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Theoretical investigation of the dynamic process of the illumination of GaAs

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The dynamic process of light illumination of GaAs is studied numerically in this paper to understand the photoquenching characteristics of the material. This peculiar behavior of GaAs is usually ascribed to the existence of $EL2$ states and their photodriven metastable states. To understand the conductivity quenching, we have introduced nonlinear terms describing the recombination of the nonequilibrium free electrons and holes into the calculation. Though some photoquenching such as photocapacitance, infrared absorption, and electron-paramagnetic-resonance quenching can be explained qualitatively by only considering the internal transfer between the $EL2$ state and its metastability, it is essential to take the recombination into consideration for a clear understanding of the photoquenching process. The numerical results and approximate analytical approach are presented in this paper for the first time to our knowledge. The calculation gives quite a reasonable explanation for n-type semiconducting GaAs to have infrared absorption quenching while lacking photoconductance quenching. Also, the calculation results have allowed us to interpret the enhanced photoconductance phenomenon following the conductance quenching in typical semi-insulating GaAs and have shown the expected thermal recovery temperature of about 120 K. The numerical results are in agreement with the reported experiments and have diminished some ambiguities in previous works.

I. INTRODUCTION

$EL2$ is one of the most important native centers appearing in GaAs. It is located near the midgap ($E_c - 0.76$) and it has been intensively studied for decades now for the following two reasons. On the one hand, the $EL2$ center is important technologically for its role in producing semi-insulating GaAs. On the other hand, it exhibits an optically driven metastability at low temperature ($T < 120$ K). Thus GaAs shows peculiar photoquenching behavior. Though there are some arguments about it (such as the electric charge transformation model), this characteristic is generally ascribed to the transition of $EL2$ to its metastable state ($EL2^*$) on illumination with white or infrared light (about 1.13 eV) and the thermal or optical recovery associated with the reverse transformation, $EL2^* \rightarrow EL2$. The metastable state is electrically inactive and not accessible by most experimental methods. Therefore very little is known about it, and only the transition between the two states has been investigated. Techniques like electron paramagnetic resonance (EPR),[1-3] photoconductance (PC),[4,5] infrared absorption (IA),[6,7] photocapacitance,[7,8] and internal friction[9] have been applied to this study. It is generally accepted that the $EL2$ defect contains $\mathrm{As_{Ga}}$, and this is confirmed by EPR and electron-nuclear double-resonance (ENDOR) measurements.[10-12] The configuration of $EL2$, however, still remains uncertain; it may be an isolated $\mathrm{As_{Ga}}$ or a complex defect such as $\mathrm{As_{Ga}}$-V_{As}, $\mathrm{As_{Ga}}$-As_i, or $\mathrm{As_{Ga}}$-V_{Ga}-V_{As}. The same uncertainties exist, of course, for the atomic configuration of $EL2^*$. In this paper we will present a theoretical study on the photoquenching process for further understanding of the $EL2$ center.

We focus our study mainly on the dynamic process of photoconductivity quenching. Semi-insulating (SI) GaAs materials show this peculiar behavior at low temperature under infrared light illumination, and some of them also present enhanced photoconductance characteristics.[23] Although there have already been some theoretical investigations on the dynamic processes of photoquenching,[13-16] such as infrared absorption, EPR, and photocapacitance quenching, no one has yet given the correct and satisfactory calculated result for photoconductivity quenching to our knowledge. The EPR and absorption quenching features are determined by $EL2$ and $EL2^*$ themselves and may be qualitatively explained when only the internal transition between the normal state $EL2$ and the metastable state $EL2^*$ is considered. Photocapacitance quenching can easily be interpreted since the measurements are usually made in p-n junctions in which the recapture of free carriers is normally negligible. Howev-

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er, the recombination of free carriers must be considered in PC measurements, since the photoconductivity is directly associated with the free electrons and holes emitted from deep centers. It is known that the concentration of photoinduced free carriers in SI GaAs is of the order of 10^8-10^{11} cm^{-3}, much smaller than the $EL2$ concentration (about 10^{16} cm^{-3}). In fact, it is the rapid recombination that leads to the low concentration of free carriers. To describe these direct and indirect recombinations with the deep center $EL2$, nonlinear terms should be introduced in the general rate equations for the overall quenching process. As a result, the equation set needs numerical calculation. Even worse, the equation set we faced here is very stiff and unstable. Correct and convergent calculation results cannot be obtained by simple methods such as the Euler and Runge-Kutta methods. We have dealt with it carefully by combining the Newton iterative method and the Gear method, and obtained quite a good result.

