Nonequilibrium carriers in GaAs grown by low-temperature molecular beam epitaxy

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Electronic properties of GaAs grown by low-temperature molecular beam epitaxy are analyzed using a model that assumes a semiconducting matrix with embedded semimetallic As clusters. The static and high-frequency conductivity, Hall effect, lifetime of photoexcited carriers, current-voltage characteristic, and the screening phenomena are all considered. Model results are compared with existing experimental data and a proposal is given for new experiments that could determine currently unknown properties of the material.

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I. INTRODUCTION

Gallium arsenide grown by low-temperature molecular beam epitaxy (LT GaAs) has become an object of intensive experimental investigations over the last decade. The most remarkable property of this material is the combination of very high resistivity and very short lifetime of nonequilibrium carriers which makes LT GaAs a very promising material for a number of micro- and optoelectronic devices.[1] It is widely accepted that these peculiarities are related to the presence of excess arsenic in the material and are usually described by two different models, the ''buried Schottky barrier'' [2] and ''arsenic antisite of defect.'' [3]

The first model is based on the experimentally confirmed fact that excess arsenic after annealing forms separate clusters in the GaAs matrix with characteristic dimensions of the order of tens of nanometers. These clusters pin the Fermi level near the middle of the band gap, creating depletion regions (Schottky barriers) adjacent to the clusters. At sufficiently high cluster densities these regions overlap and the material becomes semi-insulating.

This system has much in common with neutron-irradiated semiconductors containing disordered regions with high concentrations of deep centers encircled by depleted regions[4] and for this reason having high resistivity. However, photoelectric properties of irradiated semiconductors and of LT GaAs differ dramatically. Irradiated semiconductors, similar to many other inhomogeneous materials, are characterized by very long carrier lifetimes τ due to a separation of nonequilibrium carriers by the internal electric fields of the inhomogeneities.[5] LT GaAs, by contrast, is characterized by very short τ. This means that the simple model of chemically uniform semiconductors with parallel modulation of energy bands by an electrostatic inhomogeneous potential[5] cannot be directly applied to LT GaAs.

In the present paper we develop the concept of the ''buried Schottky barriers'' [1,2,6] to formulate a simple two-phase model of LT GaAs which gives a quantitative theoretical description of all of the major electronic properties of this material and predicts some new, still unobserved effects.

II. TWO-PHASE MODEL

We consider LT GaAs as a matrix of pure crystalline GaAs with embedded arsenic clusters having a spherical shape with radius a and concentration N. Bulk As is a semimetal with the band overlap $\Delta = 0.37$ eV and concentration of electrons and holes $n_{\mathrm{As}} = p_{\mathrm{As}} = 2\times10^{20}\,\mathrm{cm}^{-3}$ (see Ref. 7). In small clusters due to the size quantization of electrons and holes, Δ and n_{As} may have considerably lower values. (For very small a, band overlap may be completely removed so that clusters have the properties of a narrow-gap indirect semiconductor.) The resulting band diagram is shown in Fig. 1. The band offsets ΔE_c and ΔE_v are determined by the electron affinities of GaAs and As. For a sufficiently large cluster size a, the size quantization in clusters is negligible and the values of ΔE_c and ΔE_v approach those for bulk GaAs-As. As is often the case in the physics of heterojunctions, exact electron affinities have considerable uncertainty and band offset values are difficult to predict theoretically and must be determined experimentally. The position of the Fermi level ζ for the undoped matrix is determined from the condition of cluster electrical neutrality: $n_{\mathrm{As}} = p_{\mathrm{As}}$ and may depend on the energy levels in a cluster and, hence, on a. The presence of charged impurities in GaAs matrix distorts slightly the band diagram (dashed lines in Fig. 1) but if their concentration N_I is less than $4\varepsilon_0 N^{2/3}kT/e^2$ (ε_0 is the dielectric constant of GaAs), the amplitude of this distortion $e^2N_I/[\varepsilon_0(2N^{1/3})^2]$ is less than the thermal energy and can be ignored. For a typical value $N\sim10^{16}\,\mathrm{cm}^{-3}$, this condition at room temperature corresponds to $N_I \lesssim 3\times10^{17}\,\mathrm{cm}^{-3}$. In this case the electron and hole concentrations in the GaAs matrix are spatially uniform, independent of the doping level of material and equal, respectively, to $n_0 = N_c \exp[(\zeta$

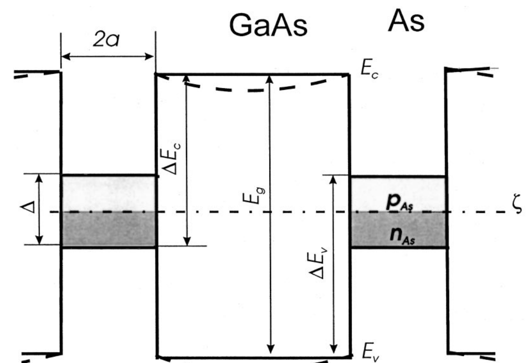

FIG. 1. Schematic band diagram of LT GaAs containing semimetallic clusters.

