TABLE I. Comparative list of reported results.

E (eV)	r_0 (s^{-1})	Method	Material	Ref.
0.34	8×10^{11}	Isothermal annealing	Conducting	6
0.30	2×10^{11}	Isothermal annealing	Conducting	5
0.20	1×10^{11}	Isochronal annealing	Conducting	5
0.26	2.5×10^{8}	TSPC	Semi-insulating	This work

ducting samples (see Table I). Although determination of r_0 by extrapolation from an Arrhenius type of plot is not accurate, errors resulting from such data analysis cannot explain the difference of three orders of magnitude. However, more detailed work would be necessary before attaching any physical significance to this difference between conductive and semi-insulating samples.

There is another source of error, as recognized by Vincent, Bois, and Chantre,[5] in methods involving diodes as used in earlier determinations. It is known that the regeneration of the EL2 metastable state can be induced by thermally activated Auger transitions in conductive samples. Hence, the interaction of the free carriers in the transition region of the depletion width in all probability interferes with the measurements of thermal deexcitation alone. In our experiments, since the material is semi-insulating, the estimated concentration of electrons under illumination is low enough to make regeneration due to Auger transitions negligible. Hence, we claim that the present method is simpler and its results are more reliable.

In conclusion, we have used a phenomenon called thermally stimulated photocurrent associated with EL2 to determine the thermal conversion rate from EL2* to EL2.

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Revised role for the Poole–Frenkel effect in deep-level characterization

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The Poole–Frenkel effect is commonly used to decide between donorlike and acceptorlike electronic character for deep-level defects in semiconductors. However, there exists at least one defect, the EL2 center in GaAs, which is experimentally established to be a deep donor and yet does not exhibit the classical Poole–Frenkel effect for thermal emission of electrons. In this communication it is proposed that the existence of another well-documented deep-level phenomenon can suppress the Poole–Frenkel effect. Namely, a thermally activated capture cross section, which identifies an energy barrier to carrier capture and is commonly ascribed to a multiphonon emission process, introduces additional mechanisms which can alter the predominance of the Coulombic potential of the emitted carrier so as to suppress the electric-field-induced barrier lowering. A simple one-dimensional model is analyzed to qualitatively illustrate the combined phenomena.

In both semiconductors and dielectrics, the Poole–Frenkel effect describes thermal emission of a charge carrier from a localized electronic state in which an applied electric field enhances the emission rate by lowering a Coulombic potential energy barrier.[1,2] For this phenomenon to occur, the defect must acquire a net charge upon emission of the carrier. Thus, a donorlike (acceptorlike) center which is initially neutral and becomes positively (negatively) charged upon emission of an electron (hole) is expected to display the Poole–Frenkel effect. Similarly, a double-donor (acceptor) center is expected to display the Poole–Frenkel effect during a charge-emission transition from $+q$ to $+2q$ ($-q$ to $-2q$), where q is the electronic charge. On the other hand, carrier emission which leaves the defect in a charge neutral state is negligibly affected by an applied field because of the absence of the Coulombic potential. Thus, the Poole–Frenkel effect is commonly used by experimentalists to decide between donorlike and acceptorlike electronic character for deep-level defects. Examples of deep-level defects which display the Poole–Frenkel effect for electron emission are the oxygen-related thermal-donor complex in silicon,[3,4] a quenched-in defect in cw laser irradiated silicon,[5] chalcogen (i.e., S, Se, and Te) double donors in silicon,[6] and unidentified levels in GaAs.[7,8] However, there exists at least one defect, the EL2 center in GaAs, which is experimentally established to be a deep donor and yet does not exhibit the classical Poole–Frenkel effect for thermal emission of electrons. In this communication it is proposed that the existence of another well-documented deep-level phenomenon can suppress the Poole–Frenkel effect. Namely, a thermally activated capture cross section introduces additional mechanisms which can alter the predominance of the Coulombic potential of the emitted carrier so as to suppress the electric-field-induced barrier lowering.

