Electron localization during nonlinear screening of the small-scale fluctuation potential of a GaAs–AlGaAs heterojunction

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Experimental confirmation of a pronounced localization of the electron gas at minima of the small-scale potential well of a GaAs–AlGaAs heterojunction has been found. The energy scale ($\Delta \simeq 18$ meV) and the length scale (200–400 Å) of the fluctuations have been found. The value of Δ is essentially equal to the typical Coulomb energy of the interaction of ionized donors in the *n*-AlGaAs layer.

Random fluctuations of the potential at an interface between solids in a quasi-2D system can lead to a trapping of charge carriers at minima of the potential well and thus to fundamental changes in the electronic properties of the structure.[1-5] Manifestations of a fluctuation potential can be studied conveniently in modulation-doped epitaxial GaAs–AlGaAs heterostructures with a thin spacer. The source of the random field in epitaxial heterostructures consists of fluctuations of the local density of ionized donors in the wide-gap *n*-AlGaAs semiconductor layer. The average density N_d and the spatial position of these donors are well known.

In this letter we show that by combining the method of the classical field effect with the magnetoresistance effect one can extract quantitative data on the energy and length scales of the fluctuation potential for heterostructures, on the degree of localization of the quasi-2D electron gas, and on the temperature dependence of the density of this gas.

In an epitaxial heterostructure with a thin spacer, the random fields of donors are effectively screened by a gate, so the fluctuation potential is induced primarily by a donor layer of thickness $\delta < d_d$ (d_d is the thickness of the *n*-AlGaAs) adjacent to the heterostructure. The charge density in this layer, $n_d = N_d\delta$, determines the characteristic energy scale of the fluctuation potential,[3] $\Delta = q^2(\pi n_d)^{1/2}/\kappa$, where κ is the average dielectric constant of GaAs and AlGaAs, and q is the elementary charge. The length scale of the fluctuation potential (the screening length R_{FP}) is bounded above by the distance between the heterojunction and field electrode, $d = d_d + d_i$, where d_i is the spacer thickness. Electrons capable of moving along the heterojunction become redistributed among the minima of the potential well. Localizing in these minima, they cancel the fluctuations in the potential with a scale greater than the nonlinear screening length $R_s = (n_d/\pi)^{1/2}/n_s = \kappa\Delta/\pi q^2 n_s$ (n_s is the total density of electrons at the

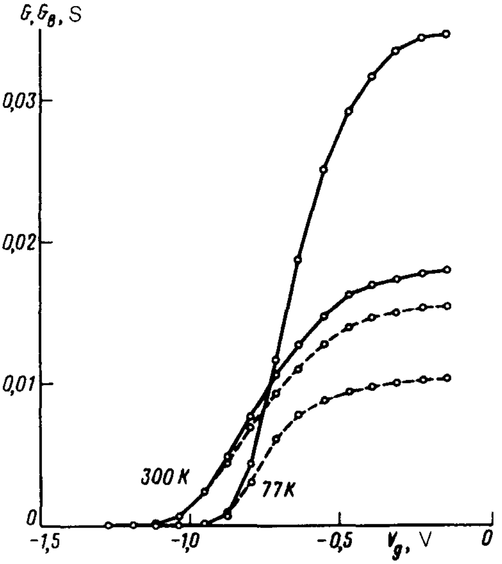

FIG. 1. Conductance of the heterostructure versus the potential of the field electrode at 300 and 77 K. Solid lines—without a magnetic field; dashed lines—in a magnetic field of 0.8 T.

heterojunction). We thus have $R_{FP}=\min\{d, R_s\}$. Expressions relating Δ, n_s, and the free-electron density n_c for a nondegenerate electron gas were derived in Refs. 3 and 4. In the case of a nonlinear screening of a strong fluctuating potential ($n_s \gg n_c$, $\Delta \gg kT$, where T is the temperature, and k is the Boltzmann constant), we have $n_c \propto \exp(q\varphi_s/kT)$ and $n_s \propto \exp(q\varphi_s/2\Delta)$. In other words, n_c is related to n_s in a power-law fashion: $n_c \propto n_s^{2\Delta/kT}$, where φ_s is the average potential of the heterojunction. The energy and length scales of the fluctuation potential can thus be found experimentally from the $n_c(n_s)$ dependence, which characterizes the degree of localization of the electron gas.

By definition we have $n_c(V_g) \equiv \sigma_c/q\mu_c$ and $n_s \propto (V_g - \varphi_s + \text{const})$, where $\varphi_s = (kT/q)\ln(n_c) + \text{const}$, σ_c is the conductivity of the quasi-2D channel, and μ_c is the electron mobility. To find the unknown function $n_c(n_s)$, all we have to do is thus measure $\sigma_c(V_g)$ and $\mu_c(V_g)$. The first of these relationships can be found from data on the field effect, and the second from data on the geometric magnetoresistance.

