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SPRING COLLEGE ON AMORPHOUS SOLIDS
AND THE LIQUID STATE

14 April - 18 June 1982

ELECTRONIC TRANSPORT IN NON-CRYSTALLINE SEMICONDUCTORS
(Part II)

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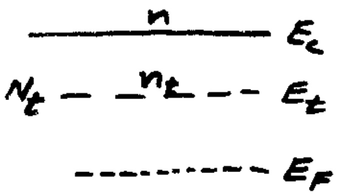
Trapping and Thermal Release of Carriers

$$\frac{dn}{dt} = -b\,n\,(N_t - n_t) + n_t\,\nu_0 \exp\left(-\frac{(E_c - E_t)}{kT}\right) \quad (1)$$

$$= -\text{capture} + \text{release}$$



$$n = N_c \exp\left[-\left(\frac{E_c - E_F}{kT}\right)\right]$$

$$\frac{n_t}{N_t} = \frac{1}{\exp\left(\frac{E_t - E_F}{kT}\right) + 1}$$

$$\frac{N_t}{n_t} - 1 = \exp\left(\frac{E_t - E_F}{kT}\right)$$

Equilibrium : $\frac{dn}{dt} = 0$ detailed balance

Hence Eq. (1) becomes

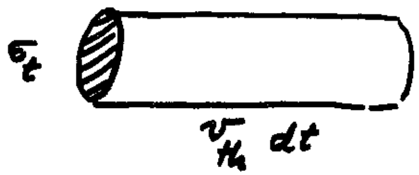
$$b N_c \exp\left[-\frac{(E_c - E_F)}{kT}\right] \exp\left(\frac{E_t - E_F}{kT}\right) = \nu_0 \exp\left[-\frac{(E_c - E_t)}{kT}\right]$$

$$\therefore \boxed{\nu_0 = b N_c}$$

ν_0 = attempt to escape frequency
b = capture coefficient

Calculation of Capture Coefficient

In Crystals :



capture per unit time

$$-\sigma_t v_{th}\, n\,(N_t - n_t) = \frac{dn}{dt}$$

hence $b = \sigma_t v_{th}$

$$\boxed{\nu_0 = \sigma_t v_{th} N_c}$$

$N_c \sim 2.5 \times 10^{19}\ \text{cm}^{-3}$
$v_{th} \sim 10^7\ \text{cm/s}$

neutral centers $\sigma_t = 10^{-16}\ \text{cm}^2$ $\quad \nu_0 = 2.5\ 10^{10}\ \text{s}^{-1}$
charged centers $\sigma_t => 10^{-13}\ \text{cm}^2$ $\quad \nu_0 \geq 2.5 \times 10^{13}\ \text{s}^{-1}$

DLTS assumed constant $\nu_0 = 10^{13}\ \text{s}^{-1}$

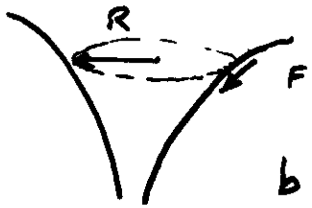
$$\tau_{max}\,\nu_0 = \exp(-E/kT_{max})$$

Factor 10 error in ν_0 yields 10% error in $(-E)$

In amorphous, low mobility semiconductors

trapping is diffusion limited

Langevin theory for charged traps:



$$F = \frac{e}{4\pi \varepsilon R^2}$$

$$b = 4\pi R^2 \mu F$$

charged $\therefore$ $\boxed{b = \frac{e}{\varepsilon}\mu} = \frac{1.6\times10^{-19}}{10^{-12}}\times 6 = 10^{-6}\ \mathrm{cm^3/s}$

$$\nu_0 = b N_c = 2.5\times10^{13}/\mathrm{s}$$

Neutral traps: $b = 4\pi D R$

$$= 4\pi \frac{kT}{e}\mu R = 2\times10^{-8}\ \mathrm{cm^3/s}$$

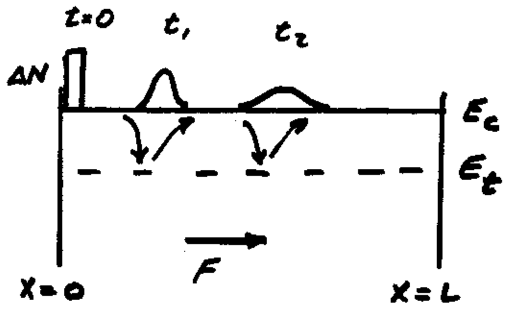
$$\nu_0 = b N_c = 5\times10^{11}/\mathrm{s}$$

