Electric field dependence of capture and emission rates by truncated cascade recombination

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The recombination of electron-hole pairs by a new and analytically tractable cascade process is used to discuss the electric field dependence of emission and capture rates by means of the Poole-Frenkel effect. Comparison with experiment gives support to the new model, which suggests decrease of capture and increase of emission coefficients with increasing electric field.

The effect of electric fields on the capture coefficients c_n, c_p of minority carriers in semiconductors and on their emission coefficients e_n, e_p are not yet understood quantitatively. This is demonstrated by the different field dependences obtained by various authors, see for example the review in Ref. 1. In this paper we propose a novel mechanism to explain such effects. It can be called truncated cascade *recombination* (TCR) and has not been discussed before. It differs from the normal cascade *capture*[2,3] by the addition of the valence band to the cascade model, thus converting capture to a generalized Shockley-Read-Hall recombination model. The cascade capture model is rather involved mathematically and the "truncated" part of TCR consists of replacing the excited states by a single effective excited state, which may represent the dominant excited state and makes the mechanism accessible to analytical treatment. These features distinguish the model proposed from previous ones (notably but not exhaustively[4–6]). It also differs from previous models by the possibility of direct transitions between the ground state and the bands. This is not a physically trivial step since direct electron capture into the ground state can become an important mechanism at elevated temperatures when excited states are able to hold electrons only with difficulty. It is this step which distinguishes the TCR from our own previous work on a related cascade recombination model.[7,8] Its omission was due to the fact that we wished to follow the cascade capture philosophy. In addition the excited state for holes which was considered in Refs. 7 and 8 is omitted here for simplicity. The capture will normally be by multiphonon process but the details are not required here.

The electric field E increases trap emission coefficients of electrons from neutral centers (e_n) and of holes from neutral centers (e_p) by virtue of the Poole-Frenkel effect. Trapping coefficients are not affected significantly. However, they may decrease by reason of hot-electron effects (for the reason noted above[9]), but this matter is not investigated here.

Replacing the spectrum of excited states by a single, effective level, one arrives at Fig. 1 as representing the TCR model. The sticking probability for electrons in this excited state is

$$P_e = t_n^{-1}/(e_{ne} + t_n^{-1}) = (1 + e_{ne}t_n)^{-1} , \tag{1}$$

where the notation of the figure has been used. This leads

to an effective capture coefficient

$$c_{n\,\text{eff}} = c_{ng} + c_{ne}P_e = c_{ng} + c_{ne}/(1 + e_{ne}t_n) . \tag{2}$$

The recombination rate per unit volume is

$$c_{n\,\text{eff}}n\,v_0 - e_{n\,\text{eff}}v_g , \tag{3}$$

where v_0 is the concentration of centers without captured electrons and v_g is the concentration of centers with a captured electron in the ground state. Detailed balance yields for the effective emission coefficient

$$e_{n\,\text{eff}} = \left[\frac{n v_0}{v_g} \right]_{\text{eq}} c_{n\,\text{eff}} \equiv n_g c_{n\,\text{eff}}$$

$$= n_g \left[c_{ng} + \frac{c_{ne}}{1 + e_{ne}t_n} \right] . \tag{4}$$

Here n_g corresponds to the concentration, usually denoted by n_1 in the Shockley-Read statistics, which gives the conduction-band electron concentration when the Fermi level is at the ground level of the trap. The term $n_g c_{ng}$ is the emission rate e_{ng} directly from the ground state.

In a three-dimensional Poole-Frenkel effect the trap activation energy is reduced by $\ln\chi$ where[10]

$$\chi = \tfrac{1}{2} + \xi^{-2}[1 + (\xi - 1)e^\xi], \quad \xi \equiv \frac{1}{kT} \left[\frac{zq^3 E}{\epsilon\pi} \right]^{1/2} . \tag{5}$$

Here E is the electric field, ϵ the dielectric permittivity of the semiconductor, and zq is the charge on the center which is here assumed positive. The factor χ has to be applied to the emission coefficients e_{ng}, e_{ne}, but not to the capture coefficients c_{ng}, c_{ne}. Hence one sees two interesting effects: First, from (2) one observes that instead of field-independent sticking probability P_e and capture coefficient c_{ng}, TCR gives quantities which *decrease* with
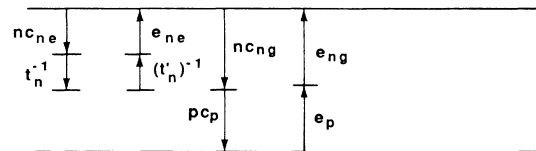

FIG. 1. Transition rates used in truncated cascade recombination.

