Charge carrier transport in organic semiconductors

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

2009. 5.12.

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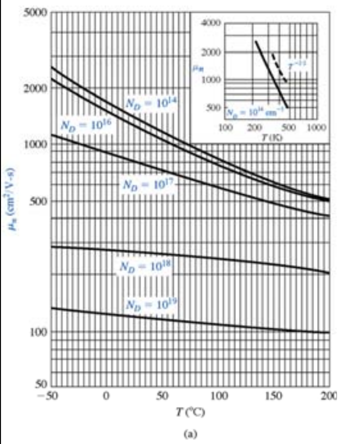
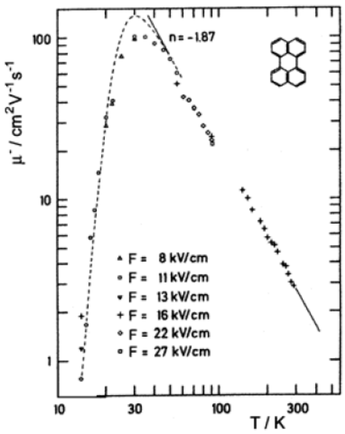
Carrier mobility of Si and Organic Materials

Electron mobility of Si

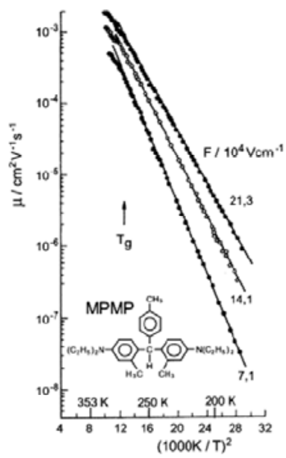


hole mobility of Perylene



370 nm thick perylene crystal

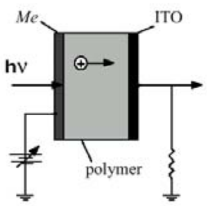
hole mobility of MPMP



8.7 um thick unordered layer
of
MPMP (sublimed).

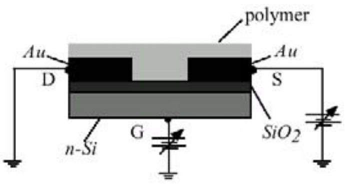
Mobility Measurement Techniques

$\mu\,(cm^2/Vs)$: 10^{-8}, 10^{-6}, 10^{-4}, 10^{-2}, 10^{0}, 10^{2}



$$\tau = \frac{d^2}{\mu V}$$

$$\therefore \mu = \frac{d^2}{V\tau}$$



TOF
Mobility in the bulk
d = 0.5~5 mm

FET
Mobility in a thin layer
d ~ 50 nm

Other mobility measurement techniques
- Dark injection in the space-charge limited current regime
- I-V characteristics of space charge limited current
- Transient EL
- SHG measurement [T. Manaka, E. Lim, R. Tamura, M. Iwamoto, *Nature Photon.* **1,** 581–584 (2007).]

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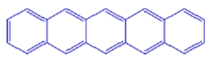
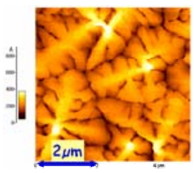
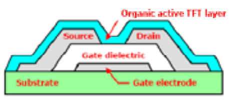
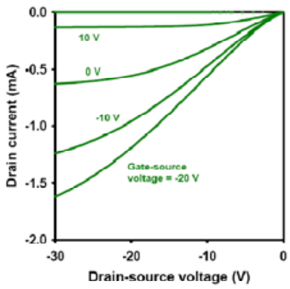
Mobility Measurement Techniques: Organic TFT

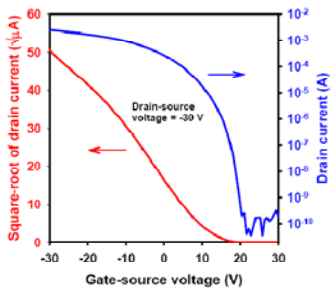






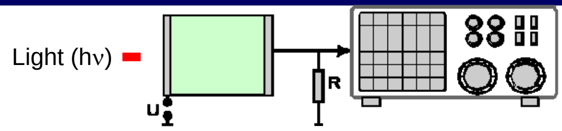
W / L = 500 μm / 5 μm, t_{ox} = 150 nm
μ = 1.7 cm²/V-s, I_{on} / I_{off} = 10^8, S = 0.9 V/dec





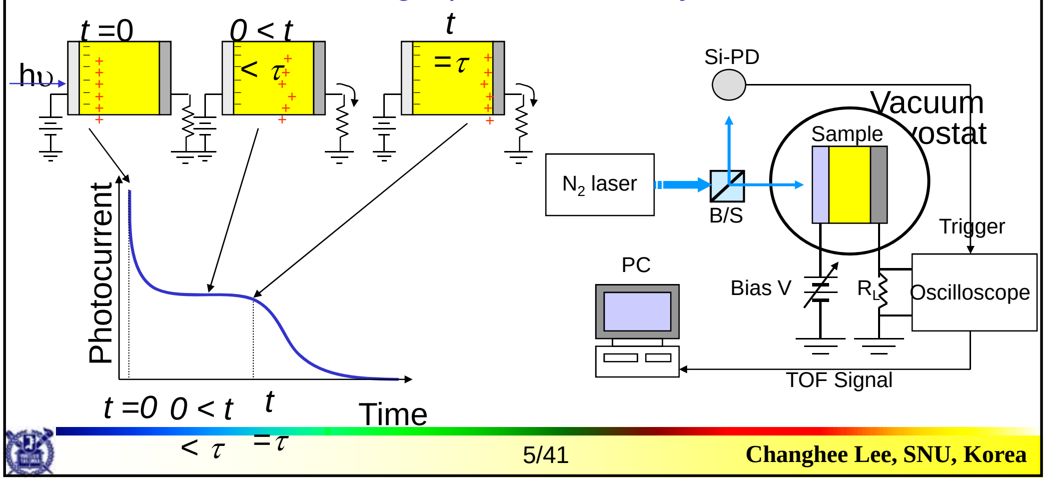
T. N. Jackson, Penn State U.

Mobility measurement techniques: TOF-PC

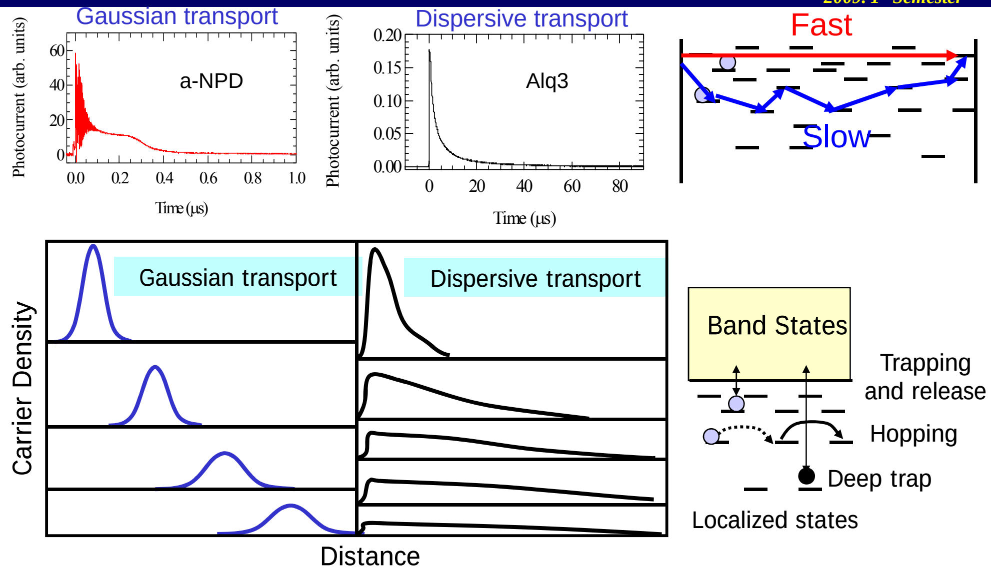


$$\mu = \frac{d^2}{V\tau}$$

Time-of-flight photoconductivity

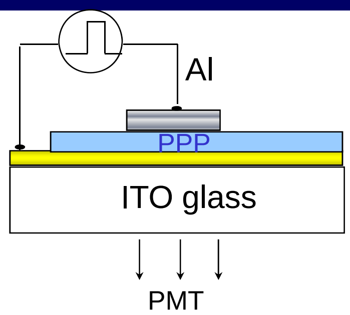


Transport of charge carriers in organic materials



Ref.) Harvey Scher, Michael F. Shlesinger and John T. Bendler, Physics today, Jan. p.26 (1991)

