Role of deep-level trapping on the surface photovoltage of semi-insulating GaAs

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Dual-beam (bias and probe) transient surface photovoltage (SPV) measurements were made on undoped semi-insulating GaAs over an extended temperature range. Above 270 K, SPV recovery transients following a bias pulse were shown to reflect near-surface conductivity changes; these are in turn controlled by surface-interface-state thermal emission. Owing to the absence of a strong surface electric field in this material, the emitted carriers are not immediately removed from the near-surface region. The recapturing of the emitted carriers is shown to be responsible for nonexponential conductivity and reciprocal-SPV transients. This behavior is considered to be characteristic of relaxation-type semiconductors with near-surface ungated structures. Below 150 K, the photoinduced transition of EL2 from its ground to metastable state EL2* was shown to change the effective electron and hole mobilities and augment the SPV signals immediately following the bias pulse. Thermally induced EL2* recovery above 120 K decreases the SPV signal from its maximum. This decay transient was analyzed and the decay rate fitted to a single exponential. An activation energy of 0.32 eV and a preexponential constant of 1.9×10^{12} s^{-1} were obtained, and attributed to the thermal recovery rate for EL2*. [S0163-1829(97)00416-5]

I. INTRODUCTION

Surface photovoltage (SPV) is a well-established nondestructive technique suitable for determining bulk minority-carrier diffusion lengths[1,2] and for surface-state characterization.[3,4] The SPV signal is generally considered to arise from separation of photogenerated carriers by a near-surface electric field. However, for undoped semi-insulating (SI) GaAs, the SPV mechanism is quite different to that for low-resistivity (doped) semiconductors.[5] Steady-state SPV measurements on SI GaAs were recently discussed at both room and low temperatures.[5,6] It was found that SPV of SI GaAs reflects the characteristic photoresponse of a trap-dominated relaxation-type semiconductor. To a first approximation the Dember potential plays a dominant role in the large apparent SPV at room temperature.[5] However, at low temperatures deep-level impurity trapping plays an important role in the photocarrier transport and influencing the steady-state SPV signal. In this paper, we further discuss these phenomena by providing an analysis of photoinduced carrier transport in trap-dominated relaxation-type semiconductors. This approach is then extended to address transient SPV phenomena. As a result, transient SPV measurements of SI GaAs samples are discussed in the light of the former model and the usefulness of this approach as a nondestructive deep-level characterization technique is thus revealed.

Based on initial work by van Roosbroeck and Casey, semiconductor materials which are perturbed from equilibrium ($np=n_i^2$) can be divided into two categories: lifetime and relaxation semiconductors.[7] This classification is usually based on the relative values of two characteristic times, the carrier lifetime τ_0, and the dielectric relaxation time τ_d. In a lifetime semiconductor, $\tau_0 \gg \tau_d$, the bulk space-charge neutrality is generally maintained. Before injected minority carriers recombine or are trapped, local fields created by the excess carriers will be instantaneously compensated for by the majority-carrier redistribution through dielectric relaxation. The extrinsic Debye length describes the spatial distribution of nonuniform charge density, which is very short in the case of lifetime semiconductors. In these materials, deep-level trapping often plays a less important role in the carrier transport. This is the common case, describing, for example, doped GaAs ($\tau_d \sim 10^{-15}$ s for GaAs:Si with $[Si]=10^{18}$ cm^{-3}) or room-temperature high-purity Si($\tau_d \sim 10^{-9}$ s for Si:B with $[B]=10^{13}$ cm^{-3}). Thus in a standard analysis of semiconductor devices the deep-level trapping effect is commonly neglected, and $\Delta n \approx \Delta p$ is often assumed, where Δn and Δp are nonequilibrium free-carrier concentrations for electrons and holes, respectively.

However, for trap-dominated high-resistivity semiconductors, the assumption of charge neutrality among free carriers is not always applicable. Due to the high density of trapping and recombination centers, the carrier lifetime is often very short compared to the dielectric relaxation time, which is determined by the sample resistivity ($\tau_d=\rho\varepsilon_r\varepsilon_0$). The implication of a charge neutrality breach is that an internal electrical field can develop throughout the sample. Ambipolar diffusion- and/or space-charge-limited current flow may dominate the excess carrier transport. A typical example is the majority-carrier response to nonequilibrium minority-carrier injection. Rather than a carrier concentration enhancement that is often observed in low-resistivity materials, majority carriers tend to become locally depleted. This result was clearly expressed in Ref. 8.

Intrinsic (above-band-gap) optical excitation for a relaxation semiconductor was first discussed by Schetzina.[9,10] Although both electrons and holes are introduced simultaneously by above-band-gap photoexcitation, a space charge can still be created owing to unbalanced deep-level trapping and mobility deviation.[11] Midgap impurities are expected to play an important role in the SI GaAs SPV response. The characteristic times in undoped SI GaAs are the relaxation time $\tau_d \approx 10^{-5}$ s (based on $\rho_0=10^7$ Ω cm) and the carrier lifetime $\tau_a \approx 10^{-10}$ s at room temperature.[12] Properties of this

material reflect the dominant role of the native defect level EL2 near mid-band-gap ($N_d \approx 10^{16}$ cm^{-3}).[13] EL2 has a donor level located at 0.76 eV below the conduction-band minimum, and acts as a donor and an electron trap ($\sigma_n \approx 4\times10^{-16}$ cm^2; $\sigma_p \approx 2\times10^{-18}$ cm^2).[14] These defects can closely compensate for shallow acceptors, thereby pinning the Fermi level near the middle of the band gap. In this paper, we extend studies of SPV characteristics of undoped SI GaAs using optically biased low-temperature transient SPV measurements.

