Different conduction mechanisms

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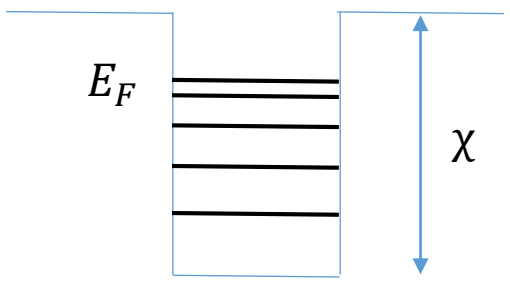
Conduction mechanisms

- Ohmic conduction ($j = n\mu E$)
- Thermoemission
- Schottky emission
- Direct tunneling
- Space change limited current
- Hopping conduction

Thermoemission



- Kinetic energy

$$E(k) = \frac{1}{2}mv^2, v(k) = \frac{\hbar k}{m}$$

- Electron density

$$dn = 2\left(\frac{m}{2\pi\hbar}\right)^3 \exp\left(-\frac{\frac{1}{2}mv^2 - E_F}{k_B T}\right) dv$$

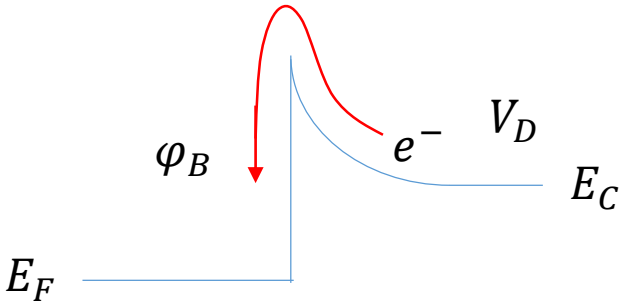
- Current density

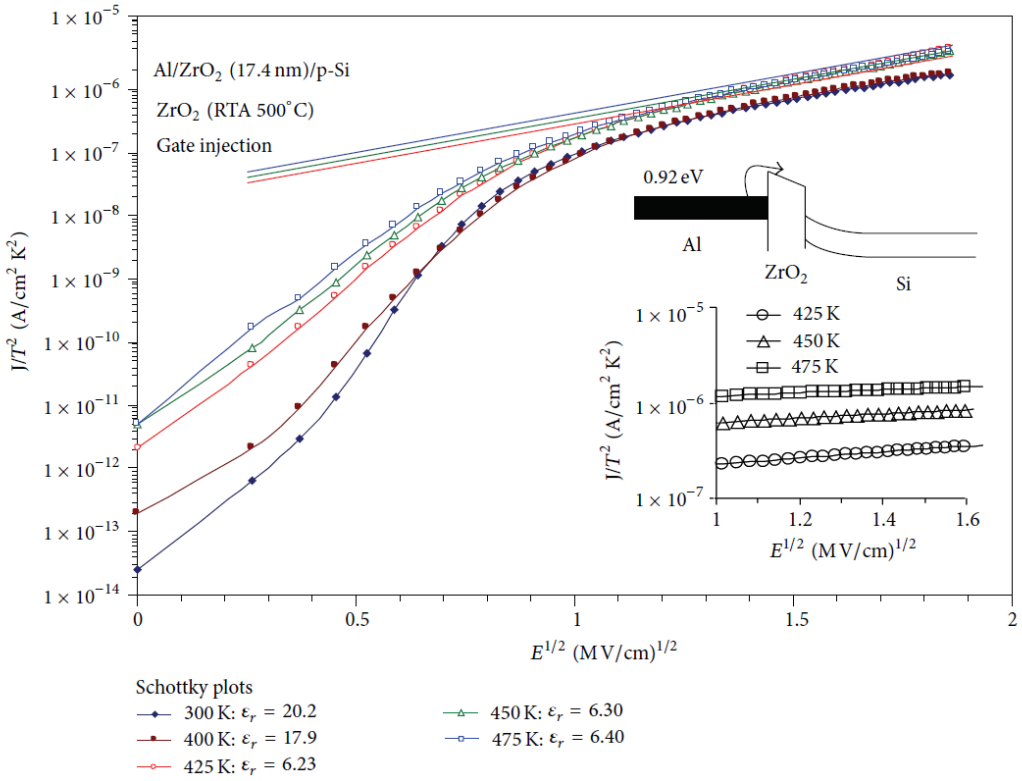
$$j = -qvn$$

$$= 2\left(\frac{m}{2\pi\hbar}\right)^3 \exp\left(\frac{E_F}{k_B T}\right) \int_{-\infty}^{\infty} dv_x \int_{-\infty}^{\infty} dv_y \int_{\chi - E_F}^{\infty} (-qv_z) \exp\left(-\frac{\frac{1}{2}mv^2}{k_B T}\right) dv_z$$

