown in Figure 2.

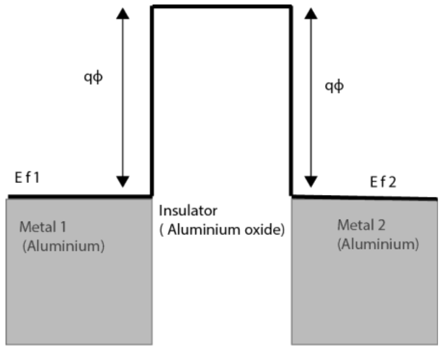

Figure 2. Energy band diagram of Al-Al_2O_3-Al under zero external bias

Under external applied bias, the current, J , flows from Metal 1 to Metal 2 (J_{12}) and also from Metal 2 to Metal 1 (J_{21}). Depending on the polarity of applied bias, one of the currents J_{12} or J_{21} dominates. Under zero applied bias $J_{12} = J_{21}$, hence both currents nullify each other and net current flowing through the device is zero.

2.2. Band profile at low external applied bias, $V_{applied} < q\Phi$

Under external applied bias band bending occurs as shown in Figure 3. Here, a small positive voltage ($V_{applied} < q\Phi$) is applied to right hand side contact Metal 2 which lowers the fermi level, Ef_2, of Metal 2 by the magnitude of applied bias. Under this condition, current J_{12} from Metal 1 to Metal 2 dominates the current J_{21} from Metal 2 to Metal 1 ($J_{12} > J_{21}$) hence a net current flows from Metal 1 to Metal 2. Two current components exist under this condition as shown in Figure 3. One is Fowler- Nordheim tunnelling current component which flows through triangular barrier and other is Direct tunnelling current component through rectangular barrier. Under low applied bias, a small current flows through the device.

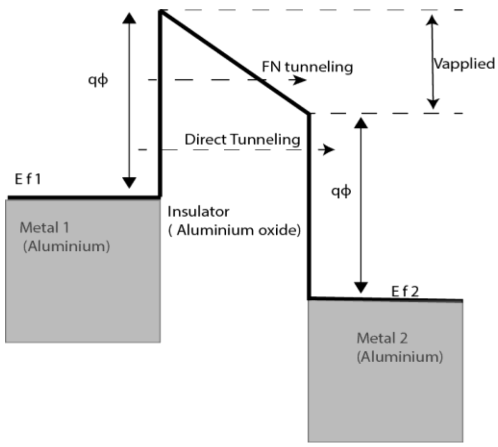

Figure 3.Energy band diagram of Al-Al_2O_3-Al under low external bias.

2.3. Band profile under low external applied bias, $V_{applied} > q\Phi$

Under high external applied bias ($V_{applied} > q\Phi$) applied to Metal 2 with respect to Metal 2, whole barrier between Metal 1 and Metal 2 reduces to triangular barrier as shown in Figure 4 and high current ($J_{12} >> J_{21}$) flows from left side to right side of contact. Under high applied bias, only Fowler-Nordheim (FN) current flows through the device.

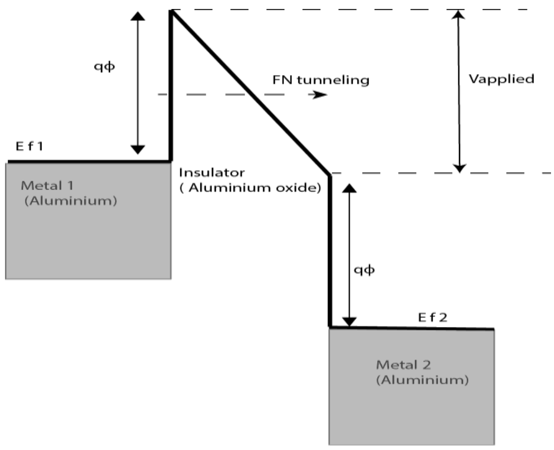

Figure 4. Energy band diagram of $Al\text{-}Al_2O_3\text{-}Al$ under high external bias

3. CALCULATION OF TUNNELING CURRENTS

For calculation of tunnelling currents in Metal-Insulator Metal junction, Tsu-Esaki model [3] is used. In this model, tunnelling of electrons from conduction band is considered between Metal 1 and Metal 2 through insulator. Two metal regions are separated by an energy barrier qΦ measured from Fermi energy level to conduction band edge of insulator. Consider the band diagram under small applied bias as shown in Figure 5.