In the next section, we will discuss the calculation model in detail, give the general rate equation set describing the overall photoquenching process, and present an approximate analytical approach under certain conditions. Section III analyzes and discusses the numerical results in different initial conditions corresponding to different type of GaAs. Finally, Sec. IV summarizes this paper and presents a conclusion.

II. CALCULATION MODEL

A. General rate equation set

It is generally accepted that the metastable state ($EL2^*$) can only be accessed by an internal transition when the $EL2$ is filled with electrons, i.e., in the neutral state of the defect, $EL2^0$. The photoquenching behavior of GaAs at low temperature can then be interpreted by considering this internal transition, the free-carrier emission from $EL2$, and the free-carrier recombination. The optical transition involved is depicted in Fig. 1. The free electrons and holes emitted by $EL2$ occur with the rates $\sigma_p^0\phi$ and $\sigma_p^0\phi$, respectively, while $\sigma^*\phi$ is the rate of emission to the metastable state. Here, ϕ represents the photon flux, σ_n^0, and σ_p^0 are the electron and hole photoionization cross sections of the $EL2$ center, and σ^* is the optical cross section describing the emission $EL2 \rightarrow EL2^*$. Let us denote the concentrations of the neutral state $EL2^0$, ionized state $EL2^+$, and metastable state $EL2^*$ as N, N^+, and N^*, respectively. Then the general rate equation set for the overall photoquenching process, can be written as

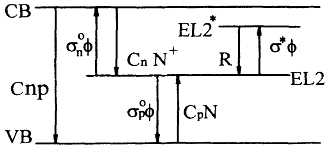

FIG. 1. Optical transitions of the $EL2$ center.

$$
\begin{aligned}
&dn/dt = N\sigma_n^0\phi - C_n n N^+ - Cnp\ ,\\
&dp/dt = N^+\sigma_p^0\phi - C_p p N - Cnp\ ,\\
&dN/dt = -(\sigma_n^0+\sigma^*)\phi N\\
&\qquad\qquad +\phi_p^0\phi N^+ + RN^* + C_n n N^+ - C_p p N\ , \qquad (1)\\
&dN^*/dt = N\sigma^*\phi - RN^*\ ,\\
&N + N^* + N^+ = N_T\ ,
\end{aligned}
$$

where t is the illumination time, n and p are the concentrations of free electrons and holes emitted from the $EL2$ centers, and N_T is the total concentration of $EL2$ defects which is usually of the order of 10^{16} cm^{-3} in SI GaAs. R represents the recovery rate for the reverse transition $EL2^* \rightarrow EL2$, which consists of two parts, the thermal recovery R_{th} and the optical regeneration R_{op} (σ_r^* is the optical cross section for $EL2^0$ regeneration):

$$R = R_{\text{th}} + R_{\text{op}} = R_{\text{th}} + \sigma_r^*\phi\ .$$

C is the direct recombination coefficient of the free carriers which takes the value[17]

$$C \cong 2\times 10^{-10}\ \text{cm}^3\,\text{s}^{-1}\ .$$

C_n and C_p denote the free-electron and -hole indirect recombination rates with the $EL2$ center, which are defined by the usual relations

$$C_n = \sigma_n V_n\ , \quad C_p = \sigma_p V_p\ ,$$

where σ_n (σ_p) is the electron (hole) capture cross section and V_n (V_p) is the thermal velocity of the electrons (holes).

Equation (1) is a set of nonlinear differential equations for there are nonlinear recombination terms, which need numerical calculation. Since the nondimensional coefficients $C_n N_T/(\sigma_p^0\phi)$, $C_p N_T/(\sigma_p^0\phi)$, and $CN_T/(\sigma_p^0\phi)$ are about 10^6-10^9 (much greater than 1), this differential equation set is very stiff and unstable, as we mentioned in the previous section, and must be dealt with carefully. However, we managed to obtain numerical results by combining the Gear method and the Newton iterative method. The calculation results will be shown and discussed in the next section. Now we are going on to discuss an approximate analytical solution and a steady-state solution under certain conditions.

B. Analytical approach for *n*-type SI GaAs

Suppose the initial concentrations of the neutral state $EL2^0$ and the ionized state $EL2^+$ before illumination are N_0 and N_p respectively in the semi-insulating GaAs. It is known that N^+ remains nearly unchanged during the whole quenching process, according to the numerical calculation shown in the next section. The free holes can be neglected ($p \cong 0$) when the illumination time is not long. Therefore we can obtain a simplified differential equation set for this situation:

$$
\begin{aligned}
&dn/dt=N\sigma_n^0\phi-C_n nN^+ ,\\
&dN/dt=-(\sigma_n^0+\sigma^*)\phi N+\sigma_p^0\phi N^+ +RN^* +C_n nN^+ ,\\
&N+N^*+N^+=N_T ,\\
&N^+=N_p+n-p\cong N_p ,
\end{aligned}
\tag{2}
$$

since $n,p \ll N_p$. From the above equation set, one has

$$dn^2/dt^2+2A\,dn/dt+Bn=N_0R\sigma^*\phi , \tag{3}$$

where

$$
\begin{aligned}
&A=0.5[(\sigma_n^0+\sigma^*)\phi+R+C_nN_p] ,\\
&B=C_nN_p(\sigma^*\phi+R) .
\end{aligned}
$$