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$-E_c)/kT]$ and $p_0 = N_v \exp[(E_v - \zeta)/kT]$ where N_c, N_v are the effective densities of states in the conduction and valence bands of GaAs.

The sign and concentration of majority carriers in the matrix between clusters depend on the relationship between electron $(E_c - \zeta)$ and hole $(\zeta - E_v)$ activation energies, being determined by the smaller of them. We assume that $\zeta > (E_c + E_v)/2$ so that the majority carriers are electrons. This is in accordance with the experimental data[8,9] showing the Schottky barrier height at the interface n-GaAs/As to be 0.65 eV, which is less than the $(E_c - E_v)/2$. The value of $E_c - \zeta = 0.65$ eV in LT GaAs is also in a good agreement with many transport measurements (see, e.g., Refs. 9–14) demonstrating the activation energy of conductivity and Hall effect in the interval 0.6–0.75 eV and negative sign of majority carriers.

III. TRANSPORT PHENOMENA

It has already been mentioned that the static values of conductivity σ and Hall coefficient R_H in LT GaAs have an activation temperature dependence with the activational energy $E_c - \zeta \simeq 0.65$ eV. The pre-exponent in σ depends on the relation between the mean free path of majority carriers in the matrix l_o determined by impurities, phonons, and other scatterers besides clusters and the average distance l_c between two collisions of ballistic electrons with clusters. Since the cross section for scattering by an uncharged cluster is πa^2, then $l_c \simeq (\pi N a^2)^{-1}$.

At $l_o \ll l_c$ the situation is purely classical. We have a conducting medium with the conductivity $\sigma_0 = n_0 e^2 l_o/(mv)$ (m and v are the effective mass and the thermal velocity of electrons in GaAs) containing embedded metallic clusters with a conductivity much higher than σ_0. If the relative volume of clusters $C = 4\pi N a^3/3 \lesssim 0.2$ so that no percolation exists, the effective conductivity of the system σ is well described by effective medium theory (EMT) (see, e.g., Ref. 5) which gives

$$\sigma = \frac{\sigma_0}{1-3C}. \tag{1}$$

It is worth noting that EMT predicts the Hall coefficient R_H in the system to be equal to $(1-3C)^2/en_0$. This means that the "Hall mobility" σR_H is always less than the real mobility in the matrix $\mu_0 = e l_o/(mv)$:

$$\sigma R_H = \mu_0(1-3C),$$

which is typical for inhomogeneous semiconductors.[5]

At $l_o \gg l_c$ the carrier motion between clusters is ballistic and the role of mean free path is played by l_c so that $\sigma_0 \sim n_0 e^2/(mvNa^2)$.

Frequency dispersion of the LT GaAs conductivity $\sigma(\omega)$ in the case of ac voltage is the subject of a separate discussion. The simplest way to find $\sigma(\omega)$ is to use the EMT generalized to the ac case by replacing all σ with complex conductivities $\sigma - i\varepsilon/(4\pi)$ where ε is the dielectric constant.[15] However, for high conductivity of clusters, EMT gives the real part of the ac conductivity as the same formula as Eq. (1), containing no frequency dispersion. This contradicts both more general theoretical models[16,17] and experiments on LT GaAs[18] where noticeable dispersion was predicted and observed at frequencies $\omega \sim \tau_M^{-1}$ with $\tau_M = \varepsilon_0/(4\pi\sigma_0)$ being the Maxwell time in the matrix. To explain this discrepancy, let us imagine the qualitative picture of electric field in the system.

We assume that at the moment $t = 0$ the system was exposed to an electric field created by external electrodes. Almost immediately (in a time equal to the Maxwell time in the clusters which is assumed to be vanishingly small) the field inside the clusters will be screened and the clusters become equipotential spheres. The processes of charge redistribution between different clusters will be characterized by the relaxation time τ_M. If clusters form an ideal periodic lattice, then, by symmetry, there would be no such redistribution and no relaxation processes. In other words, σ would have no dispersion at $\omega \sim \tau_M^{-1}$, in agreement with the EMT predictions. But fluctuations in position or size of clusters, ignored in EMT, change the picture. If, for instance, there exists a pair of clusters with anomalously small separation in the direction of external field, this pair tends to be polarized and a corresponding charge distribution is established in a time $\sim \tau_M$, and becomes the origin of the frequency dispersion $\sigma(\omega)$ at $\omega \sim \tau_M^{-1}$ which at the room temperature has the order of 10 kHz.

