Field-enhanced mobility in the multiple-trapping regime

A. V. Nenashev,[1,2] J. O. Oelerich,[3] K. Jandieri,[3] V. V. Valkovskii,[3] O. Semeniuk,[4] A. V. Dvurechenskii,[1,2] F. Gebhard,[3] G. Juška,[5] A. Reznik,[6] and S. D. Baranovskii[3]

[1]*Institute of Semiconductor Physics, 630090 Novosibirsk, Russia*
[2]*Novosibirsk State University, 630090 Novosibirsk, Russia*
[3]*Department of Physics and Material Sciences Center, Philipps-University, D-35032 Marburg, Germany*
[4]*Chemistry and Material Science Program, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1*
[5]*Department of Solid State Electronics, Vilnius University, Saultekio 9 III k., 10222 Vilnius, Lithuania*
[6]*Department of Physics, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1*

(Received 5 February 2018; revised manuscript received 5 May 2018; published 3 July 2018)

Charge transport in disordered inorganic semiconductors is governed by the multiple trapping (MT) of carriers from delocalized states in the conduction band into localized traps in the band tail. Although it is well known that carrier mobility in these materials strongly depends on electric field, a consistent description of this effect in the MT regime is still missing. We analyze experimental data obtained in a series of disordered inorganic semiconductors and show that the combined effects of temperature and of the electric field on the carrier mobility can be described by a single parameter, the field-dependent effective temperature. This conclusion is supported by the theoretical analysis of the MT transport, which takes into account the field-assisted release of carriers from the traps into the conduction band.

DOI: 10.1103/PhysRevB.98.035201

I. INTRODUCTION

Disordered inorganic semiconductors, such as hydrogenated amorphous silicon (a-Si:H), amorphous selenium (a-Se), amorphous silicon-germanium alloys (a-$Si_{1-x}Ge_x$:H), and polycrystalline led oxide (poly-PbO) are widely used in electrophotography, solar cells, field effect transistors for flat-panel displays, optical memories, light-emitting diodes, and other devices [1]. Charge transport is decisive for all these applications. The study of charge transport in amorphous semiconductors has been, for decades, in the focus of intensive experimental and theoretical research. It has been well established that charge transport in inorganic amorphous semiconductors occurs in the form of the so-called multiple-trapping (MT) process [1–5]. In the MT process, a charge carrier moves only via delocalized states with energies above the mobility edge. This motion is interrupted by trapping into the localized states with subsequent activation of carriers back into the conducting states above the mobility edge. Transport in the framework of the MT model is shown schematically in Fig. 1.

In spite of intensive experimental and theoretical efforts, there is no consistent and transparent theory that can describe the dependence of the carrier mobility μ on the applied electric field F in the MT model. This is in drastic contrast to the cases of band and hopping transport, which are complementary to the MT process. In the case of pure band transport, when capture of carriers on traps does not play any essential role, the effect of the electric field on the carrier mobility can be described [6,7] by introducing a so-called effective temperature, T_{eff}, which depends on the magnitude of the electric field F, $kT_{\text{eff}} \sim eFl/\hbar\omega$, where e is the carrier charge, k is the Boltzmann constant, $\hbar\omega$ is the phonon energy, and l is the mean-free path. This regime is valid in amorphous semiconductors only at very high temperatures, when the thermal energy kT is larger than the energy scale ε_0 and most carriers are in delocalized states above the mobility edge.

In the opposite case of the very low temperatures, when the inequality $kT \ll \varepsilon_0$ is valid, activation of carriers from traps into extended states is not possible and charge transport occurs via tunneling (hopping) of carriers between the localized states. The effect of the electric field F on the carrier mobility μ in the hopping regime received a transparent interpretation already in the 1970s, when Shklovskii [8] recognized that for hopping conduction a strong electric field plays a role similar to that of temperature. In a tunneling transition over some distance x in the field direction, a carrier gains energy $\delta = eFx$ even at $T = 0$. The tunneling probability $\nu(x) \propto \exp(-2x/a)$ (where a is the localization length) can be then presented [8] as $\nu(\delta) \propto \exp(-\delta/kT_{\text{eff}})$ with $T_{\text{eff}} \simeq eFa/2$, i.e., as if it were "activated" at temperature T_{eff}. A very similar result was obtained later by Grünewald and Movaghar in their study of the hopping energy relaxation of electrons through band tails at very low temperatures and high electric fields [9]. The same idea was also used by Shklovskii *et al.* [10], who suggested that, at $T = 0$, one can calculate the field dependence of the conductivity in amorphous semiconductors by replacing the laboratory temperature T in formulas for the low-field finite-temperature theory by an effective temperature $T_{\text{eff}} \simeq eFa/2$.

For the case $T \neq 0$, Marianer and Shklovskii [11] suggested on the basis of numerical calculations that the combined effects of the electric field F and temperature T on the hopping conduction can be expressed in the form of the effective temperature

$$T_{\text{eff}} = \left[T^2 + \left(\gamma \frac{eFa}{k}\right)^2\right]^{1/2}, \tag{1}$$

 ©2018 American Physical Society

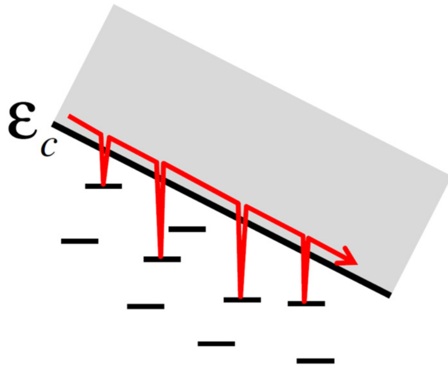

FIG. 1. Sketch of the multiple-trapping process.