Using the initial conditions

$$n|_{t=0}=0 \quad\text{and}\quad dn/dt|_{t=0}=N_0\sigma_n^0\phi ,$$

it is given that

$$
\begin{aligned}
n=0.5N_0\sigma_n^0\phi\Big[&\exp(-At-\sqrt{A^2-B}\,t)\\
&-\exp(-At+\sqrt{A^2-B}\,t)\Big]\Big/\sqrt{A^2-B} .
\end{aligned}
\tag{4}
$$

Since $C_nN_p \gg (\sigma_n^0+\sigma^*)\phi+R$ with normal light intensity at low temperature, we can further simplify the expression to

$$
\begin{aligned}
n\cong N_0\sigma_n^0\phi\{&[R+\sigma^*\phi\exp(-\sigma^*\phi t-Rt)]/(\sigma^*\phi+R)\\
&-\exp(-C_nN_pt)\}/(C_nN_p) .
\end{aligned}
\tag{5}
$$

Finally, it can be written as

$$n\cong N_0\sigma_n^0\phi[\exp(-\sigma^*\phi t)-\exp(-C_nN_pt)]/(C_nN_p) , \tag{6}$$

when $R \ll \sigma^*\phi$, which is satisfied at low temperature. Based on Eq. (6), we can deduce that

$$
\begin{aligned}
t=t_m&\cong\ln[C_nN_p/(\sigma^*\phi)]/(C_nN_p-\sigma^*\phi)\\
&\cong\ln(C_nN_p/\sigma^*\phi)/(C_nN_p)\cong 1\text{ ms} ,
\end{aligned}
$$

and the photoinduced free-electron concentration will take its maximum value

$$n=n_m\cong N_0\sigma_n^0\phi/(C_nN_p)\ll N_0 .$$

Thus it is known that the photoconductance reaches its maximum value at a very early time t_m, and the conductance decay time $\tau\cong 1/\sigma^*\phi$. The above result agrees with previous experiments. It was reported[5,18] that the photoconductivity of SI GaAs at low temperature reached its maximum point at the very beginning, the peak conductance was proportional to photon flux ϕ, and its quenching time was inversely proportional to ϕ.

Under the same conditions, we can further obtain

$$N^+\cong N_p+N_0\sigma_n^0\phi\{[R+\sigma^*\phi\exp(-\sigma^*\phi t-Rt)]/(\sigma^*\phi+R)-\exp(-C_nN_pt)\}/(C_nN_p)\cong N_p , \tag{7}$$

$$
\begin{aligned}
N\cong N_0\{&[R+\sigma^*\phi\exp(-\sigma^*\phi t-Rt)]/(\sigma^*\phi+R)-\sigma_n^0\phi[\exp(-\sigma^*\phi t-Rt)-\exp(-C_nN_pt)]/(C_nN_p)\}\\
\cong{}& N_0\exp(-\sigma^*\phi t) .
\end{aligned}
\tag{8}
$$

Clearly, the $EL2^0$ concentration N decays nearly exponentially and is dominated by $\sigma^*\phi$.

The above results are quite different from the results obtained from a simple model excluding the free-carrier recombination. According to the simple model calculation,

$$
\begin{aligned}
N=N_T&[C_1\exp(-\lambda_1t)+C_2\exp(-\lambda_2t)]\\
&+N_T\sigma_p^0\phi R/(\lambda_1\lambda_2) ,
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
n=N_T\sigma_n^0\phi(&\{C_1[1-\exp(-\lambda_1t)]/\lambda_1\\
&+C_2[1-\exp(-\lambda_2t)]/\lambda_2\}\\
&+t\sigma_p^0\phi R/(\lambda_1\lambda_2)) ,
\end{aligned}
\tag{10}
$$

where C_1, C_2, λ_1, and λ_2 are defined as

$$
\begin{aligned}
&C_1=(N_0/N_T-\sigma_p^0\phi/\lambda_1)(R-\lambda_1)/(\lambda_2-\lambda_1) ,\\
&C_2=(N_0/N_T-\sigma_p^0\phi/\lambda_2)(R-\lambda_2)/(\lambda_1-\lambda_2) ,\\
&\lambda_{1,2}=0.5\{e\pm\sqrt{e^2-4[R(\sigma_n^0+\sigma_p^0)\phi+\sigma^*\sigma_p^0\phi^2]}\} ,\\
&e=(\sigma_n^0+\sigma_p^0+\sigma^*)\phi+R .
\end{aligned}
$$