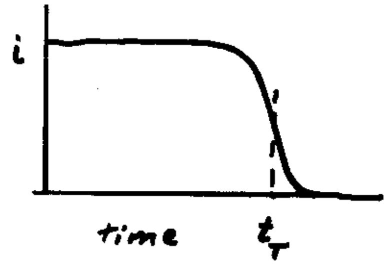
Here μ = microscopic mobility μ_0

because in Eq. (1) n = free carrier density

Drift Mobility

Non-dispersive transport



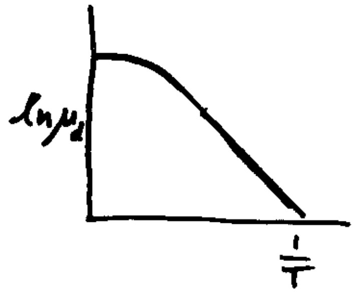


$$t_T = \frac{L}{\mu_d F} \quad \text{when } t_T < t_{diel.} = \varepsilon/\sigma$$

also $q\Delta N \ll CV$ in order not to disturb field F

drift mobility $\mu_d = \mu_0 \frac{\tau_f}{\tau_f + \tau_t} \sim \mu_0 \frac{\Delta n}{\Delta N}$

$$\mu_d = \mu_0 \frac{1}{1 + \frac{N_t}{N_c}\exp\left(\frac{E_c - E_t}{kT}\right)}$$



G. Pfister and H. Scher, Advances in Physics 27 (1978) 747

T. Tiedje and A. Rose, Solid State Commun. 37 (1980) 49

J. Orenstein and M. Kastner, Phys. Rev. Lett. 46 (1981) 1421

V. Vaninov, J. Orenstein, M. Kastner, Phil. Mag B (1982)

A. I. Rudenko + ~~[illegible]~~ .. B 95 (1982)

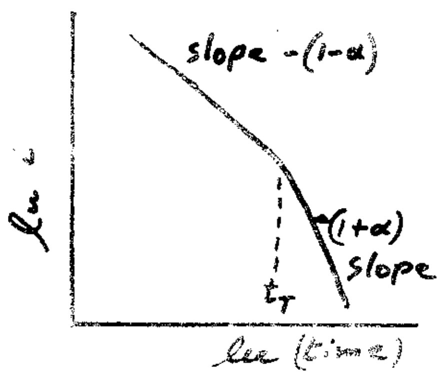
E. A. Schiff, Phys. Rev. B 24 (19[illegible]) 61[illegible]

T. Tiedje, [illegible], D. L. Morel, B. Abeles
Phys. Rev. Lett. 86 (1981) 1[illegible]

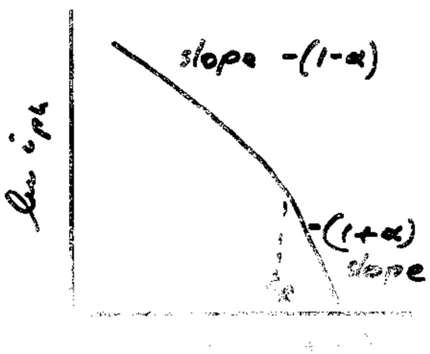
1. Assume exponential tail of localized states

