Persistent Photoconductivity in Si-doped $Al_xGa_{1-x}As$

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Persistent photoconductivity in Si-doped molecular-beam epitaxial $Al_{0.28}Ga_{0.72}As$ was studied. The carrier concentration decreases with time according to a simple power law. The decay is explained semiquantitatively by an effective-mass-like model of the impurity with a wave packet centered near but not at the Γ point in the Brillouin zone. The shift of the impurity wave function in $\mathbf{k}$ space may be explained in terms of long-range composition ordering in the AlAs-GaAs system. Other physical properties may also be influenced by periodic composition fluctuations observed in many semiconducting alloys.

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$Al_xGa_{1-x}As$ has been the subject of considerable recent study because of its application in semiconductor lasers[1] and modulation-doped high-mobility transistors,[2] and because of the study of the quantum Hall effect in the two-dimensional electron gas at the GaAs/$Al_xGa_{1-x}As$ interface.[3]

Persistent photoconductivity was first observed in *n*-type $Al_xGa_{1-x}As$ by Nelson.[4] Subsequently it was studied by several other researchers.[5-10] The main features of the phenomenon can be summarized as follows: (a) *n*-type $Al_xGa_{1-x}As$ with a composition in the range of $0.2 \leq x \leq 0.6$ exhibits, at temperatures below 150 K, very long lifetime photoconductivity (many hours). (b) The magnitude of the effect varies from sample to sample in an unpredictable manner. (c) The persistent photocarriers originate from the donor level. (d) An unusually large Stokes shift is observed. (e) The persistent photoconductivity cannot be quenched optically. (f) The persistent-photoconductivity decay is not exponential (nor is it a sum of exponentials).

Lang, Logan, and Jaros proposed a model for the explanation of the phenomenon based on a donor complex which they called the *DX* center.[8,9] According to this model, ionization of the *DX* center involves a giant lattice relaxation and an associated shift of the *DX*-center energy level from within the energy gap to an energy resonant with the conduction band.

Chand *et al.*[10] offered an alternative explanation for the persistent photoconductivity based on an effective-mass donor level associated with the *L* minimum. According to this model, optical transitions are possible between the donor level and the *L* minimum, but not between the donor level and the Γ minimum.

Both models explain qualitatively certain aspects of persistent photoconductivity. However, on the one hand it is difficult to understand the nature of the *DX* center. On the other hand, the model of Chand *et al.* fails to explain the large photon energy required for photoexcitation, or why the effect is present in some samples but absent in others with like composition,[11] or finally why the effect is observed in material with $x > 0.4$ for which the *L* minimum is the lower of the two. Neither model has been used to explain persistent photoconductivity quantitatively.

The purpose of the present paper is to provide data on the time dependence of carrier concentration during the decay of persistent photoconductivity in *n*-type $Al_xGa_{1-x}As$ and to suggest an alternative model for explaining the features of the phenomenon.

The samples consisted of a 4.2-μm layer of silicon-doped $Al_{0.28}Ga_{0.72}As$ grown by molecular-beam epitaxy on a [100] semi-insulating GaAs substrate at 610 ± 10 °C. Several thin buffer heterostructure GaAs/$Al_xGa_{1-x}As$ layers were grown between the semi-insulating GaAs and the $Al_xGa_{1-x}As$ epitaxial layer to minimize the propagation of crystal defects of the semi-insulating substrate into the epitaxial layer. A thin cap layer of GaAs (nominal thickness 200 Å) was deposited on top of the $Al_xGa_{1-x}As$ to prevent degradation of the highly reactive $Al_xGa_{1-x}As$ surface. A set of Au/Ge/Ni contacts was alloyed onto the cap layer to allow for Hall-effect measurements. The sample was mounted in a stainless-steel Dewar flask containing a 4-W incandescent lamp and placed in a magnetic field of 0.3 T.

