전자물리특강:
OLED I-V Characteristics

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전자물리특강
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Charge –voltage characteristics of organic semiconductors

- Current
  - Injection limited
    - Thermionic emission

      $$J = J_s[\exp(\frac{eV}{k_B T}) - 1] \quad J_s = A^* T^2 \exp(\frac{-e\phi_{bn}}{k_B T})$$

    - Tunneling

      $$J \approx E^2 \exp(\frac{-b}{E}) \quad b = \frac{8\pi\sqrt{2m^*}(q\phi)^{3/2}}{3qh}$$

  - Bulk Limited
    - Ohmic (Doped semiconductor)

      $$J = ep\mu E$$

    - SCLC (undoped semicond. or Insulator)

      $$J_{SCLC} = \frac{9}{8}\varepsilon_o \varepsilon_r \mu \frac{V^2}{d^3}$$

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Carrier Injection

Thermionic Emission

$$J = J_s[\exp(\frac{eV}{k_B T}) - 1]$$

$$J_s = A^* T^2 \exp(\frac{-e\phi_{bn}}{k_B T})$$

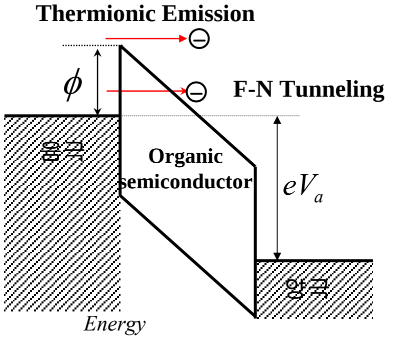
effective Richardson constant for thermionic emission

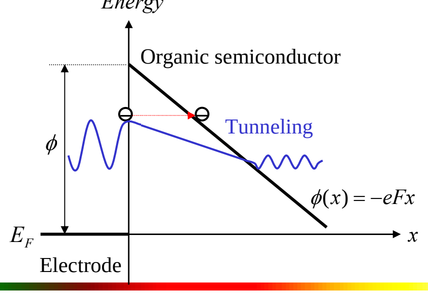
$$A^* = \frac{4\pi e m_n^* k_B}{h^3} = 120(\frac{m^*}{m})\ \mathrm{A/cm^2/K^2}$$

Fowler-Nordheim Tunneling

$$J \approx E^2 \exp(\frac{-b}{E})$$

$$b = \frac{8\pi\sqrt{2m^*}(q\phi)^{3/2}}{3qh}$$





Carrier Injection : Fowler-Nordheim Tunneling

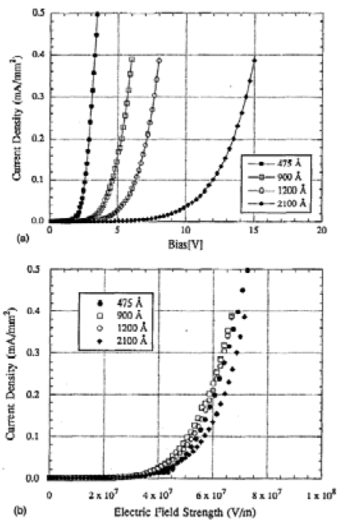


FIG. 2. (a) Thickness dependence of the *I-V* characteristics in an ITO/MEH-PPV/Ca device. (b) Electric field *v* current dependence for the above devices.

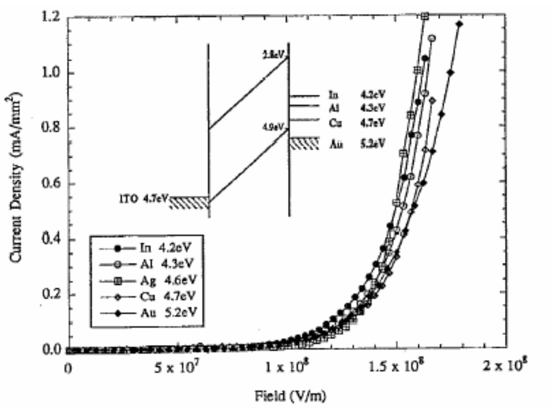


FIG. 3. *I-V* characteristics of 1200 Å thick "hole-only" devices. Inset shows band models indicating the relative position of the Fermi energies of the various materials.

I. D. Parker, J. Appl. Phys. **75**, 1656 (1994).

Carrier Injection : Fowler-Nordheim Tunneling

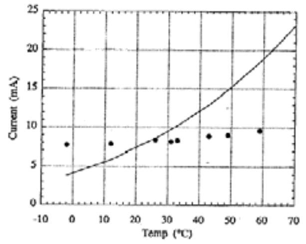


FIG. 5. Temperature dependence of a 1200 Å thick ITO/MEH-PPV/Au device operating at 17 V bias. For comparison, the solid line indicates the I-V characteristics of a 0.2 eV Schottky barrier device.