At much higher frequencies when ω becomes comparable with the inverse Maxwell frequency of clusters, the field partially penetrates the clusters, which results in a strong absorption of microwave and infrared radiation. A similar problem was discussed in the literature[5,19] in connection with the intraband absorption by strongly compensated semiconductors containing electron droplets. Considering our system as a dielectric matrix with spherical conducting inclusions having the conductivity σ_i, we have the following expression for the absorption coefficient:

$$\alpha = \frac{\sqrt{\varepsilon_0}\,\omega}{c}\,\mathrm{Im}\,\frac{4\pi i \sigma_i}{3\varepsilon_0\omega + 4\pi i \sigma_i}. \tag{2}$$

Using the Drude formula $\sigma_i = e^2 n_{\mathrm{As}} \tau_p [m(1 - i\omega\tau_p)]^{-1}$ (τ_p is the momentum relaxation time in clusters)—the formula is exact if one type of carrier is dominating in conductivity; if the contributions of electrons and holes are comparable, by m and τ_p one should mean some effective values determined by both types of carriers—we obtain eventually

$$\alpha = \frac{\sqrt{\varepsilon_0}\,\Omega^2\omega^2\tau_p}{c[\omega^2 + (\Omega^2 - \omega^2)^2\tau_p^2]}, \tag{3}$$

where $\Omega = \sqrt{4\pi e^2 n_{\mathrm{As}}/(3m\varepsilon_0)}$ is the plasma frequency in clusters. The α vs ω dependence given by Eq. (3) has a maximum at $\omega = \Omega$. For pure bulk As, Ω would have the value $\sim 5 \times 10^{14}\,\mathrm{s}^{-1}$. But, as mentioned in Sec. II, in clusters n_{As} and hence, Ω, may acquire much smaller values. It is clear from Eq. (3) that by studying infrared absorption spectra in LT GaAs, one can obtain information on the carrier concentration in clusters.

Another important high-frequency kinetic coefficient is the off-diagonal conductivity component in a magnetic field σ_{xy}. This ac Hall conductivity determines the amplitude of Faraday rotation and for this reason can be easily measured experimentally. In inhomogeneous structures, σ_{xy} for each type of carrier at sufficiently high frequency, $\omega > 4\pi\sigma_i/\varepsilon_0$, is proportional to the average carrier concentration in the sample.[20] Thus, in a medium with separate metallic inclusions, the effective carrier concentration determined from the Faraday effect may be orders of magnitude larger than the concentration found from the dc conductivity. This was shown to be the case in experimental studies of strongly compensated semiconductors containing microscopic droplets of degenerate electrons.[21] In our case of semimetallic inclusions, electron and hole contributions to σ_{xy} have different signs but do not cancel each other due to the difference of electron and hole mobilities $\mu_{n,p}$ in clusters. As a result, the sign of the Faraday effect is determined by carriers with higher mobility in clusters and its amplitude is proportional to the carrier density in clusters. This conclusion is valid for low magnetic fields H when $\mu_{n,p}H/c \ll 1$. In the high field limit, σ_{xy} for each type of carrier is independent of mobility and for $\omega \to \infty$, $\sigma_{xy} \to 0$ so that the total σ_{xy} vs ω dependence has a maximum. We do not consider the effect in more detail since the mobility of carriers in clusters is presumably very low and the high field situation is unrealistic.

IV. CURRENT-VOLTAGE CHARACTERISTIC

The current-voltage characteristic (CVC) of macroscopically uniform LT GaAs has been reported in a number of experimental works (see, e.g., Refs. 11–13). The results show that at moderate temperatures ($T > 200$ K) CVC contains three characteristic parts: (a) an initial linear region corresponding to the electric fields $F < 5$ kV/cm, (b) followed by a sublinear region with a tendency to saturation and, eventually, (c) at $F > 100$ kV/cm the CVC acquires an exponentially growing character.

A qualitative explanation of the phenomenon in terms of the space-charge-limited currents[6,12,13] appears inadequate. First, this explanation ignores the cluster structure of LT GaAs and could be equally applied to any high-resistive material, whereas the described CVC's are typical only for LT GaAs. Second, the space charge theory itself does not predict a sublinear region of CVC and to explain it, saturation of the drift velocity in strong fields was additionally assumed.[12,6] However, LT GaAs is characterized by a very effective energy relaxation inside the semimetallic clusters (relaxation times of momentum and energy must be almost equal). For these reasons, strong carrier heating necessary for the saturation can be reached only in sufficiently high electric fields, larger than those responsible for other mechanisms of nonlinearity described in the following. Third, the space-charge theory does not offer a direct explanation for the suppression of sublinearity as the temperature decreases.

At the same time, the model used in the previous sections for description of linear transport phenomena in LT GaAs also gives an adequate description of all of the characteristic features of CVC introducing no additional adjustable parameters.

Let us calculate the flux of electrons of energy E (measured from the conduction band edge in GaAs) emitted by unit area of a cluster, $q(E)$. In the equilibrium $q(E)$ is isotropic and equal to $\rho(E)v(E)f(E)/4 = \rho(E)\sqrt{E/(8m)}\exp[-(\Delta E_c+E)/kT]$, where ρ is the density of states in the GaAs conduction band, m is the electron effective mass, and f is the Boltzmann distribution function.