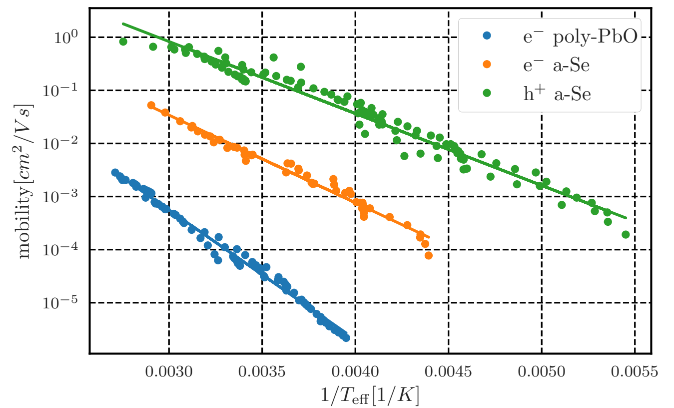

FIG. 2. Experimentally measured dependence of the charge carrier mobility on temperature T and electric field F versus the effective temperature $T_{\rm eff}$ given by Eq. (1). Fits of Eq. (2) are also shown.

with $\gamma \approx 0.67$. The validity of the approach based on the effective temperature in this or a slightly modified form has been confirmed in numerous studies [12–14] performed by numerical simulations. Values of γ in the range $0.5 \leqslant \gamma \leqslant 0.7$ were reported, depending on the considered transport phenomena [11–14].

However, neither pure band transport nor hopping transport but rather MT transport is inherent in amorphous semiconductors at temperatures relevant to experimental studies and to applications, when the thermal energy kT is neither *much* larger nor *much* smaller than $\varepsilon_0 \sim 0.1$ eV. A theoretical description of the field-dependent mobility in the MT regime is still missing. The only attempt to adjust the description based on the field-dependent effective temperatures to materials with MT transport was performed by Chen *et al.* [15], who showed that Eq. (1) with $\gamma = 0.5$ and $a = 8$ Å provides "very acceptable agreement" with experimental data obtained in a-Si:H by the time-of-flight technique in a broad range of electric fields and temperatures. No theoretical justification for the validity of this approach for the MT process has been provided by Chen *et al.* [15], who simply inserted $T_{\rm eff}$ given by Eq. (1) instead of T into the standard simulation algorithm of the MT transport and automatically obtained all dependencies of transport coefficients on $T_{\rm eff}$ known previously for the dependencies on T.

The aim of our paper is to analyze the validity of the approach based on the effective temperature for the description of the field-dependent MT mobility $\mu(T)$ in experimental studies on other materials, and also theoretically. For that purpose, we analyze experimental data on the dependencies of the carrier mobility on the electric field and temperature in other than a-Si:H amorphous semiconductors, such as a-Se and poly-PbO. It appears that the concept based on $T_{\rm eff}$ is applicable to these materials with MT charge transport. Furthermore, we analyze theoretical results derived for the field-induced release of carriers from traps into the conduction band and show that these results allow the description via $T_{\rm eff}$.

The paper is organized as follows. In Sec. II, we analyze experimental data on the dependencies of the mobility on temperature and on electric field for holes and electrons in a-Se and for electrons in poly-PbO, where the validity of the MT approach has been proven. The approach based on $T_{\rm eff}$ is validated. In Sec. III we analyze theoretical results for thermal release of carriers from traps into conducting states, which plays the decisive role for the MT transport. Again the approach based on $T_{\rm eff}$ is shown to be valid. Concluding remarks are gathered in Sec. IV.

II. EXPERIMENTAL DATA ALLOW THE DESCRIPTION VIA $T_{\rm eff}$

Experimental studies [16–20] of the field-dependent carrier mobility in materials with MT transport, such as a-Si:H, a-Se, and a-$Si_{1-x}Ge_x$:H, $0 < x < 0.3$, have shown that the effect of an electric field on the carrier mobility is determined by the ratio eFa/kT, where the length parameter a is of order 10 Å. The role of such a length for the materials with MT transport was not clarified. The parameter a was merely introduced to fit experimental data for the dependence $\mu(F)$ [16–18,20].

While it has been shown by Chen *et al.* [15] that the effective temperature $T_{\rm eff}$ in the form of Eq. (1) is capable of describing experimental data obtained by the time-of-flight measurements in a-Si:H, this approach has not yet been checked for other amorphous materials, in which charge transport is determined by the MT mechanism. Here, we check the ability of $T_{\rm eff}$ to describe the T and F dependencies of the carrier mobility in a-Se and in poly-PbO.

In Fig. 2, we plot the data for the mobilities of electrons (e^-) and of holes (h^+) measured in a-Se [16], and the data for the electron mobility measured in poly-PbO [5]. The data are plotted on a logarithmic scale versus the inverse effective temperature $1/kT_{\rm eff}$ given by Eq. (1). The numerical coefficient γ is fixed to $\gamma = 0.6$ for all data sets. The localization length a was varied to minimize the mean square deviations of the mobility data to a straight line in those semilogarithmic plots. It is apparent that the experimental results are nicely reproduced as an Arrhenius-type behavior with the temperature T replaced by $T_{\rm eff}$.

Assuming the temperature-dependent and field-dependent mobility $\mu(T,F)$ in the form

$$\mu(T,F) = \mu_0 \exp\left(-\varepsilon_a/kT_{\rm eff}\right), \quad (2)$$

we can then extract the conduction band mobility μ_0, the activation energy ε_a, and the localization length a from the data. The results are summarized in Table I.