2. Constant trapping coefficient b

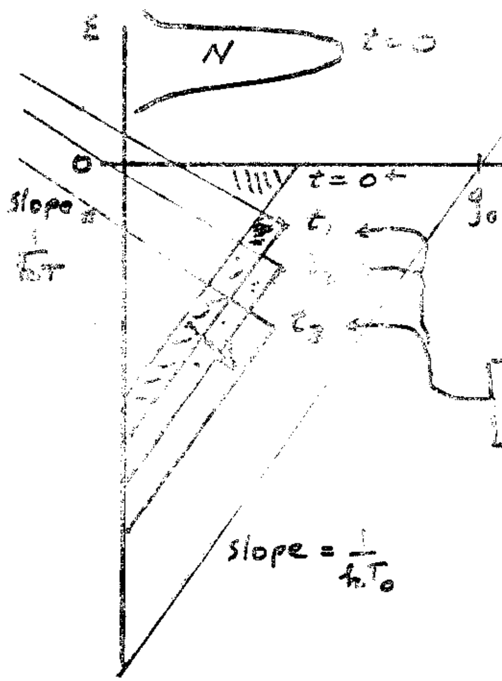
then drift mobility:



photoconductive decay:



<u>[illegible] Regime</u>



$$g(E) = g_0 \exp\left(\frac{E}{kT_0}\right)$$

$$\frac{1}{t} = \nu \exp\left(\frac{E}{kT}\right)$$

$$t = \nu^{-1} \exp\left(-\frac{E_d}{kT}\right)$$

$$\boxed{E_d(t) = -kT \ln(\nu t)}$$

$$N = F(t) \int_{-\infty}^{+\infty} dE\, g(E) \frac{1}{\exp\left(\frac{E - E_d(t)}{kT}\right) + 1}$$

$E_d(t)$ = "quasi" Fermi level

$$\text{distribution fct} = \frac{F(t)}{\exp\left(\frac{E - E_d(t)}{kT}\right) + 1}$$

$$F(t) = \frac{N}{kT_0\, g_0} \frac{\sin \alpha\pi}{\alpha\pi} (\nu t)^{\alpha}$$

$$\boxed{\alpha = T/T_0}$$

$$\mu_d = \mu_0 \frac{n(t)}{N} = \mu_0 F(t) N_c \exp(E_d(t)/kT)$$

$$= \mu_0 \frac{N_c}{kT_0 g_0} \frac{\sin\alpha\pi}{\alpha\pi} (\nu t)^{-(1-\alpha)}$$

$$i_{ph} = e\mu_0 n(t) = e\mu_0 N \frac{\sin\alpha\pi}{\pi} (\nu t)^{-(1-\alpha)}$$

↑ photocurrent decay before recombination

t_T = transit time

$$\int_0^{t_T} F\mu_d(t)\,dt = \frac{L}{2} \qquad \text{here } F = \text{field}$$

$$t_T = \frac{1}{\nu} \frac{\nu^{1/\alpha}}{\alpha} \left(\frac{\alpha\pi}{2\sin\alpha\pi}\right)^{1/\alpha} \left(\frac{L}{\mu_0 F}\right)^{1/\alpha}$$

For $t > t_T$ or $t > t_R$

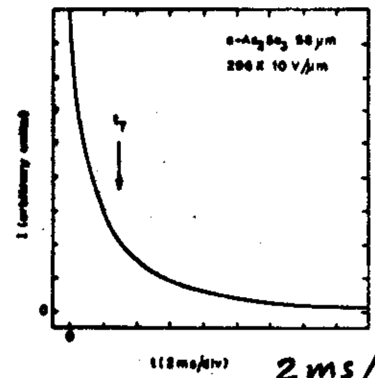
current is limited by thermal emission from reservoir of electrons in deep tail states.

Emission rate is slower than $\frac{1}{t_T}$ or $1/t_R$

G. Pfister + H. Scher, Adv. in Phys. 27 (1978) 747

Fig. 2

current

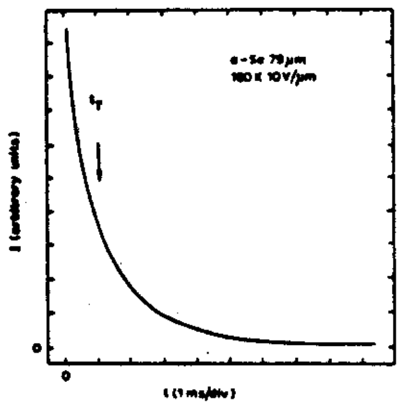


2 ms/division

(a)

