Recombination process in photodoping

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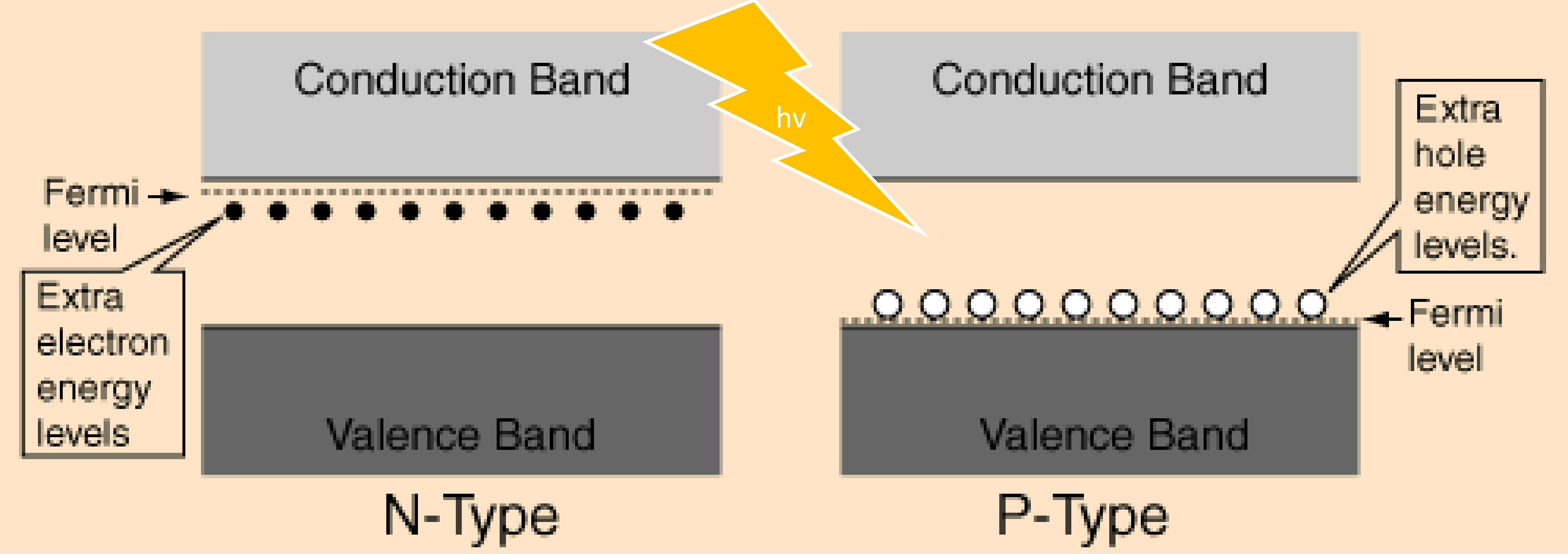
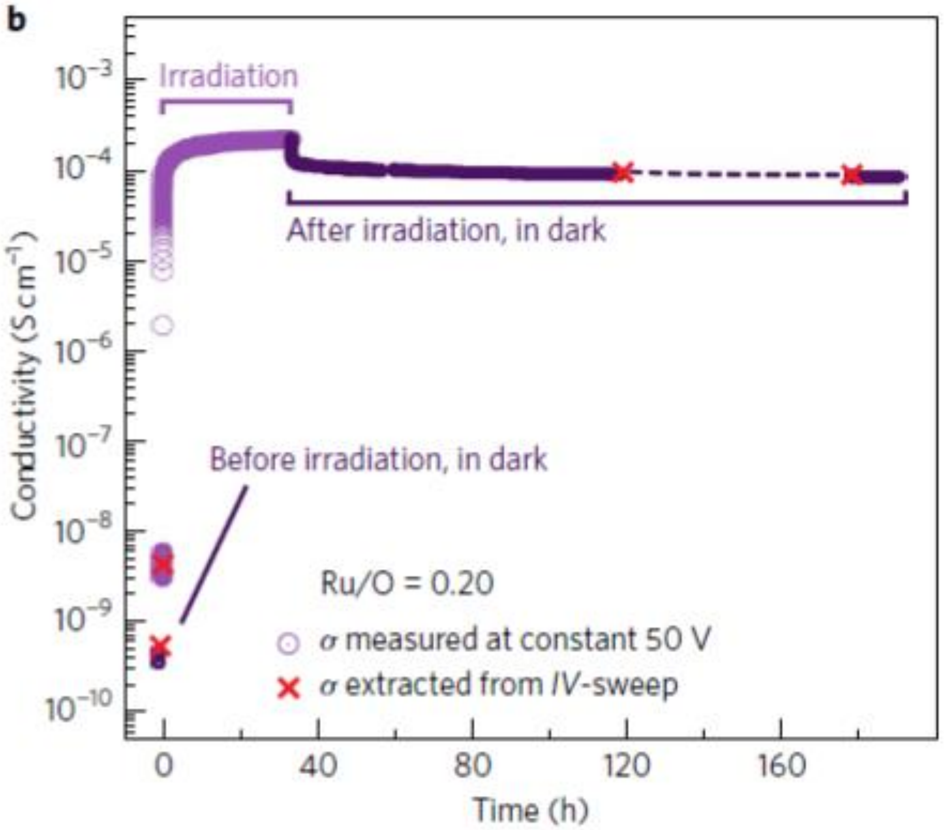
What is photodoping?