$$= -\frac{4\pi m q \left(k_B T\right)^2}{h^3} \exp\left(-\frac{\chi - E_F}{k_B T}\right)$$

Schottky emission





$$dn = \frac{(2m)^{3/2}}{2\pi^2\hbar^3}\sqrt{E - E_C}\exp\left(-\frac{E - E_F}{k_B T}\right)dE = 4\pi n_0\left(\frac{m}{2\pi k_B T}\right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)dv,$$

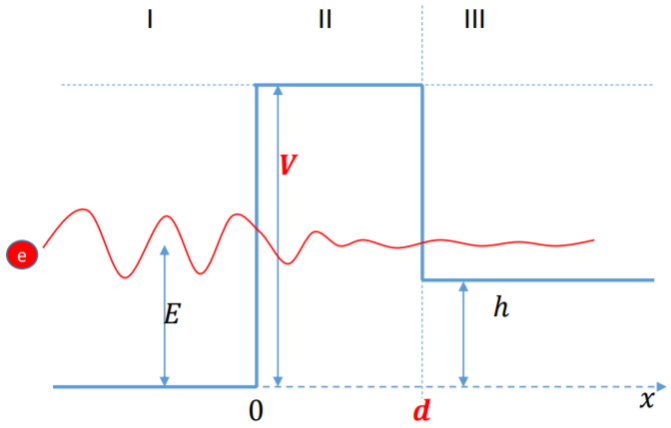
$$n_0 = N_C \exp\left(-\frac{E_C - E_F}{k_B T}\right)$$

$$j = qn_0\left(\frac{m}{2\pi k_B T}\right)^{3/2}\int dy \int dz \int_{v_{x0}}^{\infty} v_x \exp\left(-\frac{v_x^2 + v_y^2 + v_z^2}{2k_B T}\right)dv_x = AT^2 \exp\left(-\frac{q\varphi_B}{k_B T}\right)\exp\left(\frac{qV}{k_B T}\right)$$

$$A = \frac{qmk_B^2}{2\pi^2\hbar^3}, v_{x0} = \sqrt{\frac{-2q(V_D + V)}{m}}$$

F.-C. Chiu, Z.-H. Lin, C.-W. Chang et al., *Journal of Applied Physics*, vol. 97, no. 3, 034506, 2005

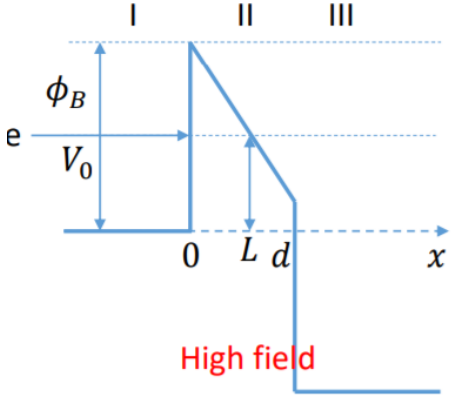
Direct tunneling



$$T = |t|^2 = \frac{4(kk')^2}{k'^2(k+k'')^2\cosh^2(k'd) + (kk''-k'^2)^2\sinh^2(k'd)}$$