II. THEORETICAL CONSIDERATION

Following van Roosbroeck's model, a major effect of traps in semiconductors is to decrease the drift mobility μ^d (Ref. 7), which is determined by the mean time t it takes injected carriers to move a distance d under the influence of an electric field ξ: $\mu^d = d/\xi t$ (Ref. 15). In the absence of carrier trapping, the injected carriers behave as quasifree, and the drift mobility is identical to the conductivity mobility μ^e. However, if traps are present, we may write[15]

$$\mu_n^d = \left(\frac{n}{n+n_t}\right)\mu_n^e, \tag{1}$$

where n is the injected carrier concentration in extended states, and n_t is the concentration of injected carriers that are trapped. The effective electron drift mobility μ_n^d may be treated as constant if the electron quasi-Fermi level is located within the band gap.[16] Thus, under weak intensity intrinsic photoexcitation the electron current density J_n can be expressed in terms of the total injected electron concentration $n_{\rm inj} = n + n_t$ as

$$J_n = q\mu_n^d(n_0 + n_{\rm inj})\xi + kT\mu_n^d \frac{dn_{\rm inj}}{dx}, \tag{2}$$

where n_0 is the dark equilibrium electron concentration and ξ is the electric field originating from the Dember effect.[5] Analogous to electrons, the injected hole current density J_p under similar photoexcitation conditions is

$$J_p = q\mu_p^d(p_0 + p_{\rm inj})\xi - kT\mu_p^d \frac{dp_{\rm inj}}{dx}. \tag{3}$$

$\xi(x)$ can be obtained under open-circuit conditions (i.e., $J_t = J_n + J_p = 0$),

$$\xi(x) \approx \frac{kT\mu_p^d \dfrac{dp_{\rm inj}}{dx} - kT\mu_n^d \dfrac{dn_{\rm inj}}{dx}}{\sigma_0 + q\mu_p^d p_{\rm inj}(x) + q\mu_n^d n_{\rm inj}(x)}, \tag{4}$$

where σ_0 is the dark conductivity. An expression for the open-circuit photovoltage $V_{\rm oc}$ may then be derived by integrating $\xi(x)$ over the sample thickness d_0, assuming that the above-band-gap photoexcitation results in $p_{\rm inf} = n_{\rm inj}$:[5]

$$V_{\rm oc} = \int_0^{d_0} \xi(x)\,dx \approx \frac{kT}{q}\frac{\mu_n^d - \mu_p^d}{\mu_n^d + \mu_p^d} \ln\left(1 + \frac{(\mu_n^d + \mu_p^d)n_{\rm inj}(0)}{\sigma_0}\right). \tag{5}$$

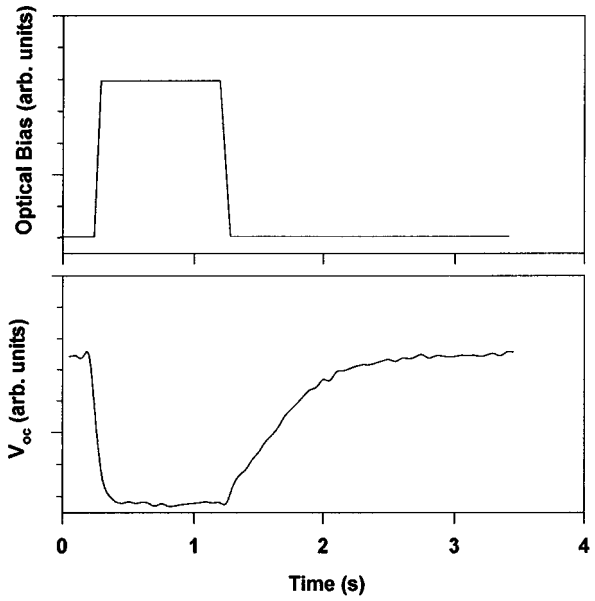

FIG. 1. Typical photovoltage transient waveform (A) for undoped semi-insulating GaAs at $T = 280$ K, due to the optical bias pulse (B).