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field

$$P_e(E) = (1 + c_{ne} t_n n_e \chi)^{-1} ,$$

$$c_{n \text{ eff}}(E) = c_{ng} + c_{ne} / (1 + c_{ne} t_n n_e \chi) . \qquad (6)$$

Here $n_e \equiv e_{ne}/c_{ne}$ refers to capture and emission from the effective excited state, in analogy with n_g. Secondly, from (4), instead of a field dependence $e_n = n_g c_{ng} \chi$, a *less strong* field dependence

$$e_{n \text{ eff}}(E) = [c_{ng} + c_{ne} / (1 + n_e c_{ne} t_n \chi)] n_g \chi \qquad (7)$$

is found, and arises from $n_e \rightarrow n_e \chi$ and $n_g \rightarrow n_g \chi$. In fact, for low fields and high temperatures $e_{n \text{ eff}}$ has only a weak field dependence. The reason is that for $n_e c_{ne} t_n \gg 1$, which is the appropriate approximation,

$$e_{n \text{ eff}}(E) = n_g c_{ng} \chi + n_g / n_e t_n , \qquad (8)$$

and the second term is liable to dominate.

In the above the capture coefficients c_{ng}, c_{ne} have been treated as independent of electric field. There are at least two corrections to this. First, if the electric field is large enough for the potential maximum to drop below the energy level of the excited state, then $e_{ne} \chi = n_e c_{ne} \chi$ becomes large and one finds Eq. (8) again. Since c_{ne} has now dropped out, our main equations which treat it as field independent can still be used. Secondly, the trapping coefficients may decrease by reason of hot-electron effects,[10] but this matter is not investigated here.

Figure 2 shows a comparison of Eq. (6) and Fig. 3 shows a comparison of Eq. (7) with experiments on sulfur centers in silicon (Ref. 11, Figs. 10 and 7 respectively). The data used are given in Table I. In Fig. 2 we have added a background capture $c_{n0} = 1.6 \times 10^{-9}$ cm^{3}s^{-1}, independent of electric field, which may be due to neutral

FIG. 3. The effect of an electric field (a) on the Poole-Frenkel factor χ given by (5) and (6), and (b) on $e_{n \text{ eff}}$ using Eq. (7) and the data of Table I. The experimental points apply to S in Si at 121 and 130 K (Ref. 11). The value of $e_{n \text{ eff}}(E)$ is normalized by its value at $E = 2 \times 10^4$ V/cm.

centers. Such a correction is needed to obtain agreement with the experimental results[11] and also with the observed capture cross section for S in Si[12] At the larger fields capture into excited states becomes insignificant and direct capture into the ground state, usually neglected in cascade models, becomes important. Figure 3 for the emission coefficient also shows the pure Poole-Frenkel factor χ to illustrate the drop in the electric field dependence brought about by passing from e_n to $e_{n \text{ eff}}$ when TCR is envisaged. However, even the present theory will yield an emission coefficient proportional to χ at sufficiently low temperatures. In that case $n_e c_{ne} t_n \ll 1$ and (6) gives rise to