TABLE I. Fitted values for the conduction band mobility μ_0, the activation energy ε_a, and the localization length a of the experimental data shown in Fig. 2.

	μ_0 (cm^2/Vs)	ε_a (eV)	a (nm)
e^- poly-PbO [5]	2.24	0.48	0.56
e^- a-Se [16]	2.08	0.33	0.78
h^+ a-Se [16]	2.22	0.27	0.76

All values are reasonable for the materials under study. The activation energy $\varepsilon_a = 0.48$ eV for e^- in poly-PbO matches the values reported by Semeniuk *et al.* [5] and the activation energy $\varepsilon_a \simeq 0.3$ eV for e^- and h^+ in a-Se matches the values reported by Juska and Arlauskas [16]. The idea to scale experimental data on the dependencies of the mobility on the electric field F and temperature T in the form of the Arrhenius law using T_{eff} is based on the Arrhenius temperature dependence evidenced experimentally [1–4] in the classical inorganic amorphous materials for the T dependence of the mobility in the Ohmic regime at small F.

The energy spectrum of localized states in the band tails of inorganic amorphous semiconductors is widely considered to exhibit a purely exponential shape [1–5]:

$$g(\varepsilon) = \frac{N_c}{\varepsilon_0} \exp\left(-\frac{\varepsilon}{\varepsilon_0}\right), \tag{3}$$

where ε is the energy of the trap counted positively downwards from the mobility edge ε_c in Fig. 1, ε_0 is the energy scale, and N_c is the concentration of states at the mobility edge. The value of ε_0 depends on the material and it is usually estimated below 0.1 eV [1–5].

Under nonequilibrium conditions, charge carriers in the exponential DOS relax towards the Fermi level in the course of transport [1–5]. In such a case, the temperature dependence of the carrier mobility in the Ohmic regime at small electric fields can be described by the Arrhenius law [1–5,16,18] with some effective activation energy ε_a that depends not only on the energy scale of the DOS ε_0, but also on the experimental conditions determining the time domain, in which charge transport is measured. The longer is the time scale of the measurements, the larger is the obtained characteristic activation energy ε_a, because the deeper in energy the carriers can relax at longer times. The data used for fittings in Fig. 2 were obtained in this regime of the so-called dispersive transport [5,16]. In this transport regime, the activation energies in Table I should not be considered as fixed parameters for the corresponding materials. Not the absolute values of ε_a is the message of our paper but rather the ability to fit experimental data on the dependences of the mobility on F and T by a single parameter T_{eff}. No restrictions for the capability of the description via T_{eff} with respect to the concentration of carriers n are to be expected in the MT regime with dispersive transport. In the equilibrium conditions, the MT charge transport in the exponential DOS is determined by the activation of carriers from the Fermi level ε_f towards the mobility edge ε_c [1–3,21,22]. The position of the Fermi level ε_f is determined by the energy scale of the DOS ε_0 and by the concentration of carriers n. Therefore, the activation energy ε_a in Eq. (2) should depend on the carrier concentration n if experimental data were obtained in equilibrium conditions. No restrictions for the capability of the description via T_{eff} with respect to the concentration of carriers n are to be expected in the equilibrium MT regime.

The deviations of the data in Fig. 2 from the Arrhenius dependence at large $1/T_{\mathrm{eff}}$, i.e., at small T_{eff}, are probably caused by the transition from the MT transport to the hopping transport at small T and F. Hopping transport at small T and F undergoes a non-Arrhenius dependence of the mobility on T_{eff} [13]. The results of the current manuscript are valid for the MT regime. They are not applicable at very small T and F, when transport is determined by tunneling of charge carriers between the localized tail states instead of their activation towards the mobility edge. From Fig. 2 one can estimate the range of applicability for transport of holes in a-Se as $T_{\mathrm{eff}} \geqslant 220$ K and for transport of electrons in a-Se as $T_{\mathrm{eff}} \geqslant 200$ K. At very high values of T_{eff}, the MT regime merges with the band transport, to which the results of this report are also not applicable. In a-Se, the carrier mobility loses its activated temperature dependence at $F \geqslant 10^8$ V/m [16]. Inserting this value into Eq. (1) and using the lowest temperature value $T = 166$ K studied experimentally for the field-dependent mobility in a-Se [16], one obtains the restriction $T_{\mathrm{eff}} \leqslant 560$ K. The range of the applicability of the concept of the effective temperature in the MT regime to the carrier mobility in a-Se can be thus estimated as $220 \text{ K} \leqslant T_{\mathrm{eff}} \leqslant 560$ K.

III. THEORETICAL STUDIES FOR THE FIELD-ENHANCED DETRAPPING ALLOW THE DESCRIPTION VIA T_{eff}

The carrier mobility in the MT transport regime is proportional to the probability for electrons to be released from the traps into conducting states [1–3]. The external electric field enhances the release rate ν_{esc} and affects the carrier mobility. Let us consider the field dependence of the release rate $\nu_{\mathrm{esc}}(F)$.

Without electric field, the escape rate from a trap into the conduction band is equal to

$$\nu_{\mathrm{esc}}(\varepsilon) = \nu_0 \exp\left(-\frac{\varepsilon}{kT}\right), \tag{4}$$

where ε is the energy of the trap counted positively downwards from the mobility edge and ν_0 is a preexponential factor determined by the interaction mechanism responsible for the transition. If a transition is caused by the interaction with phonons, ν_0 is usually assumed to be of the order of the phonon frequency. Focusing on the effect of F on the exponential factors, we will not consider the effect of the electric field on the value of ν_0.