If an external electric field $\mathbf{F}$ is applied to the system, metallic clusters become polarized and disturb the field to establish the surface equipotential. The resulting field distribution near a spherical cluster (see, e.g., Ref. 22) has a normal component $F_n = 3F\cos\theta$, where θ is measured from the direction of $\mathbf{F}$. In the regions of large positive F_n, electrons with $E<0$ can also leave the cluster via tunneling. As a result, the electron flux from a cluster is different in different directions. Applying the standard quasi-classical formula for the tunneling probability through a triangular barrier, we obtain for $E<0$ and $0<\theta<\pi/2$,

$$q(E,\theta) = \frac{mE}{2\pi^2\hbar^3}\exp\left(-\frac{\Delta E_c+E}{kT}\right) \times \exp\left[-\frac{4\sqrt{2m}}{9\hbar eF\cos\theta}(-E)^{3/2}\right]. \tag{4}$$

For other regions of E and θ the last exponent in Eq. (4), describing tunneling, must be replaced by 1.

If $l_o > l_c$, then each electron emitted along an arbitrary direction θ, will end its flight of average length l_c by being captured by another cluster. In equilibrium, the corresponding local current will be exactly compensated by an equal current in the opposite direction. The applied voltage, however, causes the establishment of a potential difference $eFl_c\cos\theta$ between these two clusters. As a result, for electrons moving to the positive electrode ($\cos\theta>0$), the opposite current is diminished by the factor $\exp[-eFl_c\cos\theta/(kT)]$.

The local current between some given cluster and another cluster at an average distance l_c away, in the direction θ with $0\leq\theta\leq\pi/2$, is

$$I(\theta) = \frac{ema^2}{\pi\hbar^3}\exp\left(-\frac{\Delta E_c}{kT}\right)\left[1-\exp\left(-\frac{eFl_c\cos\theta}{kT}\right)\right] \times\left\{\int_{-\infty}^{0}\exp\left[-\frac{4\sqrt{2m}}{9\hbar eF\cos\theta}(-E)^{3/2}-\frac{E}{kT}\right]E\,dE + \int_0^\infty \exp\left(-\frac{E}{kT}\right)E\,dE\right\}. \tag{5}$$

The total current density in the system j is given by the sum of these local currents:

$$j = Nl_c\int_0^{\pi/2} I(\theta)\sin\theta\cos\theta\,d\theta. \tag{6}$$

We restrict ourselves to the region of $\cos\theta>0$ since from the charge conservation the number of electrons entering some plane from the region of negative $\cos\theta$ is the same as that of electrons leaving to the direction of positive $\cos\theta$.

Calculating the integral in Eq. (5) by Laplace's method (see, e.g., Ref. 23) and using the formula $l_c=(\pi Na^2)^{-1}$, we obtain from Eqs. (5) and (6) the final expression for the CVC

$$j(F)=\frac{em(kT)^2}{\pi^2\hbar^3}\exp\left(-\frac{\Delta E_c}{kT}\right)\int_0^1\left[1-\exp\left(-\frac{F}{F_1}x\right)\right]\times\left[\frac{3\sqrt{3\pi}x^3F^3}{F_2^3}\exp\left(\frac{F^2}{F_2^2}x^2\right)+1\right]x\,dx,$$

$$F_1=\frac{kT}{el_c},\quad F_2=\sqrt{\frac{8m(kT)^3}{3e^2\hbar^2}}. \tag{7}$$

The formula contains two characteristic electric fields: F_1 and F_2. The field F_2 depends only on T and in LT GaAs at the room temperature is of the order of 70 kV/cm. F_1 depends also on l_c which, in turn, is determined by the cluster parameters N and a, and typically is much less than F_2. For instance, at $a=50$ Å and $N=5\times10^{16}$ cm^{-3}, $l_c\simeq2.5\times10^{-5}$ cm and $F_1\simeq1$ kV/cm.

For $F_1\ll F_2$ the formula for CVC can be simplified. At small F when $\exp(-(F/F_1)x)$ is comparable with unity, the exponential term in the second bracket is negligibly small whereas at larger F the opposite situation applies. This allows us to neglect the product of these exponents, which gives

$$j(F)=\frac{em(kT)^2}{\pi^2\hbar^3}\exp\left(-\frac{\Delta E_c}{kT}\right)\left\{\frac{1}{2}-\left(\frac{F_1}{F}\right)^2\times\left[1-\exp\left(-\frac{F}{F_1}\right)-\frac{F}{F_1}\exp\left(-\frac{F}{F_1}\right)\right]+\frac{3\sqrt{3\pi}F^3}{F_2^3}\int_0^1\exp\left(\frac{F^2}{F_2^2}x^2\right)x^4\,dx\right\}. \tag{8}$$

Equation (8) for the CVC consists of two parts. The first part depends only on F_1 and bears similarities to the characteristic of a reversely biased Schottky diode. The second part depends only on F_2 and grows exponentially for $F\gtrsim F_2$ due to thermally assisted tunneling through the local barriers surrounding the clusters. Figure 2 demonstrates the character of CVC for three different ratios F_1/F_2. For a considerable difference between F_1 and F_2, there exists a sublinear region where the thermal emission from clusters tends to saturation whereas the tunneling is not yet noticeable. This gives a qualitative explanation of the above-mentioned experimental results.