Mobility Measurement Techniques: Transient EL



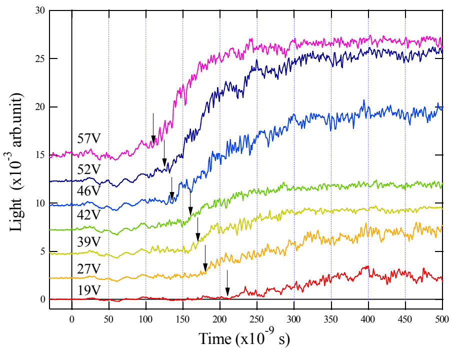
Mobility from the delay time

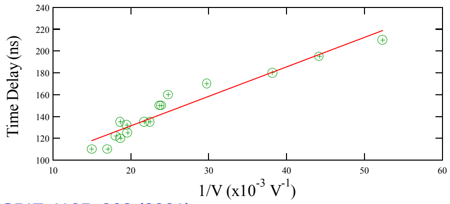
$\tau = d^2 / \mu V$

Hole mobility

in the vacuum-deposited PPP:

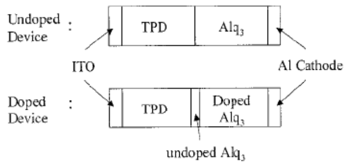
ITO/PPP/Al: $\mu = 4.5 \times 10^{-6}$ cm^2/Vs

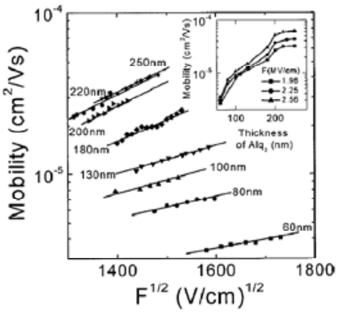


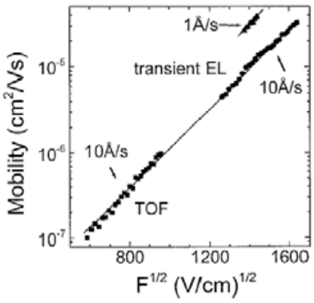


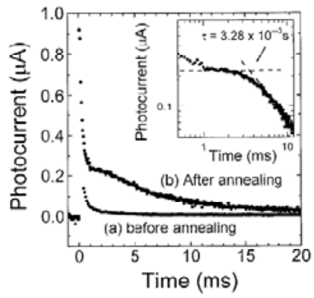
G. W. Kang, C. H. Lee, W. J. Song, and C. Seoul, SPIE 4105, 362 (2001).

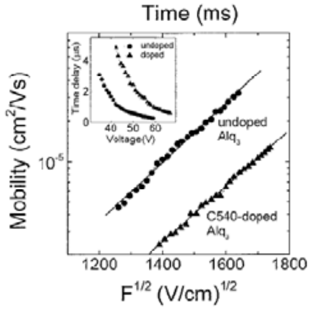
Transient EL Mobility *vs* TOF-PC mobility in Alq3









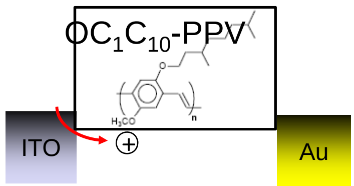


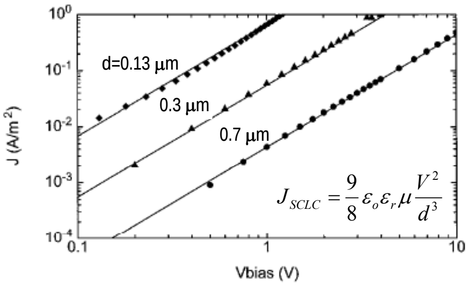
For a thin layer of Alq3 (d<180 nm), it is found that t_d is affected by both the charging effect and carrier transit time through the Alq3 layer. For a thicker layer of Alq3 (d>200 nm), t_d approaches the intrinsic electron transit time through Alq3 .

S. C. Tse, H. H. Fong, and S. K. So, J. Appl. Phys. 94, 2033 (2003)

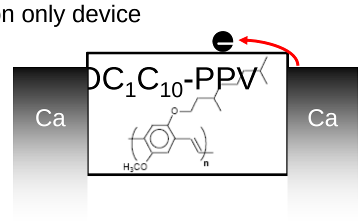
Space-charge-limited current

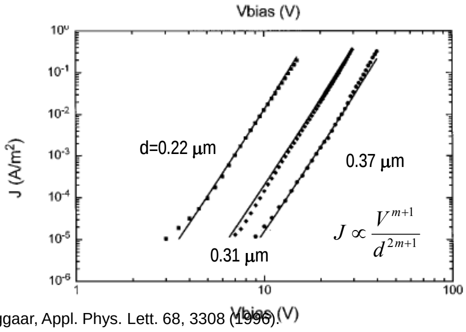
Hole only device





Electron only device

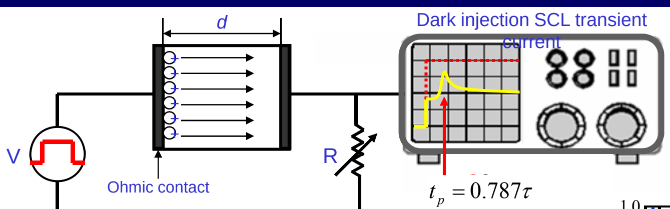




Poly(dialkoxy-p-phenylene vinylene) (OC_1C_{10}-PPV)

P. W. M. Blom M. J. M. de Jong, and J. J. M. Vleggaar, Appl. Phys. Lett. 68, 3308 (1996).

Transient SCLC



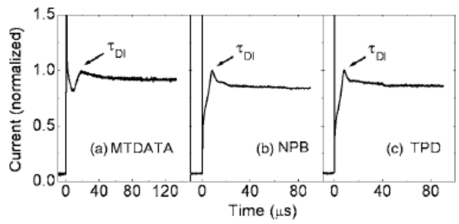
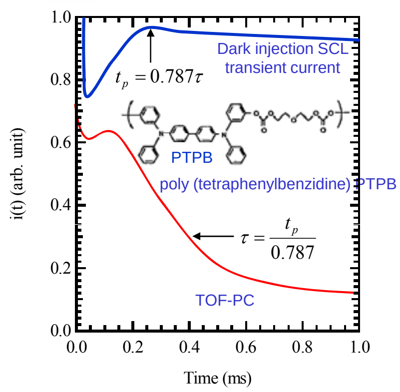


FIG. 5. Room temperature DI signals for MTDATA, NPB, and TPD under applied field strengths of 0.10, 0.09, and 0.09 MV/cm, respectively. The film thicknesses for MTDATA, NPB, and TPD were 0.76, 4.11, and 5.13 μm, respectively.

S.C. Tse, S.W. Tsang, and S.K. So, J. Appl. Phys. 100, 063708 (2006).



M. Abkowitz, J. S. Facci, and M. Stolka, Appl. Phys. Lett. 63, 1892 (1993).

Mobility Measurement Techniques: dark charge injection

In a monopolar and single-layer configuration, the carrier transit time is shorter than in the absence of space-charge effects due to the enhancement of the electric field at the leading edge of the carrier packet.

$$t_{tr} = 0.786\frac{d}{\mu E}$$

The transient current overshoots its steady-state value by a factor of 1.21 and starts at 0.44 times the steady-state value.