If $V_{\rm oc}$ is sufficiently small (i.e., by controlling the probe photon flux) such that $V_{\rm oc} < (kT/q)(\mu_n^d - \mu_p^d)/(\mu_n^d + \mu_p^d)$, then Eq. (5) can be further approximated as

$$V_{\rm oc} \approx \frac{kT}{q}(\mu_n^d - \mu_p^d)\frac{n_{\rm inj}(0)}{\sigma_0}. \tag{6}$$

The injected carrier concentration $n_{inj}(0)$ on the front surface can be calculated from[17]

$$2\frac{kT}{q}\left(\frac{\mu_n^d\mu_p^d}{\mu_n^d + \mu_p^d}\right)\frac{d^2 n_{\rm inj}}{dx^2} - \frac{n_{\rm inj}}{\tau_n + \tau_p} + \alpha\Phi\,\exp(-\alpha x) = 0, \tag{7}$$

with solution

$$n_{\rm inj}(x) = C\,\exp(-x/L_d) + \frac{\alpha\Phi(\tau_n + \tau_p)}{1 - \alpha^2 L_d^2}\exp(-\alpha x), \tag{8}$$

where L_d is the ambipolar diffusion length given by

$$L_d = \left[2\frac{kT}{q}\left(\frac{\mu_n^d\mu_p^d}{\mu_n^d + \mu_p^d}\right)(\tau_n + \tau_p)\right]^{1/2}, \tag{9}$$

and C is a constant determined by the front surface recombination velocity.[17]

From Eqs. (6), (8), and (9) we can see how μ_n^d and μ_n^d influence the magnitude of $V_{\rm oc}$. For SI GaAs with above-band-gap photoexcitation, deep-level trapping reduces the effective mobilities μ_n^d and μ_n^d compared with those associated with extended states. The measured SPV for these samples under fixed low-level optical excitation decreases rapidly as the temperature falls, as shown in Ref. 6 (i.e., Fig. 1); this reveals that, on lowering the temperature, the difference between μ_n^d and μ_p^d reduces as deep-level trapping becomes more effective for the faster-moving electrons. It is important to realize that only the SPV of high-resistivity GaAs is sensitive to the difference in the carrier drift mobilities: For

doped semiconductors, the Dember potential plays a minor role in controlling the SPV response. SPV of doped n-GaAs is actually insensitive to the sample temperature, at least for $T>200$ K (Ref. 6).

As discussed previously and illustrated using Eq. (6), under weak excitation conditions V_{oc}^{-1} is proportional to the sample's dark conductivity.[5] This is one of the main reasons why the Dember potential plays such a dominant role in the SPV response of high-resistivity relaxation-type semiconductors under open-circuit conditions.[5] Using an intense second beam as an optical bias (i.e., with above-band-gap photon energy), the steady-state reciprocal SPV increases linearly with the bias flux (see Fig. 2 of Ref. 5), indicating that the near-surface conductivity can be monitored under optical bias in a nondestructive manner using the small-signal SPV method. This approach was further explored in the transient mode for the undoped SI GaAs. Essentially this is a transient photoconductivity measurement having the advantage of not requiring the use of any metal contacts.

III. EXPERIMENTAL SETUP AND RESULTS

Measurements were made using a system discussed previously.[5] The sample is placed in a helium-based cryostat system. The detailed structure of the sample holder has been discussed previously.[5] The sample temperature can be set either manually or by a computer using the Lakeshore 320 temperature controller. Sample temperatures can be maintained within 0.1° of the setpoint for periods as long as 30 min in the range 15–350 K. The optical system consists of a bifurcated optical fiber bundle with two tungsten-halogen lamps. One lamp (100 W) is used as the probe light source. Light from this source passes through a monochromator (Chromex 500IS/SM), a variable neutral density filter, and a mechanical chopper (Stanford Research SR540). The other lamp (250 W) is used as a deep-level pumping source. Light from this source passes through an electromechanical shutter (Vincent UniBlitz LS6T2) driven by a shutter driver (UniBlitz D122). The SPV signal was measured using either a Stanford Research SR830 digital lock-in amplifier or an EG&G analog lock-in amplifier. The choice of measurement frequency was a compromise between the SPV signal amplitude (favoring low-measurement frequencies) and system response time. Typically 2 kHz was chosen as a good compromise. The output time constant of the lock-in amplifier was set at 1 ms in all cases, in order to follow the SPV transient. The SPV signal in the dark (minimum background light) was controlled to remain below 10 μV by limiting the incident probe photon flux. Thus perturbation of the sample dark Fermi energy due to probe light could be minimized.

Having established the steady-state conditions, an optical bias pulse of selected duration and intensity was applied to facilitate analysis of SPV recovery transients following the pulse. The signal was first fed through a variable gain, high impedance preamplifier (Stanford Research SR560), and then into the lock-in amplifier.

Rather than monitor differences in the SPV signal at two times during the recovery transient while the temperature is swept, isothermal conditions were maintained, and the entire transient was recorded. Up to 16 625 data points (equally spaced in time) could be sampled with 12-bit accuracy using the SR830 digital lock-in amplifier, or using a SCC1220 digital oscilloscope to measure the analog output of the EG&G lock-in amplifier. Stored data can then be averaged as many times as required to achieve a given signal-to-noise ratio. Typically, averaging of five consecutive transients proved sufficient at each temperature, although in extreme cases considerably more transients were used before the temperature could be raised to the next setpoint. By recording the entire transient we can acquire all pertinent information in a series of fixed temperature data sets. The stored data can then be further analyzed using, for example, a rate window approach or by various curve fitting procedures. Meaningful fitted transient time constants τ or rate window selections are limited in the fast response regime by the time required to extinguish the pump light ($\sim$5 ms), and in the slow response regime by the recovery of the SPV transient itself. Typical data showing an entire SPV transient obtained for an undoped SI GaAs sample at $T=280$ K is shown in Fig. 1.