Figure 2 also shows the results of quantitative comparison of theory and experiment. We took experimental points from Ref. 12 and plotted them together with our theoretical curves assuming $\Delta E_c=0.65$ eV, $m=0.07m_0$ corresponding to n-GaAs, and no additional fitting parameters.

The theory explains adequately not only the shape of CVC but also its temperature dependence. It was shown[12] that the sublinear region is noticeable at temperatures compared to or exceeding room temperature, decreasing dramatically at 250 K. This results directly from our theory where the sublinearity is suppressed at small F_2/F_1 (i.e., compare curves 1–3 in Fig. 2) if we note that $F_2/F_1\sim\sqrt{T}$.

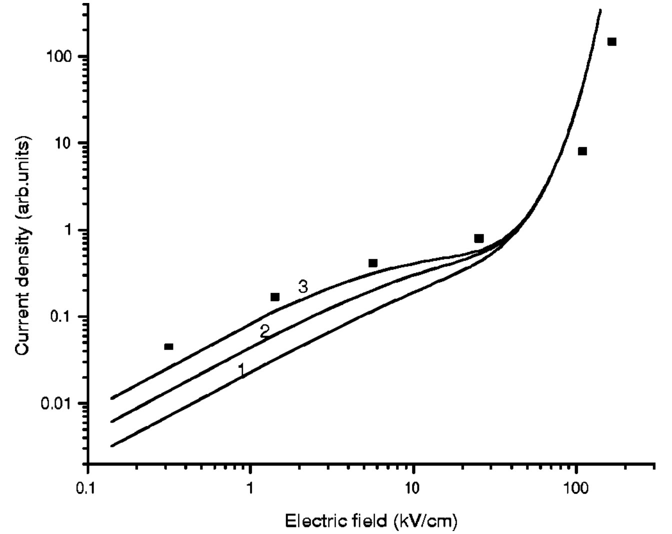

FIG. 2. CVC given by Eq. (8) for $F_2/F_1=5$ (curve 1), 10 (curve 2), 20 (curve 3). Closed squares show experimental points of Ref. 12 measured at $T=335$ K. Theoretical curves were calculated also for this temperature.

Thus far we have considered the scattering by the clusters to be the only scattering mechanism. The presence of other elastic scatterers (i.e., single impurities) characterized by the partial mean free path l_o will not change our results dramatically. The only differences will result from the fact that the carrier motion from cluster to cluster would then have a diffusive, rather than ballistic, character. As a result, the final formulas Eqs. (7) and (8) will acquire an additional factor of order $D/(l_cv)\sim l_o/l_c\ll1$ without any substantive changes in the CVC shape.

V. NONEQUILIBRIUM CARRIERS AND PHOTOCONDUCTIVITY IN LT GaAs

Properties of light-induced carriers in LT GaAs are the object of particular interest due to the anomalously short lifetime τ of photocarriers.[1] Qualitatively the effect is explained by a very effective recombination in semimetallic clusters. To describe the main characteristics of the phenomena, we should, as in Sec. III, distinguish between two different cases: ballistic and classical.

In the ballistic case τ coincides with the scattering time l_c/v (v is the carrier velocity) determining the mobility of carriers and discussed in Sec. III.

In the classical case the carrier motion between clusters is described by the diffusion equation. To formulate proper boundary conditions for it, we use the following simple procedure. Assume that clusters form a periodic lattice with unit cells centered by a cluster. By symmetry, the concentration gradient must vanish at the cell boundaries. By analogy with the Wigner-Seitz method for describing band structure (see,

e.g., Ref. 24), we replace the unit cell by a sphere having the same volume, that is, the radius $R=[3/(4\pi N)]^{1/3}$. In this case the diffusion equations for electrons and holes acquire spherical symmetry with the boundary conditions

$$\frac{dn}{dr}(r=R)=\frac{dp}{dr}(r=R)=0,$$
$$n(a)=p(a)=0. \tag{9}$$

The last equation reflects the very fast recombination at the cluster interface.

If diffusion coefficients of electrons and holes do not differ noticeably: $D_n \simeq D_p \simeq D$, then charge separation and electrostatic effects in diffusion are weak and for a stationary optical generation with a rate G, both types of carriers have the same spatial distribution

$$n(r)\simeq p(r)\simeq \frac{G}{3D}\left(\frac{R^3}{a}-\frac{R^3}{r}+\frac{a^2}{2}-\frac{r^2}{2}\right). \tag{10}$$

One can see that for $R \gg a$, the lifetime determined from the stationary concentration of nonequilibrium carriers is

$$\tau \simeq \frac{R^3}{3Da}. \tag{11}$$

Thus, for both cases considered, the lifetime of nonequilibrium carriers is very short and depends cubically on the cluster spacing: $\tau \sim R^3 \sim N^{-1}$. A superlinear character of the τ vs R dependence was confirmed experimentally in Ref. 1. Note that Eq. (11) differs from the $\tau \sim R^2$ dependence which is typical for one-dimensional diffusion.