Photoexcited electrons or holes trapped by defect levels



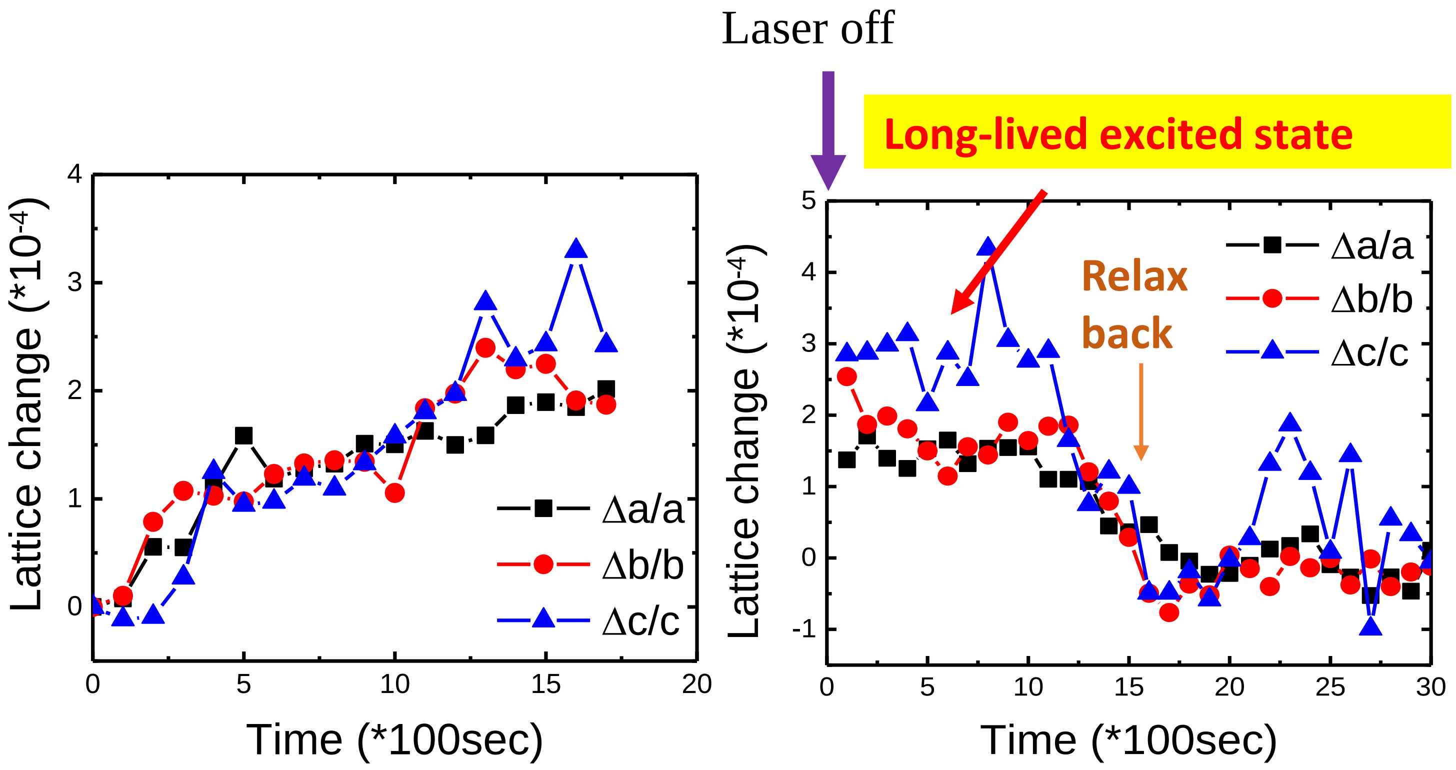
Why we want to study photodoping?