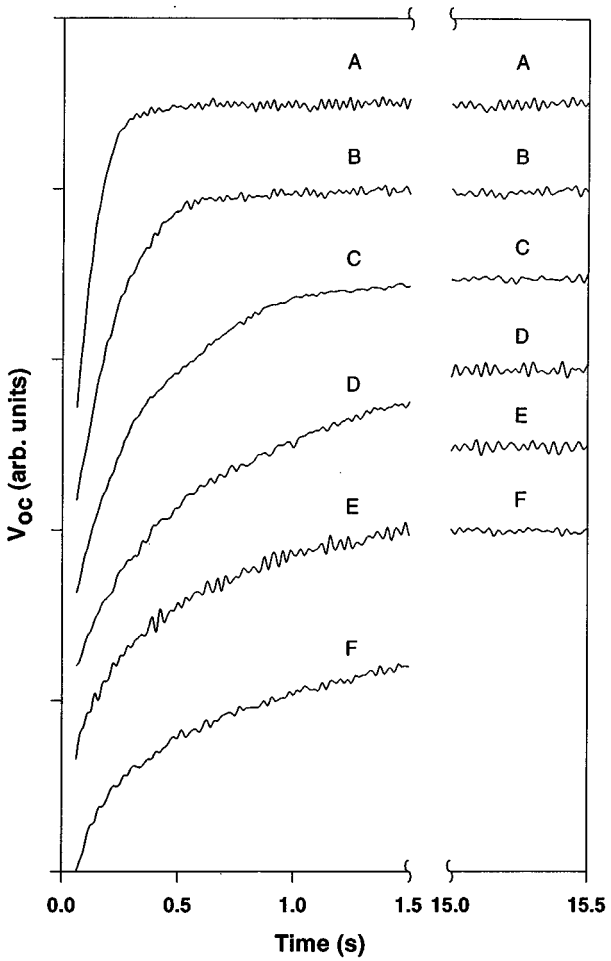

FIG. 2. Surface photovoltage V_{oc} transients for undoped semi-insulating GaAs as a function of time and optical bias at temperatures: 259 K (A), 290 K (B), 285 K (C), 280 K (D), 275 K (E), and 270 K(F).

It has been found that, at all temperatures, the SPV signal is sharply suppressed by the strong optical bias pulse. The SPV recovery transient following the bias pulse strongly depends on temperature. Figure 2 shows a series of transient curves in the temperature range 270–295 K. If the SPV suppression can be considered as the optical-bias-induced local

free-carrier enhancement or conductivity enlargement, then the SPV signal recovery reflects the conductivity transient or the free-carrier relaxation, which is controlled by deep level emission. A detailed discussion will be given in Sec. IV.

Results of two-beam transient SPV measurements of SI GaAs at low temperatures (i.e., $T \leqslant 160$ K) is shown in Fig. 6. In the narrow temperature range of 130–150 K, the SPV response shows a distinct *negative* transient following the optical bias: initially V_{oc} quickly rises above the steady-state value, and then decays within a given time period. This phenomenon has never been reported before, and is a unique characteristic of undoped SI GaAs. The distinct SPV line shape in this temperature range (compared to that discussed above for the same SI GaAs sample) cannot be simply explained by deep-trap emission and a corresponding ''dark'' conductance decrease. A key feature that alerted us to a possible mechanism for the phenomena was the fact that the temperature window for observing the negative transient is well matched to the temperature for thermal recovery of the dominant electron deep trap, EL2, from its metastable to ground state.[4] In Sec. IV we provide detailed discussions.

IV. DISCUSSION

As mentioned earlier, for temperatures close to room temperature, the SPV of SI GaAs is influenced by near-surface ''dark'' conductance. Optical bias increases the free-carrier concentration and thus the near-surface conductance, suppressing the SPV response. Moreover, using an optical bias it is possible to fill electron (hole) traps in the upper (lower) half of the band gap (compared with their equilibrium occupancy). After termination of the bias pulse, detrapping (from the traps) will modify the near-surface free-carrier concentration as well as the measured SPV signal. This is analogous to digital transient photoconductivity measurements reported on such material.[18,19] Common practice is to assume that the near-surface conductance (or free-carrier concentration) is solely controlled by deep-level emission, and thus to fit the entire waveform to a simple exponential function. However, we found that the V_{oc}^{-1} decay was *not* a simple exponential function. Many researchers have experienced similar problems with nonexponential behavior when they tried to fit transient conductivity from SI GaAs.[19,20] The underlying reason for nonexponential characteristics needs to be clarified, otherwise, the results from the best multiple exponential fitting procedures requiring as many as four or five emission rates have little physical meaning.[19] Here we propose one possible answer to the phenomenon of nonexponential transients.[21]