In the simple model calculation, N and N^+ are somewhat complicated and mainly controlled by σ_n^0,[15] and the concentration of emitted free electrons n may be greater than N_T. Equation (10) is obviously an incorrect result since it can be simplified as $n\cong N_T(1+Rt)\sigma_n^0/\sigma^*$, if $R\sim 0$ and $\sigma_n^0\phi t\gg 1$. Thus the simple model without the free-carrier recombination is of doubtful validity.

Our calculated result for N can be used to fit the infrared absorption experimental data [see Fig. 6(c) below]. The absorption $\alpha(t)$ after irradiation can be expressed as

$$\alpha(t)\cong\text{const}+\alpha_{EL2^0}N_0\exp(-\sigma^*\phi t) ,$$

assuming $\alpha_{EL2^*}\ll\alpha_{EL2^0}$, where α_{EL2^*} and α_{EL2^0} are the optical cross sections of $EL2^*$ and $EL2^0$ defects.

C. Steady-state solution for SI GaAs

In this part, we continue to discuss the steady-state situation following a long duration of light illumination. After the $EL2^0$ defects are transformed to the electrically inactive metastable state by light, the photoinduced holes will dominate the electrical conductance instead of electrons. Thus an enhanced photoconductivity appears following the photoconductance quenching, and at last a steady photocurrent will occur. For this stationary state, we obtain

$$\begin{aligned} &N\sigma_n^0\phi - C_n n N^+ - Cnp = 0\ , \\ &N^+\sigma_p^0\phi - C_p p N - Cnp = 0\ , \\ &N\sigma^*\phi - RN^* = 0\ , \\ &N + N^* + N^+ = N_T\ , \\ &N^+ = N_p + n - p\ . \end{aligned} \tag{11}$$

Since $C\sigma_n^0\phi/(C_pC_nN_p) \ll 1$ at low temperature, $n \cong 0$ can be simply eliminated. Substituting this into the above equation set, we obtain

$$\begin{aligned} p &\cong -0.5(D+N_0) + 0.5\sqrt{(D+N_0)^2 + 4N_0D} \\ &\cong N_p/(1+N_0/D)\ , \end{aligned} \tag{12}$$

where $D = (1+\sigma^*\phi/R)\sigma_p^0\phi/C_p$. We see that $D/N_0 \ll 1$ is usually satisfied, and therefore

$$\begin{aligned} p &\cong N_p(\sigma_p^0\phi/C_pN_0)\sigma^*\phi/R \\ &\cong N_p(\sigma_p^0\phi/C_pN_0)\sigma^*\phi/(R_{\text{th}} + R_{\text{op}})\ , \end{aligned} \tag{13}$$

where $\sigma^*\phi \gg R$ is required, which is satisfied at low temperature as mentioned above. It is known that the optical regeneration dominates at low temperature.[19,20] Consequently, we can predict that the stationary photocurrent is proportional to $\phi N_p/N_0$ at low temperature ($T < 100$ K). The above result may be applied to investigate the compensation of the $EL2$ center in SI GaAs, which will be discussed in detail elsewhere.

III. NUMERICAL RESULTS AND DISCUSSION

Numerical values of the parameters used for the calculation are listed in Table I unless otherwise specified. The results of the calculation under different conditions are shown in the figures below. In Table I, the photoionization cross sections are defined under infrared light of 1.17 eV, and $\sigma_r^*/\sigma^* = 0.005$ and $\mu_n/\mu_p = 15$, are fitting parameters, where μ_n and μ_p are the electron and hole mobility. The total concentration of $EL2$, N_T, is set to be 10^{16} cm^{-3}, and n, p, N, and N^+ in the figures are normalized by N_T.

In Fig. 2, we show the numerical results for typical n-type SI GaAs. The calculation indicates that the photoconductivity reaches a maximum at the very beginning, and then decreases gradually down to a minimum point. As light illumination goes on, the concentration of photoinduced electrons will be diminished and the holes will become dominant. As a result, the conductance increases again, the enhanced photoconductivity. Finally it reaches a stationary state. PC quenching is a well-known feature of SI GaAs. Besides the photoconductivity quenching, some authors have also reported[5,18,21] enhanced photoconductance (EPC) in SI GaAs, and photo-Hall measurement has confirmed that the photocurrent has converted from n type to p type after $EL2$ is completely quenched.[5] Our calculation results are in good agreement with these experiments, and predict a necessary condition of EPC, that is, $N_p/N_T > 0.01$. However, if the nonlinear recombination is neglected, as some authors have done in their calculation,[13-16] the concentration of emitted electrons and holes will never decrease. Therefore PC quenching and the EPC phenomenon cannot be deduced theoretically from a simple model calculation.