a – As_2Se_3
58 µm thick
296 K
10 V/µm

current

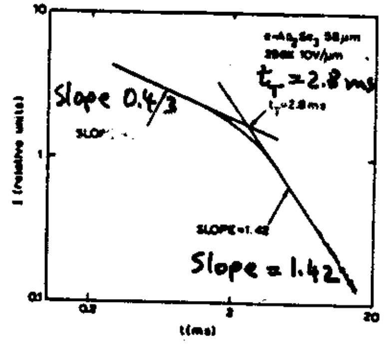


(b)

a – Se
79 µm thick
160 K
10 V/µm

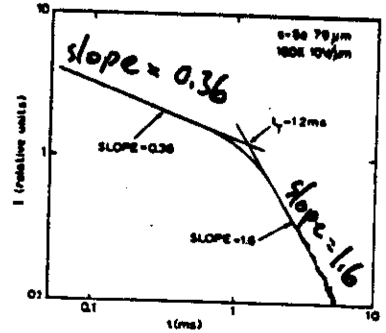
time (1 ms/division)

Pfister & Scher Adv. in Phys. (40)



(c)

a - As_2Se_3
58 µm thick
296 K
10 V/µm



(d)

a - Se
79 µm thick
160 K
10 V/µm
t_T = 12 ms

(a) Transient hole current in a-As_2Se_3. $L = 58$ µm, $T = 296$ K, $E = 10$ V/µm. Pulse illumination through semi-transparent aluminium (blocking) contact. (b) Transient hole current in a-Se. $L = 79$ µm, $T = 160$ K, $E = 10$ V/µm. Pulse illumination through semi-transparent gold contact. Before the application of gold a ~1 µm polycarbonate insulating layer was coated onto the selenium sample to provide blocking contact. (c) Transient hole current in a-As_2Se_3 of fig. 2 (a) in units log I versus log t. (d) Transient hole current in a-Se of fig. 2 (b) in units log I versus log t.

(41)

D. Allan, Phil Mag B 38 (1978) 381

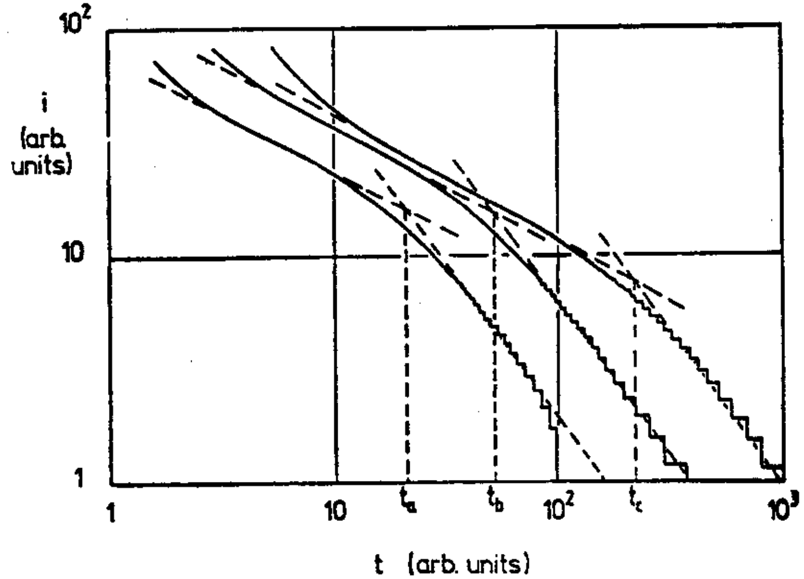
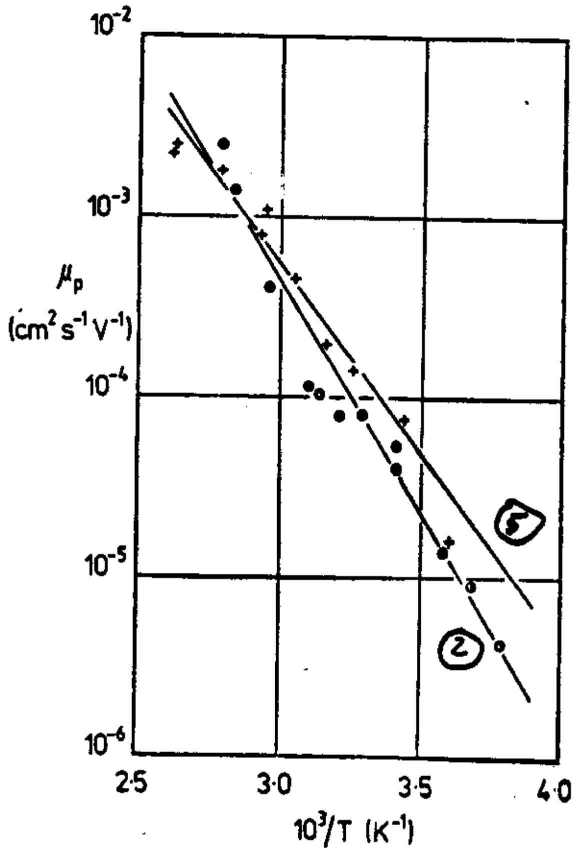