Contrary to doped GaAs, where there is an effective *native* surface electric field created by the Fermi-level pinning on the free surface that can quickly sweep the emitted carriers out of the space-charge region, undoped SI GaAs has no such strong field under normal conditions.[2] Thus thermally emitted carriers from deep levels have a good chance of being recaptured by the same traps during the SPV transient. Using the Shockley-Read model, a quasistationary state between traps and extended states can be assumed due to strong retrapping. That is,

$$C_n n^0(t)[N_t - n_t(t)] \approx e_n n_t(t), \tag{10}$$

where C_n is the trap electron-capture coefficient, N_t, is the trap concentration, e_n is the electron emission rate, and $n^0(t)$ $[n_t(t)]$ is the electron concentration in extended (trap) states. In principle, with active retrapping involved the transient of $n^0(t)$ or the near-surface conductivity becomes nonexponential. (See the Appendix for a detailed discussion.) For this reason a simple single-exponential function cannot be extracted from the whole SPV transient. In practice, however, we found that the slow transient can always be satisfactorily fitted to an exponential function. Similar observations have also be reported by Abele, Kremen and Blakemore on their transient photoconductivity data.[19] In the Appendix we show that if the trap concentration is high and their occupation is low, the ''instantaneous lifetime τ_n^{eff}'' can be treated as a constant and independent of $n^0(t)$. Thus the transient free-carrier concentration in the extended states (or the near-surface conductance) will have the following form:

$$n^0(t) = n^0(0)\exp(-t/\tau_n^{\text{eff}}), \tag{A3}$$

with

$$\tau_n^{\text{eff}} \approx \frac{\tau_n^0 N_t \exp(E_t/kT)}{N_c}, \tag{A12}$$

where τ_n^0 is the electron recombination lifetime, N_c is the effective density of states in the conduction band, E_t is the trap activation energy, and a simplified form of τ_n^{eff} can also be called the *effective* free-carrier transient time constant.

From Eq. (A3) the free-carrier concentration indeed exponentially decreases with time. It represents the slow transient in the real situation. Equation (A12) indicates that investigation of the temperature dependence of τ_n^{eff} still yields the trap depth E_t, but not the capture coefficient C_n or the capture cross section σ_n. Since e_n cannot be directly determined from Eq. (A12), a conventional Arrhenius plot is no longer applicable. Instead, $\ln(T^{3/2}\tau_n^{\text{eff}})$ versus $1000/T$ should be plotted and the slope can be used to determine E_t. This modification is believed to be appropriate to the analysis of transient data generated from other ungated structures and structures with a weak internal electric field. Writing the reciprocal SPV in the form

$$\Delta(1/V_{oc}) = (1/V_{oc}^0)\exp(-t/\tau_n^{\text{eff}}), \tag{11}$$

where

$$\Delta(1/V_{oc}) \equiv \frac{1/V_{oc}(t) - 1/V_{oc}(t=\infty)}{1/V_{oc}(t=\infty)}, \tag{12}$$

τ_n^{eff} is obtained at each temperature by standard curve fitting (i.e., the Marquardt-Levenberg algorithm) using the slow transient part of the data. It was found that by fitting τ_n^{eff} starting at different times in the transient t_0, the results obtained can be slightly different: By creating data from the partial exponentials and attempting to analyze them, we found that the normalized standard error (or coefficient of variation, CV%) of τ_n^{eff} can be used as a good criteria for selecting t^0. The t^0 with minimum CV% of τ_n^{eff} corresponds to the smallest influence of fast nonlinear exponential transients to the slower and linear portion. The fitted τ_n^{eff} then has the closest value to the known parameter. Figure 3 illustrates

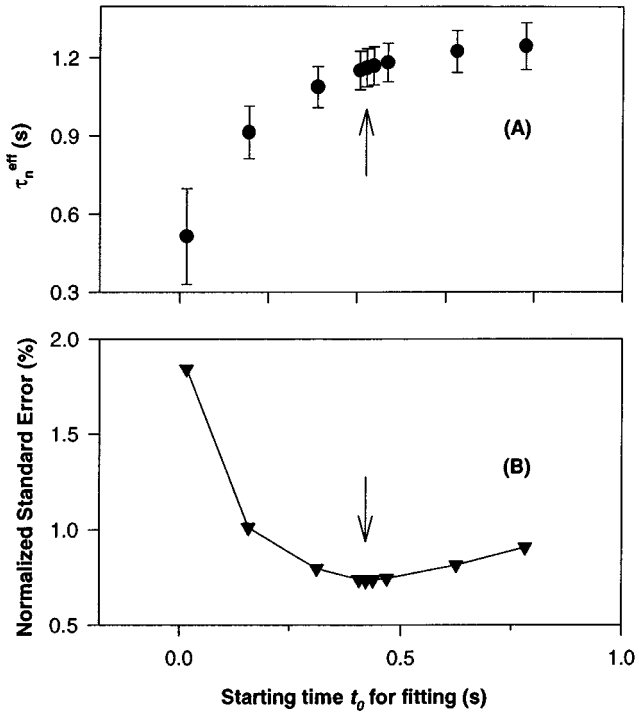

FIG. 3. Curve-fitting results for the effective time constant τ_n^{eff} of reciprocal SPV transients at $T=275$ K using different starting time t_0 (see text) with enlarged error bar (by factor of 50) (A), and the normalized standard error [i.e., coefficient of variable (CV%)] vs t_0 (B). The minimum CV% of 0.732% is found at $t_0=422$ ms (marked with arrows), and the corresponding τ_n^{eff} is 1.163 g.