Analysis of the Poole–Frenkel effect, summarized here for a donor center, begins with the potential energy of an emitted electron in the combined fields of the ionized donor and an applied field. In the one-dimensional model, the Poole–Frenkel potential is[1]

$$U_{\mathrm{PF}}(x) = -\eta q^2/(\epsilon x) - qFx\,, \tag{1}$$

where ϵ is the semiconductor permittivity, F is the electric field intensity, x is the distance from the defect, and η equals 1 or 2 depending upon whether the defect is singly or doubly charged, respectively, after electron emission. This potential has a peak at

$$x_{\mathrm{PF}} = \sqrt{[\eta q/(\epsilon F)]}\,, \tag{2}$$

and the potential at the peak determines the barrier lowering as follows:

$$\Delta U_{\mathrm{PF}} \equiv |U_{\mathrm{PF}}(x_{\mathrm{PF}})| = 2q\sqrt{(\eta q F/\epsilon)}\,. \tag{3}$$

Then the thermal emission rate e_n is enhanced by the applied field as follows:

$$e_n(F) = e_{n0}\exp[\Delta U_{\mathrm{PF}}/(kT)]\,, \tag{4}$$

where e_{n0} is the zero-field emission rate, k is Boltzmann's constant, and T is the absolute temperature.

In view of the utility of the Poole–Frenkel effect for defect-type characterization, an apparent inconsistency is contained in the known properties of the EL2 center in GaAs. Experimental studies indicate that the EL2 center incorporates the arsenic-antisite defect, either solely[9] or as part of a larger complex.[10] Current theoretical models also favor the arsenic-antisite defect as a major constituent of the EL2 complex[11,12] and predict that this defect should have (double) donorlike electronic character.[12] These developments are satisfyingly consistent with experiment results[13] which clearly establish that the EL2 center is indeed a deep donor; this is the essential property of EL2 required to compensate acceptor impurities to produce semi-insulating GaAs. On the other hand, reliable experimental studies of thermal emission of electrons from EL2, by deep-level transient spectroscopy (DLTS), reveal that the emission rate is only weakly dependent on the applied electric field up to extremely high-field intensities (i.e., $F \geqslant 3\times10^5$ V cm^{-1}).[7,14–16] (An early report[17] to the contrary was later shown[15] to be the consequence of excessive reverse-bias leakage currents and impact ionization rather than field-induced barrier lowering.) The dramatic difference between the predicted and measured response of EL2 to an applied field in illustrated in Fig. 1. The emission data in the high-field region (i.e., $F > 1\times10^5$ V cm^{-1}) are from Ref. 15 and were measured by DLTS at 303 K. The experimental results for moderate fields (i.e., $F < 1\times10^5$ V cm^{-1}) were obtained in the present study from DLTS spectra recorded with three emission rate windows for each field intensity and analyzed to obtain the activation energy and prefactor for thermally activated emission; the material and devices used in the present study are described elsewhere.[8] In both studies the measurements were performed with the double-correlation DLTS technique[18] to obtain emission rates corresponding to well-defined electric field intensities. Also displayed in Fig. 1 are the emission rates predicted by the Poole–Frenkel effect, from Eqs. (3) and (4). The comparison in Fig. 1 clearly demonstrates that the electron emission rate for EL2 does not display the classical Poole–Frenkel effect.