The concentration variations of the $EL2^+$ and $EL2^0$ are also given in Fig. 2(b). As we mentioned, $N^+(EL2^+)$ could hardly be changed by illumination while the neutral-defect ($EL2^0$) concentration N keeps decaying exponentially. The calculation results are drastically different quantitatively from the simple model calculation excluding free-carrier recombination[15] [see Eqs. (9) and (10) in Sec. II B]. In Fig. 2(c), we give a comparison of the calculated photocurrent I_{ph} with experiment.[23] The sample size is $5\times2\times0.3$ mm^3, $\sigma_n^0 = 4\times10^{-17}$ cm^2, and $\sigma_p^0 = 3\times10^{-17}$ cm^2 at a photon energy of 1.12 eV.[8] We set the applied voltage at 1 V, $\phi = 5.5\times10^{13}$ cm^{-2}s^{-1}, $\sigma^* = 5\times10^{-17}$ cm^2, $N_p/N_T = 0.3$, $\sigma_r^*/\sigma^* = 0.002$, and the other parameters are as listed in Table I. The calculation agrees well with experiment. From Fig. 2(c), we also see that the simple model calculation cannot give a reasonable result for photoconductance quenching, for the calculated result for I_{ph} (dashed line) is much higher than expected and never decreases. Therefore we can conclude that the free-carrier recombination is very important in photoquenching, especially in photoconductance quenching, and should not be neglected in the calculation.

Figures 3(a) and 3(b) give the calculation results for

TABLE I. Typical values of the calculation parameters.

$\sigma_n^0 = 1.2\times10^{-16}$ cm^2 [a]	$\sigma^*/\sigma_n^0 = 0.08$ [b]	$\mu_n = 4.5\times10^4$ cm^2/V s
$\sigma_p^0 = 1.3\times10^{-17}$ cm^2 [a]	$\sigma_r^*/\sigma^* = 0.005$	$\mu_p = 3\times10^3$ cm^2/V s
$\phi/N_T = 0.05$ cm/s	$N_p/N_T = 0.15$	$T = 77$ K
$R_{\text{th}} = 2\times10^{11}\exp[(-0.3\ \text{eV})/kT]$ s^{-1} [c]		$C = 2\times10^{-10}$ cm^{-3}s^{-1} [d]
$\sigma_n = 5\times10^{-19} + 6\times10^{-15}\exp[(-56.6\ \text{meV})/kT]$ cm^2 [e]		$\sigma_p = 2\times10^{-18}$ cm^2 [e]

[a] References 8, 15.

[b] Reference 15.

[c] Reference 20.

[d] Reference 17.

[e] Reference 19.

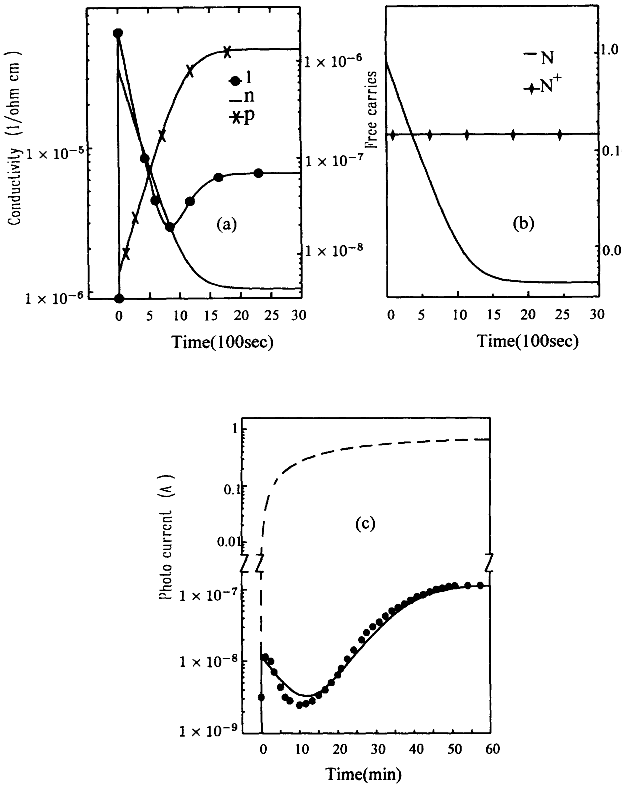

FIG. 2. (a) Variation of conductivity (1), free electrons (n), and free holes (p) under light. (b) Variation of concentrations of $EL2^0$ (N) and $EL2^+(N^+)$ under light. (c) Comparison of the photocurrent calculation (solid curve) with experiment data (solid points) from Ref. 23. The dashed line shows the I_{ph} calculation from the simple model without free-carrier recombination; it is much higher than experiment and never decreases.