Long relax time with stable photoexcited state



X. Lin, nat. matt. 2017, 16 1209-1215

Photostriction in FE CA thin film


Laser off

Long-lived excited state

Relax back

Processes of recombination via traps

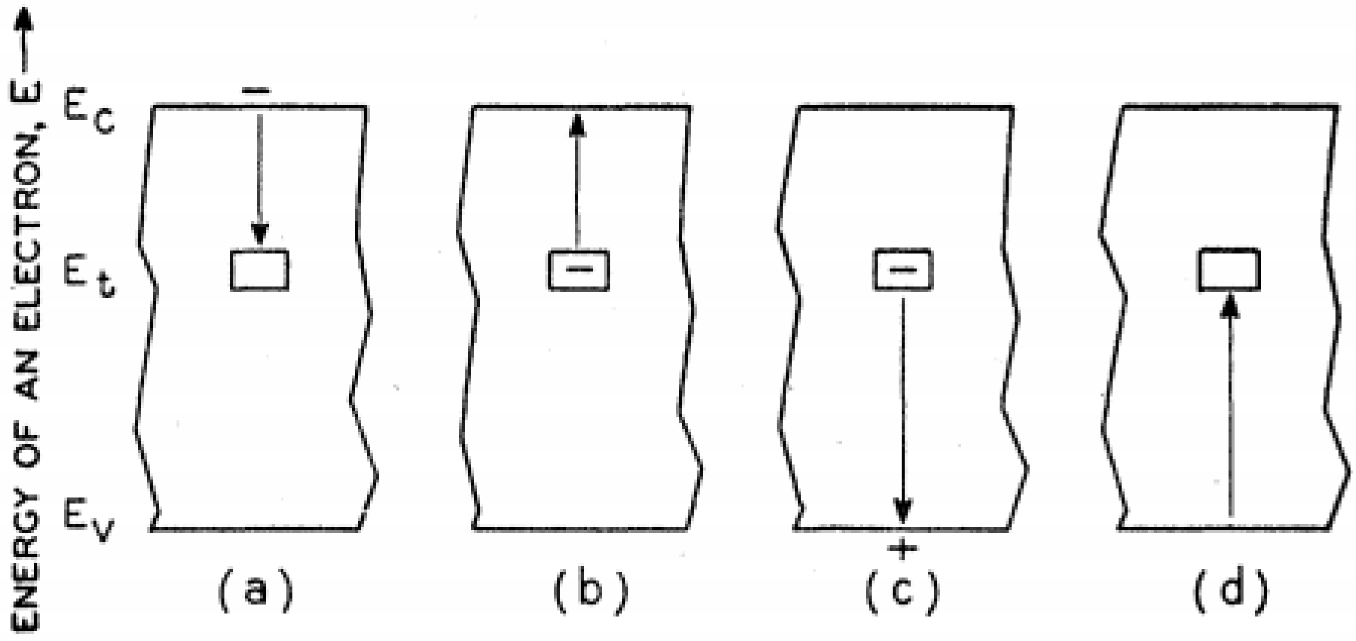


FIG. 1. The basic processes involved in recombination by trapping: (a) electron capture, (b) electron emission, (c) hole capture, (d) hole emission.

W. SHOCKLEY & W. T. READ, Jr, PHYS. REV. 1952, 87, 5

Electron capture rate

Probability of an electron be captured by traps in dE range per unit volume

$$P_{cn} = f_{pt} N_t c_n(E) f(E) N(E) dE$$

Probability of an electron be emitted from traps in dE range per unit volume

$$P_{en} = f_t N_t e_n(E) f_p(E) N(E) dE$$

From thermal equilibrium $F_n = F_t, P_{cn} = P_{en}$;
Total rate of electron capture

$$U_{cn} = P_{cn} - P_{en} = \left[1 - \exp\left(\frac{F_t - F_n}{k_B T}\right)\right] f_{pt} N_t \int_{E_C}^{\infty} \quad f(E) N(E) c_n(E) dE$$

When $F_n > F_t$, the electron density is larger in CB than in traps, so the electrons are captured