For a large difference between D_n and D_p, the electric field caused by charge separation influences noticeably the diffusion processes. In samples with macroscopic inhomogeneities (say, p-n junctions) these effects result in ambipolar diffusion with a single coefficient D_a having the value between D_n and D_p. In our case the distance between clusters is less than the screening length, ambipolar diffusion has no place to form, and the situation is more complicated but allows an approximate analytical treatment.

We assume $D_n \gg D_p$. In this case almost all electrons are removed into clusters very fast and nonequilibrium carriers in the matrix are represented by holes moving toward clusters by both diffusion and drift in their own field $E(r) = (4\pi e/\varepsilon_0 r^2)\int_r^R r_1^2 p(r_1)dr_1$. The corresponding continuity equation is

$$D_p\frac{dp(r)}{dr}+\frac{4\pi e\mu_p}{r^2}p(r)\int_r^R r_1^2 p(r_1)dr_1=\frac{GR}{3}\left(\frac{R^2}{r^2}-\frac{r}{R}\right). \tag{12}$$

The character of its solution depends on which term on the left-hand side is dominating. For a very low light intensity (the criterion will be given later) the electric field is weak, the first term dominates, and we have the same answer as before [Eqs. (10) and (11)]. For r close to a, the concentration varies linearly:

$$p(r)\simeq (GR^3/D_p a^2)(r-a). \tag{13}$$

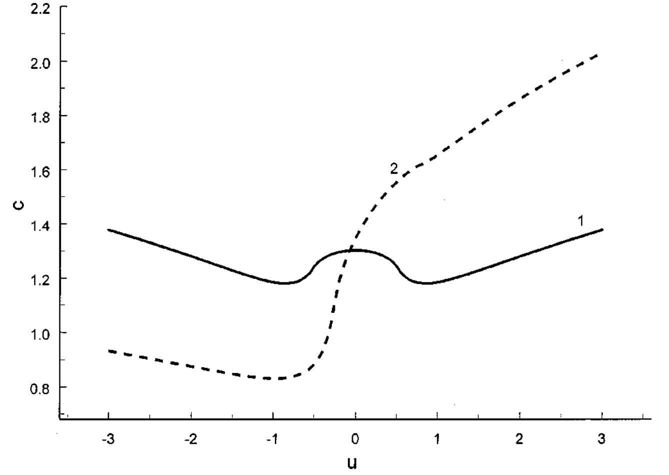

FIG. 3. The contact capacitance of LT GaAs for $\gamma=1$ (1) and $\gamma=3$ (2).

If we neglect the first term, Eq. (12) is satisfied by the constant concentration

$$p=\sqrt{\frac{G}{4\pi e\mu_p}}. \tag{14}$$

It is remarkable that the answer—Eq. (14)—is independent of any cluster parameters. This solution does not satisfy the boundary condition $p(a)=0$ since at $r \to a$ the first term can never be neglected (due to the vanishing factor p in the second term). In this region the solution is always given by Eq. (13). By comparing Eqs. (13) and (14), we find the distance r_0 where these two solutions are equal. If $r_0 \ll R$ then Eq. (14) is adequate always everywhere. In this case the effective carrier concentration determining photoconductivity is given by the same formula. The corresponding criterion is

$$G \gg \frac{a^4 D_p^2}{4\pi e\mu_p R^8}. \tag{15}$$

VI. CONTACT PHENOMENA

Semimetallic clusters in LT GaAs must provide an effective screening of external electric field resulting, particularly, in a series of unusual contact phenomena. The description of these phenomena should depend on the relation between the effective screening length λ (penetration length of the electric field) and the intercluster distance $N^{-1/3}$.

If $N\lambda^3 \gg 1$, then we can average the electric field in the plane xy parallel to the surface and consider the screening problem as one dimensional. In this case it is described by the Poisson equation:

$$\frac{d^2\varphi}{dz^2}=-\frac{4\pi}{\varepsilon_e}Nq[\varphi(z)], \tag{16}$$

where $q(\varphi)$ is the charge of a single cluster with the chemical potential ζ shifted from its equilibrium value ζ_0 by $e\varphi$. It is determined by the electron $\rho_n(\varepsilon)$ and hole $\rho_p(\varepsilon)$ densities of states: $q=-\int_0^{e\varphi}[\rho_n(\zeta_0+w)+\rho_p(\zeta_0+w)]dw$. We can

obtain an analytical solution by neglecting energy quantization in clusters and using for $\rho_{n,p}$ three-dimensional expressions: $\rho_n(\varepsilon)=\sqrt{2m_n^3\varepsilon}/(\pi^2\hbar^3)$; $\rho_p(\varepsilon)=\sqrt{2m_p^3(\Delta-\varepsilon)}/(\pi^2\hbar^3)$. In this case $\zeta_0=m_p\Delta/(m_n+m_p)$. We introduce dimensionless variables $u=e\varphi/\Delta$, $\xi=z/\lambda$ where

$$\lambda=\left[\frac{9\varepsilon_e\hbar^3}{32e^2Na^3(m_nm_p)^{3/4}(2\Delta)^{1/2}}\right]^{1/2} \tag{17}$$