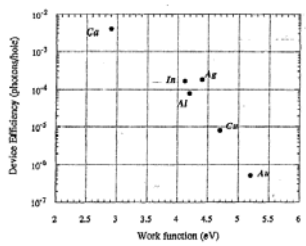


FIG. 10. Device efficiency vs cathode work function for ITO/MEH-PPV devices.

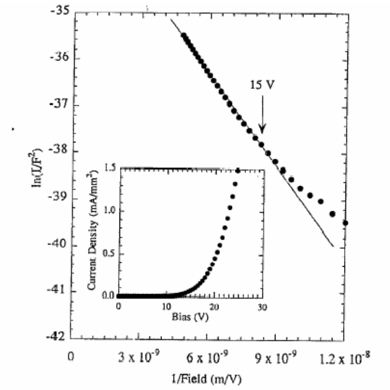


FIG. 6. Fowler-Nordheim plot for a 1200 Å thick ITO/MEH-PPV/Au device. Inset shows the I-V characteristics of the device.

$$J_s \approx E^2 \exp\left(\frac{-b}{E}\right) \qquad b = 8\pi(2\,m^*)^{1/2}\,(q\Phi)^{3/2}/3qh$$

I. D. Parker, J. Appl. Phys. **75**, 1656 (1994).

Charge –voltage characteristics

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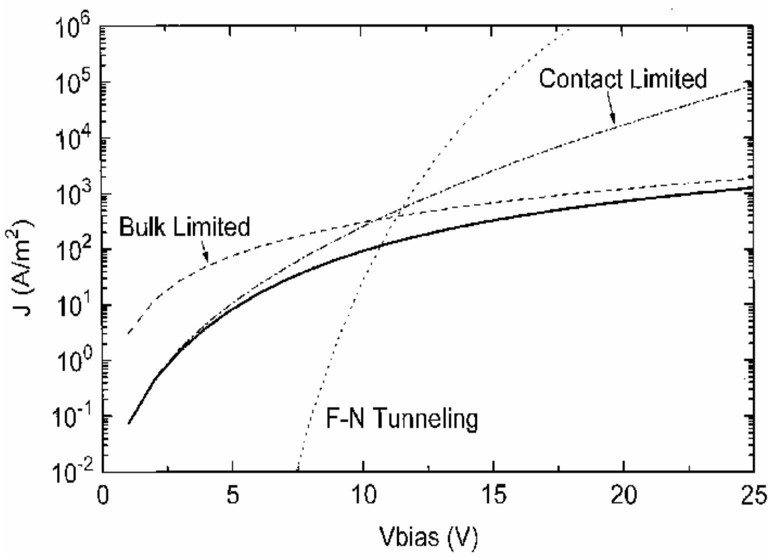

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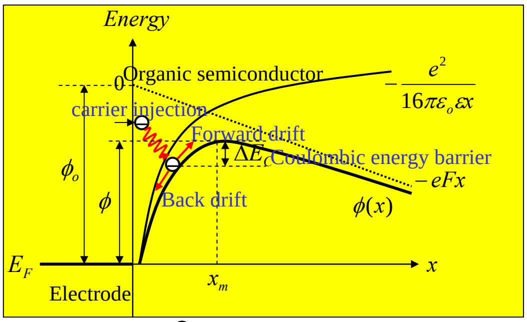
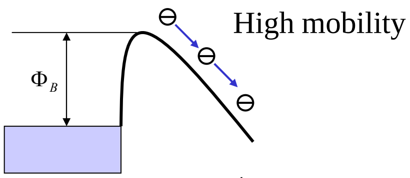
Thermionic emission over potential barrier

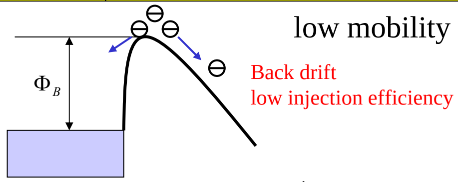
For current injection into low-mobility semiconductors diffusion effects have to be taken into account.