The test samples were heterostructures grown by the method of molecular beam epitaxy. They consisted of layers of TiAu (the field electrode), n-Si:Al$_{0.3}$Ga$_{0.7}$As ($d_d=350$ Å, $N_d=10^{18}$ cm^{-3}), i-Al$_{0.3}$Ga$_{0.7}$As (the spacer, $d_i=30$ Å), i-GaAs (1 μm thick), and Cr:GaAs (a semi-insulating substrate). The length l and width W of the field electrode were 0.6 and 60 μm. The distance between the current contacts and the heterojunction (the alloy NiAuGe) was $L=3$ $\mu\text{m} \ll W$. This spacing satisfied the conditions for observing a geometric magnetoresistance. Using the method of Ref. 6, we measured the channel conductance as a function of V_g in the presence and absence of a magnetic field $B=0.8$ T: $G(V_g)$ and $G_B(V_g)$, respectively. This field was normal to the heterojunction. Figure 1 shows the corresponding curves for 300 and 77 K. In general, the shape of these curves corresponds to the classical understanding of the

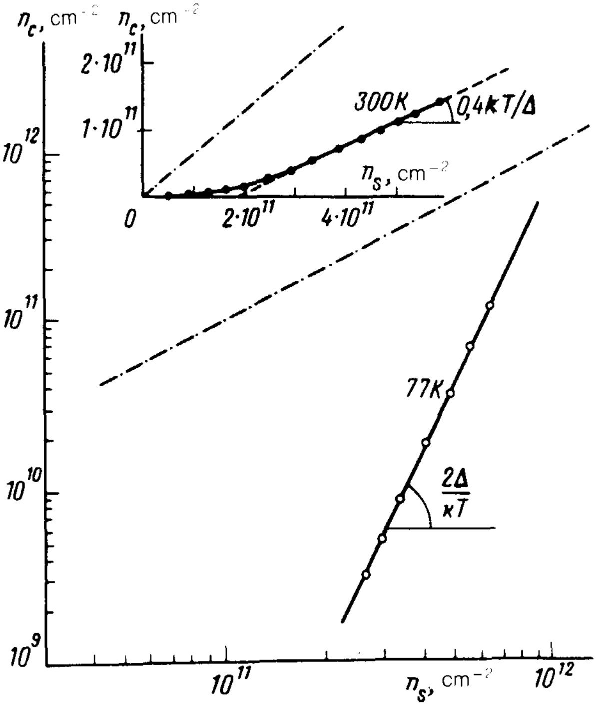

FIG. 2. Density of free electrons, n_c, versus the total electron density n_s at a heterojunction at 77 and 300 K (the inset). The dot-dashed lines show the difference $n_c - n_s$.

electronic properties of heterostructures:[7] G and G_B increase with V_g and then reach a plateau, because the conductance of the structure is limited by passive regions of the heterojunction adjacent to the current contacts ("passive" here means that they are not modulated by the field effect). Here we obviously have $G = (\sigma_c W/l) \times [1 + \sigma_c(L - l)/\sigma_0 l]^{-1}$ and $G_B = (\sigma_c W/l)[1 + \mu_c^2 B^2 + (1 + \mu_0^2 B^2)\sigma_c(L - l)/\sigma_0 l]^{-1}$. The subscript *c* corresponds to the active part of the heterojunction, and the subscript *o* to the passive part. The measured characteristics $G(V_g)$ and $G_B(V_g)$ contain, in addition to the unknown functions $\sigma_c(V_g)$ and $\mu_c(V_g)$, the two constants σ_0 and μ_0. It is a simple matter to find these constants from the height of the plateaus on the $G(V_g)$ and $G_B(V_g)$ curves. This height is determined by the conditions $\sigma_0 \simeq \sigma_c$ and $\mu_0 \simeq \mu_c$,[7] where $G \simeq \sigma_0 W/L$ and $G/G_B - 1 \simeq \mu_0^2 B^2$. As a result, from the experimental data in Fig. 1 we find $\sigma_c(V_g)$, $\mu_c(V_g)$, $n_c(V_g)$, and $n_s(V_g) = (\kappa_0/4\pi q d) \times [V_g - V_g^* - (kT/q)\ln(n_c/n_c^*)] + n_s^*$,[8] where κ_0 is the dielectric constant of AlGaAs, V_g^* is the potential of the field electrode corresponding to the threshold for flashover of the channel, $n_c^* = n_c(V_g)\,|_{V_g = V_g^*}$, and

$$n_s^* = [\kappa_0(kT)^2/4\pi q^3 d]\,[(dV_g/d\ln n_c) - kT/q]/[d^2 V_g/d(\ln n_c)^2]\,|_{V_g = V_g^*}.$$

Figure 2 shows curves of $n_c(n_s)$ plotted in this manner for 77 and 300 K. Clearly, the condition $n_c \ll n_s$ holds at 77 K, and n_c is a power function of n_s with a power $\alpha = 5.4$. This result corresponds in principle to the theoretical ideas of Refs. 3 and 4 regarding a nonlinear screening of a strong fluctuation potential. According to Refs. 3 and 4 we