For nondegenerate statistics, $f_p \to 1$ in CB, so the expression is simplified

$$U_{cn} = C_n f_{pt} n - C_n f_t n_1, n = N_C exp \frac{F_t - E_C}{k_B T}, n_1 = N_C exp \frac{E_t - E_C}{k_B T}$$

$$U_{cp} = C_p f_t p - C_p f_{pt} p_1$$

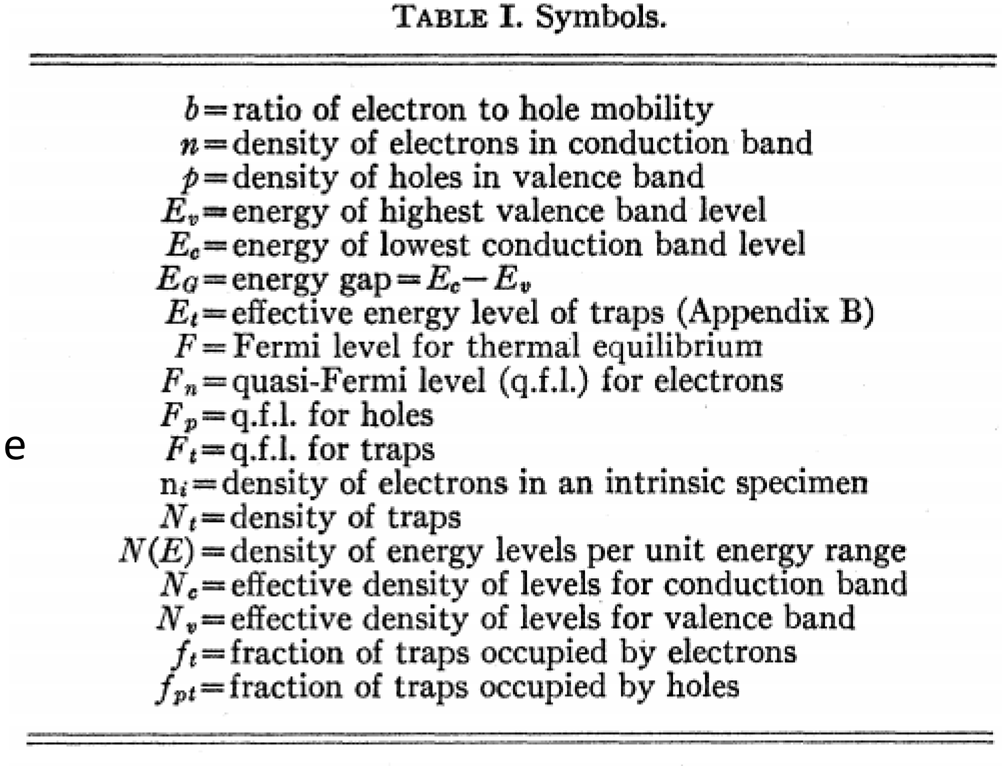


TABLE I. Symbols.

b = ratio of electron to hole mobility
n = density of electrons in conduction band
p = density of holes in valence band
E_v = energy of highest valence band level
E_c = energy of lowest conduction band level
E_G = energy gap = $E_c - E_v$
E_t = effective energy level of traps (Appendix B)
F = Fermi level for thermal equilibrium
F_n = quasi-Fermi level (q.f.l.) for electrons
F_p = q.f.l. for holes
F_t = q.f.l. for traps
n_i = density of electrons in an intrinsic specimen
N_t = density of traps
$N(E)$ = density of energy levels per unit energy range
N_c = effective density of levels for conduction band
N_v = effective density of levels for valence band
f_t = fraction of traps occupied by electrons
f_{pt} = fraction of traps occupied by holes

Recombination time

From steady state condition $U_{cn} = U_{cp}$

Recombination rate

$$U = U_{cn}U_{cp} = C_nC_p(pn - p_1n_1)/[C_n(n + n_1) + C_p(p + p_1)]$$

$$p_1n_1 = N_CN_v \exp\left(\frac{E_v - E_c}{k_BT}\right) = N_CN_v \exp\left(\frac{-E_G}{k_BT}\right) = n_i^2$$

When photoexcited density change δn is small,

$$n = n_0 + \delta n, p = p_0 + \delta n$$

$$\tau = \frac{\delta n}{U} = \tau_{P0}\frac{n_0 + n_1}{n_0 + p_0} + \tau_{n0}\frac{p_0 + p_1}{n_0 + p_0}, \tau_{P0} = \frac{1}{C_p}, \tau_{n0} = \frac{1}{C_n}$$