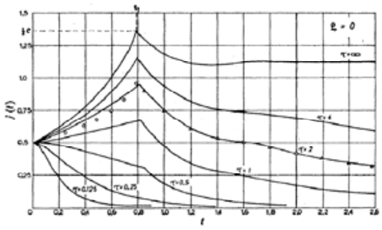
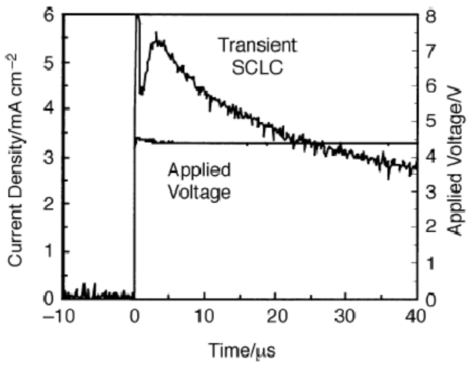


FIG. 5. The time dependence of the SCLC density for insulating crystals characterized by various trapping times, and $\theta_0 = 0$.

A. Many and G. Rakavy, Phys. Rev. 126, 1980 (1962)

ITO/300nm m-MTDATA/Ag with ITO biased positively.



M. Stossel *et al*, Phys. Chem. Chem. Phys.1, 1791 (1999)

Organic Semiconductor
EE 4541.617A
2009. 1st Semester

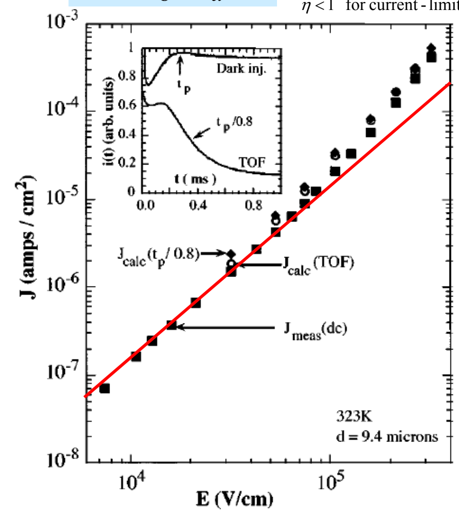
Carrier injection efficiency

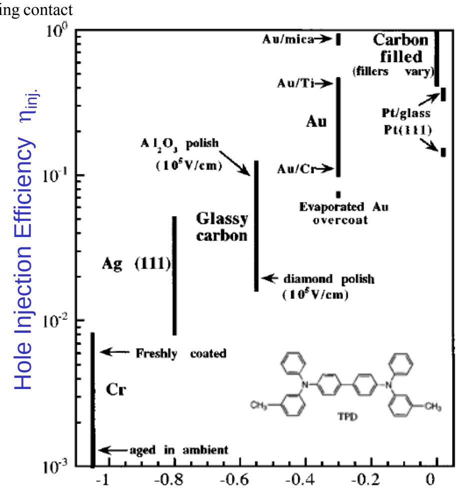
$$J_{SCLC} = \frac{9}{8}\frac{\varepsilon_o \varepsilon_r \mu V^2}{d^3}$$

Injection efficiency : $\eta = \frac{\text{injected current}}{SCLC}$

$\eta = 1$ for ohmic contact

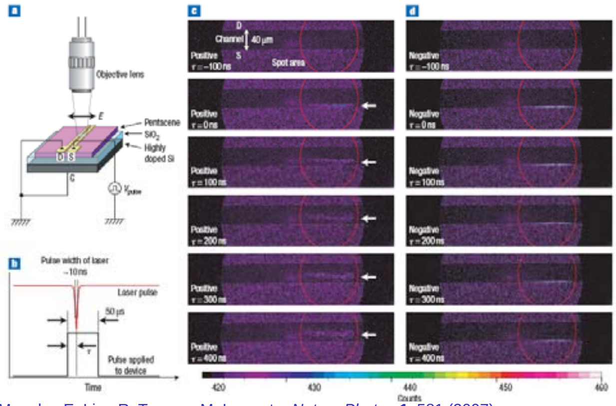
$\eta < 1$ for current-limiting contact

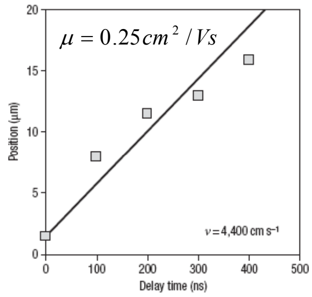




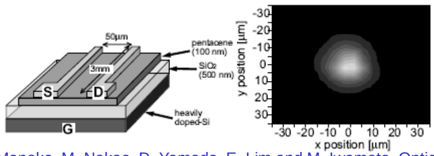
M. Abkowitz, J. S. Facci, J. Rehm, J. Appl. Phys. 1998, 83, 2670.

Mobility Measurement Techniques: TRM-SHG



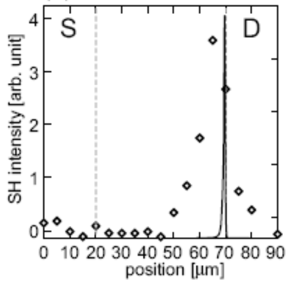


T. Manaka, E. Lim, R. Tamura, M. Iwamoto, *Nature Photon.***1,** 581 (2007).



$$I(2\omega) \propto \left|\chi^{(3)}(2\omega;0,\omega,\omega)E(0)E(\omega)E(\omega)\right|^2$$

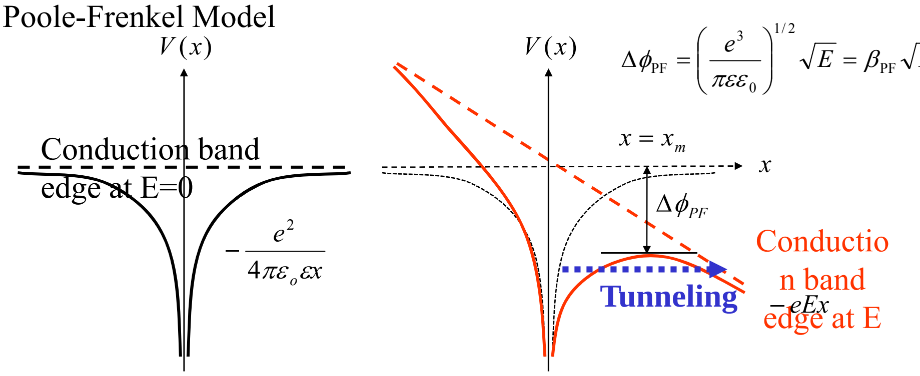
$$I_{2\omega}(x) \propto \left|\int_{-\infty}^{\infty} E(\xi)I_{\omega}(x-\xi)d\xi\right|^2$$



T. Manaka, M. Nakao, D. Yamada, E. Lim and M. Iwamoto, Optics Express 15, 15964 (2008).

Charge Transport in Disordered Organic Solids

(1) Poole-Frenkel Model



$$\Delta\phi_{PF} = \left(\frac{e^3}{\pi\varepsilon\varepsilon_0}\right)^{1/2}\sqrt{E} = \beta_{PF}\sqrt{E}$$

Zero field (E=0) E≠0

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

$$\beta_{PF} = \sqrt{\frac{e^3}{\pi\varepsilon\varepsilon_0}}$$

ΔE : Activation energy at E=0

μ_{PF} : PF Mobility

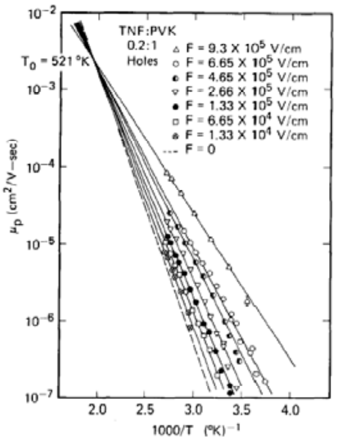
β_{PF} : PF constant

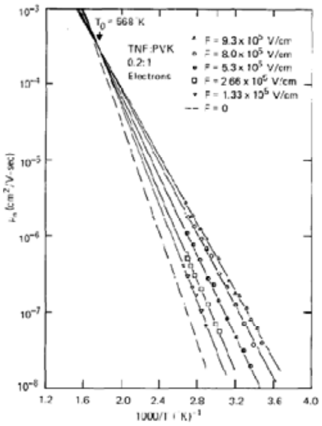
Charge Transport in Disordered Organic Solids