Thermionic emission-diffusion theory

[C.R. Crowell, S.M. Sze, Solid State Electron. **9**, 1035 (1966).]





$$J_s = A^* T^2 \exp\left(\frac{-e\phi_{bn}}{k_B T}\right)$$

$$J_s = eN_c \mu E(0) \exp\left(\frac{-e\phi_{bn}}{k_B T}\right)$$

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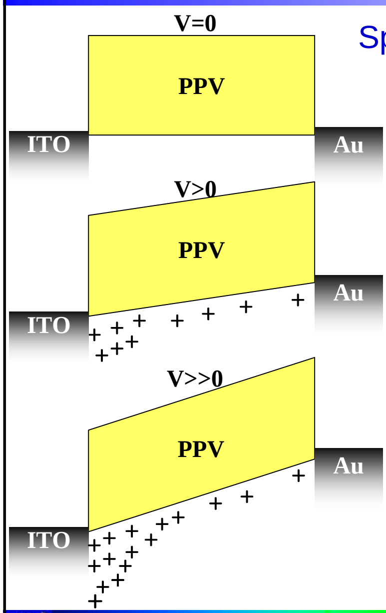
Space-charge-limited current (SCLC)



Space-charge-limited current (SCLC)

OLED acts as a capacitor

$$J_{SCLC} \approx (\text{charge density}) \times \text{velocity}$$

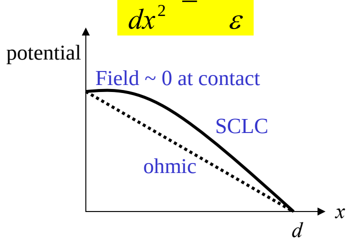
$$= \left(\frac{CV}{d \cdot \text{area}}\right) \times (\mu E)$$

$$= \frac{\varepsilon_o \varepsilon_r}{d^2} \cdot V \cdot \mu \cdot \frac{V}{d}$$

$$= \frac{\varepsilon_o \varepsilon_r \mu V^2}{d^3}$$

$$J_{SCLC} = \frac{9}{8} \varepsilon_o \varepsilon_r \mu \frac{V^2}{d^3}$$

$$\frac{d^2 V}{dx^2} = -\frac{\rho}{\varepsilon}$$



Ohmic Contact (1)

Poisson equation : $\frac{dF}{dx} = \frac{qn}{\varepsilon}$.

Current flow equation : $J = qn\mu F - qD\frac{dn}{dx} = 0$,

since there is no external applied field.

$\therefore \frac{dn}{n} = \frac{\mu}{D}Fdx = \frac{q}{k_B T}Fdx,$

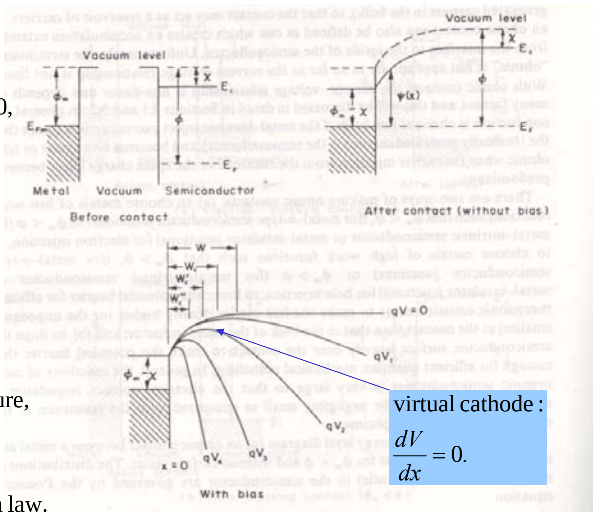
where the Einstein relation $\frac{D}{\mu} = \frac{k_B T}{q}$ is used.

$\therefore \log\frac{n}{n_s} = \frac{q}{k_B T}\int_0^x Fdx.$

From the boundary condition in the right figure,

$\psi(x)\text{-}(\varphi_m - \chi) = -q\int_0^x Fdx.$

$\therefore n = n_s \exp[-\frac{\psi(x)\text{-}(\varphi_m - \chi)}{k_B T}]$, i.e., Boltzmann law.