Aiming to study the release of carriers from traps in amorphous semiconductors such as a-Si:H, a-Se, and poly-PbO, we will consider electrically neutral traps in the absence of carriers, and charged if carriers are present on the traps. It is widely accepted that localized states forming the band tails in amorphous materials appear not due to the introduction of electrically active donors or acceptors, but rather due to fluctuations of the distances between the atoms and of the angles between the covalent bonds [1–4]. States in the band tails can, for instance, appear on the elongated covalent bonds, in which the energy difference between the bonding and

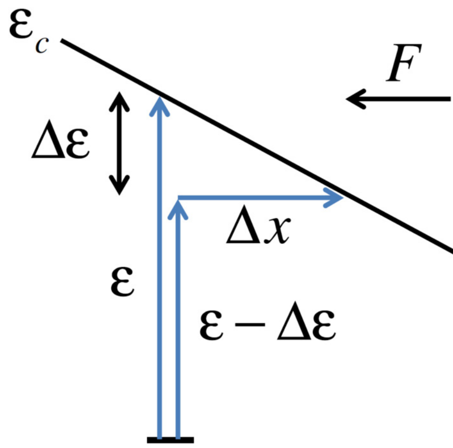

FIG. 3. Schematic picture for the field-enhanced escape.

antibonding orbitals are smaller than on average. Therefore, traps are neutral in the absence of carriers. The release of carriers from traps in our study is in contrast to the ionization of traps studied, for instance, by Frenkel [23], who considered traps to be neutral when occupied by electrons and to be ionized (positively charged) when electrons are released from the traps.

The effect of the electric field on $\nu_{\rm esc}(\varepsilon)$ has been first studied theoretically by Keldysh [24], who showed that the field can diminish the activation barrier for the electron escape from a trap, as illustrated schematically in Fig. 3, where the process of a thermally assisted tunneling due to the electron-phonon coupling is depicted. This is a thermal equivalent of the well-known Franz-Keldysh effect. In this scheme, the escape event consists of two processes: activation with the energy deficit $\Delta\varepsilon$, as compared to the trap depth ε, and tunneling over the distance $\Delta x = \Delta\varepsilon/(eF)$ under the triangle energy barrier. Ascribing a universal value ν_0 to the preexponential factor and introducing the variable $z \equiv (\Delta\varepsilon)/kT$, one can represent the result of Keldysh in the form [25]

$$\nu_{\rm esc}(\varepsilon) = \nu_0 \exp\left(-\frac{\varepsilon}{kT}\right)\left[1 + \int_0^{\varepsilon/kT} \exp\left(z - \frac{4\sqrt{2m}(zkT)^{3/2}}{3e\hbar F}\right)dz\right], \quad (5)$$

where m is the effective mass. One can use the saddle-point method to evaluate the integral in the exponent, which yields the expression [24,25]

$$\nu_{\rm esc}(\varepsilon) \propto FT^{-3/2} \exp\left(-\frac{\varepsilon}{kT} + \frac{1}{24m}\frac{(e\hbar F)^2}{(kT)^3}\right). \quad (6)$$

Apparently, the saddle point exists, and Eq. (6) is valid, only in the case $\varepsilon > (e\hbar F/kT)^2/8m$. In the opposite case, it is favorable for carriers to leave the traps via isoenergetic tunneling without thermal activation. The same equations were obtained later by Vincent *et al.* [25]. These results were slightly modified by Karpus and Perel [26], who also predicted a parabolic field dependence in the exponent of the escape probability at low fields and found that only tunneling is responsible for carrier escape from the traps at high fields. Hijazi and Kabir [27] recently addressed Eq. (6) and claimed that "considering the wide variation of the vibrational energy, the enhancement factor for the carrier release can be written as $\exp[(a'F + b'F^2)/kT]$, where a' is the effective tunneling distance in the direction of the electric field" and b' is related to "a fitting parameter for amorphous materials." However, it has not been explained [27] how this result could be derived.

Aiming to analyze the field dependence of the mobility $\mu(F)$ using Eq. (5), let us express μ in terms of the escape rate $\nu_{\rm esc}$. In the case of the exponential density of states given by Eq. (3), most electrons in the steady state at $kT < \varepsilon_0$ have energies in the vicinity of the Fermi level ε_f. The fraction of the *conducting* electrons in the states above the mobility edge is proportional to the ratio between the escape rate $\nu_{\rm esc}(\varepsilon_f)$ from a trap at the Fermi level and a rate for a capture of an electron to such a trap. The drift mobility is proportional to the fraction of carriers in the conducting states:

$$\mu(T,F) \propto \frac{\nu_{\rm esc}(\varepsilon_f,T,F)}{\nu_0}. \quad (7)$$

Let us check whether it is possible to present the results of Eqs. (5) and (7) in the form of Eq. (2) using $T_{\rm eff}$ given by Eq. (1), that was shown in Sec. II to be capable of describing experimental results. The rate of the carrier detrapping given by Eq. (5) depends on the carrier effective mass m. The carrier effective masses in amorphous semiconductors are not known with high accuracy yet. Usually, the values range from m_0 to $0.25m_0$, where m_0 is the free electron mass, and are used for chalcogenide glasses [28]. The values $m = 0.34m_0$ for a-Si:H, $m = 0.22m_0$ for a-Ge:H, and $m = 0.46m_0$ for a-As_2S_3 have been reported in the literature [29]. To be definite, we use the value $m = 0.3m_0$ in the calculations. This assumption is not crucial for the results. The effective mass m enters Eq. (5) in the combination $\sqrt{m}/F$. The results for another choice of m can be obtained from our calculations for $m = 0.3m_0$ by a corresponding rescaling the F axis.