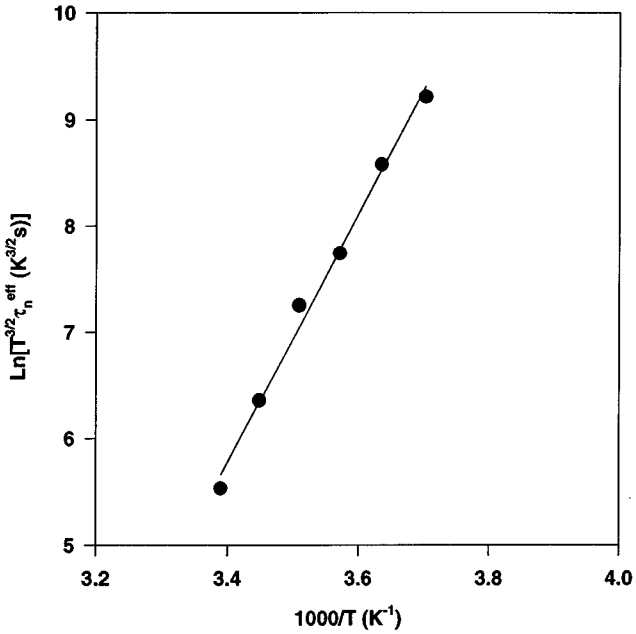

FIG. 4. Modified Arrhenius plot for the transient SPV data fitted from Fig. 2. The energy depth of the dominant traps is found to be $E_t=0.99\pm0.05$ eV.

the different fitting results for $T=275$ K using different t^0 with the corresponding CV% values. The minimum CV% of τ_n^{eff} is 0.732% obtained at $t_0=422$ ms, and the corresponding $\tau_n^{\text{eff}}=11.63$ s.

After τ_n^{eff} is obtained from the refined curve fitting procedure, it is a simple matter to analyze the activation energy E_t shown in Fig. 4. The slope of the plot was determined by using a least-square fit. The result shows $E_t=0.99\pm0.05$ eV. Unlike standard capacitance DLTS, where only bulk deep-level filling and emptying participate in the capacitance transient, surface-trapped charge plays an important role in transient SPV, as discussed previously.[3] The strong retrapping revealed from the transient SPV data indicates that the deep level being probed may be related to surface states. Furthermore, very long SPV recovery transients (up to 8 s) are only observed in SI samples, and not in conducting material; this suggests that the low background level associated with the low dark conductivity enhances the Dember effect in SI GaAs, and makes the SPV transient very sensitive to near surface deep-level emission.

Considering the nature of two-beam SPV of a photon-induced nonequilibrium process at low temperatures, EL2 intracenter transitions ($^1A_1\rightarrow{}^1T_2$) are very likely involved during the white-light biasing (the photon energy window for the EL2 transition is 1.0 eV$<h\upsilon<$1.4 eV (Ref. 22). At these temperatures the large lattice relaxation associated with metastable EL2* makes EL2 insensitive to extrinsic excitation (see Figs. 5 and 6). This is known as low-temperature photoquenching or the photoinduced EL2 metastable state transition: EL2°$\rightarrow$EL2*.[4] As discussed previously, the SPV response of SI-GaAs can be influenced by deep-level trapping through changes in the carrier drift mobilities μ_n^d and μ_p^d. The metastable state EL2* has been shown to be responsible for the nonrecoverable IR-induced SPV enhancement below 130 K.[23,24] Consequently, we attribute the negative transient V_{oc} as the thermal recovery of metastable state EL2*. Thus, right after photoquenching, $\mu_n^d-\mu_p^d$ approaches the difference in the mobilities between the extended states $\mu_n^e-\mu_p^e$. Since as an electron trap EL2 will lower the electron mobility more effectively than the hole mobility, $(\mu_n^d-\mu_p^d)<(\mu_n^e-\mu_p^e)$ will hold under normal conditions. When temperatures exceed 130 K, EL2* is no longer a stable atomic configuration,[25] and thermal recovery will restore EL2* to the ground state. This can explain why the SPV response cannot maintain its high value following the optical bias pulse and the decay of V_{oc} can be observed. The SPV decay rate is controlled by the thermal deexcitation (recovery) rate for the metastable state of EL2. By analyzing the SPV decay characteristics, we should therefore be able to evaluate the EL2* thermal recovery.