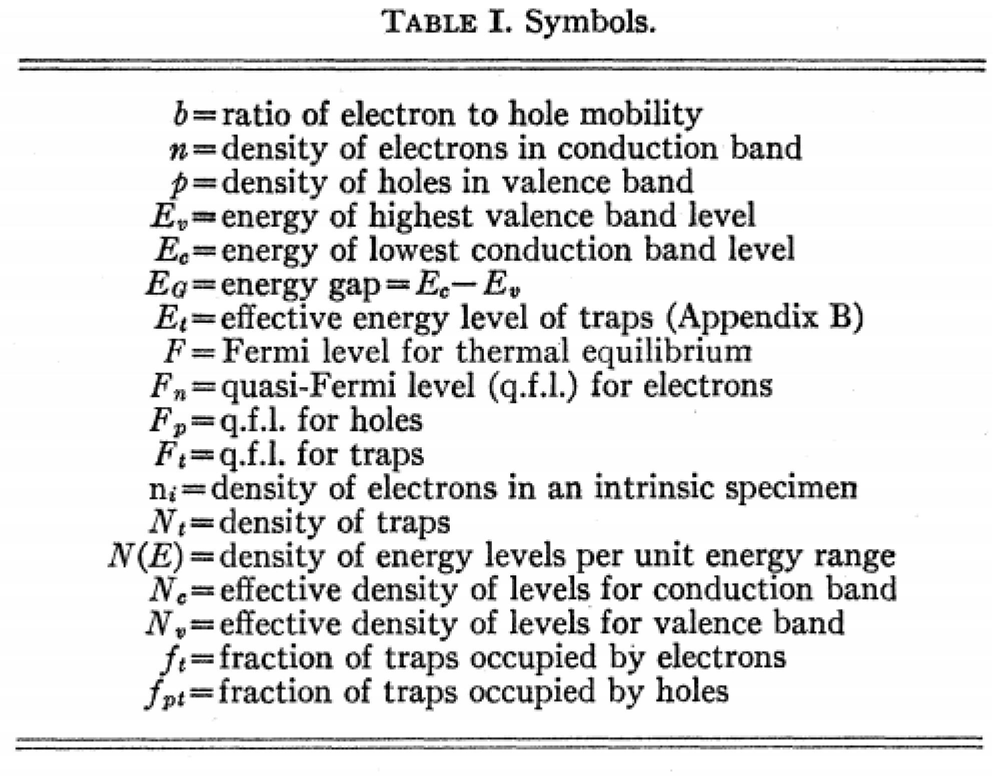
In n-type, $F_0 > E_i, n_0 \gg p_0$

$$\tau = \tau_{P0}\frac{n_0 + n_1}{n_0} = \tau_{P0}\left(1 + exp\frac{E_t - F_0}{k_BT}\right)$$

In p-type, $F_0 < E_i, n_0 \ll p_0$

$$\tau = \tau_{n0} + \tau_{P0}\frac{n_1}{p_0}$$

$$= \tau_{n0} + \tau_{P0}exp\frac{E_t + F_0 - 2E_i}{k_BT},$$



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When photoexcited density change δn is large, in n-type,

$$\frac{\tau}{\tau_0}\left(1 + \frac{\delta n}{n_0}\right) = 1 + \frac{\delta n(\tau_{P0} + \tau_{n0})}{\tau_{P0}(n_0 + n_1)}$$

Recombination rate linear to photoexcited charge carriers.

Dependence of recombination time

$F_0 > 2E_i - E_t, p_0 \ll n_1$

Traps are mostly empty but there are not a sufficient number of holes to recombine with every trapped electron before the latter is re-emitted to CB

$F_0 < E_t, n_0 \ll n_1$

Traps are largely empty, recombination is limited by that an empty trap cannot capture a hole.

$F_0 < 2E_i - E_t, p_0 \gg n_1$

All traps are empty and the number of holes is large enough that a hole will immediately recombine with every trapped electron

$F_0 > E_t, n_0 \gg n_1$

Traps are full, all set to capture holes, and sufficient electrons that an electron recombines at once with every hole is trapped.