In Figs. 4 and 5, we show the results for the carrier mobility $\mu(T,F)$ obtained via Eqs. (5) and (7) for $\varepsilon_f = 0.5$ eV and for $\varepsilon_f = 0.3$ eV, respectively. In Figs. 4(a) and 5(a), the data are plotted as functions of the electric field for a set of temperatures between $T = 200$ K and $T = 300$ K with step size 20 K, while in Figs. 4(b) and 5(b), the data are plotted as functions of temperature for a set of electric fields between $F = 0.05$ MV/cm and $F = 0.4$ MV/cm with step size 0.05 MV/cm.

In analogy with fitting the experimental results in Fig. 2, we fit in Fig. 6 the theoretical data given in Figs. 4 and 5 to become straight lines when $\ln\mu(T,F)$ is plotted versus $1/T_{\rm eff}$, where $T_{\rm eff}$ is given by Eq. (1). The only fitting parameter necessary to achieve this goal, i.e., the data to align, is the product γa present in Eq. (1). For the results calculated via Eq. (5) with $\varepsilon_f = 0.5$ eV and shown in Fig. 4, the data in Fig. 6 were fitted with the value $\gamma a = 0.28$ nm, while for the results calculated via Eq. (5) with $\varepsilon_f = 0.3$ eV and shown in Fig. 5, the data in Fig. 6 were fitted with the value $\gamma a = 0.40$ nm.

From the data in Fig. 6, one can estimate the values of the activation energies ε_a via the slopes of the straight lines fitted by Eq. (2). Apparently, the data calculated via Eqs. (5) and (7) for $\varepsilon_f = 0.5$ eV provide the activation energy $\varepsilon_a = 0.506$ eV, while the data calculated via Eqs. (5) and (7) for $\varepsilon_f = 0.3$ eV

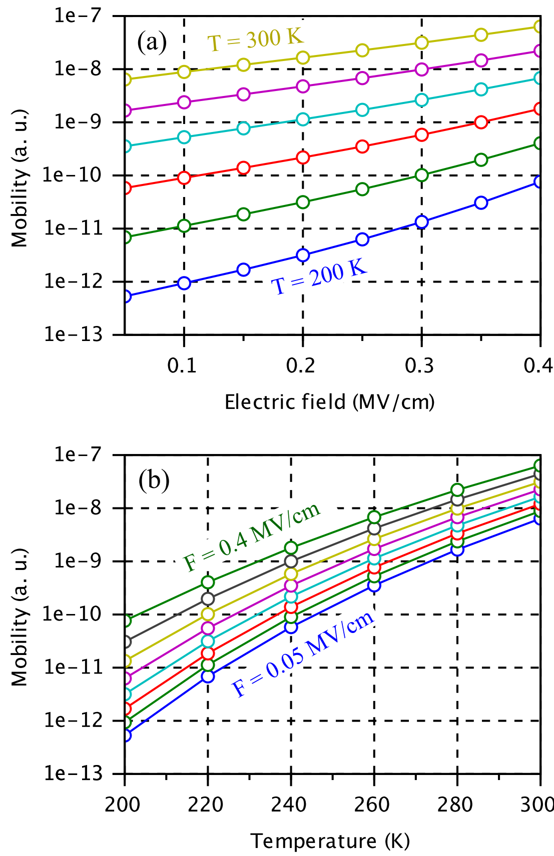

FIG. 4. Results of Eqs. (5) and (7) for $\varepsilon_f = 0.5$ eV.

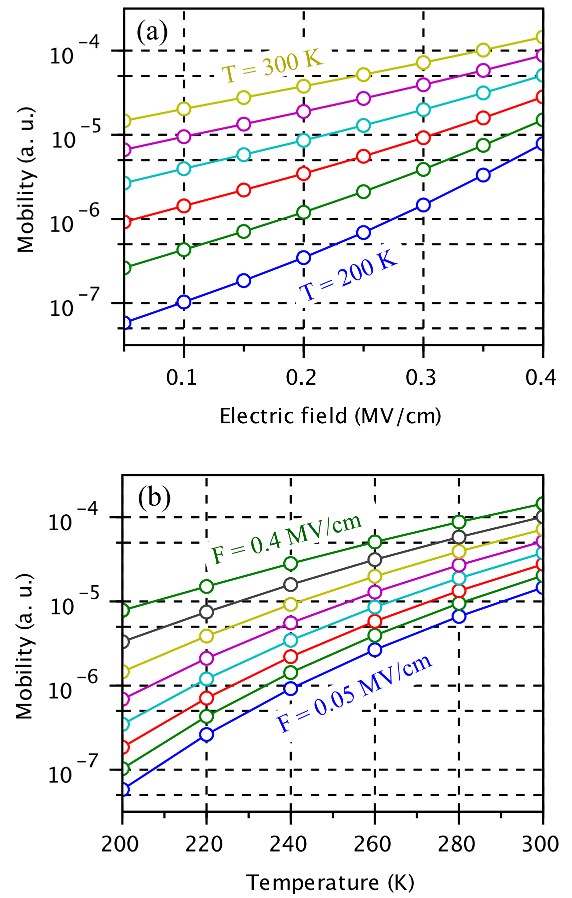

FIG. 5. Results of Eqs. (5) and (7) for $\varepsilon_f = 0.3$ eV.

point at the activation energy $\varepsilon_a = 0.306$ eV. The values obtained for ε_a are in perfect agreement with the values of $\varepsilon_f = 0.5$ eV and $\varepsilon_f = 0.3$ eV used in our calculations. This result is not trivial. It shows the ability of the approach based on the effective temperature T_{eff} to account for the effect of the electric field F on the release rate.