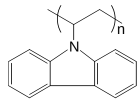
(2) Gill's modified Poole-Frenkel model

$$\mu(F,T) = \mu_{PF}\exp\left(-\frac{\Delta E}{k_B T_{eff}}\right)\exp\left(\frac{\beta_{PF}\sqrt{E}}{k_B T_{eff}}\right) \qquad \frac{1}{T_{eff}} = \frac{1}{T} - \frac{1}{T_0}$$

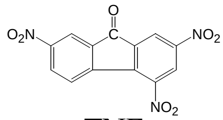
T_0 : Empirical parameter







PVK
poly-n-vinylcarbazole
(hole conductor)



TNF
2,4,6-trinitro-9-fluorenone
(electron acceptor)

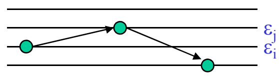
W. D. Gill, J. Appl. Phys. **43**, 5033 (1972).

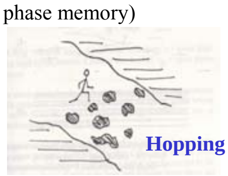
Charge Transport in Disordered Organic Solids

(3) Bassler's Gaussian Disorder Model

- The energy of each site is distributed in accordance with the Gaussian distribution
- Energies of adjacent sites are uncorrelated and motion between sites is Markovian (no phase memory)
- The transition rates for phonon-assisted tunneling (Miller and Abrahams):

$$W_{ij} = \nu_{ph}\exp(-2\alpha R_{ij})\begin{cases}\exp\left(-\frac{\varepsilon_i - \varepsilon_j}{kT}\right), & \varepsilon_i > \varepsilon_j \\ 1, & \varepsilon_i > \varepsilon_j\end{cases}$$

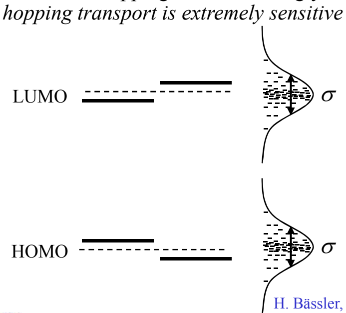


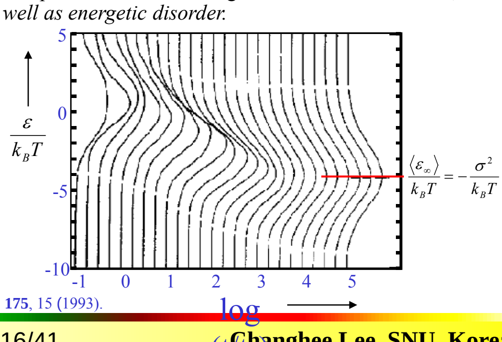


A. Miller, E. Abrahams, Phys. Rev. **120** (1960) 745.

α = inverse localization length, R_{ij} = distance between the localized states, ε_i = energy at the state i.

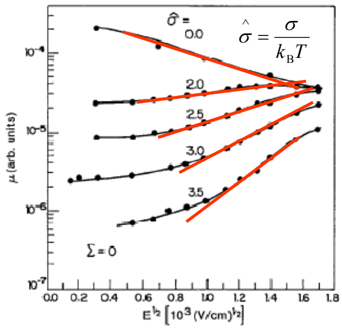
- Since the hopping rates are strongly dependent on both the positions and the energies of the localized states, *hopping transport is extremely sensitive to structural as well as energetic disorder.*

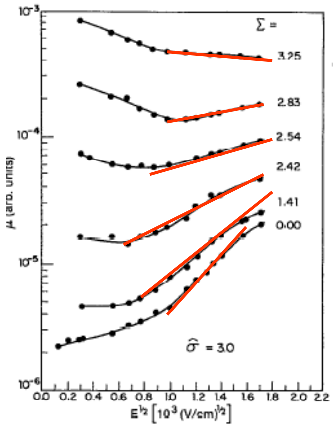




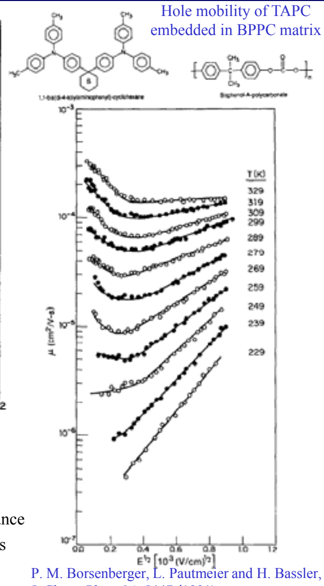
H. Bässler, Phys. Status Solidi B **175**, 15 (1993).

Charge Transport in Disordered Organic Solids





Hole mobility of TAPC embedded in BPPC matrix



σ : Energetic disorder
Σ : Positional disorder
C : Constant ~2.9x10^{-4} (cm/V)$^{1/2}$
μ_o : High temperature limit of the mobility

$$\mu(E,T) = \mu_o \exp\left[-\left(\frac{2\sigma}{3k_B T}\right)^2\right] \exp\left\{C\left[\left(\frac{2\sigma}{3k_B T}\right)^2 - \Sigma^2\right]\sqrt{E}\right\}, \ (\Sigma < 1.5)$$

$$\mu(E,T) = \mu_o \exp\left[-\left(\frac{2\sigma}{3k_B T}\right)^2\right] \exp\left\{C\left[\left(\frac{2\sigma}{3k_B T}\right)^2 - \Sigma^2\right]\sqrt{E}\right\}, \ (\Sigma \geq 1.5)$$

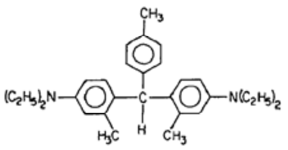
$$\mu_o(\rho) = a_o \rho^2 \exp(-2\rho/\rho_o),$$
where ρ = average inter-site distance
and ρ_o = carrier localization radius

H. Bässler, Phys. Status Solidi B **175**, 15 (1993).

M. Stolka, J. F. Janus and D. M. Pai, J. Phys. Chem. **88**, 4707 (1984).

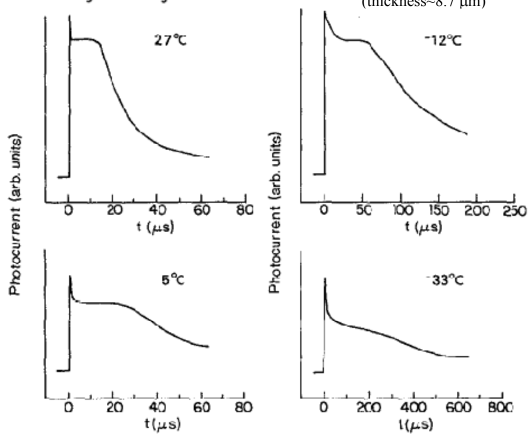
P. M. Borsenberger, L. Pautmeier and H. Bassler, J. Chem. Phys. **94**, 5447 (1991).

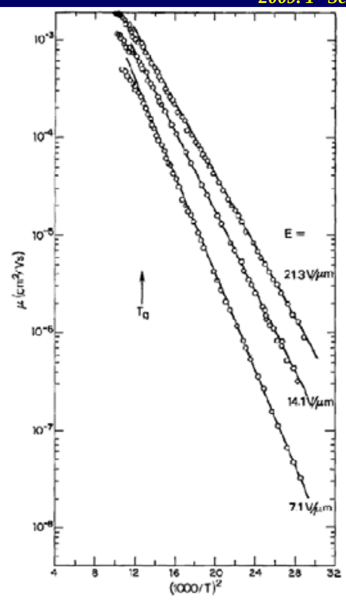
Charge Transport in Disordered Organic Solids



Hole mobility of MPMP

MPMP
bis(4-N,N-diethylamino-2-methylphenyl)-4-methylphenylmethane
(thickness~8.7 μm)





P. M. Borsenberger, L. Pautmeier and H. Bässler, J. Chem. Phys. **95**, 1258 (1991)

Disorder parameters

Disorder parameters

• σ: The width of the DOS. Random distribution of both permanent and van der Waals dipoles lead to local fluctuations in electric potential → increase σ by an amount proportional to the square root of the dipole concentration and to the strength of the dipole moment. → reduce the carrier mobility. The smaller dipolar interaction is better for the carrier transport.