Fig.2. Log i against log t plots for Sample 6 at 335K. The curves have been repositioned for clarity but the transit times, t_a, t_b and t_c are 38, 105 and 220 µs for V_A's of 6, 3 and 1.5V respectively. The pairs of tangents to the curves have slopes of −0.55 and −1.37. The step structure is due to the transient recorder.

a - Si : H $B_2H_6 / SiH_4 = 10^3$ ppm

D. Allan, Phil. Mag. B38 (1978) 381



$\mu_p \sim \exp(-\frac{0.45 eV}{kT})$

Fig.4. Graph of log μ_p against 1/T. Plots are for Samples 2(o) and 5(+).

a-Si:H 2 60 ppm B_2H_6/SiH_4
5 600 ppm

The drift mobility for holes in a-Si:H is typically activated by 0.45 eV

Does this mean that there are specific trap levels 0.45 eV above E_V ??

How can we get an activation energy when

$$t_T = \frac{1}{\nu}\left(\frac{\nu\alpha\pi}{2\sin\alpha\pi}\frac{L}{\mu_0 F}\right)^{1/\alpha} \quad \boxed{??}$$

none of these quantities is thermally activated.

I believe* it comes in the following manner:

$$t_T = \frac{1}{\nu} C^{1/\alpha} \qquad \text{with } C = \frac{\nu\alpha\pi}{2\sin\alpha\pi}\frac{L}{\mu_0 F}$$

$$\frac{1}{t_T} = \nu \exp\left(-\frac{\Delta}{kT}\right) \qquad \frac{\Delta}{kT} = \frac{1}{\alpha}\ln C = \frac{T_0}{T}\ln C$$

$$\mu_d = \frac{L}{F}\frac{1}{t_T} = \frac{L}{F}\nu\exp\left(-\frac{\Delta}{kT}\right)$$