It is proposed here that the absence of the Poole–Frenkel effect for the EL2 center is related to the fact that the cross section for electron capture is thermally activated. Specifically, the cross section is[19]

$$\sigma_n = \sigma_{n\infty}\exp[-E_{\sigma_n}/(kT)] + \sigma_{n0}\,, \tag{5}$$

where $\sigma_{n\infty} = 6\times10^{-15}$ cm^2, $E_{\sigma_n} = 0.066$ eV, and $\sigma_{n0} = 5\times10^{-19}$ cm^2; the term σ_{n0} is negligible above 100 K. The energy E_{σ_n} accounts for the difference between the thermal equilibrium activation energy of 0.76 eV obtained from

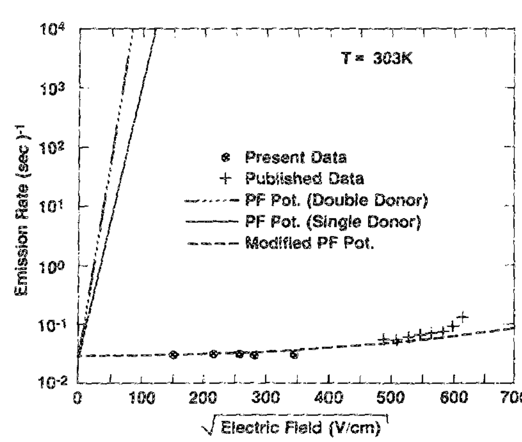

FIG. 1. A comparison of experimental results and model calculations for the electric field dependence of the electron emission rate for the EL2 center in GaAs. The previously-published experimental data are from Ref. 28. Predictions from one-dimensional models are presented for both the Poole–Frenkel (PF) potential (for both doubly charged and singly charged donors) and for a model which combines the PF potential with a short-range (repulsive) potential (see Fig. 2).

Hall-effect measurements when EL2 is the dominant donor[20] and the emission activation energy of 0.83 eV from DLTS. It is generally accepted that the activated cross section implies an energy barrier to the thermal capture of free electrons. While this barrier could be purely electronic in origin, it is generally accepted that it involves electron-phonon coupling such that electron capture proceeds by multiphonon emission.[21,22] In a now-classic paper, Henry and Lang[21] calculated the free-to-bound transitions between the continuum and bound states, respectively, of an attractive spherical square-well potential whose radius was modulated by the lattice. Similarly, Goto, Adachi, and Ikoma[23] used a superposition of an attractive square well, with a fixed radius equal to the nearest-neighbor distance, and a second (repulsive) square well which extended over several lattice constants with the height modulated by lattice motion. Both defect models feature a short-range electronic potential which depends on the lattice configuration. For the EL2 center it is proposed here that the existence of a short-range potential, which is inferred from the thermally-activated capture rate, alters the purely Coulombic potential of an emitted electron and thereby suppresses the field-induced barrier lowering.

The effect of a short-range repulsive potential superimposed on the Poole–Frenkel potential can be conceptually illustrated with a simple one-dimensional model. For this purpose virtually any short-range repulsive potential can be adopted. Here, we use an inverted Morse potential with the following analytical form[24]:

$$U_M = -U_0\{\exp[-2(x-x_0)/\lambda] - 2\exp[-(x-x_0)/\lambda]\}, \qquad (6)$$

where U_0 is the magnitude and x_0 the position of the peak in the absence of other potentials, and λ scales the width of the barrier and is chosen such that $x_0 = 2\lambda$. This is combined with $U_{\rm PF}$ to obtain the composite potential, $U_{\rm PF} + U_M$, shown in Fig. 2. The parameters are chosen to reflect features of the EL2 center, that is, a doubly charged donor with a zero-field barrier height of 66 meV which peaks within several lattice constants (0.56 nm) from the defect. We ignore other aspects of this simplified model such as tunneling through the narrow barrier. A high electric field (i.e., 1×10^5 V cm^{-1}) causes a substantial lowering of the long-range Coulombic potential, $\Delta U_{\rm PF}$, as predicted by Eqs. (2) and (3). However, the short-range barrier is only slightly affected by the field. Consequently, the emission rate is only weakly dependent on the applied field as illustrated in Fig. 1 for comparison with the Poole–Frenkel model and experimental results for EL2. This view is consistent with the general recognition[2,25] that the sensitivity of the emission rate to an applied electric field can be used to evaluate the range of a defect potential. This communication offers the new perspective that a thermal emission event involving a long-range Coulombic attraction between the emitted carrier and the ionized center need not display the classical Poole–Frenkel effect as a consequence of other short-range potential properties, such as those that are manifested by a thermally activated capture cross section.