Figure 1 shows the Hall-carrier concentration as a function of temperature in the dark and in the presence of illumination. The activation energy computed from the dark $\ln(n_{\mathrm{Hall}})$ vs $1/T$ curve indicates that the impurity level is located about 0.04 eV below the conduction-band edge. This result is in agreement with the value obtained by Chand *et al.*[10] for similar material. It is seen that for temperatures below about 150 K the lifetime of optically excited carriers becomes very large. Measurements of carrier lifetime were performed near

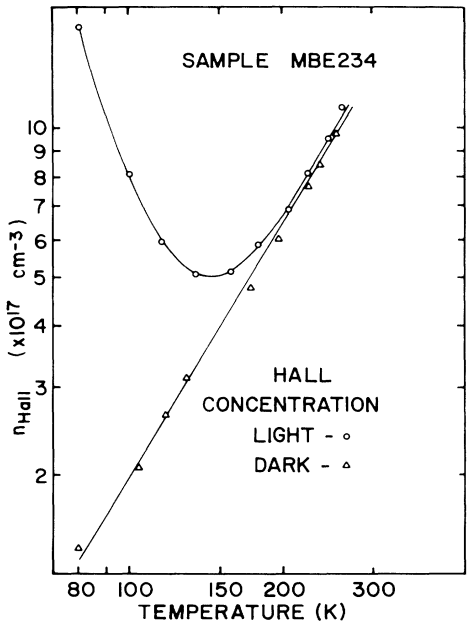

FIG. 1. Hall concentration of $Al_{0.28}Ga_{0.72}As$ sample vs temperature in the absence and in the presence of optical excitation.

liquid-nitrogen temperature. The light was turned off and the decay of the Hall voltage was measured as a function of time for about 300 s. The sample was thermally quenched and the measurement was repeated several times reversing the magnetic field. The $\ln(n_{\rm Hall})$ as function of ln(time) is plotted in Fig. 2. The Hall concentration was found to be related to time through a power law:

$$n_{\rm Hall}=1.5\times10^{18}t^{-0.28}\,{\rm cm}^{-3} \quad (1)$$

for $0.5\ {\rm s}\le t\le 300$ s. We estimate the error in the determination of the parameters in Eq. (1) to be $\pm 5\%$. The decay implies that the probability of electron capture by an impurity decreases with time or that the probability of transition into the impurity level decreases with electron concentration.

Considering the energy separation of the Γ and L minima[12] it can be shown that at the temperature of the experiment the population of the L minimum is insignificant as compared to the population of the Γ minimum (see Table I). Therefore, the Hall measurement yields the concentration of carriers in the Γ minimum.

Assuming that the conduction band is parabolic close to the Γ minimum and using the effective mass of carriers obtained from a linear interpolation between the effective masses in GaAs and AlAs,[10] we can express the carrier concentration as

$$n_\Gamma=2\int\frac{4\pi k^2}{(2\pi)^3}\frac{dk}{1+\exp[(E_{\mathbf k}-E_{Fn})/k_BT)]}, \quad (2)$$

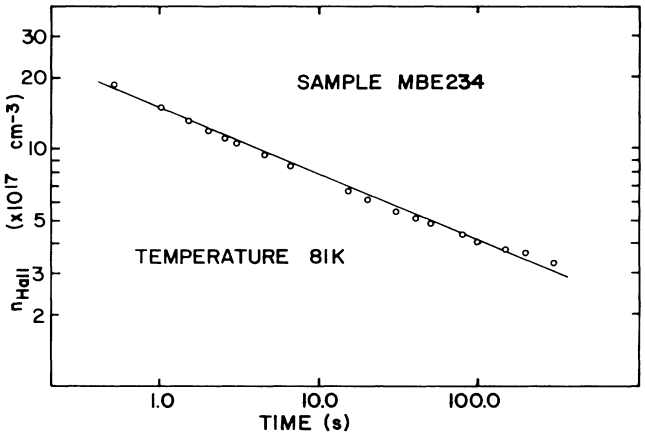

FIG. 2. Decay of Hall concentration following the removal of optical excitation.

where

$$E_{\mathbf k}=\frac{\hbar^2k^2}{2m^*}\quad (m^*=0.09m_0 \text{ for } x=0.28),$$

and E_{Fn} is the quasi-Fermi level for electrons. Using Eqs. (1) and (2) we can determine the change of the value of E_{Fn} with time during the conductivity decay.