$$\Delta = kT_0 \ln C = 0.05 \ln(10^{12}\,10^{-8})$$

$$= 0.05 \times 9 = \underline{0.45\ eV}$$

* due to M. Kastner

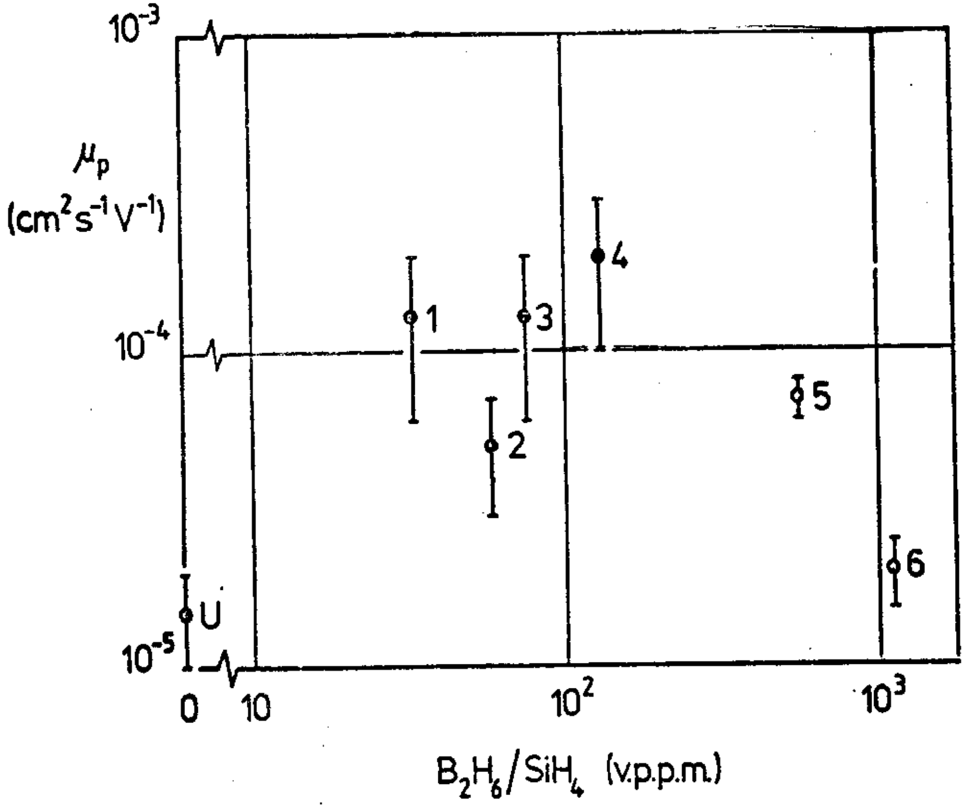


Fig.5. Room temperature value of μ_p against B_2H_6/SiH_4 gaseous doping ratio. Numbers identify the samples.