Fittings of the theoretical data by Eq. (2) shown in Fig. 6 were achieved using the values $\gamma a = 0.28$ nm and $\gamma a = 0.40$ nm for $\varepsilon_f = 0.5$ eV and $\varepsilon_f = 0.3$ eV in Eq. (1), respectively. Taking the value $\gamma = 0.6$ used in Sec. II to fit experimental data by the effective temperature T_{eff} given by Eq. (1) results in the estimates $a = 0.47$ nm and $a = 0.67$ nm for $\varepsilon_f = 0.5$ eV and $\varepsilon_f = 0.3$ eV, respectively.

The length scale a that appears in Eq. (1) must be a combination of the model parameters—namely, of the effective mass m, Fermi energy ε_f, and the Planck constant $\hbar$. There is only one combination of these parameters that has the dimensionality of length. It is the localization length of an electron trapped at the energy level ε_f [30]

$$a = \frac{\hbar}{\sqrt{2m\varepsilon_f}}. \tag{8}$$

Inserting in Eq. (8) the value $m = 0.3m_0$ used in our calculations, one obtains $a = 0.48$ nm and $a = 0.62$ nm for $\varepsilon_f = 0.5$ eV and $\varepsilon_f = 0.3$ eV, respectively. These values are similar to the estimates for a obtained from the fitting of Eqs. (5) and (7) with the effective temperature T_{eff} given by Eq. (1).

Let us discuss the range of temperatures T and fields F, in which the Arrhenius model illustrated in Fig. 6 holds. This range depends on the system parameters: the effective mass m and the Fermi energy ε_f. For this reason, it is convenient to express the range in terms of the "dimensionless temperature" T^* and the "dimensionless field" F^* defined as follows:

$$T^* = \frac{kT}{\varepsilon_f}, \quad F^* = \frac{e\hbar}{\sqrt{m\varepsilon_f^3}} F. \tag{9}$$

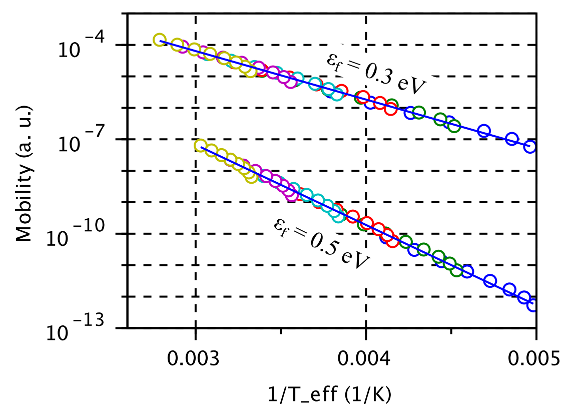

FIG. 6. Arrhenius plot for the dependence of the mobility calculated via Eqs. (5) and (7) vs the effective temperature given by Eq. (1). The color scheme is the same as in Fig. 4(a) and Fig. 5(a).

For instance, if $m = 0.3m_0$ and $\varepsilon_f = 0.3$ eV, then $T^* \approx T/(3.5 \times 10^3\ \mathrm{K})$ and $F^* \approx F/(3.3\mathrm{MV/cm})$. In these notations, the range of applicability becomes independent of the material parameters.

We have checked that for moderate temperatures and fields, $0.055 < T^* < 0.1$ and $0.03 < F^* < 0.15$, the calculated mobility as a function of the effective temperature is well described by the Arrhenius law. Deviations of the mobility from the Arrhenius plot do not exceed 20%, whereas the mobility itself varies over four orders of magnitude. The parameter a extracted from the fitting is equal to 1.08 times the localization length (taking $\gamma = 0.6$). At larger electric fields, $0.15 < F^* < 1$, and temperatures in the range $0.035 < T^* < 0.1$, the Arrhenius approximation also works with an accuracy of 25% for the mobility varied over four orders of magnitude, though with a somewhat larger parameter a: 1.20 times the localization length. The even larger fields, when the carriers leave the traps without thermal activation, are beyond our consideration. There are deviations from the Arrhenius plots at small electric fields ($F^* < 0.03$), seen in Fig. 6 on the right edges of each colored data set. The reason for these deviations can be understood by considering the low-F approximation of Eq. (5),

$$\nu_{\mathrm{esc}} \approx \nu_0 \exp\left(-\frac{\varepsilon}{kT}\right)\left[1 + \frac{0.59(e\hbar)^{2/3}}{m^{1/3}}\frac{F^{2/3}}{kT}\right]. \quad (10)$$

This expression (valid at low fields) cannot be mimicked by a function of the effective temperature, which is defined in Eq. (1).

Although the appearance of a length scale a in the MT transport regime at finite F is the most intriguing feature of the fittings by $T_{\mathrm{eff}}(T,F)$ shown in Fig. 2 and in Fig. 6, we are not able to present any deeper explanation of this quantity, but pointing at the only combination of material parameters in Eq. (8) that can provide a characteristic length in the model of the MT transport. The argument that a corresponds to the localization length is thus based on the comparison of the fitted values with those calculated by Eq. (8) assuming that $\gamma = 0.6$ holds. We use here T_{eff} in the form of Eq. (1) suggested by Marianer and Shklovskii [11] simply because our numerical calculations, as well as the fittings in Fig. 2, do not evidence a deviation from this previously suggested expression. Furthermore, the estimates for a are based on $\gamma = 0.6$ chosen without much justification. Therefore, one cannot recommend to use Eq. (8) for estimating the values of the effective mass m via Eq. (8). If one would insert into Eq. (8) the fitted data for a and ε_a from Table I, one would come to the estimates of the effective mass $m \approx 0.26m_0$ and $m \approx 0.23m_0$ for electrons in poly-PlO and a-Se, respectively, and $m \approx 0.26m_0$ for holes in a-Se. These values do not contradict those reported previously for amorphous inorganic semiconductors [28,29]. It is nevertheless worth noting that the localization length usually appears in the theory of *hopping* transport. In our analysis of the *multiple-trapping* transport, hopping does not play any role, but, remarkably, the localization length seems to be involved.