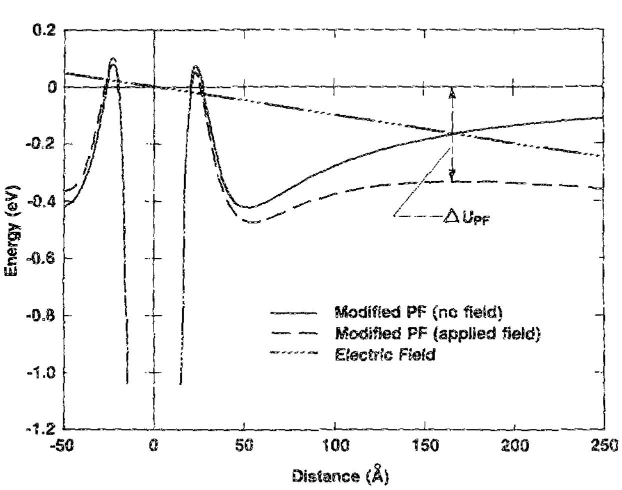

FIG. 2. A one-dimensional model for the potential energy of an electron near an ionized donor defect with an applied electric field. The model consists of the superposition of the Poole–Frenkel potential and a short-range (repulsive) potential. The center is envisaged as a doubly charged donor, and the short-range potential is represented by an inverted Morse potential with parameters applicable to the EL2 center.

Equation (6) can also be used to obtain a closed-form analytical solution for field-induced barrier lowering. The superposition of U_M and the field-induced potential, $-qFx$, can be considered an approximation for the potential energy of an emitted electron e^- during field-assisted thermal ionization of a doubly charged deep acceptor, A^{--}, such that $A^{--}\rightarrow A^- + e^-$. Beyond the short-range attractive potential, which defines the bound state of the defect, the Morse potential approximates the repulsive Coulombic interaction between the emitted electron and the negatively charged center. With the variable transformation

$$z \equiv \exp[-(x-x_0)/\lambda], \qquad (7)$$

the composite potential $U(x)$ has a peak at x_p which varies with field as follows:

$$z_p = \{1+\sqrt{[1+(2q\lambda F/U_0)]}\}/2. \qquad (8)$$

Then, the field-induced change in the barrier height is

$$\Delta U(F) \equiv U_0 - U(x_p) = U_0(z_p-1)^2 + qF[x_0 - \lambda\ln(z_p)], \qquad (9)$$

and the emission rate is $e_n = e_{n0}\exp[\Delta U/(kT)]$. For the purpose of illustration, parameters compatible with the EL2 center (e.g., $U_0 = 66$ meV, $\lambda = 1$ nm, and $x_0 = 2\lambda$) yield $\Delta U = 2.4$ meV for $F = 3\times10^5$ V cm^{-1} which corresponds to $e_n/e_{n0} = 1.1$ at 303 K. Thus, here again the emission rate is only weakly enhanced by an electric field because of the predominance of a short-range contribution to the potential.

From the above considerations, it is evident that the role of the Poole–Frenkel effect for determining electronic type in deep-level characterization requires reevaluation. Certainly, observation of the classical Poole–Frenkel effect continues to provide strong evidence for an attractive Coulombic interaction between the emitted carrier and the ionized center, from which the electronic type can be identified. However, the absence of the Poole–Frenkel effect does not by itself provide information for deciding electronic type; the EL2 center in GaAs should be recognized as the classic example of this fact. The arguments presented in this communication further suggest that a reliable inference of electronic type may be drawn if a defect displays neither the Poole–Frenkel effect nor a thermally activated capture cross section. However, this should be considered a hypothesis that requires further scrutiny from theorists as well as experimentalists.

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