Ohmic Contact (2)

$$\frac{d^2\psi}{dx^2} = -q\frac{dF}{dx} = -\frac{q^2 n}{\varepsilon} = -\frac{q^2 n_s}{\varepsilon}\exp[-\frac{\psi(x)\text{-}(\varphi_m - \chi)}{k_B T}].$$

Integrating both sides after multiplying $2(\frac{d\psi}{dx})$

and using the boundary condition $\frac{d\psi}{dx} = 0$ when $\psi = \varphi - \chi$,

$$(\frac{d\psi}{dx})^2 = \frac{2q^2 n_s k_B T}{\varepsilon}\{\exp[-\frac{\psi(x)\text{-}(\varphi_m - \chi)}{k_B T}] - \exp[-\frac{(\varphi - \varphi_m)}{k_B T}]\}.$$

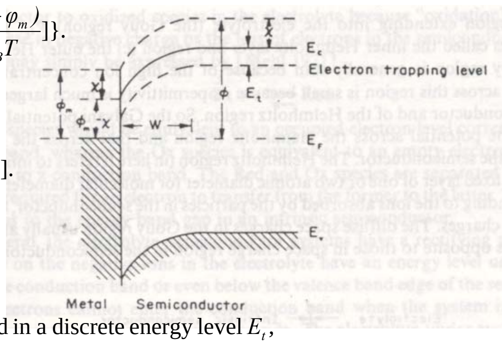
Integrating this equation gives

the width of the accumulation region

$$W = (\frac{2\varepsilon k_B T}{q^2 N_c})^{1/2}\exp(\frac{\varphi - \chi}{2k_B T})[\frac{\pi}{2} - \sin^{-1}\{\exp(-\frac{\varphi - \varphi_m}{2k_B T})\}].$$

If $\varphi - \varphi_m > 4k_B T$,

$$W \approx \frac{\pi}{2}(\frac{2\varepsilon k_B T}{q^2 N_c})^{1/2}\exp(\frac{\varphi - \chi}{2k_B T}).$$



For semiconductors containing shallow traps confined in a discrete energy level E_t,

$$W \approx \frac{\pi}{2}(\frac{2\varepsilon k_B T}{q^2 N_t})^{1/2}\exp(\frac{\varphi - \chi - E_t}{2k_B T}).$$

Space-charge-limited current (1)

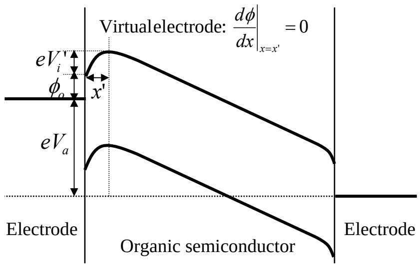
Distribution function of trap density

$h(E,x) = N_t(E)S(x).$

Poisson equation : $\dfrac{dF(x)}{dx} = \dfrac{\rho}{\varepsilon} = \dfrac{q[p(x)+p_t(x)]}{\varepsilon}.$

Current flow equation : $J = q\mu_p p(x)F(x).$

$p_t(x) = \int_{E_l}^{E_u} h(E,x) f_p(E)dE, \quad p(x) = N_v \exp[-\dfrac{E_{F_p}}{k_B T}].$



For $p_t(x) = 0,$

$$2F(x)\frac{dF(x)}{dx} = \frac{d[F(x)]^2}{dx} = \frac{2J}{\varepsilon\mu_p}. \quad \therefore [F(x)]^2 - [F(x=0)]^2 = [F(x)]^2 = \frac{2J}{\varepsilon\mu_p}x.$$

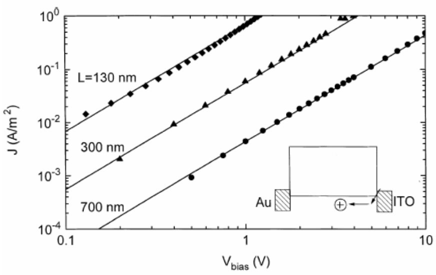
$$\therefore F(x) = \sqrt{\frac{2J}{\varepsilon\mu_p}x}.$$

The distance W_a between the actual electrode surface and the virtual anode ($-dV/dx=F=0$) is so small that we can assume $F(x=W_a \rightarrow 0)=0$ for simplicity.

Boundary condition, $V = \int_0^d F(x)dx.$

$$J = \frac{9}{8}\varepsilon\mu_p\frac{V^2}{d^3}.$$ Mott - Gurney law. (no trap)

Space-charge-limited current

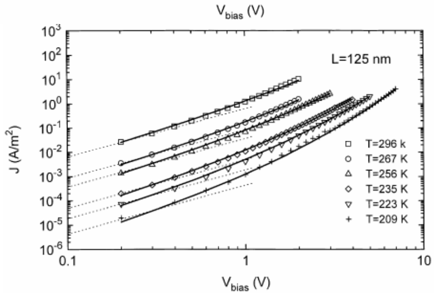


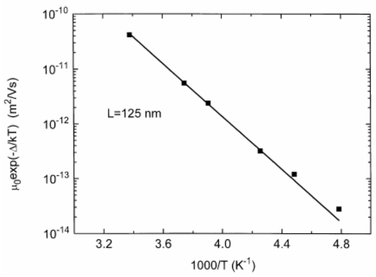
ITO/PPV/Au hole-only devices

$$J_{SCLC} = \frac{9}{8}\varepsilon_o\varepsilon_r\mu\frac{V^2}{d^3}$$

Fit using $\mu = 0.5\times10^{-6}\ cm^2/Vs$ & $\varepsilon_r = 3$

$$\mu(F,T) = \mu_o \exp\left(-\frac{\Delta E - \beta_{PF}\sqrt{F}}{k_B T_{eff}}\right)$$