plays the role of characteristic screening length in our system. This is virtually the Thomas-Fermi length in a system with the Fermi energy $\sim\Delta$ and the carrier concentration equal to the average concentration in LT GaAs $n_{\mathrm{As}}Na^3$. In these variables Eq. (16) acquires a simple form:

$$\frac{d^2u}{d\xi^2}=\gamma^{3/4}\left(\frac{1}{1+\gamma}+u\right)^{3/2}\Theta\left(\frac{1}{1+\gamma}+u\right)-\gamma^{-3/4}\times\left(\frac{\gamma}{1+\gamma}-u\right)^{3/2}\Theta\left(\frac{\gamma}{1+\gamma}-u\right), \tag{18}$$

where $\gamma=m_n/m_p$ and $\Theta(x)$ is the unit step function.

Equation (18) can be integrated, which gives us a connection between u and $du/d\xi$ at the surface $(z=0)$. The dimensionless electric field $(du/d\xi)(0)$ is proportional to the voltage-induced surface charge density and its derivative by $u(0)$ gives us the capacitance of the space charge layer C:

$$C=\frac{\varepsilon_e}{4\pi\lambda}\frac{d\left[\frac{du}{d\xi}(0)\right]}{d[u(0)]}=\frac{\sqrt{5}\varepsilon_e}{8\pi\lambda}\frac{\left|\gamma^{3/4}\left(\frac{1}{1+\gamma}+u\right)^{3/2}-\gamma^{-3/4}\left(\frac{\gamma}{1+\gamma}-u\right)^{3/2}\right|}{\left\{\gamma^{3/4}\left[\left(\frac{1}{1+\gamma}+u\right)^{5/2}-\left(\frac{1}{1+\gamma}\right)^{5/2}\right]+\gamma^{-3/4}\left[\left(\frac{\gamma}{1+\gamma}-u\right)^{5/2}-\left(\frac{\gamma}{1+\gamma}\right)^{5/2}\right]\right\}^{1/2}}. \tag{19}$$

This formula is derived for $-1<u(1+\gamma)<\gamma$ when the Fermi level everywhere lies inside the overlap of conduction and valence bands of As clusters. Outside this interval we should omit the brackets with negative arguments.

The capacity given by Eq. (19) at $u\to 0$ tends to a constant value determined by the density of states at the Fermi level. At large voltages, C increases $\sim|u|^{1/4}$, which is due to growth of the density of states with energy. For intermediate voltages the $C(u)$ behavior depends on the electron–hole asymmetry described by the parameter γ and may be nonmonotonic, as it is shown in Fig. 3.

Equation (19) has a limited applicability and is adequate only if the characteristic thickness of the space-charge layer λ exceeds the average distance between clusters $N^{-1/3}$ and our continuum approximation can be applied. This corresponds to a low enough cluster density N. At higher N our continuum approach based on averaging in the xy plane is inadequate and we should consider screening by each cluster separately so that the effective screening length becomes equal to the intercluster separation. A similar situation was predicted for a system of metallic wires[25] where at some critical density of wires the crossover from collective screening to that by individual wires is realized. In our case the critical cluster density $\tilde{N}$ corresponding to such a crossover and found from the condition $\tilde{N}\lambda^3$ and Eq. (17), is extremely sensitive to the cluster size a. As an example, for $a=10$ nm, $\tilde{N}=5\times10^{12}$ cm^{-3} whereas for $a=4$ nm, $\tilde{N}=3\times10^{17}$ cm^{-3}. This means that both screening mechanisms may occur in real LT GaAs structures.

The characteristic feature of LT GaAs is a high density of electron states providing an effective screening in combination with a very low conductivity. Similar properties are observed in some disordered systems, so-called ''Fermi glasses'' (see, e.g., Ref. 26) containing a high density of localized states at the Fermi level. The important consequence of this fact should be a strong frequency dispersion of C at relatively low frequencies $\sim\tau_M^{-1}$. In this frequency region (which depends exponentially on temperature) the contact capacitance of LT GaAs will decrease from large static values given by Eq. (19) to much lower values determined by the contact geometry. The observation of such strong, temperature-dependent dispersion was reported in Ref. 27.

VII. CONCLUSIONS

We have analyzed the model of LT GaAs considering this material as a GaAs matrix with semimetallic As inclusions, which fix the Fermi level position near the middle of the GaAs band gap and causing complete depletion of the matrix. As a result, the system is characterized by a very low carrier concentration in the matrix combined with a high density of states in the gap. The theory explains and predicts the following major properties of LT GaAs.

(1) The static conductivity σ has a very low value independent of the doping level, with the activation energy slightly less than one half of the GaAs band gap.

(2) ''Hall mobility'' σR_H is less than the real mobility in the matrix and decreases with the density of clusters simultaneously with the increase in σ.

(3) The conductivity has a strong frequency dispersion beginning from rather low frequencies $\omega\sim\tau_M^{-1}$ exponentially depending on temperature.

(4) The ac conductivity versus frequency dependence has a maximum at the plasma frequency in clusters.