The rate of decay of conduction electrons through direct transitions can be expressed as

$$\frac{dn}{dt}=N_D^+\int T(\mathbf k)f(E_{\mathbf k})\frac{d^3k}{4\pi^3}, \quad (3)$$

where N_D^+ is the number of unoccupied donors and is approximately equal to n. $T(\mathbf k)$ is the transition probability and $f(E_{\mathbf k})$ is the Fermi-Dirac distribution function. The impurity wave function can be written as[14]

$$\Psi=\int A_0(\mathbf k)\Psi_0(\mathbf k)\frac{d^3k}{(2\pi)^3}, \quad (4)$$

where $\Psi_0(\mathbf k)$ is the Bloch wave function for the lowest band and $A_0(\mathbf k)$ is given by

$$A_0(\mathbf k)=\frac{8\pi^{1/3}}{V^{1/2}a_B^{*3/2}}\frac{1}{(a_B^{*2}k^2+1)^2}, \quad (5)$$

where a_B^* is the effective Bohr radius.

It can be shown that if Eq. (5) is used directly in Eq. (3) $[T(\mathbf k)\propto|A_0|^2]$, the resulting rate of decay is a power function of time, but it is very high and no appre-

TABLE I. Summary of experimental results. It was assumed that $\mu_\Gamma/\mu_L=7.5$ (see Ref. 13).

	$E_{Fn}-E_\Gamma$ (eV)	n_Γ (cm^{-3})	μ_Γ (cm^2/V s)	n_L/n_Γ
Dark	−0.005	1.4×10^{17}	400	1.3×10^{-8}
Illuminated	0.059	1.8×10^{18}	480	8.9×10^{-6}

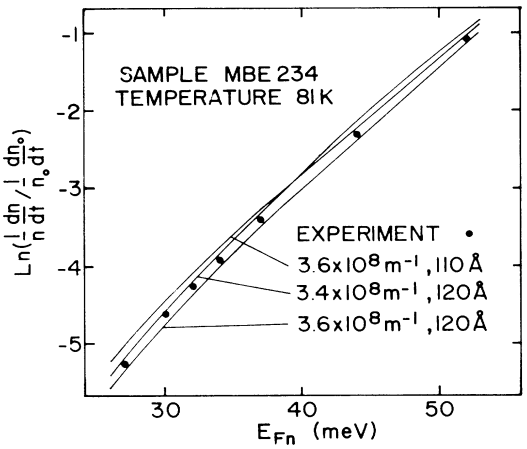

FIG. 3. Variation of

$$\ln\left[\frac{1}{n}\frac{dn}{dt}\left(\frac{1}{n_0}\frac{dn_0}{dt}\right)^{-1}\right]$$

vs E_{Fn} for various values of k_0 and Bohr radius.

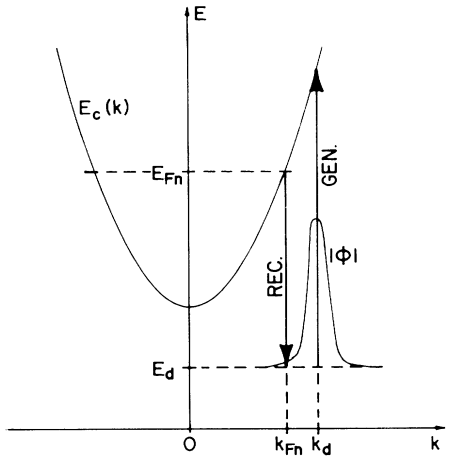

FIG. 4. Proposed model of the wave-function envelope of the Si impurity and its position relative to the Γ conduction-band minimum. The direct optical generation and recombination paths are shown.

