3.9. Currents through insulators

Current mechanisms through materials, which do not contain free carriers can be distinctly different from those in doped semiconductors or metals. The following section discusses Fowler-Nordheim Tunneling, Poole-Frenkel emission, Space charge effects as well as Ballistic transport

3.9.1. Fowler-Nordheim tunneling

Fowler-Nordheim tunneling has been studied extensively in Metal-Oxide-Semiconductor structures where it has been shown to be the dominant current mechanism, especially for thick oxides. The basic idea is that quantum mechanical tunneling from the adjacent conductor into the insulator limits the current through the structure. Once the carriers have tunneled into the insulator they are free to move within the valence or conduction band of the insulator. The calculation of the current is based on the WKB approximation (as derived section 3.4.4) yielding the following relation between the current density, J_{FN}, and the electric field in the oxide, $\mathcal{E}_{ox}$:

$$J_{FN} = C_{FN}\mathcal{E}_{ox}^{2} \exp_{ox}\left(-\frac{4}{3}\frac{\sqrt{2m_{ox}^{*}}}{q\hbar}\frac{(q\phi_{B})^{3/2}}{\mathcal{E}_{ox}}\right) \quad (3.9.1)$$

where ϕ_B is the barrier height at the conductor/insulator interface in Volt, as shown in the figure below for electron tunneling from highly[1] n-type doped silicon into the silicon dioxide.

To check for this current mechanism, experimental *I-V* characteristics are typically plotted as $\ln(J_{FN}/\mathcal{E}_{ox}^{2})$ versus $1/\mathcal{E}_{ox}$, a so-called Fowler-Nordheim plot. Provided the effective mass of the insulator is known (for SiO_2, $m_{ox}^{*} = 0.42\ m_0$) one can then fit the experimental data to a straight line yielding a value for the barrier height.

It is this type of measurement which has yielded experimental values for the conduction band difference between silicon and silicon-dioxide. The same method could also be used to determine heterojunction energy band off-sets provided Fowler-Nordheim tunneling is indeed the dominant current mechanism[2]. It is important to stress that carriers must tunnel through the insulator, which requires:

$$\mathcal{E}_{ox} d \geq \phi_B \quad (3.9.2)$$

which is typically the case for thick oxides and high electric fields.

3.9.2. Poole-Frenkel emission

The expression for Fowler-Nordheim tunneling implies that carriers are free to move through the insulator. Whereas this is indeed the case in thermally grown silicon-dioxide it is frequently not so in deposited insulators which contain a high density of structural defects. Silicon nitride (Si_3N_4) is an example of such material. The structural defects cause additional energy states close to the bandedge called traps. These traps restrict the current flow because of a capture and

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[1]This condition is added to eliminate additional complexity caused by bandbending at the interface.

[2]This condition would required very large energy band discontinuities.

emission process, thereby becoming the dominant current mechanism. The current is a simple drift current described by

$$J = qnm E_N \tag{3.9.3}$$

while the carrier density depends exponentially on the depth of the trap which is corrected for the electric field[3].

$$n = n_0 \exp[-\frac{q}{kT}(f_B - \sqrt{\frac{qE_N}{pe_N}})] \tag{3.9.4}$$

The total current then equals:

$$J_{PF} = qn_0 m E_N \exp[-\frac{q}{kT}(f_B - \sqrt{\frac{qE_N}{pe_N}})] \tag{3.9.5}$$

The existence of a large density of shallow[4] traps in CVD silicon nitride makes Poole-Frenkel emission[5] a frequently observed and well-characterized mechanism.

3.9.3. Space charge limited current

Both Fowler-Nordheim tunneling and Poole-Frenkel emission mechanism yield very low current densities with correspondingly low carrier densities. For structures where carriers can readily enter the insulator and freely flow through the insulator one finds that the resulting current and carrier densities are much higher. The density of free carriers causes a field gradient, which limits the current density. This situation occurs in lowly doped semiconductors and vacuum tubes. Starting from an expression for the drift current and Gauss's law (where we assume that the insulator contains no free carriers if no current flows)

$$J = qpm E \tag{3.9.6}$$

$$\frac{dE}{dx} = \frac{qp}{e} \tag{3.9.7}$$

we can eliminate the carrier density, *p*, yielding:

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[3]This correction is equivalent to the Schottky barrier lowering due to the presence of an electric field.

[4]deep traps also exist in silicon nitride. While these easily capture carriers, they are too deep to allow emission even in the presence of large fields. This causes a fixed charge in the silicon nitride which remains when the applied bias is removed. This charge trapping mechanism is used in non-volatile MNOS memory devices.

[5]J. Frenkel, "On Pre-Breakdown Phenomena in insulators and Electronic Semiconductors," Phys. Rev., Vol 54, p 647, 1938.

$$\frac{J}{em} = E\frac{dE}{dx} \qquad (3.9.8)$$

Integrating this expression from 0 to x, where we assume the electric field to be zero[6] at $x = 0$ one obtains:

$$\frac{Jx}{em} = \frac{E^2}{2} \text{ or } E(x) = \sqrt{\frac{2xJ}{em}} \qquad (3.9.9)$$

integrating once again from $x = 0$ to $x = $ d with $V(0) = V$ and $V(d) = 0$, one finds:

$$V = \int_0^d E dx = \sqrt{\frac{2J}{em}} \frac{d^{3/2}}{3/2} \qquad (3.9.10)$$

from which one obtains the expression for the space-charge-limited current:

$$J = \frac{9e\,mV^2}{8d^3} \qquad (3.9.11)$$

3.9.4. Ballistic Transport in insulators

Ballistic transport is carrier transport without scattering or any other mechanism, which would cause a loss of energy. Combining energy conservation, current continuity and Gauss's law one finds the following current-voltage relation:

$$J = \frac{4e}{9}\sqrt{\frac{2q}{m^*}}\frac{V^{3/2}}{d^2} \qquad (3.9.12)$$

where d is the thickness of the insulator and m^* is the effective mass of the carriers.

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[6]This implies an infinite carrier density. The analysis can be modified to allow for a finite carrier density. However the carrier pile-up do to the current restriction typically provides a very high carrier density at x=0.