• Σ: The degree of positional disorder. Amorphous morphology of molecular solids or doped polymers lead to the variation in the intermolecular distances.

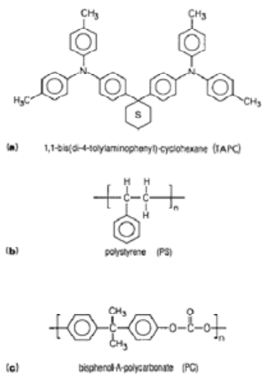


FIG. 1. Molecular structures of compounds used in this study.

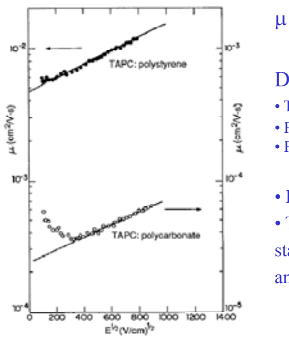


FIG. 2. Logarithm of the mobility vs $E^{1/2}$ for TAPC doped polystyrene and TAPC doped polycarbonate measured at 295 K.

$\mu_{\text{TAPC doped polystyrene}} >> \mu_{\text{TAPC doped polycarbonate}}$

Dipole moment:
- TAPC [1,1-bis(di-4-tolylaminophenyl)cyclohexane] = 1.0 D
- PC (bisphenol-*A*-polycarbonate) = 1.0 D
- PS (polystyrene) = 0.1 D

- Larger dipolar interaction increases both σ and Σ.
- The elimination of random dipolar fields due to static dipole moments of PC reduces both σ and Σ and thereby increases the mobility.

P. M. Borsenberger and H. Bässler, J. Chem. Phys. **95**, 5327 (1991).

Disorder parameters

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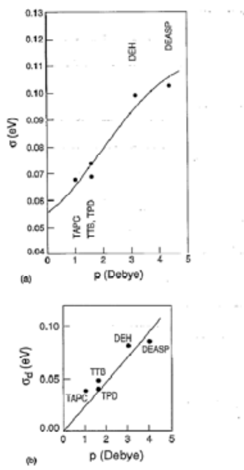


FIG. 3. (a) Experimental data for the total width of the DOS for a series of molecular glasses as a function of the dipole moment (from Ref. 9). The datum for MPMP has been deleted, as discussed in the text. (b) The dipolar contribution σ_d derived from the data of (a) assuming σ_{vdW} =0.055 eV. The full line is a fit based upon Eq. (2) with a=6 Å and σ=3.5.

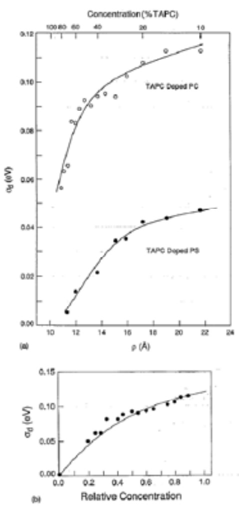


FIG. 5. (a) The concentration dependence of the width of the DOS in TAPC doped poly(carbonate) as a function of the distance between the TAPC molecules (from Ref. 21). (b) The dipolar contribution σ_d as a function of the concentration of poly(carbonate) repeat units derived from 5(a). The full curve is the prediction based upon $\sigma_d(c)$ from Fig. 2 assuming a=4.2 Å, ϵ=3, and p=2.3 D.

the total Gaussian width of the DOS is

$$\sigma=(\sigma_d^2+\sigma_{vdW}^2)^{1/2}.$$

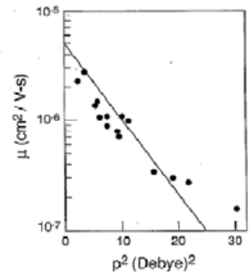
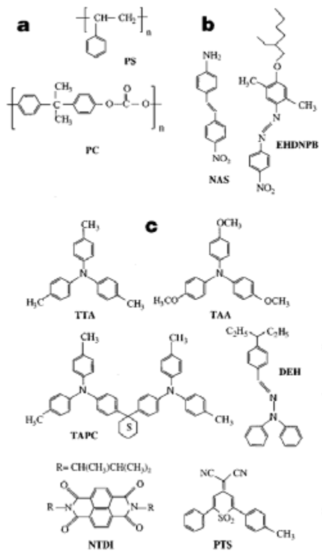
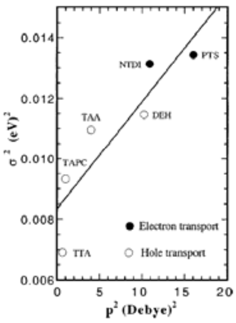


FIG. 4. Hole mobilities measured by Sugiuchi and Nishizawa (Ref. 8) at room temperature for a series of polar transport molecules dispersed in a poly(carbonate) host in a 1:1 ratio. The full line is the prediction of the current calculation for a=6 Å and ϵ=3.5.

A. Dieckmann, H. Bässler and P. M. Borsenberger, J. Chem. Phys. 99, 8136 (1993).

Effect of dipolar molecules on carrier mobilities





Transport agent	Dipole moment (D)	σ (eV)	Σ	μ_0 (cm²/V s)	C 10^{-4} (cm/V)$^{1/2}$
Hole transport agents					
TTA	0.8 (*h*)	0.0831	1.82	1.1×10^{-5}	3.1
TAPC	1.0 (*h*)	0.0966	1.97	4.1×10^{-4}	2.7
TAA	2.1 (*h*)	0.1047	1.73	8.2×10^{-6}	3.3
DEH	3.2 (*h*)	0.1071	1.78	8.6×10^{-5}	3.2
Electron transport agents					
NTDI	3.3 (*e*)	0.1146	2.91	2.7×10^{-4}	2.6
PTS	4.0 (*e*)	0.1154	3.89	1.6×10^{-4}	2.6

- Conduction through the dopant.
- Mobility is strongly affected by the dipole moment of the dopant for holes and electrons

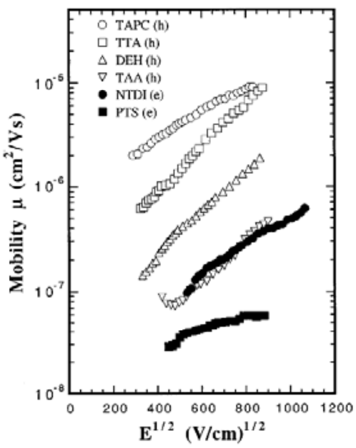
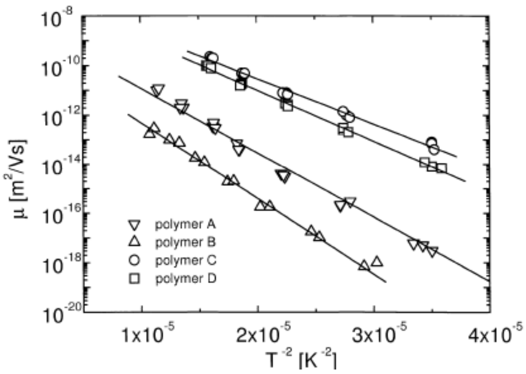


FIG. 11. Field dependence of the mobility at $T=303$ K for PS+25 wt %EHNDPB+30 wt % of the six different charge transport agents.