It should be pointed out that the probe light intensity is very weak (i.e., photon flux $\leqslant 10^{12}$ cm^{-2} s^{-1}), which is generally too weak to disturb the EL2 configuration and contribute to changes in the effective drift mobilities. Also at these temperatures (i.e., 130–150 K), dark conductance changes should have negligible influence on the SPV transient, as thermal emission from deep-level traps will be very small. Based on these considerations the V_{oc} decay rate following its maximum can be fitted to an exponential function of temperature,

$$r=1.9\times10^{12}\exp(-0.32\ \text{eV}/kT)\ \ (\text{s}^{-1}). \tag{13}$$

The correlation coefficient was larger than 0.998. This is consistent with the EL2* recovery rates measured for con-

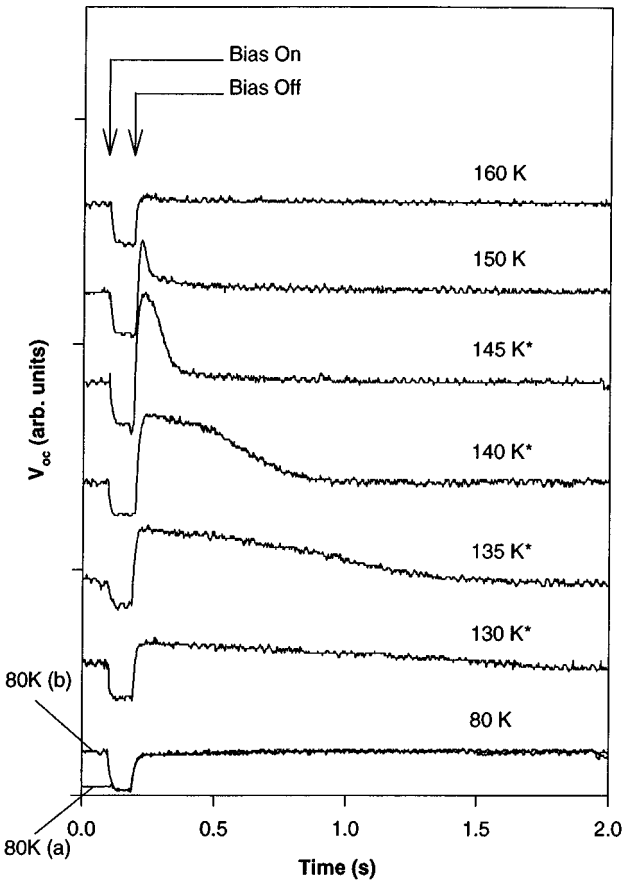

FIG. 5. Surface photovoltage transients and bias induced V_{oc} enhancement at low temperatures. Initial ''dark'' V_{oc} at $T=80$ K (cooled in dark without bias) is shown as 80 K (a). This is not recoverable after the optical bias pulse is applied at this temperature. V_{oc} after the first cycle is shown as 80 K (b). SPV enhancement due to optical bias pulse cannot be maintained at $T>130$ K. This *negative* SPV transient ends at $T=160$ K. Data sets identified by asterisks were used to calculate the thermal recovery rate of V_{oc}.

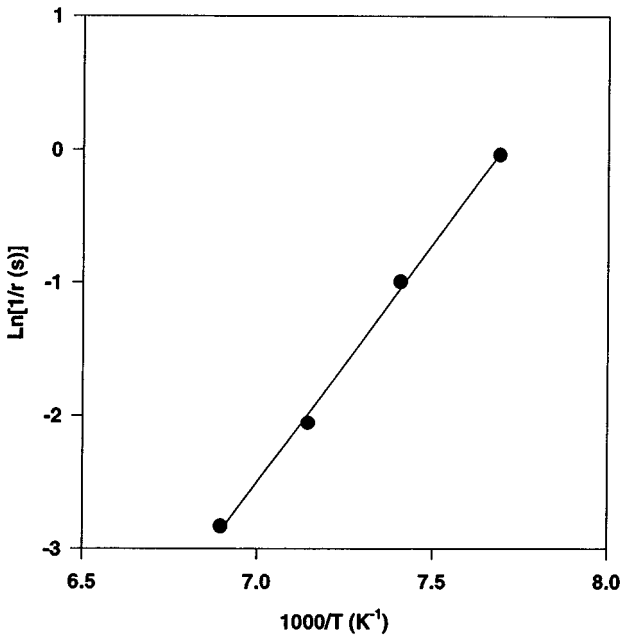

FIG. 6. Arrhenius plot for the data fitted from Fig. 5. The EL2* thermal recovery rate is given by $1.9\times10^{12}\exp(-0.32\ \text{eV}/kT)\ \text{s}^{-1}$.

ducting GaAs [i.e., $r=8\times10^{11}\exp(-0.34\ \text{eV}/kT)\ (\text{s}^{-1})$ using photocapacitance measurements[25]].