ciable persistent photocurrent can be observed. However, if the impurity envelope function $A_0(\mathbf{k})$ were to be peaked at a point in $\mathbf{k}$ space other than the Γ point, the direct recombination rate of conduction electrons with empty impurity levels would be decreased. To see if this approach can be used to explain the basic features of the persistent photoconductivity decay, we use the form of the impurity envelope function, Eq. (5), but allow for $A_0(\mathbf{k})$ to be peaked at a certain wave vector $\mathbf{k}_0$; hence

$$A_0(\mathbf{k}) \propto \frac{1}{[a_B^{*2}|\mathbf{k}-\mathbf{k}_0|^2+1]^2}. \tag{6}$$

We insert the form (6) into Eq. (3) and adjust $\mathbf{k}_0$ and a_B^* to obtain the best fit between the experimental and theoretical values of $n^{-1}dn/dt$. In fact, we allow $A_0(\mathbf{k})$ to have a symmetric peak at $-\mathbf{k}_0$ and in order to dispense with numerical coefficients in Eq. (3), we normalize all values (experimental and theoretical) to the initial value of $n^{-1}dn/dt$ at $E_{Fn}=0.052$ eV. We also use a step function to approximate the Fermi-Dirac distribution.

Figure 3 shows the results of this procedure. The circles represent values obtained with data points of Fig. 2 and Eq. (2). We show theoretical curves for several different values of a_B^* and k_0; it can be seen that the best fit is obtained with $a_0^* \approx 120$ Å and $k_0 \approx 3.6\times10^8$ m^{-1}.

In order to evaluate these results, we note that using the effective mass of the carriers [$0.09m_0$ (Chand *et al.*[10])] and the dielectric constant of the material [$13.1\epsilon_0$ (Sze[15])] one would expect the Bohr radius of the impurity state to be about 100 Å which is in good agreement with the value obtained from our model. The value of k_0 which our model yields is only about 7% of the distance from the Γ point the L point, i.e., the impurity level is moved only slightly away from the Γ point. Such a behavior is suggestive of an underlying periodicity in the system with a wavelength $\lambda = 2\pi/k_0 \approx 170$ Å and indeed there is both theoretical[16] and experimental[17] evidence that $Al_xGa_{1-x}As$ has a tendency to develop long-range periodic concentration fluctuations in the Al-Ga subsystem. We also note that for impurity concentrations characteristic for our samples ($\simeq 10^{18}$ cm^{-3}) the mean distance between impurities ($\simeq 130$ Å) is of the order of their Bohr radius and hence a substantial interaction between impurities can be expected. Periodic fluctuations in the electron density of the crystal matrix caused by Al vs Ga concentration fluctuations are expected to lead to periodic variations in the impurity distribution and a shift in the impurity-state wave packet away from $\mathbf{k}=0$.[18] This is schematically illustrated in Fig. 4.

In conclusion we suggest that the persistent photoconductivity in the $Al_xGa_{1-x}As$:Si system is caused by periodic fluctuations in the Al vs Ga concentration which lead to such modifications of the impurity states that the $\mathbf{k}$-space density of impurity levels is very low in the range of $\mathbf{k}$ values corresponding to the region of the Brillouin zone occupied by photoexcited carriers.

The most direct experimental consequence of this model is that for $T \to 0$ the relative rate of decay of the carrier concentration would stabilize at a constant, nonzero value. We have seen indications of such behavior and plan to perform conclusive experiments in the near future.

The model also suggests that the decay of the persistent photocurrent will be accompanied by recombination radiation with a high-energy edge that shifts to lower energies as the concentration of the carriers decreases. Other models proposed to date[8-10] require phonon in-

teractions and predict that at very low temperatures, with few phonons present, the rate of decay of the photocurrent would tend to zero. Recombination radiation would be either nonexistent or have a fixed frequency.

Long-period ordering has been observed recently in several metal and semiconductor alloys.[19-21] Considering the profound influence it has on photoconductivity, we expect that periodic composition fluctuations may lead to important modifications in other physical properties of such systems, in particular those properties which are influenced by the quantum structure of impurity states.

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