A. Goonesekera and S. Ducharme, J. Appl. Phys. 85, 6506 (1999)

Temperature dependence of the hole mobility of PPVs



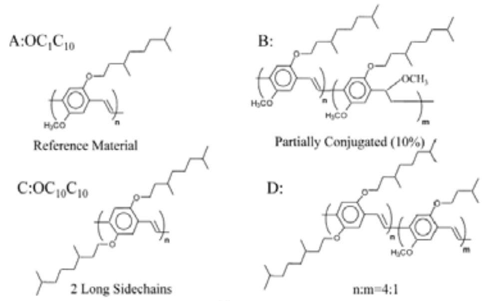


Table 1
Parameters μ_∞, σ (energetic disorder bandwidth) and a (site-spacing) describing the temperature dependence of the zero-field mobility μ_0 and field activation factor γ for the different polymers studied

Sample	μ_∞ (m²/V s)	σ (meV)	a (nm)
A	5.1×10^{-9}	112	1.2
B	4.0×10^{-10}	121	1.7
C	1.6×10^{-7}	93	1.1
D	1.5×10^{-7}	99	1.2

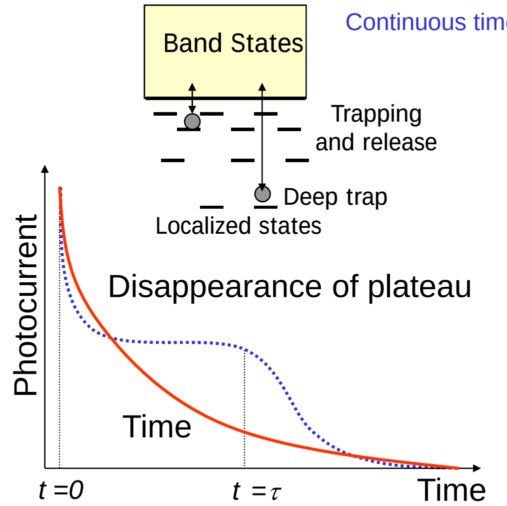
P.W.M. Blom, M.C.J.M. Vissenberg, Materials Science and Engineering 27, 53-94 (2000)

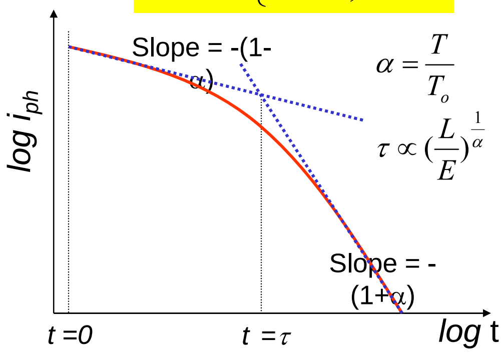
Charge Transport in Disordered Organic Solids

(4) Scher-Montroll dispersive transport model

Continuous time random walk (CTRW) $\Psi(t) \approx t^{-\alpha}$

$$J_{ph}(t) = \begin{cases} t^{-(1-\alpha)}, & t < \tau \\ t^{-(1+\alpha)}, & t > \tau \end{cases}$$





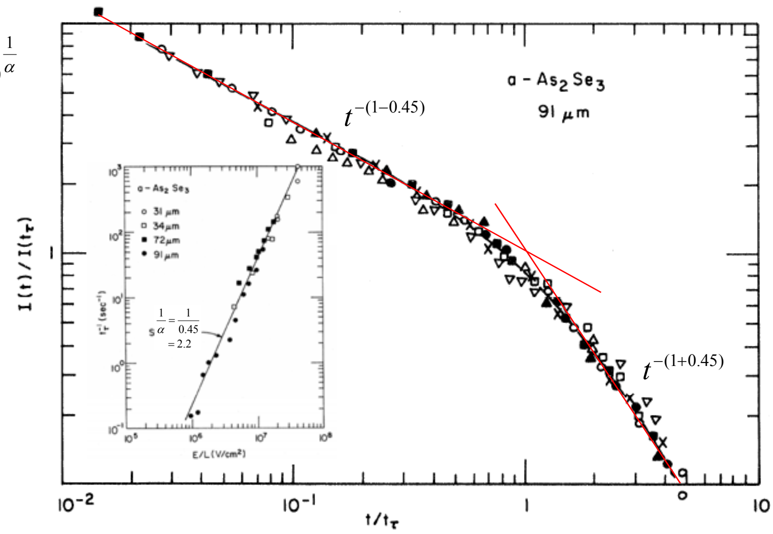
$$\alpha = \frac{T}{T_o}$$

$$\tau \propto \left(\frac{L}{E}\right)^{\frac{1}{\alpha}}$$

Scher and Montroll, Phys. Rev. B 12, 2455 (1975)

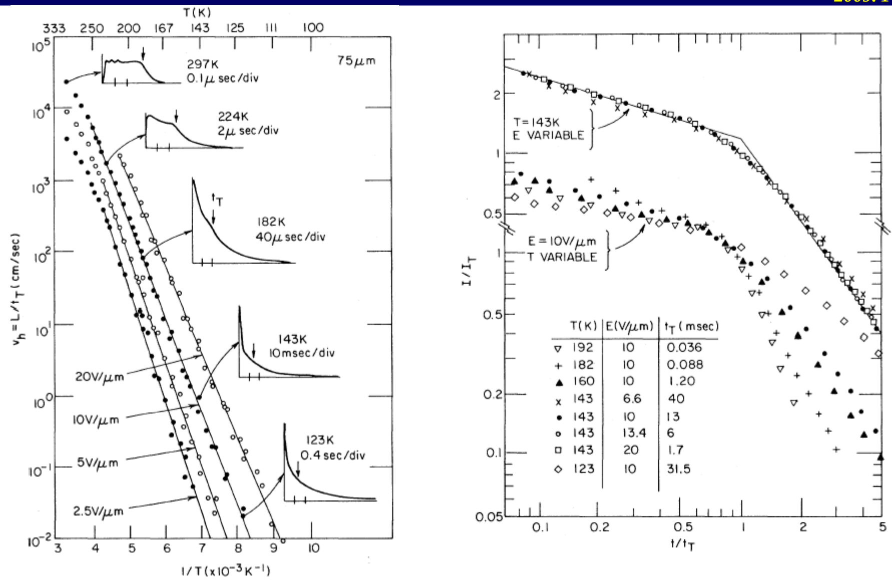
Scher-Montroll model of dispersive transport

$$\tau \propto \left(\frac{L}{E}\right)^{\frac{1}{\alpha}}$$



H. Scher and E. W. Montroll, Phys. Rev. B 12, 2455 (1975)

Dispersive Transport in *a*-Selenium



G. Pfister, Phys. Rev. Lett. 36, 271 (1976)

Space-charge-limited current in organic semiconductors

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

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

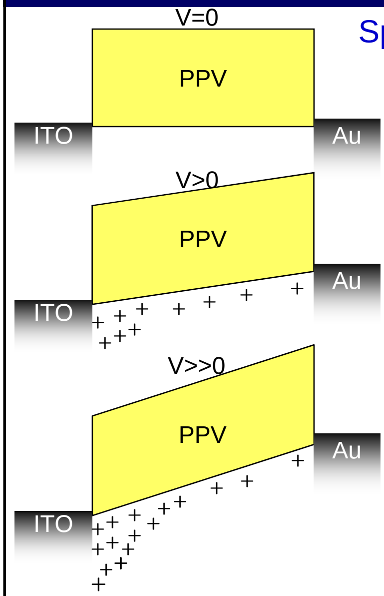
- Bulk Limited
  - Ohmic (Doped semiconductor)

    $$J = ep\mu E$$

  - SCLC (undoped semicond. or Insulator)

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

Space-charge-limited current (SCLC)



Space-charge-limited current (SCLC)

OLED acts as a capacitor

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

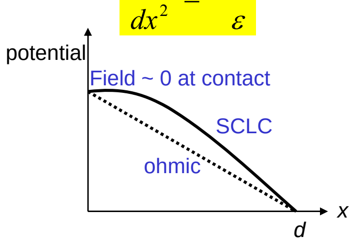
$$= (\frac{CV}{d \cdot \text{area}}) \times (\mu E)$$

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

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

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

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



Ohmic Contact (1)

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

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

since there is no external applied field.