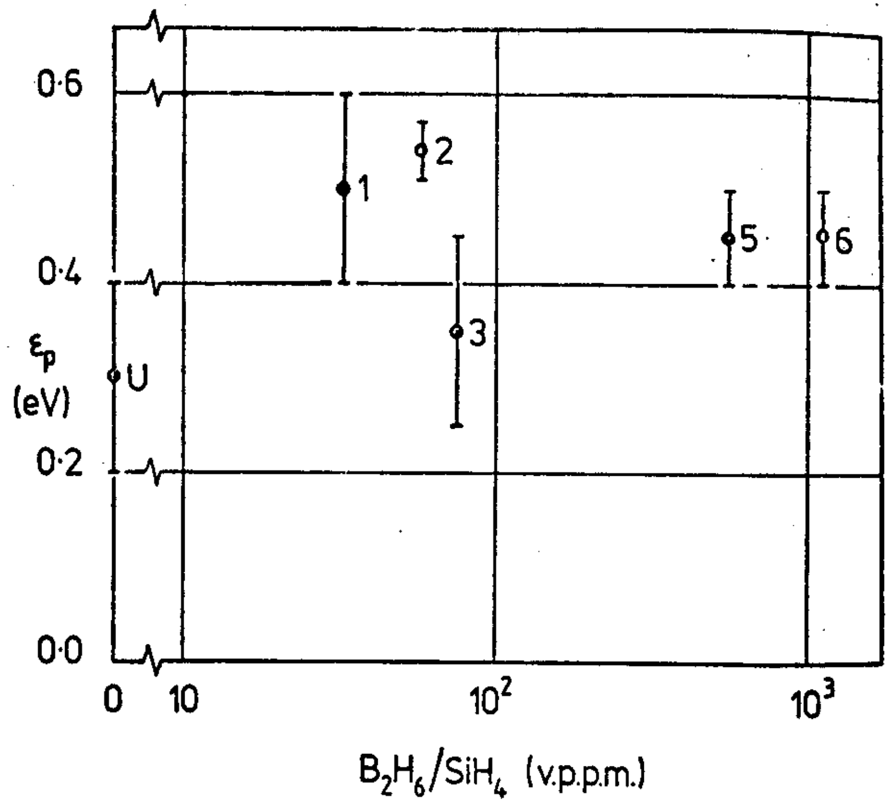
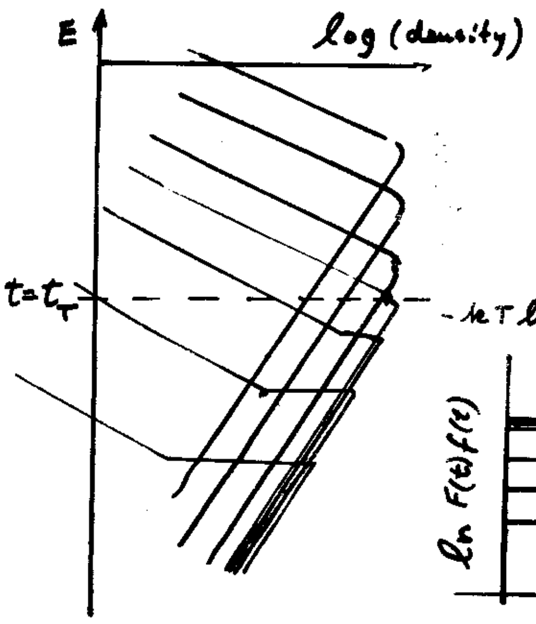
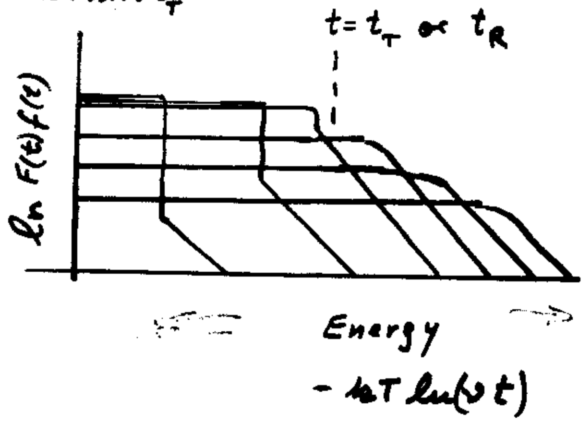


Fig.6. ε_p against B_2H_6/SiH_4 gaseous doping ratio. Numbers identify the samples.

Thermal emission current after t_T or t_R





After t_T a thermally emitted carrier is swept out (or recombines) without being retrapped in a deep state

During the emission time $t = \frac{1}{\nu} \exp\left(-\frac{E_d(t)}{kT}\right)$ a slice of electrons kT wide at $E_d(t)$ is emitted and collected.

$$i = F(t_T)\, g_0 \exp\left(\frac{E_d(t)}{kT}\right) \frac{kT}{t}\, e L$$

From last page:

$$i = F(t_T)\, g_0 \exp[E_d(t)/kT]\, \frac{kT}{t}\, e L$$

with $$F(t_T) = \frac{N}{kT_0\, g_0} \frac{\sin \alpha\pi}{\alpha\pi} (\nu t_T)^{\alpha}$$

and $$\exp[E_d(t)/kT] = (\nu t)^{-\alpha}$$

and $$\frac{1}{t} = \frac{\nu}{\nu t} = (\nu t)^{-1} (\nu t_T)^{\alpha} \frac{\sin \alpha\pi}{\alpha\, \alpha\pi} \frac{2F\mu_0}{L}$$

$$i = e\mu_0 N F\, 2\left(\frac{\sin\alpha\pi}{\alpha\pi}\right)^2 (\nu t_T)^2 (\nu t)^{-(1+\alpha)}$$

Tiedje, Cebulka, Morel, Abeles P.R. Lett. 46 (1981) 1425

For a-Si:H

electrons $\mu_0 = 13\ cm^2/Vs$
holes $\mu_0 = 0.67\ cm^2/Vs$
conduction band $T_0 = 300\,K$
valence band $T_0 = 500\,K$

Kastner As_2Se_3 $\mu_0 \sim 1\ cm^2/Vs$ $T_0 = 550\,K$