Electric field

$$V(x) = V_0 - \varepsilon x$$



$$I \propto T \propto e^{-2\int k'dx}, k' = \sqrt{2m(V-E)}$$

$$I \propto e^{-\frac{4\sqrt{2me}}{3\hbar}\frac{(\Phi_B^{2/3})}{\varepsilon}}$$

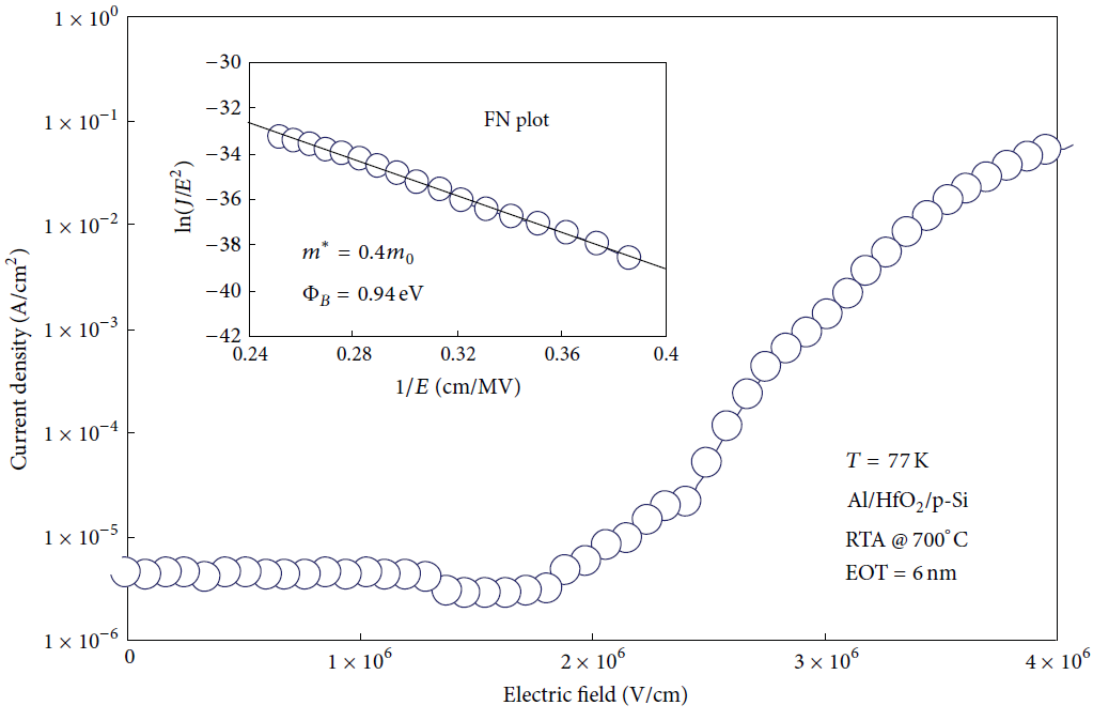
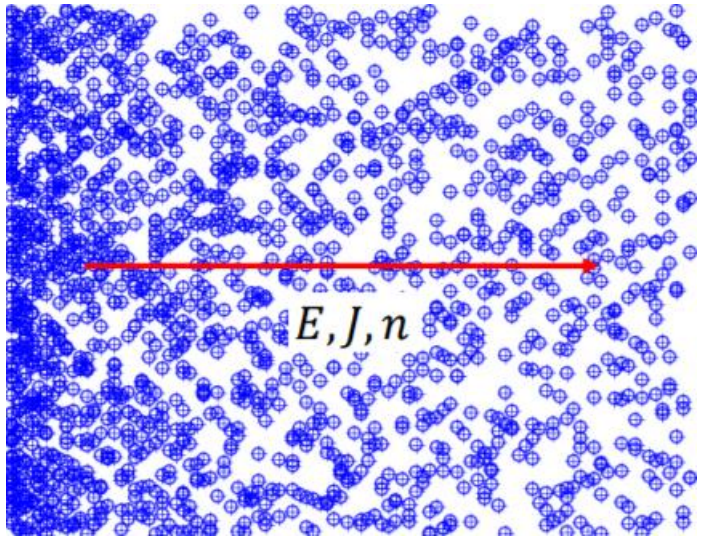


FIGURE 6: Characteristics of J-E plots for HfO_2 MIS capacitor at 77 K. The inset graph presents the Fowler-Nordheim tunneling.