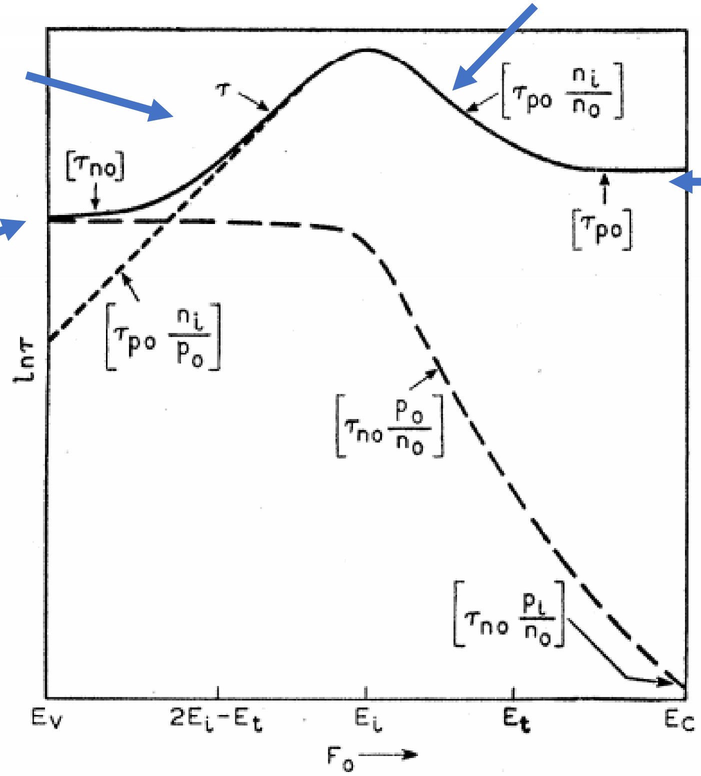
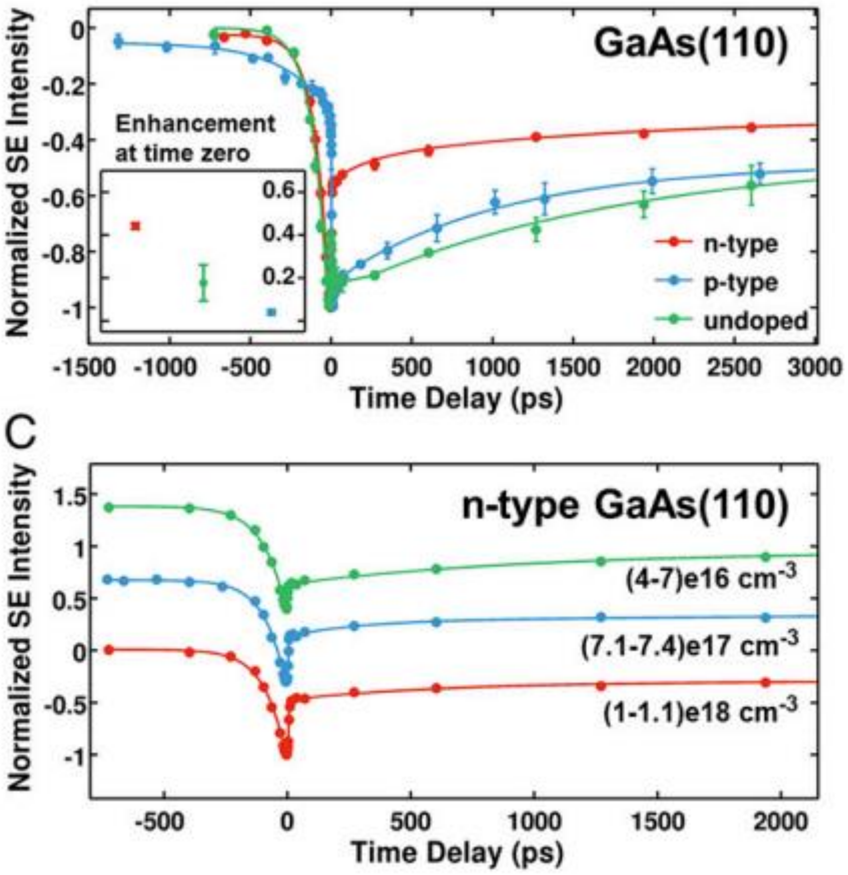
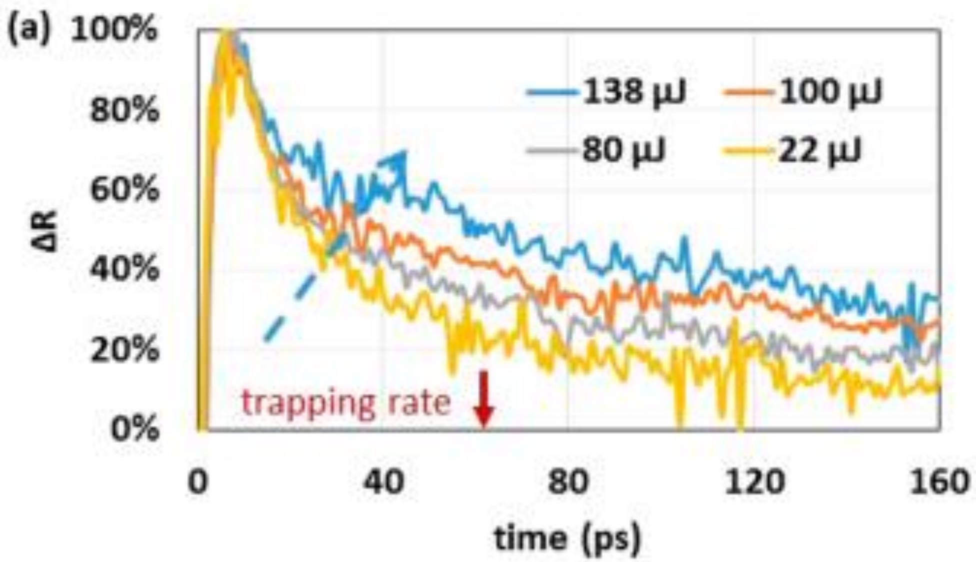