(5) The conductivity and Faraday effect at high frequencies are proportional to the carrier concentration in clusters

and can be used for its determination.

(6) The current-voltage characteristic has an initial sublinear part followed by an exponential increase at high voltages, the sublinear portion becomes more revealed with the temperature growth.

(7) The lifetime of photocarriers is very short and for low light intensities inversely proportional to the cluster density.

(8) For high light intensities, the concentration of photocarriers is $\sim\sqrt{G}$ and does not depend on the cluster parameters.

(9) The static screening length is rather small, insensitive to the doping and at high cluster density N has the order of intercluster distance $N^{-1/3}$.

(10) Low-frequency capacitance-voltage characteristic of a contact to LT GaAs may be nonmonotonic and gives information of the electron-hole asymmetry in clusters.

(11) At $\omega\sim\tau_M^{-1}$ the contact capacitance and other screening-related characteristics have a strong frequency dispersion.

Properties (1), (3), (6), (7), and (11) have already been observed experimentally. Other properties are still waiting for detailed experimental analysis which also may bring new information on the properties of LT GaAs and, particularly, on the characteristics of clusters.

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[1] M. R. Melloch, J. M. Woodall, E. S. Harmon, N. Otsuka, F. H. Pollak, D. D. Nolte, R. M. Feenstra, and M. A. Lutz, Annu. Rev. Mater. Sci. **25**, 547 (1995).

[2] A. C. Warren, J. M. Woodal, J. L. Freeout, D. Grischkowsky, D. T. McInturff, M. R. Melloch, and N. Otsuka, Appl. Phys. Lett. **57**, 1331 (1990).

[3] D. C. Look, D. C. Walters, M. O. Manasreh, J. R. Sizelove, C. E. Stutz, and K. R. Evans, Phys. Rev. B **42**, 3578 (1990).

[4] A. Y. Shik, Sov. Phys. Semicond. **11**, 1030 (1977).

[5] A. Shik, *Electronic Properties of Inhomogeneous Semiconductors* (Gordon & Breach, New York, 1995).

[6] J. P. Kreskovsky and H. L. Grubin, J. Appl. Phys. **81**, 7326 (1997).

[7] M. G. Priestley, L. R. Windmiller, J. B. Ketterson, and J. Eckstein, Phys. Rev. **154**, 671 (1967).

[8] D. V. Rossi, E. R. Fossum, G. D. Pettit, P. D. Kirchner, and J. M. Woodall, J. Vac. Sci. Technol. B **5**, 982 (1987).

[9] K. Zhang and D. L. Miller, Mater. Res. Soc. Symp. Proc. **262**, 899 (1992).

[10] D. C. Look, G. D. Robinson, J. R. Sizelove, and C. E. Stutz, J. Electron. Mater. **22**, 1425 (1993).

[11] J. P. Ibbetson, J. S. Speck, N. X. Nguen, A. C. Gossard, and U. K. Mishra, J. Electron. Mater. **22**, 1421 (1993).

[12] J. P. Ibbetson and U. K. Mishra, Appl. Phys. Lett. **68**, 3781 (1996).

[13] P. Kordos, M. Marso, A. Forster, J. Darmo, J. Betko, and G. Nimtz, Appl. Phys. Lett. **71**, 1118 (1997).

[14] N. C. Chen, P. Y. Wang, and J. F. Chen, J. Appl. Phys. **83**, 1403 (1998).

[15] M. H. Cohen and J. Jortner, Phys. Rev. Lett. **30**, 696 (1973).

[16] A. L. Efros and B. I. Shklovskii, Phys. Status Solidi B **76**, 475 (1976).

[17] A. K. Sarychev and F. Brouers, Phys. Rev. Lett. **73**, 2895 (1994).

[18] K. Khirouni, M. Stellmacher, J. Nagle, and J. C. Bourgoin, Solid-State Electron. **43**, 589 (1999).

[19] Y. S. Galpern and A. L. Efros, Sov. Phys. Semicond. **6**, 941 (1972).

[20] I. I. Fishchuk, Sov. Phys. Solid State **32**, 1467 (1990).

[21] V. T. Potapov, V. I. Trifonov, I. I. Chusov, and N. G. Yaremenko, Sov. Phys. Semicond. **6**, 1076 (1972).

[22] L. D. Landau and E. M. Lifshits, *Electrodynamics of Continuous Media* (Pergamon, New York, 1984).

[23] E. T. Copson, *Asymptotic Expansions* (Cambridge University Press, Cambridge, 1965).

[24] J. M. Ziman, *Principles of the Theory of Solids* (Cambridge University Press, Cambridge, 1972).

[25] N. S. Averkiev and A. Shik, Semiconductors **30**, 112 (1996).

[26] N. F. Mott and E. A. Davis, *Electronic Processes in Noncrystalline Materials* (Clarendon, Oxford, 1979).

[27] J. Darmo and F. Dubecky, in *Semi-insulating III-V Materials*, edited by M. Godlewski (World Scientific, Singapore, 1994), p. 355.