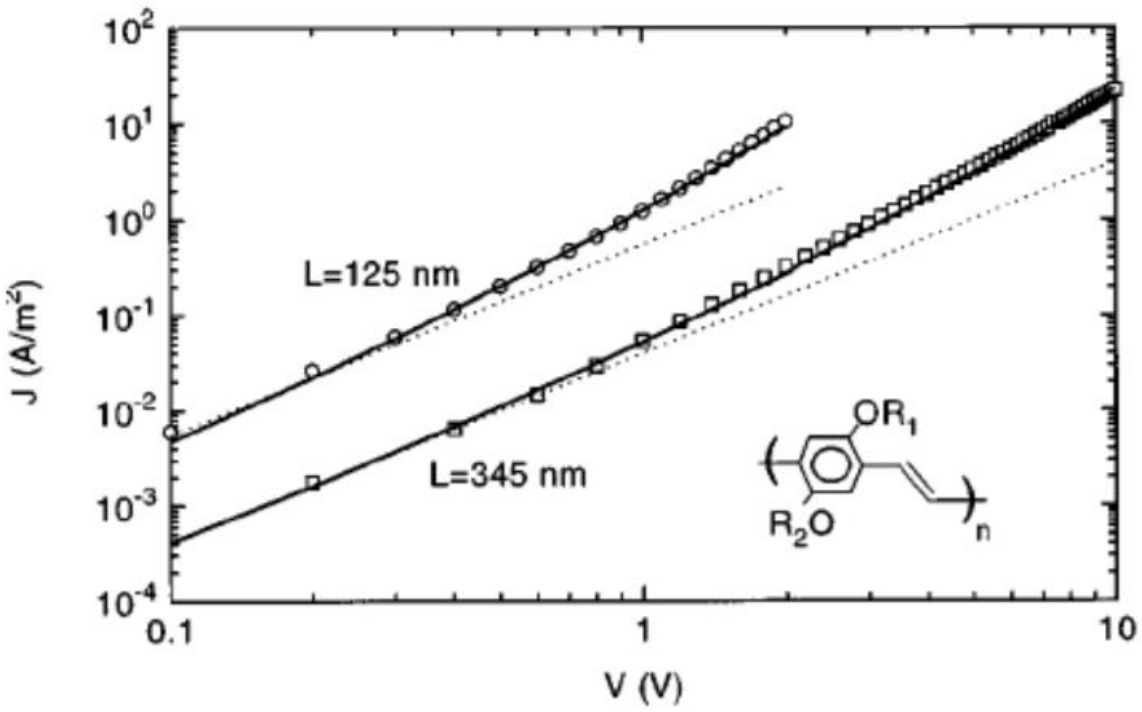
D. K. Schroder, *Semiconductor Material and Device Characterizationedition*, John Wiley & Sons, New York, NY, USA, 2nd edition, 1998

Space charge limited current



$$J = n\mu E$$

$$\frac{\varepsilon}{-e}\frac{dE}{dx} = n \quad \Rightarrow \quad n = \sqrt{\frac{\varepsilon J}{2\mu x}} \quad \Rightarrow \quad J = \frac{9}{8}\varepsilon\mu\frac{V^2}{x^3}$$



PRB, v55, R656 (1997)

Hopping conduction

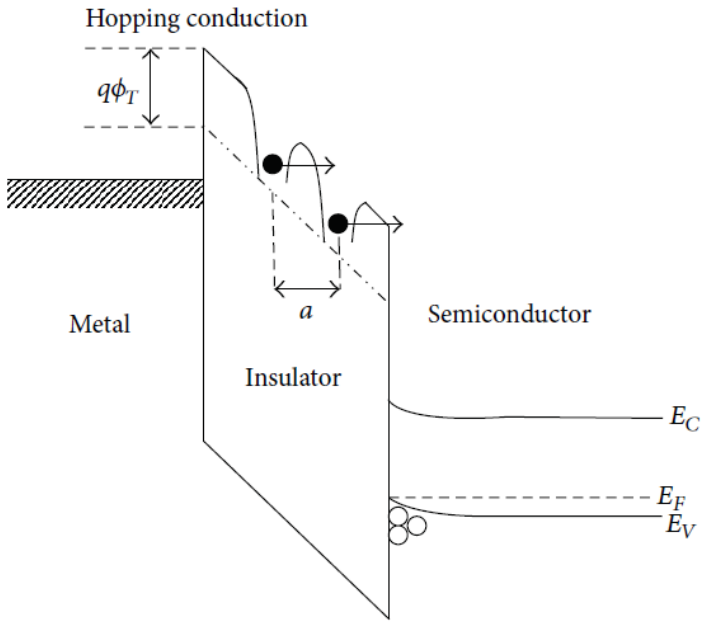


FIGURE 15: Energy band diagram of hopping conduction in metal-insulator-semiconductor structure.