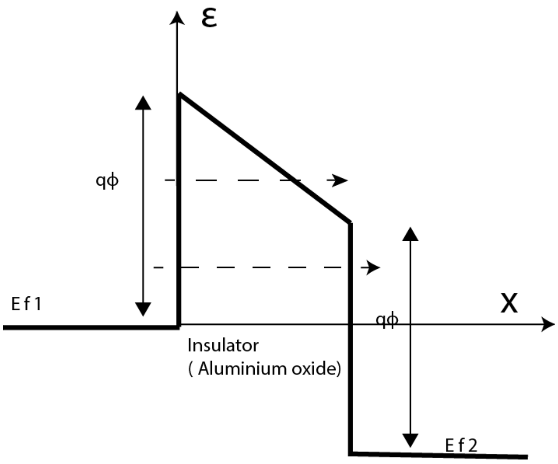

Figure 5.Tsu-Esaki formulation, band diagram under applied bias.

The net current density from metal 1 to metal 2 is given by following expression [3]

$$J = J_{1\rightarrow 2} - J_{2\rightarrow 1} \tag{1}$$

where J_{12} and J_{21} are the current densities from Metal-1 to Metal-2 and Metal-2 to Metal-1 respectively. This net current density depends Transmission coefficient, the perpendicular velocity v_x,wave-vector k_x , density of states g and Fermi-distribution function f(ε) on both the sides.

$$dJ_{12} = q.TC(k_x).v_x.g_1(k_x).\ f_1(\varepsilon).\ (1 - f_2(\varepsilon)).dk_x\ ; \tag{2}$$

$$dJ_{12} = q.TC(k_x).v_x.g_2(k_x).\ f_2(\varepsilon).\ (1 - f_1(\varepsilon)).dk_x\ ;$$

The density of states [5] is given as

$$g(k_x) = \int_0^\infty \int_0^\infty g(k_x, k_y, k_z) \tag{3}$$

Considering quantized wave vector components inside a cube of length L

$$\Delta k_x = \frac{2\pi}{L}, \qquad \Delta k_y = \frac{2\pi}{L}, \qquad \Delta k_z = \frac{2\pi}{L} \tag{4}$$

So, three dimensional density of states [5] can be given by

$$g\left(k_x, k_y, k_z\right) = 2\frac{1}{\Delta k_x\, \Delta k_y\, \Delta k_z}\frac{1}{L^3} = \frac{1}{4\pi^3} \tag{5}$$

Velocity and energy components in tunneling directions can be written as

$$\vartheta_x = \frac{1}{\hbar}\frac{\partial \varepsilon}{\partial k_x} = \frac{\hbar k_x}{m_{eff}}, \quad \varepsilon_x = \frac{\hbar^2 k_x^2}{2m_{eff}}, \quad \vartheta_x dk_x = \frac{1}{\hbar} d\varepsilon_x \tag{6}$$

Hence expression (2) becomes

$$dJ_{1\rightarrow 2} = \frac{q}{4\pi^3\hbar} TC(\varepsilon_x) d\varepsilon_x \int_0^\infty \int_0^\infty f_1(\varepsilon)\left(1 - f_2(\varepsilon)\right) dk_y dk_z\ ,$$

$$dJ_{2\rightarrow 1} = \frac{q}{4\pi^3\hbar} TC(\varepsilon_x) d\varepsilon_x \int_0^\infty \int_0^\infty f_2(\varepsilon)\left(1 - f_1(\varepsilon)\right) dk_y dk_z\ , \tag{7}$$

The above expression can be written in polar co-ordinates as

$$J_{1\to 2} = \frac{4\pi m_{eff} q}{h^3} \int_{\varepsilon_{min}}^{\varepsilon_{max}} TC(\varepsilon_x) d\varepsilon_x \int_0^{\infty} f_1(\varepsilon)\big(1 - f_2(\varepsilon)\big) d\varepsilon_\rho ,$$

$$J_{2\to 1} = \frac{4\pi m_{eff} q}{h^3} \int_{\varepsilon_{min}}^{\varepsilon_{max}} TC(\varepsilon_x) d\varepsilon_x \int_0^{\infty} f_2(\varepsilon)\big(1 - f_1(\varepsilon)\big) d\varepsilon_\rho \qquad (8)$$

The net current density as $J = J_{1\to 2} - J_{2\to 1}$ is written as

$$J = \frac{4\pi m_{eff} q}{h^3} \int_{\varepsilon_{min}}^{\varepsilon_{max}} TC(\varepsilon_x)\, N(\varepsilon_x) d\varepsilon_x \qquad (9)$$

In this final expression ε_{min} is Fermi-level of Metal 1 and ε_{max} is conduction band edge of insulator. $TC(\varepsilon_x)$is transmission coefficient given by WKB approximation. $N(\varepsilon_x)$ is supply function.