different photon flux ϕ and σ^*. They show that the maximum photoconductivity is proportional to ϕ, the conductance decay time is proportional to $1/\phi\sigma^*$, and the stationary photocurrent intensity is proportional to ϕ. The results agree with experiments[5] and also confirm the analytical approach in the previous section.

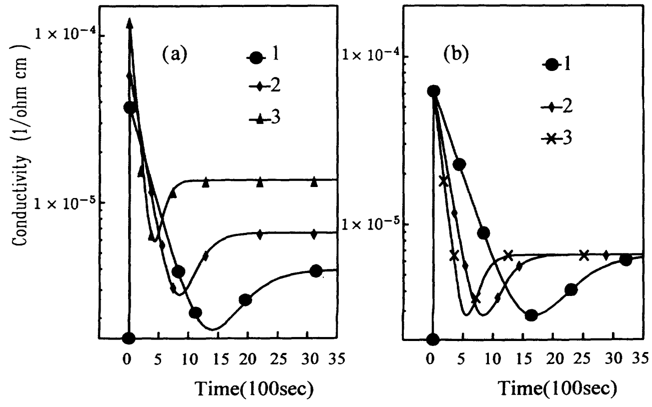

FIG. 3. (a) Conductivity under different light intensities $\phi/N_T = 0.03, 0.05, 0.1$ (lines 1,2,3). (b) Photoconductivity for different $\sigma^*/\sigma_n^0 = 0.04, 0.08, 0.12$ (lines 1,2,3).

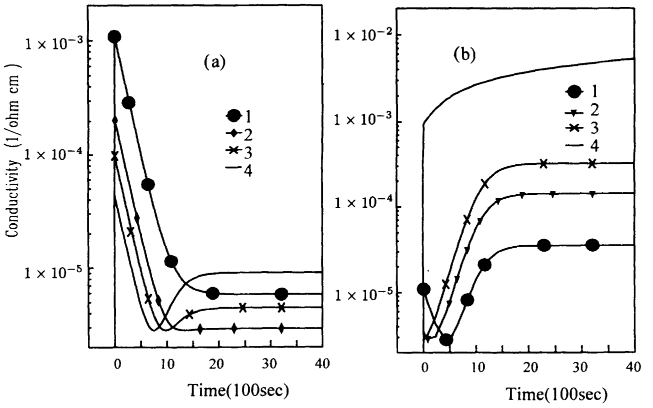

FIG. 4. Photoconductivity for different compensation ratios $k = (N_D - N_A)/N_T$. (a) $k = 0.01, 0.05, 0.1, 0.2$ (lines 1,2,3,4). (b) $k = 0.5, 0.8, 0.9, 1.0$ (lines 1,2,3,4).

Figures 4(a) and 4(b) show the corresponding plots for different initial fractions of ionized defects ($EL2^+$) $k = N_p/N_T$. Here N_p is equal to the concentration of residual acceptors ($N_A - N_D$) in SI GaAs, where N_A, N_D are the total shallow acceptors and donors. We see that the stationary photoconductance varies greatly with N_p/N_T. The higher the compensation, the higher the current intensity. According to the calculated figures, the EPC feature may not appear if the compensation is very low, e.g., $N_A - N_D$ much less than $0.05N_T$. However, with high compensation, for example, $k = N_p/N_T > 0.8$, the EPC may only be observed while the photoconductance does not show obvious quenching behavior.

Now we are going to discuss the photoquenching behavior at different temperatures. The numerical results shown in Fig. 5 indicate that the thermal recovery from $EL2^*$ to $EL2^0$ plays a major role at higher temperature as the recovery rate R_{th} increases exponentially. The calculated recovery temperature of 120 K, which will be slightly shifted by other parameters, is consistent with the measurements.[19–21]

Finally, we come to discussing the calculation for low-

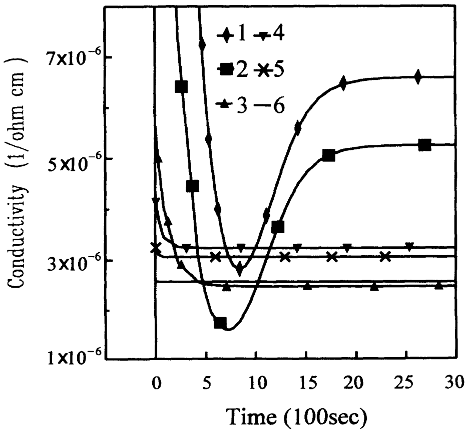

FIG. 5. Photoconductivity under different temperatures $T = 77, 90, 110, 115, 120, 125$ K (lines 1,2,3,4,5,6).