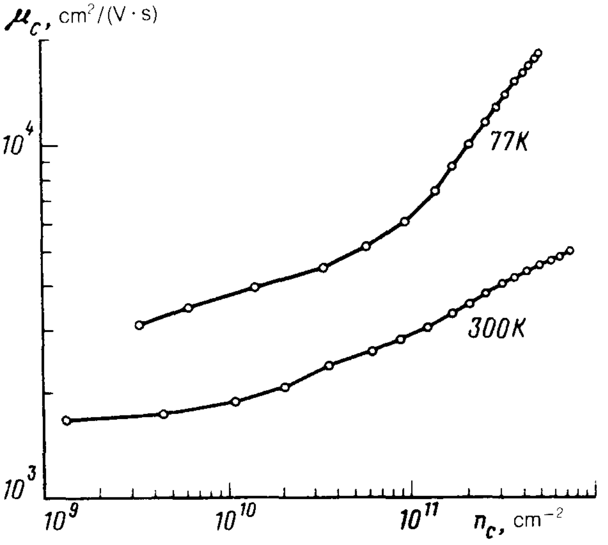

FIG. 3. Density dependence of the mobility of electrons at the heterojunction.

have $\alpha = 2\Delta/kT$; hence we find $\Delta \simeq 18$ meV$\gg kT$. The energy scale of the fluctuation potential determines the effective thickness of the donor layer which induces this potential: $\delta = n_d/N_d = \Delta^2\kappa^2/(\pi q^4 N_d) \simeq 70$ Å. This value of δ is close to the average distance between impurities, $r_d = (3/4\pi N_d)^{1/3} \simeq 60$ Å. At the same time, according to Ref. 2 the energy scale of a surface fluctuation potential is determined by the energy of the Coulomb interaction of the charged centers, $\Delta = (q^2/\kappa)(4\pi N_d/3)^{1/3}$, regardless of whether these centers have a bulk or surface distribution. In other words, the observable value is $n_d \simeq N_d r_d \simeq N_d^{2/3}$ or, in the case at hand ($N_d = 10^{18}$ cm^{-3}), $\Delta \simeq 17$ meV. This result is essentially the same as that found above. Together, these results lead to the conclusion that the theory of Refs. 2–4 gives a good description of experiment, and that an interface in a heterostructure with a thin spacer is characterized by a strong fluctuation potential, induced by ionized donors nearest the interface and manifested under conditions of nonlinear electron screening.

Since we have $\Delta \simeq 18$ meV$\leqslant$kT at 300 K, the approximation of the theory of a strong fluctuation potential is not valid at this temperature. The corresponding case was studied in Ref. 4, where it was shown that under the condition $0.5 \leqslant \Delta/kT \leqslant 2$ the density n_c is a linear function of n_s:$n_c \simeq (0.4kT/\Delta)n_s + \text{const}$. On the experimental $n_c(n_s)$ curve for 300 K, shown in the inset in Fig. 2, we can clearly see a linear region. The slope of this region corresponds to the value $\Delta \simeq 16.5$ meV, which is fairly close to the value $\Delta(77\text{ K}) \simeq 18$ meV. Consequently, for the typical doping of the n-AlGaAs layer, the electron gas can be localized extremely strongly at the heterojunction, even at room temperature.

Since we have $R_s = \kappa\Delta/(\pi q^2 n_s)$, the regime of nonlinear screening of the fluctuation potential ($R_s < d = 380$ Å) is realized experimentally at $n_s \geqslant 10^{11}$ cm^{-2}, i.e., under conditions such that the electron localization is effectively manifested (Fig. 2).

Since we have $R_{FP}=\min\{d, R_s\}$, we have $R_{FP}=R_s$. The electron mean free path $l_n=m\mu_c v_T/q$ (m is the effective mass of the charge carriers, and v_T is their thermal velocity), becomes larger than R_{FP} beginning at values $\mu_c \simeq 3.5\times 10^3$ (77 K) or 2×10^3 cm^2/(V·s)(300 K) (Fig. 3). In other words, the fluctuation potential of the heterojunction is predominantly a small-scale potential. Accordingly, the electron mobility found from the magnetoresistance should be interpreted as a microscopic mobility, so the quantity $n_c=\sigma_c/q\mu_c$ should be interpreted as the density of free electrons.

We note in conclusion that the distance between impurities, $r_d \simeq 60$ Å, and the width of the region of spatial localization of electrons at the minima of the potential well of the heterojunction,[3] $z_0 \simeq a_B^{3/4}\, r_d^{1/4} \simeq 90$ Å (a_B is the effective Bohr radius), which put a lower limit on the distance to which electrons can approach ionized donors, are much greater than the spacer thickness $d_i \simeq 30$ Å. This circumstance is definite support for describing the present experiments by the theory of Refs. 2–4, which was constructed without consideration of a spatial separation of the quasi-2D electron gas and the ionized donors in the n-AlGaAs layer.

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