P.W.M. Blom, M.C.J.M. Vissenberg, Materials Science and Engineering **27**, 53-94 (2000)

Space-charge-limited current (2)

At low field, ohm's law holds if the density of thermally generated free carriers p_o inside the specimen is predominant such that

$$qp_o\mu_p\frac{V}{d} >> \frac{9}{8}\varepsilon\mu_p\frac{V^2}{d^3}.$$

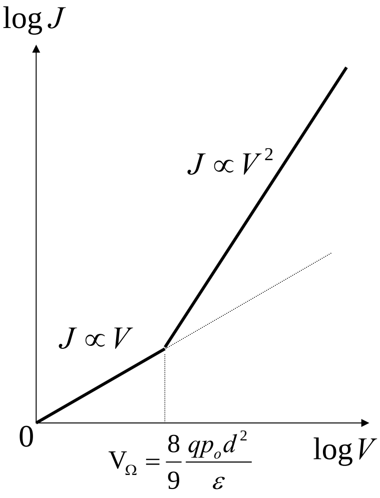
The onset of the departure from Ohm's law or the onset of the SCL conduction takes place when $V_\Omega = \frac{8}{9}\frac{qp_o d^2}{\varepsilon}$.

By rearranging this equation we have

$$\frac{d^2}{\mu_p V_\Omega} = \frac{9}{8}\frac{\varepsilon}{qp_o\mu_p} = \frac{9}{8}\frac{\varepsilon}{\sigma_o} \text{ or } \tau_t \approx \tau_d.$$

Therefore, the transition from the ohmic to the SCL regime takes place when the carrier transit time $\tau_t = \frac{d^2}{\mu_p V_\Omega}$ at V_Ω is approximately equal to the dielectric relaxation time $\tau_d = \frac{\varepsilon}{\sigma_o}$.

At $\tau_t > \tau_d$, ohmic conduction is predominant.
At $\tau_t < \tau_d$, SCLC conduction is predominant.



K. C. Kao and W. Hwang, Electrical Transport in Solids, (Pergamon, New York, 1981), p.159

Space-charge-limited current (3)

dielectric relaxation time $\tau_d = \frac{\varepsilon}{\sigma_o}$.

Continuity equation $q\frac{\partial(p+p_o)}{\partial t} = -\nabla\cdot J$,

where current is given by $J = q(p+p_o)\mu_p F - qD_p\nabla(p+p_o)$.

$$\therefore \frac{\partial p}{\partial t} = -(\frac{qp\mu_p}{\varepsilon})p + D_p\nabla^2 p.$$

If $p < p_o$ and p spreads uniformly over the specimen in a time comparable to the dielectric relaxation time $\tau_d = \frac{\varepsilon}{\sigma_o}$, the 2nd term can be ignored.

$$\therefore \frac{\partial p}{\partial t} \approx -(\frac{qp_o\mu_p}{\varepsilon})p. \quad \therefore p(t) = p(t=0)\exp(-t/\tau_d).$$

τ_d is a measure of the time required for the carrier to re-establish equilibrium.

Space-charge-limited current (4)

Traps confined in single or multiple discrete energy levels

$$h(E,x) = N_t \delta(E - E_t) S(x)$$

Trapped charge density $p_t(x) \approx \dfrac{N_t S(x)}{1 + N_t \theta_t / p(x)}$,

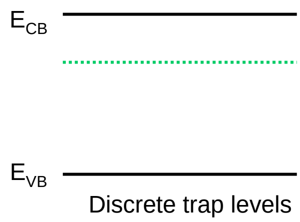
where $\theta_t = \dfrac{g_p N_v}{N_t} e^{-\frac{E_t}{kT}}$.

$$J_{SCLC} = \frac{9}{8} \varepsilon_o \varepsilon_r \mu \theta_t \frac{V^2}{{d_{eff}}^3}.$$