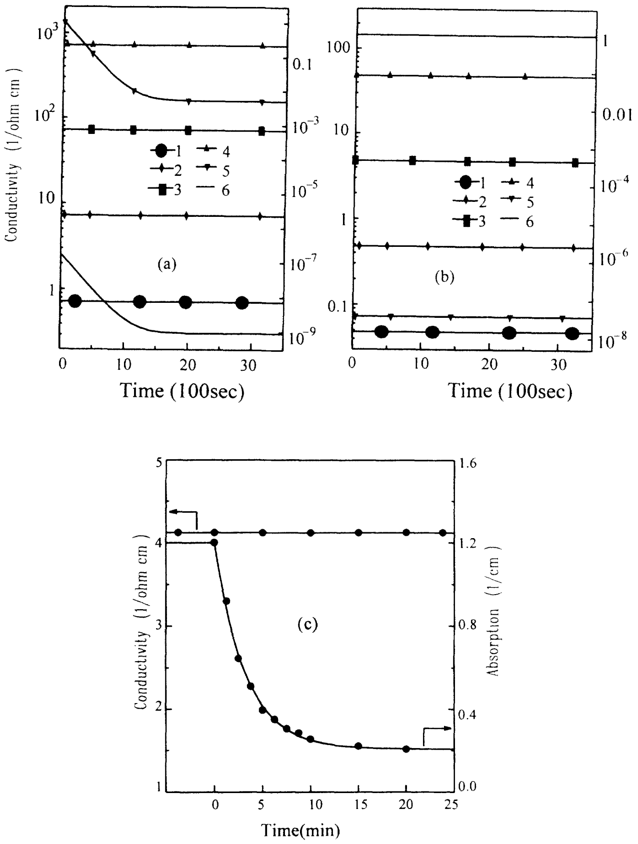

FIG. 6. Photoconductivity and $EL2$ concentration variation for doped n-type (a) and p-type (b) GaAs. n_0/N_T or $p_0/N_T=0.01,0.1,1.0,10$ (lines 1,2,3,4). Lines 5 and 6 correspond to $EL2^0$ and $EL2^+$ variation with n_0/N_T or $p_0/N_T=0.1$. (c) Comparison of the theoretical calculation with the experiment for the photoconductivity and optical absorption of n-type SC GaAs at 1.17 eV. The solid points are the experiment data from Ref. 6; the fitting photon flux ϕ is 5.4×10^{14} $\text{cm}^{-2}\,\text{s}^{-1}$.

resistance material, doped n-type and p-type semiconducting (SC) GaAs. $EL2$ usually has two different charge states, $EL2^0$ and $EL2^+$. In n-type SC GaAs, $EL2$ defects are all in the neutral state $EL2^0$, since $N_D-N_A>0$ (thermal emission from the deep level is neglected). In p-type SC GaAs, the $EL2$ defects are all ionized since $N_A-N_D>N_T$. According to the compensation situation we can determine that $N_p/N_T=0$ and $n|_{t=0}=n_0$ for n-type GaAs, $N_p/N_T=1$ and $p|_{t=0}=p_0$ for p type, where n_0 and p_0 are the corresponding residual donors and acceptors. The plots in Figs. 6(a) and 6(b) indicate that the photoconductance remains nearly unchanged in both n-type and p-type SC GaAs even if it is slightly doped, i.e., $n_0/N_T,p_0/N_T=0.01$. Moreover, the $EL2$ concentration will not be obviously changed by illumination in p-type GaAs since $EL2^+$ cannot be directly transformed into $EL2^*$. In contrast to p-type GaAs, the concentration of the neutral state $EL2^0$ in n-type GaAs can be decreased significantly by light. Thus n-type GaAs may present EPR and infrared absorption quenching while lacking quenching of the photoconductivity. The above calculation results have interpreted some experiment measurements which were not clearly explained in previous works.[6,15,22]

Figure 6(c) shows the comparison with experiment[6] of the calculation results for the photoconductance and infrared absorption for n-type SC GaAs. Our calculated results are in good agreement with the experiments and present a quite natural explanation for n-type SC GaAs to have infrared absorption quenching while lacking PC quenching. Based on the general rate equation, we can also deduce the conditions for the doped GaAs to lack additional photoconductivity: $(N_T\phi\sigma_n^0)/(C_n n_0^2)\ll 1$ for n type, $(N_T\phi\sigma_p^0)/(C_p p_0^2)\ll 1$ in p type, which are often satisfied with normal light intensity. We should mention that the Auger-like regeneration of the $EL2$ which is dominant in n-type GaAs material[17] is neglected in our calculation. Consideration of the Auger-like regeneration does not change the above conclusion except to result in a lower recovery temperature.