$$J = qanv \exp\left[\frac{qaE}{kT} - \frac{E_a}{kT}\right],$$

a is mean hopping distance, n is electron concentration in conduction band, v is thermal vibration frequency at trap site, E_a is activation erengy

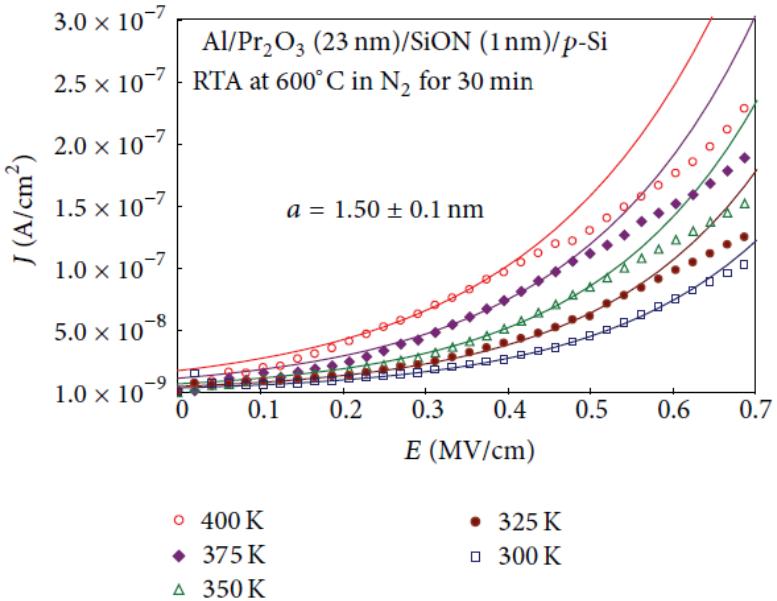


FIGURE 16: J-E characteristics and simulation of hopping conduction for a laminated Pr_2O_3/SiON MIS capacitors at low electric fields.

F.-C. Chiu, C.-Y. Lee, and T.-M. Pan, *Journal of Applied Physics*, vol. 105, no. 7, 074103, 2009

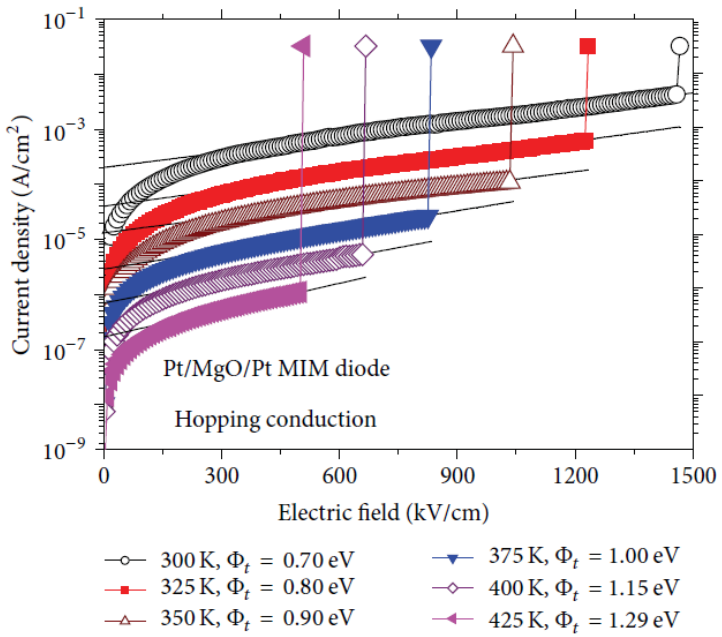


FIGURE 18: Experimental data and simulation curves of hopping conduction in high resistance state in Pt/MgO/Pt memory device.

F. C. Chiu, W. C. Shih, and J. J. Feng, *Journal of Applied Physics*, vol. 111, no. 9, 094104, 2012