Ignoring non-uniform spatial distribution of traps

$$\theta_t = \frac{p}{p + p_t}, \quad d_{eff} = d$$

$$J_{SCLC} = \frac{9}{8} \varepsilon_o \varepsilon_r \mu \theta_t \frac{V^2}{d^3}.$$



Space-charge-limited current (5)

Traps confined in single or multiple discrete energy levels

$$h(E,x) = \frac{N_t}{kT_t} e^{-\frac{E}{kT_t}} S(x).$$

$$J = q^{1-m} \mu N_v \left(\frac{2m+1}{m+1}\right)^{m+1} \left(\frac{m}{m+1} \frac{\varepsilon_o \varepsilon_r}{N_t}\right)^m \frac{V^{m+1}}{d^{2m+1}}.$$

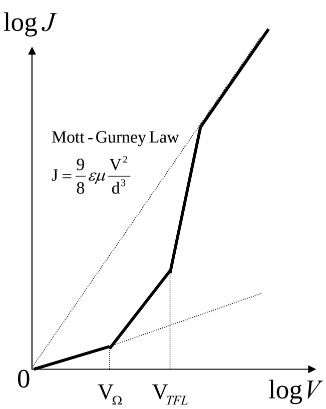
$$m = \frac{T_t}{T}.$$

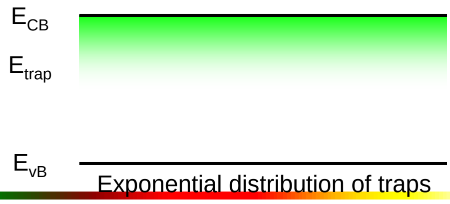
Ohmic $\Rightarrow$ Trapped SCLC

$$V_\Omega = \frac{qd^2 N_t}{\varepsilon_o \varepsilon_r} \left(\frac{p_o}{N_v}\right)^{\frac{1}{m}} \left(\frac{m+1}{m}\right) \left(\frac{m+1}{2m+1}\right)^{\frac{m+1}{m}}.$$

Trapped SCLC $\Rightarrow$ Trap-free SCLC

$$V_{TFL} = \frac{qd^2}{\varepsilon_o \varepsilon_r} \left[\frac{9}{8} \frac{N_t^m}{N_v} \left(\frac{m+1}{m}\right)^m \left(\frac{m+1}{2m+1}\right)^{m+1}\right]^{\frac{1}{m-1}}.$$

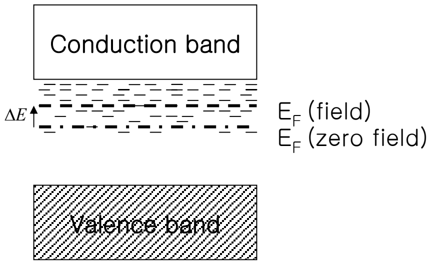




Space-charge-limited current (6)

Trap이 있는 경우의 space charge limited current (SCLC)의 근사적 계산

유기반도체 내에 트랩 (trap)이 다음과 같은 지수함수적인 분포를 하고 있다고 가정하자.



$$n_t = Ae^{-\frac{E}{kT_t}}$$

여기서 에너지 E는 conduction band 의 최저점에서부터 측정하며, T_t는 트랩분포를 결정하는 characteristic temperature이다.

(1) 두 전극 사이의 전위차가 V인 경우에 주입된 전하 Q=CV (여기서 C=capacitance)에 의한 Fermi level의 이동 ΔE는 다음 관계식으로부터 구할 수 있다.

$$\int_{E_F-\Delta E}^{E_F} n_t dE = \int_{E_F-\Delta E}^{E_F} Ae^{-\frac{E}{kT_t}} dE = \frac{Q}{e} = \frac{CV}{e}$$

$$\therefore \quad \Delta E = kT_t(K + \ln V), \ \ \mathrm{K = constant}$$

(2) 전위차가 V인 경우에 conduction band에 있는 자유 전하 밀도는 다음과 같이 쓸 수 있다.

$$n_c = N_c e^{-\frac{E_F-\Delta E}{kT}} = n_o e^{\frac{\Delta E}{kT}}$$

Space-charge-limited current (7)

(3) 전체전하 (자유전하 + 트랩 전하) 중 자유전하의 비율 θ는 다음과 같이 쓸 수 있다.