$\therefore \dfrac{dn}{n} = \dfrac{\mu}{D}Fdx = \dfrac{q}{k_BT}Fdx$,

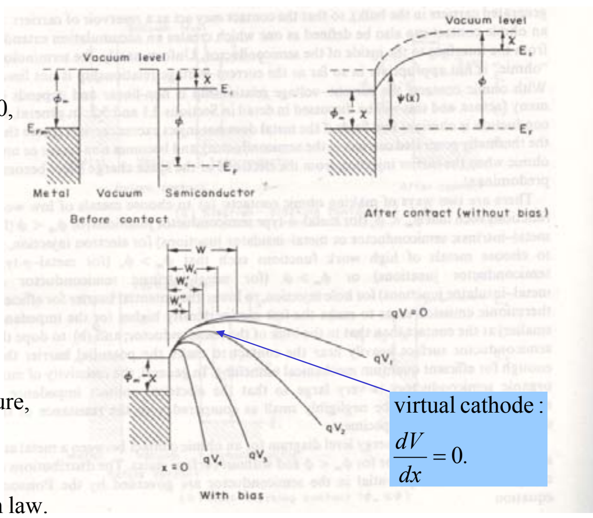
where the Einstein relation $\dfrac{D}{\mu} = \dfrac{k_BT}{q}$ is used.

$\therefore \log\dfrac{n}{n_s} = \dfrac{q}{k_BT}\int_0^x Fdx.$

From the boundary condition in the right figure,

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

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



Ohmic Contact (2)

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

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

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

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

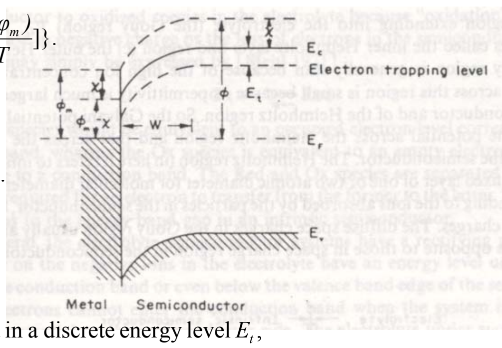
Integrating this equation gives

the width of the accumulation region

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

If $\varphi - \varphi_m > 4k_BT$,

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



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

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

Space-charge-limited current

Distribution function of trap density

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

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

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

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

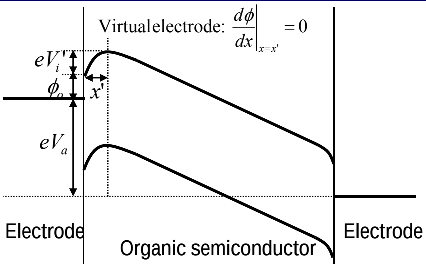
For $p_t(x) = 0$,

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

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

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)



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→ 0)=0* for simplicity.

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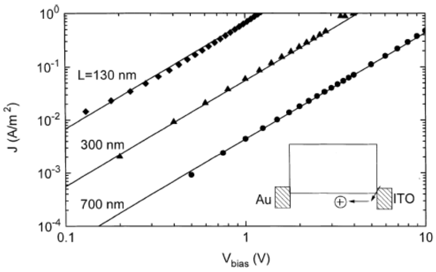
Space-charge-limited current

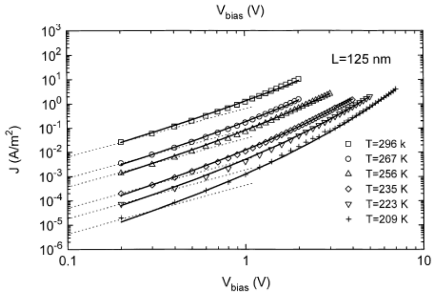


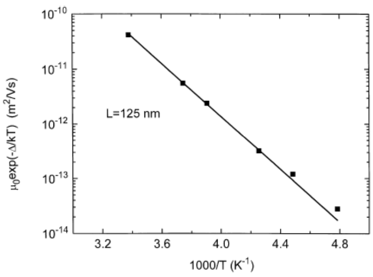
ITO/PPV/Au hole-only devices

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

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

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

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

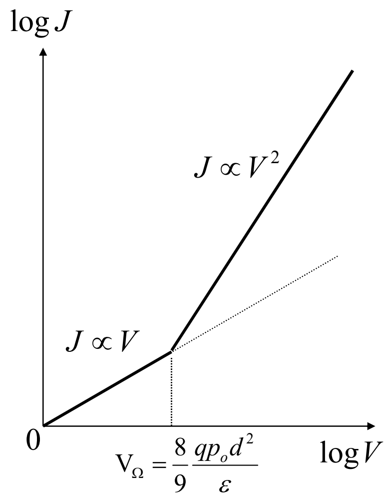
The onset of the departure from Ohm's law or the onset of the SCL conduction takes place when $V_\Omega = \frac{8}{9}\frac{qp_o d^2}{\varepsilon}$.

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

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 $J = q(p+p_o)\mu_p F - qD_p\nabla(p+p_o)$.

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

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.

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

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

Space-charge-limited current

Traps confined in single or multiple discrete energy levels

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

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

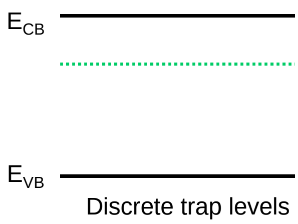
where $\theta_t = \dfrac{g_p N_v}{N_t} e^{-\frac{E_t}{kT}}$.

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

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

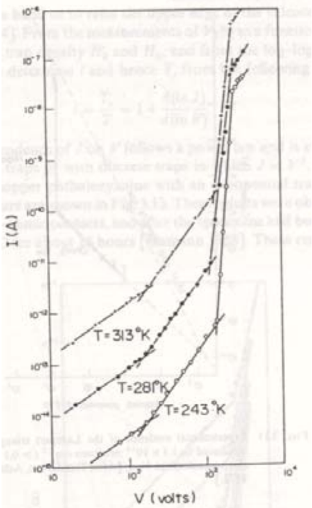


FIG. 3.10. The current-voltage characteristics of naphthalene single crystals as functions of temperature. [After Campos 1972.]

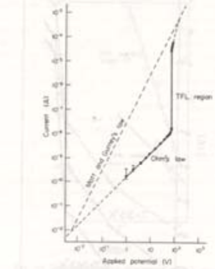


FIG. 3.11. Experimental evidence of the Lampert triangle in silicon irradiated to 1.1×10^{14} neutrons cm^{-2} (> 0.1 MeV) with a steep transition at V_{TFL}. [After Henderson, Ashley, and Shen 1972.]

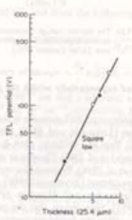


FIG. 3.12. The TFL threshold voltage (V_{TFL}) for neutron-irradiated silicon as a function of specimen thickness. [After Henderson, Ashley, and Shen 1972.]

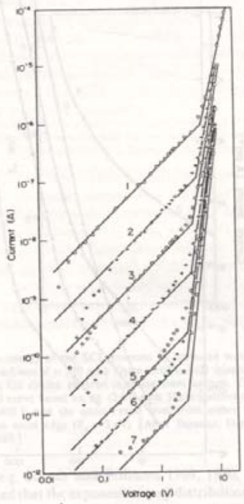
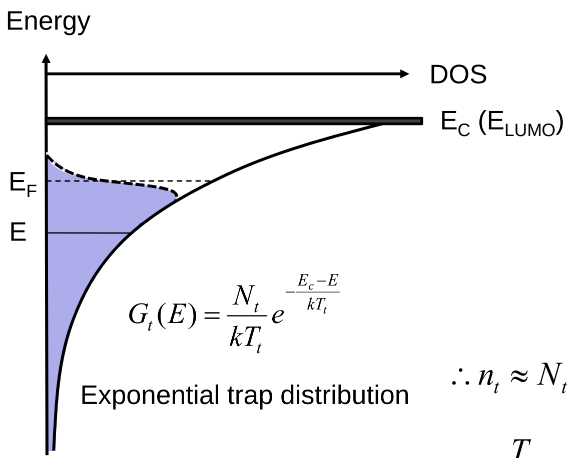


FIG. 3.13. The current–voltage characteristics of α-copper phthalocyanine films of thickness of 4 μm: (1) 144.6°C, (2) 116.9°C, (3) 96.8°C, (4) 76.5°C, (5) 54.2°C, (6) 33.8°C, (7) 20.9°C, highest heat treatment at 200°C. [After Hamann 1968.]