IV. CONCLUSION

We have studied the dynamic process of photoquenching in GaAs based on the metastability model. Our calculation shows that considering free-carrier recombination is essential to understanding the photoquenching characteristics of GaAs, otherwise some ambiguities will arise. The numerical calculation and analytical approach give the following results.

(a) *Typical SI n-type GaAs.* Besides EPR and infrared absorption quenching, it will present both photoconductance quenching and the EPC phenomenon. However, EPC does not appear in very slightly compensated GaAs, while highly compensated GaAs only presents the EPC phenomenon. Our numerical results also give an expected thermal recovery temperature of about 120 K and predict that the steady-state current intensity is proportional to $\phi N_p/N_0$ (N_p,N_0 are the concentrations of $EL2^+$ and $EL2^0$) at low temperature, which indicates a potential application in investigating $EL2$ compensation in GaAs.

(b) *Doped GaAs.* It will not present photoconductance quenching. However, n-type semiconducting GaAs may show other photoquenching behaviors such as EPR and IA quenching. p-type GaAs does not show any photoquenching behavior in contrast to n type.

The above numerical calculation results agree well with experiments and favor the metastability model.

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[1] U. Kaufmann, W. Wilkening, and M. Baeumber, Phys. Rev. B **36**, 7726 (1987).

[2] Noriaki Tsukada, Jpn. J. Appl. Phys. **24**, L689 (1985).

[3] M. Baeumber, U. Kaufmann, and J. Windscheif, Appl. Phys. Lett. **46**, 781 (1985).

[4] Noriaki Tsukada, Toshio Kikuta, and Koichi Ishida, Jpn. J. Appl. Phys. **24**, L302 (1985).

[5] Z. Q. Fang and D. C. Look, Appl. Phys. Lett. **59**, 48 (1991).

[6] J. C. Parker and Ralph Bray, Phys. Rev. B **38**, 3610 (1988).

[7] B. Dischler and U. Kaufmann, Rev. Phys. Appl. **23**, 779 (1988).

[8] P. Silverberg, P. Omling, and L. Samuelson, Appl. Phys. Lett. **52**, 1689 (1988).

[9] J. Ertel, H. G. Brion, and P. Haasen, Acta Phys. Pol. A **83**, 11 (1993).

[10] B. K. Meyer *et al.*, Phys. Rev. B **36**, 1332 (1987).

[11] B. K. Meyer, J. M. Spaeth, and M. Swcheffler, Phys. Rev. Lett. **52**, 885 (1984).

[12] J. M. Spaeth, D. M. Hofmann, and B. K. Meyer, in *Microscopic Identification of Electronic Defects in Semiconductors,* edited by N. M. Johnson, S. G. Bishop, and G. D. Watkins, MRS Symposia Proceedings No. 46 (Materials Research Society, Pittsburgh, 1985), p. 185.

[13] G. Vincent, D. Bois, and A. Chantre, J. Appl. Phys. **53**, 3643 (1982).

[14] G. Vincent, D. Bois, and A. Chantre, Phys. Rev. B **23**, 5335 (1981).

[15] T. Benchigues *et al.*, Appl. Surf. Sci. **50**, 277 (1991).

[16] G. R. Baraff and M. A. Schluter, Phys. Rev. B **45**, 8300 (1992).

[17] U. Strauss, W. W. Ruhle, and K. Kohler, Appl. Phys. Lett. **62**, 55 (1993).

[18] J. Jimenez, P. Hernandez, J. A. de Saja, and J. Bonnafe, Solid State Commun. **55**, 459 (1985).

[19] J. C. Bourgoin, H. J. V. Bardeleben, and D. Stievenand, J. Appl. Phys. **64**, R65 (1988).

[20] H. J. Von Bardeleben, N. T. Bagraev, and J. C. Bourgoin, Appl. Phys. Lett. **51**, 1451 (1987).

[21] U. V. Desinca, D. I. Desnica, and B. Santic, Appl. Phys. Lett. **58**, 278 (1991).

[22] Ralph K. Wan and J. C. Parker, Phys. Rev. Lett. **57**, 2434 (1986).

[23] J. Jimenez *et al.*, Jpn. J. Appl. Phys. **27**, 1841 (1988), and Refs. 6 and 7 therein.