주입된 전하는 거의 전부 트랩을 채우므로 Density of trapped charges $\approx \frac{Q}{ed} = \frac{CV}{ed}$

따라서 전체전하 (자유전하 + 트랩 전하) 중 자유전하의 비율은

$$\theta = \frac{n_c}{(\frac{Q}{ed})} \approx \frac{edn_o}{CV} e^{\frac{\Delta E}{kT}} = \frac{B}{V} e^{\frac{T_t}{T}\ln V} = BV^{\frac{T_t}{T}-1}$$

$$\therefore J \approx \varepsilon\mu\theta \frac{V^2}{d^3} \propto V^{\frac{T_t}{T}+1}$$

Space-charge-limited current (8)

Trap이 지수함수적인 분포를 하고 있는 경우의 space charge limited current

Poisson equation $\frac{dF}{dx} = \frac{\rho}{\varepsilon} = \frac{\rho_f + \rho_t}{\varepsilon}$ Boundary condition: F=0 at x=0.

Current density $J = \rho_f \mu F.$

Assuming $\rho_f << \rho_t$ → $\frac{dF}{dx} = \frac{\rho}{\varepsilon} \approx \frac{\rho_t}{\varepsilon}$

$$\rho_f = \theta\frac{Q}{d} = \theta\frac{CV}{d} = (BV^{\frac{T_t}{T}-1})\frac{CV}{d} = B\frac{CV^{\frac{T_t}{T}}}{d} = B\frac{(CV)^m}{C^{m-1}d} \approx A\rho_t^{\ m}$$

Here, trapped charge density is approximated as $\rho_t \approx CV = Q$ and $m = \frac{T_t}{T}$

$$n_t = Ae^{-\frac{E}{kT_t}};\ n_f \propto e^{-\frac{E}{kT}} \sim (e^{-\frac{E}{kT_t}})^{\frac{T_t}{T}} \approx n_t^{\frac{T_t}{T}} \approx n_t^{\ m}$$

$$\therefore\ \frac{dF}{dx} \approx \frac{\rho_t}{\varepsilon} \approx \frac{1}{\varepsilon}(\frac{\rho_f}{A})^{\frac{1}{m}} = \frac{1}{\varepsilon}(\frac{J}{A\mu F})^{\frac{1}{m}} = DF^{-\frac{1}{m}}$$ where $D = \frac{1}{\varepsilon}(\frac{J}{A\mu})^{\frac{1}{m}}$

Space-charge-limited current (9)

$$\int_0^x F^{\frac{1}{m}}\frac{dF}{dx}dx = \int_0^x Ddx$$

$$\frac{m}{m+1}F^{\frac{m+1}{m}} = Dx \qquad F = [(\frac{m+1}{m})Dx]^{\frac{m}{m+1}}$$

$$F = \frac{dV}{dx} = [(\frac{m+1}{m\varepsilon})x]^{\frac{m}{m+1}}(\frac{J}{A\mu})^{\frac{1}{m+1}}$$

Integrating from x=0 to d, $V = [(\frac{m+1}{m\varepsilon})]^{\frac{m}{m+1}}(\frac{J}{A\mu})^{\frac{1}{m+1}}\frac{m}{2m+1}d^{\frac{2m+1}{m+1}}$

$$\therefore\ V^{m+1} \propto (\frac{J}{A\mu})d^{2m+1}$$

$$\therefore\ J \propto \mu\frac{V^{m+1}}{d^{2m+1}} \propto \mu\frac{V^{\frac{T_t}{T}+1}}{d^{2\frac{T_t}{T}+1}}$$

Space-charge-limited current (8)

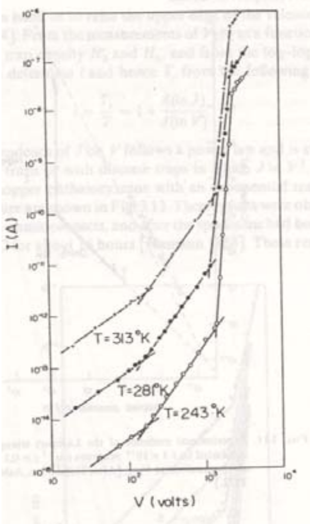


Fig. 3.10. The current–voltage characteristics of naphthalene single crystals as functions of temperature. [After Campos 1972.]

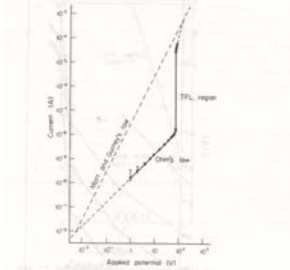


Fig. 3.11. Experimental evidence of the Lampert triangle in silicon irradiated to 1.1×10^{16} neutrons cm^{-2} (> 0.1 MeV) with a steep transition at V_{TFL}. [After Henderson, Ashley, and Shen 1972.]