Space-charge-limited current

Space-charge-limited current: analytic solution



$$n_f = N_c e^{-\frac{E_c - E_F}{kT}}$$

$$n_t = \int_{-\infty}^{E_c} \frac{N_t}{k_B T_t} e^{-\frac{E_c - E}{kT}} f_{FD}(E) dE$$

$$\approx \int_{-\infty}^{E_F} \frac{N_t}{k_B T_t} e^{-\frac{E_c - E}{kT}} dE$$

$$= N_t e^{-\frac{E_c - E_F}{kT_t}}$$

$$\therefore n_t \approx N_t \left(\frac{n_f}{N_c}\right)^{\frac{T}{T_t}} = N_t \left(\frac{n_f}{N_c}\right)^{\frac{1}{m}}$$

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

Space-charge-limited current

Poisson equation : $\frac{dF(x)}{dx} = \frac{q[n_f(x) + n_t(x)]}{\varepsilon_o \varepsilon} \approx \frac{qn_t(x)}{\varepsilon_o \varepsilon} \approx \frac{qN_t}{\varepsilon_o \varepsilon} \left(\frac{n_f}{N_c}\right)^{1/m}.$

Current flow equation : $J = q\mu n_f(x) F(x).$

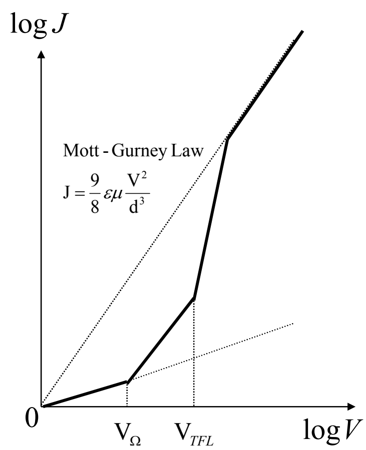
$$F^{1/m} \frac{dF(x)}{dx} = \frac{N_t}{\varepsilon_o \varepsilon} \left(\frac{J}{q\mu N_c}\right)^{1/m}.$$

$$\therefore \frac{m}{m+1} F^{\frac{m+1}{m}} = \frac{N_t}{\varepsilon_o \varepsilon} \left(\frac{J}{q\mu N_c}\right)^{1/m} x.$$

$$\therefore F(x) = \left(\frac{m+1}{m} \frac{N_t}{\varepsilon_o \varepsilon}\right)^{\frac{m}{m+1}} \left(\frac{J}{q\mu N_c}\right)^{\frac{1}{m+1}}.$$

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

$$J = q^{1-m} \mu N_c \left(\frac{2m+1}{m+1}\right)^{m+1} \left(\frac{m}{m+1} \frac{\varepsilon_o \varepsilon}{N_t}\right)^m \frac{V^{m+1}}{d^{2m+1}}, \qquad m = \frac{T_t}{T}.$$



Ohmic $\Rightarrow$ Trapped SCLC

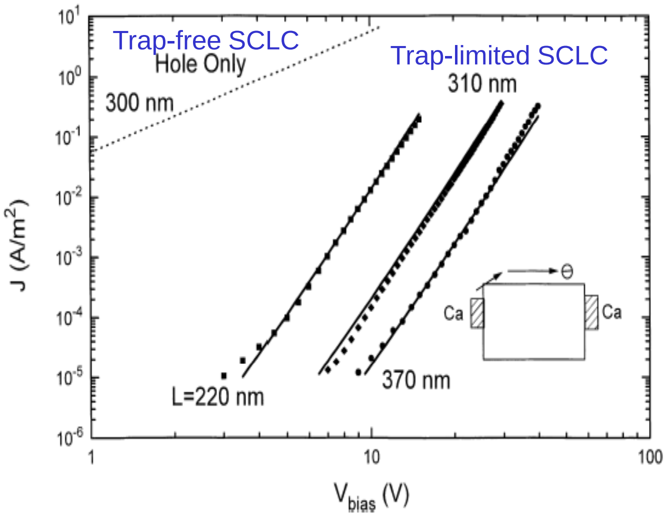
$$V_\Omega = \frac{qd^2 N_t}{\varepsilon_o \varepsilon_r} \left(\frac{p_o}{N_v}\right)^{\frac{1}{m}} \left(\frac{m+1}{m}\right) \left(\frac{m+1}{2m+1}\right)^{\frac{m+1}{m}}.$$

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

Ca/PPV/Ca electron-only devices



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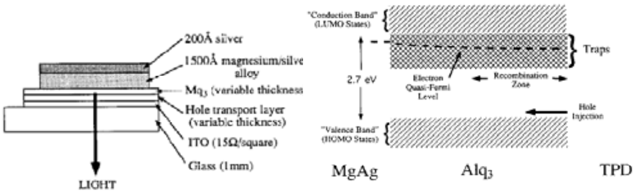
SCL current with an exponential trap distribution

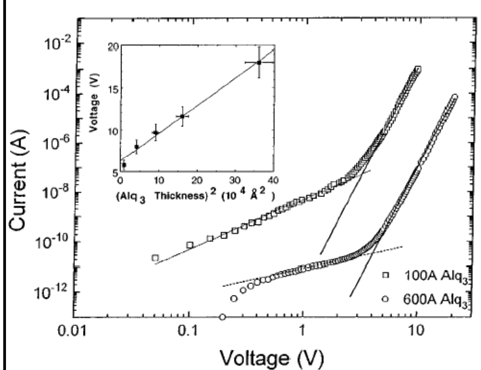


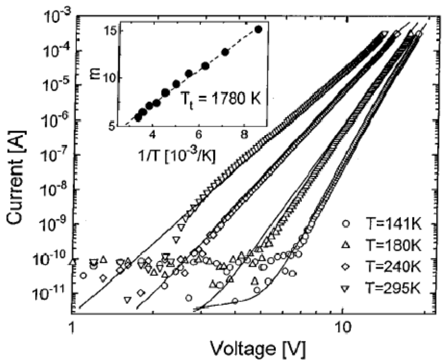
Trap-limited SCLC

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

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

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





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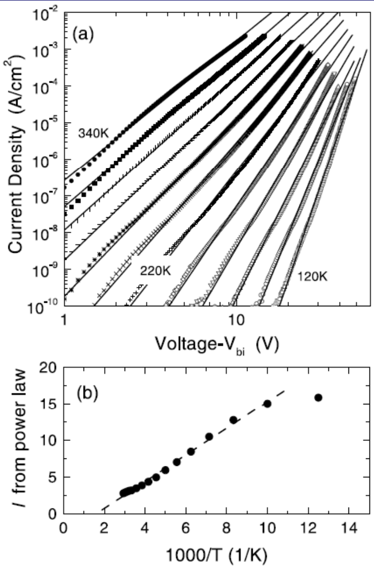
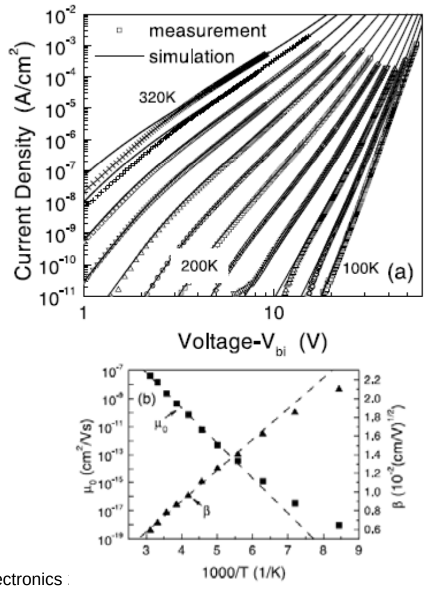
Trap-limited SCL current with field-dependent μ





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