$$e_{n \text{ eff}}(E) = (c_{ng} + c_{ne}) n_g \chi .$$

This is consistent with the approximately straight-line law connecting the logarithm of the emission rate and
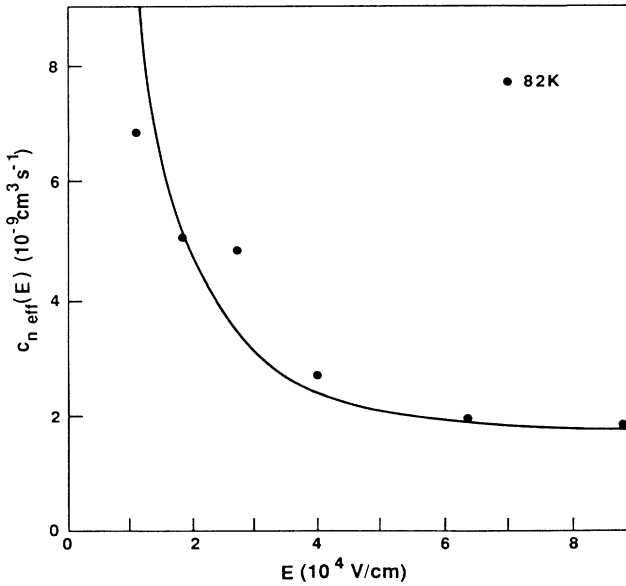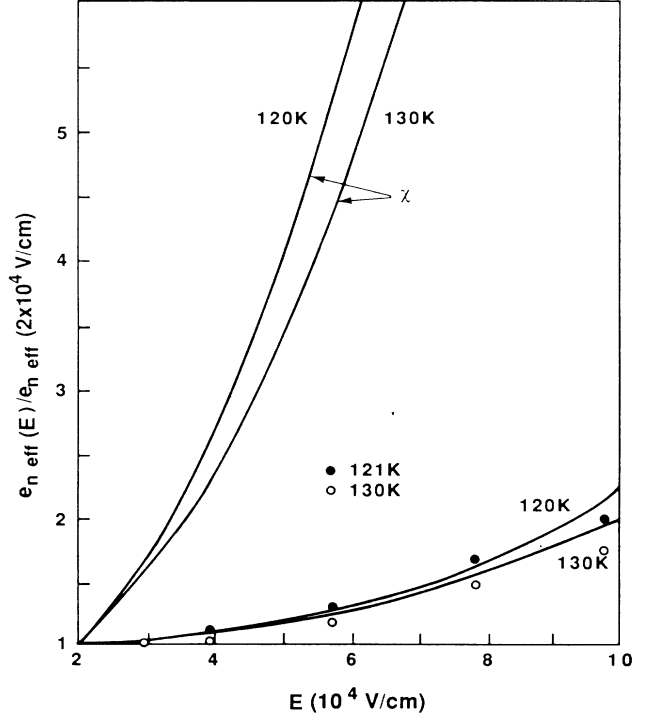

FIG. 2. The effect of an electric field on $c_{n \text{ eff}}$ using Eq. (6) and the data of Table I. The experimental points apply to S in Si at 82 K (Ref. 11).

TABLE I. Values of parameters used.

v_{th}	$10^7 (T/300)^{1/2}$ cm s^{-1}
$\sigma_{ne} \equiv c_{ne}/v_{th}$	10^{-13} cm^2 a
$\sigma_{ng} \equiv c_{ng}/v_{th}$	0.25×10^{-16} cm^2 a
$n_e c_{ne} t_n$	$0.0188 T^2 \exp(-0.017/kT)$ b

aChosen to fit the experiments shown in Figs. 2 and 3.
bInferred from Ref. 12; kT is expressed in electron volts.

$E^{1/2}$ found experimentally,[13] and expected from Eq. (5). Figures 2 and 3 show that the model is capable of yielding quantitative agreement with experiment.

Note that in Eq. (5) tunneling and phonon-assisted tunneling have not been included. They may be important at low temperatures and would increase the value of χ. However in silicon, for example, these effects can often be neglected.[14]

We now comment on the fact that the hole concentration (p) does not appear explicitly in the simple formulae given here. The reason is that the concentrations v_0 and v_g in (3) are regarded as given. A fuller analysis must consider n and p as given by conditions of doping and excitation, while the concentrations v_0, v_g and the concentration v_e of recombination centers with the electron in the excited state depend on n and p. They are subject to $v_0 + v_g + v_e = N_T$, the total concentration of centers. The remaining conditions required for the determination of the three concentrations arise from equating the three transition rates for (i) the conduction band, (ii) the ground state, and (iii) the valence band. This leads to rather complicated expressions for v_0, v_g, v_e in terms of n and p. Their derivation, together with an analysis of transients and dependence of lifetimes on temperature and injection, will be published elsewhere.

We have recently developed an improved theory of χ (Ref. 15) by taking into account that the emitted electron moves in the conduction band in a region in which the density of states depends on position, and also that this motion is terminated by a scattering event. The comparison with experiment in Figs. 2 and 3 is not significantly changed provided σ_{ng} is lowered to 10^{-17} cm^2, c_{n0} is slightly raised to 1.8×10^{-9} cm^{3}s^{-1}, and

$$n_e c_{ne} t_n = 0.0188 T^2 \exp(-0.028/kT) \ .$$

The mean free path is required in the new model and has been taken as $10^{-3}/T(K)$ cm.

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