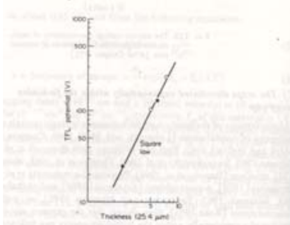


Fig. 3.12. The TFL threshold voltage (V_{TFL}) for neutron-irradiated silicon as a function of specimen thickness. [After Henderson, Ashley, and Shen 1972.]

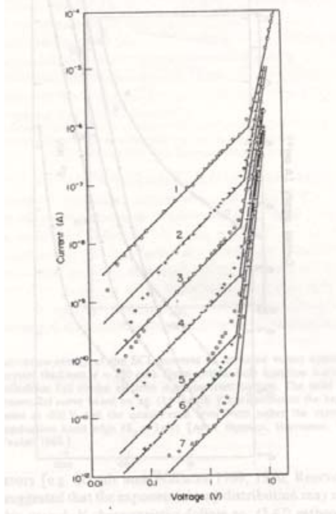
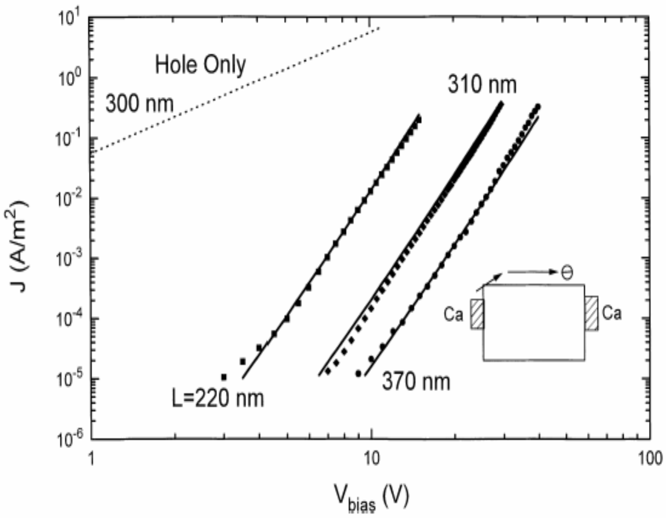


Fig. 3.13. The current–voltage characteristics of α-copper phthalocyanine films of thickness of 4 μm: (1) 144.6°C, (2) 116.9°C, (3) 96.8°C, (4) 76.5°C, (5) 54.2°C, (6) 33.8°C, (7) 20.9°C, highest heat treatment at 200°C. [After Hamann 1968.]

Trap-limited current

Ca/PPV/Ca electron-only devices



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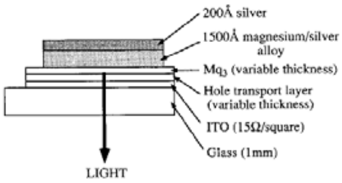
Trap-limited SCLC

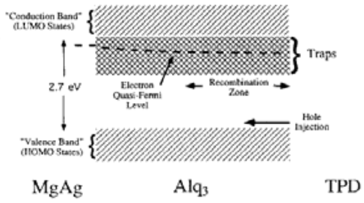
Trap - limited SCLC

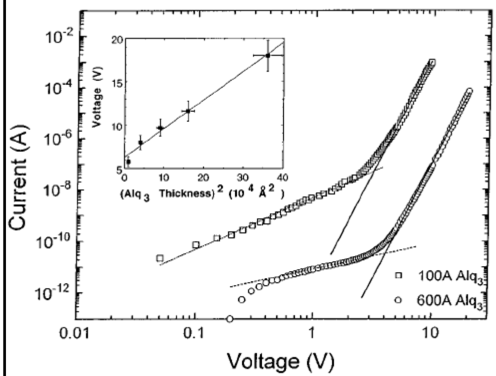
$$J \propto \mu N_v N_t^{-m} \frac{V^{m+1}}{d^{2m+1}}, \quad m = \frac{T_t}{T}.$$

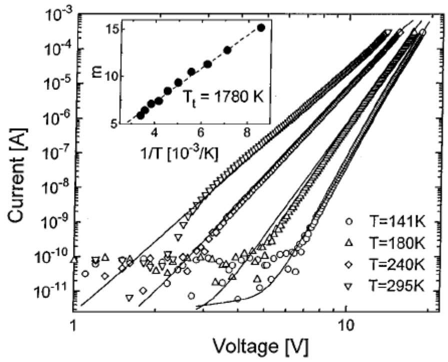
$E_t \approx 0.15\,\text{eV}$

$N_t \approx 10^{18}\ \text{cm}^{-3}$









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