FIG. 2. Dependence of lifetime upon composition of the specimen. (The composition determines F_0, the Fermi level for equilibrium.) The solid curve gives total lifetime τ; the dashed curves give the two terms of which τ is the sum. The expressions in [ ] are approximations valid for the straight segments of the curves.

Doping level and laser energy dependence

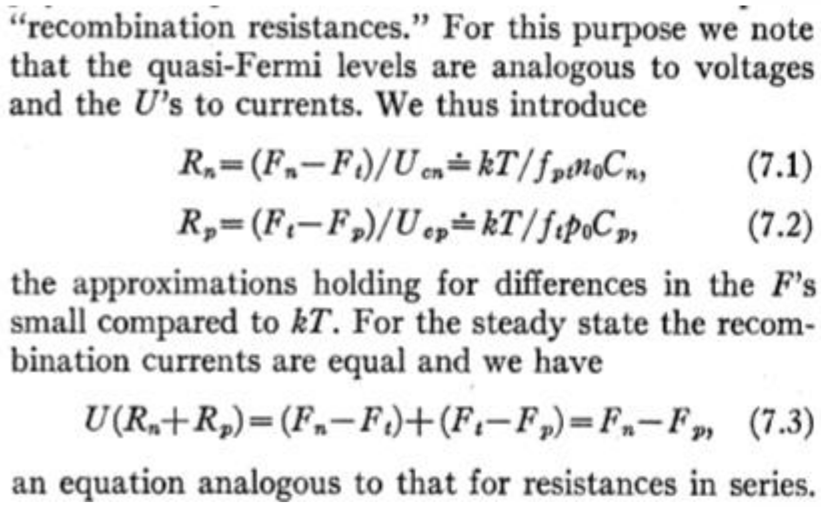


J. Cho, PNAS 2014, 111, 2094-2099



Y. Li, ACS Photonics 2015, 2, 1091–1098

Recombination resistances in various traps



"recombination resistances." For this purpose we note that the quasi-Fermi levels are analogous to voltages and the *U*'s to currents. We thus introduce

$$R_n=(F_n-F_t)/U_{cn}\doteq kT/f_{pt}n_0C_n, \qquad (7.1)$$

$$R_p=(F_t-F_p)/U_{ep}\doteq kT/f_tp_0C_p, \qquad (7.2)$$

the approximations holding for differences in the *F*'s small compared to *kT*. For the steady state the recombination currents are equal and we have

$$U(R_n+R_p)=(F_n-F_t)+(F_t-F_p)=F_n-F_p, \qquad (7.3)$$

an equation analogous to that for resistances in series.