It should be mentioned that a previous attempt at evaluating the thermal recovery rate for EL2* in SI GaAs using thermally stimulated photocurrent (TSPC) measurements provided a quite different activation energy and preexponential constant[14] compared with Eq. (13): the activation energy was only 0.26 eV, and the preexponential term r_0 (known as the attempt-to-anneal frequency) was $2.55\times10^8\ \text{s}^{-1}$, nearly four orders of magnitude lower than our results. In the TSPC measurements, the concentration of defects in the EL2* state corresponding to the maximum free-carrier concentration or the photocurrent peak ($T=T_s$) was not clearly defined. Also the limited range of heating rate (less than a factor of 14) and T_s (less than 15°) restricted the accuracy of the results.[22] Our preliminary studies of EL2* recovery using transient SPV clearly show that the nature of EL2 is the same for both conducting and SI GaAs. It also indicates the applicability of this technique to characterizing EL2 and other bulk and surface deep levels where fabricating contacts is difficult.[26]

V. CONCLUSIONS

In this work, we demonstrated that the nondestructive SPV method can be extended to analyze deep-level characteristics of SI GaAs using the two-beam configuration. Above 270 K, effective carrier drift mobilities which are determined by deep-level trapping and recapturing are hardly altered as the trap concentration (i.e., the EL2 center concentration) remains quite high, and saturation is difficult to achieve using optical excitation. The measured Dember potential is thus determined only by near-surface conductivity changes, and transient conductivity can be measured in a nondestructive manner. At low temperatures ($T<160$ K) the metastable states of EL2, induced by the optical bias, can greatly change μ_n^d and μ_p^d, and thus increase the Dember voltage which is sensitive to both electron and hole transport properties. At these low temperatures, deep-level thermal emission plays a less important role. Thus SPV transients are mainly determined by changes in the EL2 atomic configuration (metastable state thermal recovery) if the temperature is in the appropriate range. Using this technique, the EL2* recovery rate r was found to follow Eq. (13), consistent with previous results measured for conducting GaAs. From this work, the potential of the SPV technique to characterize trap-dominated high-resistivity GaAs and other semiconductors has been clearly shown. This is particularly important when other methods are difficult to apply because of low sample conductivities.

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APPENDIX

Following perturbation of the deep-level occupancy, the approach returns to the equilibrium state, and can be described by

$$\frac{dn^0}{dt}+\frac{dn_t}{dt}=-\frac{n^0}{\tau_n}, \tag{A1}$$

where n^0 and n_t are the carrier concentrations in the extended and localized states, respectively. The standard assumption used to analyze bulk and interface state transients in both DLTS and photoconductivity techniques assume a very high recombination rate, and that thermally released carriers can be instantaneously removed by a strong electric field so that Eq. (A1) reduces to

$$\frac{dn_t}{dt}=-\frac{n^0}{\tau_n}. \tag{A2}$$

The decay of the electron density is thus expressed by

$$n^0(t)=n_t(0)\,\tau_n e_n \exp(-e_n t), \tag{A3}$$

where e_n is the electron emission rate from the trap, which can readily be obtained by fitting the conductivity decay transient.

For ungated structures with only weak fields near the surface, the free-carrier decay transient can be analyzed using the Shockley-Read model for the quasistationary state,

$$C_n n^0(t)[N_t-n_t(t)]\approx e_n n_t(t). \tag{10}$$

Introducing the expression for $n_t(t)$ from Eq. (10) into Eq. (A1),

$$\left(1+\frac{C_n N_t e_n}{(C_n n(t)+e_n)^2}\right)\frac{dn}{dt}=-\frac{n^0(t)}{\tau_n}. \tag{A4}$$

Assuming linear recombination (the recombination lifetime $\tau_n=\tau_n^0$ is a constant), non-negligible retrapping causes the free carriers in extended states to have the following relationship:

$$\frac{dn^0}{dt}=-\frac{n^0(t)}{\tau_n^{\rm eff}}, \tag{A5}$$

with the instantaneous lifetime[24]

$$\tau_n^{\rm eff}=\tau_n^0\left(1+\frac{C_n N_t e_n}{[C_n n^0(t)+e_n]^2}\right). \tag{A6}$$

As $n^0(t)$ decreases, $\tau_n^{\rm eff}$ progressively increases according to Eq. (A5). In general the nonlinear equation (A5) cannot be integrated in a closed analytical form and the decay becomes nonexponential. However, the decay would be exponential again when the condition

$$C_n n^0(t)\ll e_n \tag{A7}$$

is satisfied. Then the relaxation time $\tau_n^{\rm eff}$ takes the form

$$\tau_n^{\rm eff}\approx\tau_n^0\left(1+\frac{C_n N_t}{e_n}\right), \tag{A8}$$

and then Eq. (A5) can be integrated as

$$n^0(t)=n^0(0)\exp(-t/\tau_n^{\rm eff}). \tag{A9}$$

The emission rate e_n can be written in the general form

$$e_n=C_n N_c \exp(-E_t/kT), \tag{A10}$$

then, from Eq. (A8),

$$\tau_n^{\rm eff}=\tau_n^0\left(1+\frac{N_t\exp(E_t/kT)}{N_c}\right). \tag{A11}$$

If the concentration of traps is high and the corresponding level is deep, then

$$\tau_n^{\rm eff}\approx\frac{\tau_n^0 N_f\exp(E_t/kT)}{N_c}. \tag{A12}$$

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