IV. DISCUSSION

The question might arise on why to consider the description of the field-dependent carrier mobility based on Eq. (2), proven in this manuscript, as superior in comparison to the description based on Eqs. (5) and (7). We note that, for the case of low electric fields, the theoretical description of the multiple trapping (MT) transport regime has been previously developed in all details. Our results show that this theoretical description can be literally used also to account for the field-dependent mobility at high electric fields with just replacing the laboratory temperature T by the field-dependent $T_{\mathrm{eff}}(T,F)$ in all theoretical expressions derived for the case of low fields. This recipe to describe the nonlinear effects at high electric fields by just renormalizing the temperature T is not at all trivial. There is no general reason that the effect of a large electric field on the carrier mobility can be reduced to the renormalization of the temperature $T \to T_{\mathrm{eff}}(T,F)$. In this work, we present a proof for the capability of a single parameter $T_{\mathrm{eff}}(T,F)$ to account for the combined effects of temperature and of the electric field on the carrier mobility in the MT transport regime. This conclusion is supported by the analysis of the experimental data for the dependences of the carrier mobility μ on temperature T and on the applied electric field F obtained previously in a-Se [16] and in poly-PbO [5]. We show that these data can be described by a single parameter, the field-dependent effective temperature $T_{\mathrm{eff}}(T,F)$.

Furthermore, the strength of the electric field F can enter the expression for the effective temperature $T_{\mathrm{eff}}(T,F)$ only in the form of the product eLF, where L is some characteristic length. In the case of band transport, there is an apparent characteristic length, the mean free path of charge carriers. Therefore, it is not surprising that it is the mean free path that relates the effective temperature to the electric field for the case of the band transport [6,7]. In the case of hopping transport, there also is an apparent fundamental length scale, the localization length a responsible for the tunneling of charge carrier between the localized states. Recently, it has been proven [31] that a is the length that relates the effective temperature $T_{\mathrm{eff}}(T,F)$ to the strength of the electric field F in the case of hopping transport. In the MT regime, on the contrary, there is no apparent fundamental length scale that anyhow affects the charge transport at low electric fields. At low fields, charge carriers are released from the traps into conducting states by thermal activation with the rate dependent solely on the depth of the energy traps ε and on temperature T, as described by Eq. (4). Our results show that a characteristic length appears to affect charge transport in the MT regime at high electric fields and that this characteristic length is close to the localization length of charge carriers a.

A question should be addressed on the possibility to describe by the parameter T_{eff} the charge transport in the more modern inorganic disordered materials, for instance, in amorphous oxide semiconductors (AOS), such as InGaZnO materials used in thin-film transistors [32,33]. The transport mechanism in such materials is still under debate [34–44]. Band transport with scattering of carriers on potential fluctuations was first suggested as the appropriate transport mechanism in such materials [34,35,37,38]. The model of the band transport is supported by the observations of a

well-developed Hall effect, which points at the essential occupation of bandlike states [32,38]. A trap-limited band transport in the spirit of the MT model has also been considered as a possible transport mechanism in AOS materials [39–41]. Furthermore, estimates of the DOS in the band tails of InGaZnO systems point at the exponential DOS in the form of Eq. (3) in the vicinity of the mobility edges [39,40,42,43]. The results of the current manuscript should be applicable to describe the mobility dependences on T and F in the case of the MT regime, particularly in systems with the exponential DOS. However, Germs *et al.* recently argued [43] that not the MT transport, but rather the interplay between the hopping transport and the band transport should be considered as the appropriate transport mechanism in InGaZnO materials. The concept of $T_{\mathrm{eff}}(T,F)$ can hardly be expected to be valid for such a combination between the two transport mechanisms, since the characteristic length that describes the field effect on the mobility in the band transport is the mean free path [6,7], while the corresponding length for hopping transport is the localization length. Apparently, more study of the transport mechanism in AOS is necessary in order to make conclusions on the applicability of the concept based on $T_{\mathrm{eff}}(T,F)$ to such materials.

ACKNOWLEDGMENTS

Financial support of the Deutsche Forschungsgemeinschaft (GRK 1782), of the State Programme (Grant No. 0306-2016-0015), and that of the National Science and Engineering Research Council (NSERC), Canadian Institute for Health Research (CIHR), and Ontario Research Fund-Research Excellence (ORF-RE) programs are gratefully acknowledged.