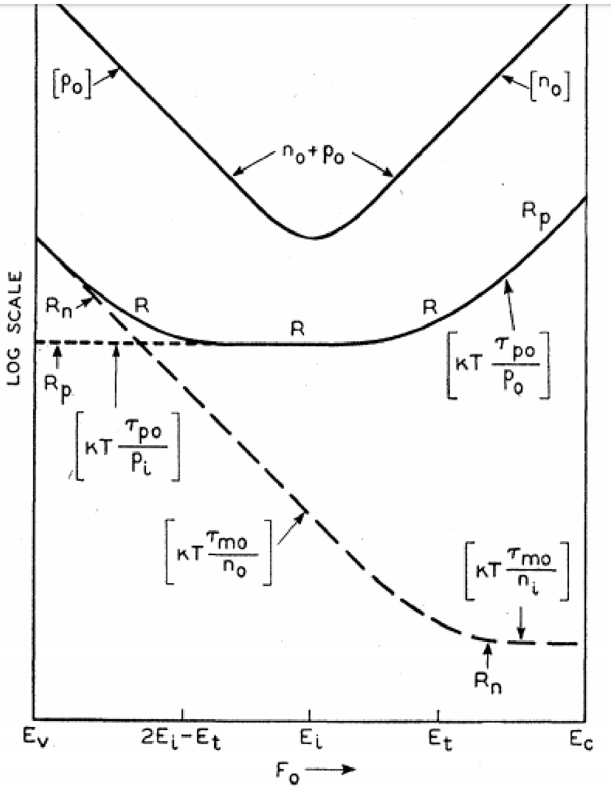
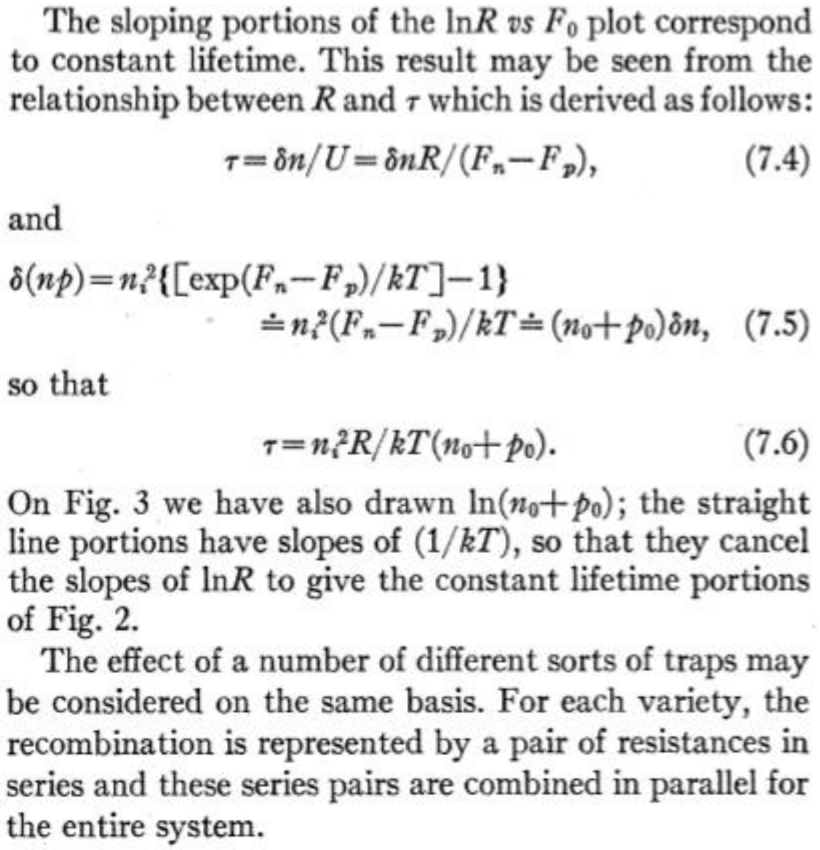


FIG. 3. Variation of recombination resistances with F_0. Solid curve represents total resistance $R=R_p+R_n$; dashed curves give R_p and R_n. Expressions in [ ] are approximations valid for the straight segments of the curves.



The sloping portions of the ln*R* *vs* F_0 plot correspond to constant lifetime. This result may be seen from the relationship between *R* and τ which is derived as follows:

$$\tau=\delta n/U=\delta nR/(F_n-F_p), \qquad (7.4)$$

and

$$\delta(np)=n_i^2\{[\exp(F_n-F_p)/kT]-1\}$$
$$\doteq n_i^2(F_n-F_p)/kT\doteq(n_0+p_0)\delta n, \qquad (7.5)$$

so that

$$\tau=n_i^2R/kT(n_0+p_0). \qquad (7.6)$$

On Fig. 3 we have also drawn $\ln(n_0+p_0)$; the straight line portions have slopes of $(1/kT)$, so that they cancel the slopes of ln*R* to give the constant lifetime portions of Fig. 2.

The effect of a number of different sorts of traps may be considered on the same basis. For each variety, the recombination is represented by a pair of resistances in series and these series pairs are combined in parallel for the entire system.