The Transmission coefficient, TC, for electron tunneling a barrier from x1 to x2 is calculated by WKB approximation [1] as

$$TC \cong e^{\int_{x1}^{x2} \beta(x) dx}$$

(10)

Where

$$\beta(x) = \sqrt{\frac{2m^*}{\hbar^2}(V(x) - E)}$$

(11)

4. RESULTS

The Tsu-Esaki model along with WKB approximation was implemented for Al -Al_2O_3-Al Metal-Insulator-Metal structure in Mat lab. All the calculations were done in Hartree units. The WKB and Tsu-Esaki equations are discretized using Finite difference scheme. The device parameters were taken as shown in Table 1.

Table 1: Device parameters taken for simulation

Parameter	**Value**
Thickness of insulator (Al_2O_3)	2nm, 4 nm
Thickness of Metal-1, Metal-2 (Aluminium)	10nm

Fermi-level, Ef, of Al	11.7 eV
Al -Al_2O_3 band gap difference, qϕ	3.9eV
Applied voltage range, Vs	5-15 volts

The obtained results for Transmission coefficient calculated at Vs = 5 volts is shown in Figure 6. The incoming electron has energy value between Fermi-level of Metal 1 (Efl = 11.7 eV) [1] and top of conduction band of Al_2O_3 (Efl + qϕ = 15.6eV) Current density (A/cm^2) variation with applied voltage variation from Vs = 5 to 15 volts and thickness of insulator (T_{in} = 2 nm and 4nm) are shown in Figure 7

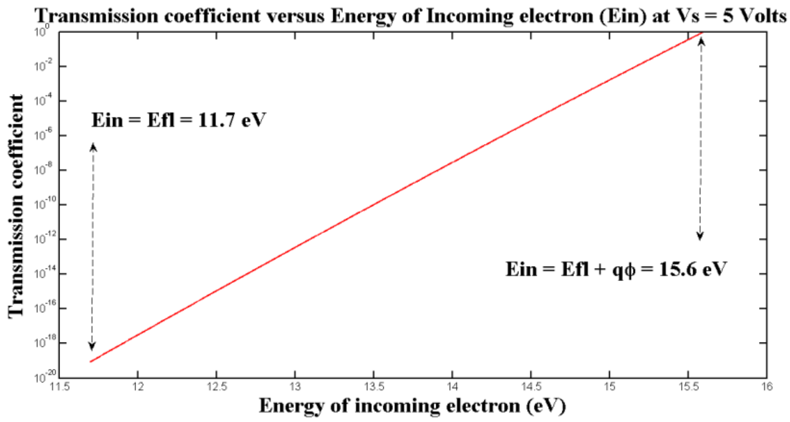

Figure 6. Variation of Transmission coefficient with incoming electron energy at Vs = 5 volts

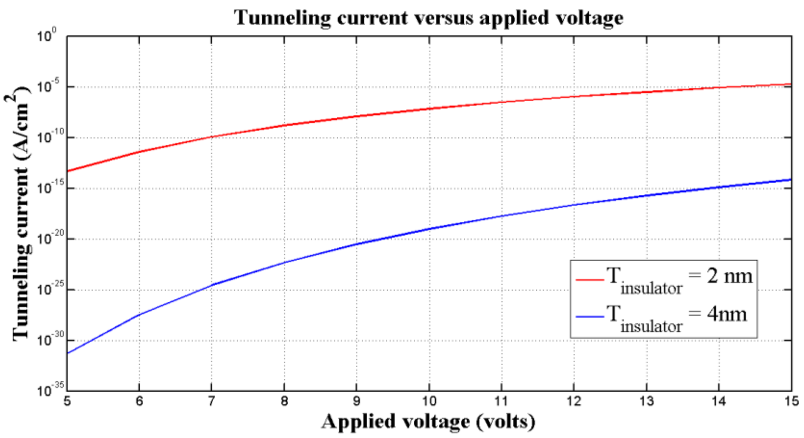

Figure 7: Tunneling current (A/cm^2) versus Applied voltage (Volts) for different thickness

3. CONCLUSIONS

In this paper, a model to calculate the leakage tunneling currents in metal-insulator-metal structure by demonstrating the case of Al-Al_2O_3-Al system is presented. Leakage currents at different voltages and insulator thickness have been demonstrated. This model can be used determine the minimum distance between interconnects to keep the leakage currents below the desired level.

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