[1] *Charge Transport in Disordered Solids with Applications in Electronics*, edited by S. Baranovski (John Wiley & Sons, Ltd, Chichester, 2006).
[2] N. F. Mott and E. A. Davis, *Electronic Processes in Non-Crystalline Materials*, 2nd ed. (Clarendon Press, Oxford, 1979).
[3] H. Overhof and P. Thomas, *Electronic Transport in Hydrogenated Amorphous Semiconductors* (Springer, Heidelberg, 1989).
[4] R. A. Street, *Hydrogenated Amorphous Silicon*, Cambridge Solid State Science Series (Cambridge University Press, Cambridge, UK, 1991).
[5] O. Semeniuk, G. Juska, J. O. Oelerich, K. Jandieri, S. D. Baranovskii, and A. Reznik, J. Phys. D **50**, 035103 (2017).
[6] P. A. Wolff, Phys. Rev. **95**, 1415 (1954).
[7] L. V. Keldysh, Sov. Phys. JETP **21**, 1135 (1965).
[8] B. I. Shklovskii, Sov. Phys. Semicond. **6**, 1964 (1973).
[9] M. Grünewald and B. Movaghar, J. Phys.: Condens. Matter **1**, 2521 (1989).
[10] B. I. Shklovskii, E. I. Levin, H. Fritzsche, and S. D. Baranovskii, *Advances in Disordered Semiconductors,* Vol. 3, Chap. Hopping photoconductivity in amorphous semiconductors: dependence on temperature, electric field and frequency, (World Scientific, Singapore, 1990), pp. 161–191.
[11] S. Marianer and B. I. Shklovskii, Phys. Rev. B **46**, 13100 (1992).
[12] S. D. Baranovskii, B. Cleve, R. Hess, and P. Thomas, J. Non-Cryst. Solids **164-166**, 437 (1993).
[13] B. Cleve, B. Hartenstein, S. D. Baranovskii, M. Scheidler, P. Thomas, and H. Baessler, Phys. Rev. B **51**, 16705 (1995).
[14] F. Jansson, S. D. Baranovskii, F. Gebhard, and R. Österbacka, Phys. Rev. B **77**, 195211 (2008).
[15] W. C. Chen, L.-A. Hamel, and A. Yelon, J. Non-Cryst. Solids **258**, 223 (1999).
[16] G. Juška and K. Arlauskas, Phys. Status Solidi B **59**, 389 (1980).
[17] G. Juška, J. Kočka, K. Arlauskas, and G. Jukonis, Solid State Commun. **75**, 531 (1990).
[18] G. Juška, K. Arlauskas, J. Kočka, M. Hoheisel, and P. Chabloz, Phys. Rev. Lett. **75**, 2984 (1995).
[19] G. Juška and Arlauskas, Solid State Phenom. **44-46**, 551 (1995).
[20] H. Antoniadis and E. A. Schiff, Phys. Rev. B **43**, 13957 (1991).
[21] S. D. Baranovskii, Phys. Status Solidi B **251**, 487 (2014).
[22] A. V. Nenashev, J. O. Oelerich, and S. D. Baranovskii, J. Phys.: Condens. Matter **27**, 093201 (2015).
[23] J. Frenkel, Phys. Rev. **54**, 647 (1938).
[24] L. Keldysh, Sov. Phys. JETP **7**, 665 (1958).
[25] G. Vincent, A. Chantre, and D. Bois, J. Appl. Phys. **50**, 5484 (1979).
[26] V. Karpus and V. I. Perel, Sov. Phys. JETP **64**, 1376 (1986).
[27] N. Hijazi and M. Z. Kabir, Can. J. Phys. **93**, 1407 (2015).
[28] K. Tsendin, J. Optoelectron. Adv. Mater. **3**, 215 (2001).
[29] J. Singh, J. Non-Cryst. Solids **299-302**, 444 (2002).
[30] B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors* (Springer, Berlin, 1984).
[31] A. V. Nenashev, J. O. Oelerich, A. V. Dvurechenskii, F. Gebhard, and S. D. Baranovskii, Phys. Rev. B **96**, 035204 (2017).
[32] T. Kamiya, K. Nomura, and H. Hosono, Sci. Technol. Adv. Mater. **11**, 044305 (2010).
[33] J.-Y. Kwon, D.-J. Lee, and K.-B. Kim, Electron. Mater. Lett. **7**, 1 (2011).
[34] K. Nomura, H. Ohta, A. Tkagi, T. Kamiya, M. Hirano, and H. Hosono, Nature (London) **432**, 488 (2004).
[35] A. Takagi, K. Nomura, H. Ohta, H. Yanagi, T. Kamiya, M. Hirano, and H. Hosono, Thin Solid Films **486**, 38 (2005).
[36] K. Jeon, C. Kim, I. Song, J. Park, S. Kim, S. Kim, Y. Park, J.-H. Park, S. Lee, D. M. Kim, and D. H. Kim, Appl. Phys. Lett. **93**, 182102 (2008).
[37] T. Kamiya, K. Nomura, and H. Hosono, Appl. Phys. Lett. **96**, 122103 (2010).
[38] M. Kimura, T. Kamiya, T. Nakanishi, K. Nomura, and H. Hosono, Appl. Phys. Lett. **96**, 262105 (2010).
[39] J.-H. Park, K. Jeon, S. Lee, S. Kim, S. Kim, I. Song, J. Park, Y. Park, C. J. Kim, D. M. Kim, and D. H. Kim, J. Electrochem. Soc. **157**, H272 (2010).

[40] S. Lee, S. Park, S. Kim, Y. Jeon, K. Jeon, J.-H. Park, J. Park, I. Song, C. J. Kim, Y. Park, D. Kim, and D. Kim, IEEE Electron Device Lett. **31**, 231 (2010).
[41] S. Lee, K. Ghaffarzadeh, A. Nathan, J. Robertson, S. Jeon, C. Kim, I.-H. Song, and U.-I. Chung, Appl. Phys. Lett. **98**, 203508 (2011).
[42] S. Lee and A. Nathan, Appl. Phys. Lett. **101**, 113502 (2012).
[43] W. C. Germs, W. H. Adriaans, A. K. Tripathi, W. S. C. Roelofs, B. Cobb, R. A. J. Janssen, G. H. Gelinck, and M. Kemerink, Phys. Rev. B **86**, 155319 (2012).
[44] I. I. Fishchuk, A. Kadashchuk, A. Bhoolokam, A. de Jamblinne de Meux, G. Pourtois, M. M. Gavrilyuk, A. Köhler, H. Bässler, P. Heremans, and J. Genoe, Phys. Rev. B **93**, 195204 (2016).