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Electron mobility engineering in semiconductor heterostructures

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Abstract

It is well known that at low temperatures the acoustic-phonon limited mobility of a two-dimensional electron gas in GaAs heterostructures is determined predominantly by piezoelectric scattering. We suggest a way of significantly enhancing of the acoustic-phonon limited mobility by reducing piezoelectric scattering via inserting thin metal layers at finite distances from the electron channel. As an example, for a GaAs quantum well of 100 Å width placed between two metal layers and separated from them by 50 Å, the mobility at $T = 0.2$ K increases by about 10 times. Moreover, the mobility increases several times when only one metal layer or highly doped semiconductor is placed near a narrow well.

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1. Introduction

At low temperatures, a two-dimensional electron gas (2DEG) in a GaAs-based heterostructure has a very high electron mobility. The mobility measured at low temperatures exceeds 10^7 cm^2/V s [1–4] and is limited by scattering from impurities and lattice imperfections. The ultimate limits on the mobility, μ, do not depend on the temperature. With increasing temperature, T, the mobility starts to drop due to an increase in the contribution of acoustic phonons to the scattering. Assuming Mathiessen's rule, a temperature dependence of the total mobility, $\mu(T)$, within the low temperature range is determined as $\mu^{-1}(T) = \mu_i^{-1} + \mu_{ac}^{-1}(T)$ where μ_i and μ_{ac} are mobilities limited by the impurities and acoustic phonons, respectively. The theory of the acoustic-phonon limited mobility, μ_{ac}, of 2DEG was developed in Refs. [5–8].

Extremely high mobilities are achieved as a result of the progress in semiconductor technology, which facilitates the fabrication of heterostructures where scattering from impurities and lattice imperfections is reduced dramatically. Although the situation where the scattering from acoustic phonons is the

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main process that limits mobility has not been realized, this limit can be determined. In Ref. [3], this idealized limit was considered by subtracting a temperature-independent quantity from measured data for $\mu^{-1}(T)$. It was shown in accordance with theory [5–8] that at the lowest temperatures, the acoustic-phonon limited mobility is determined mainly by screened piezoacoustic (PA) scattering. An indirect estimate of the phonon limited mobility was obtained in Refs. [9,10] from measurement of the electron energy relaxation time. In addition to reducing the scattering from impurities by further improvement of epitaxy conditions, another way to enhance the mobility is to reduce undesirable acoustic-phonon scattering. The aim of this paper is to demonstrate this possibility. At low temperatures, μ_{ac} is determined by PA scattering as a result of its weaker temperature dependence compared to that associated with deformation potential (DP) scattering. For temperatures, T, far below the Bloch–Grüneisen temperature $T_0 = 2s\hbar k_F/k_B$ the partial relaxation rates, $1/\tau_{PA}$ and $1/\tau_{DP}$, associated with PA and DP screened interactions drop as T^5 and T^7, respectively [5–8]. The factors determining the Bloch–Grüneisen temperature T_0 are the sound velocity, s, the electron Fermi wavevector, k_F, and Boltzmann's constant, k_B.

2. Simulated structure and theoretical model

Enhanced mobility can be achieved in the structures where the PA interaction is suppressed. Such a possibility occurs for a 2DEG placed between two metal layers which are incorporated in the potential barriers at finite distances from the quantum well (QW) or when the QW is placed near a single metal layer; see the inset of Fig. 1. Indeed, as far as the piezoelectric potential vanishes at a metal surface, in the long-wavelength limit (valid at low temperatures) the potential remains small at a finite distance from the metal as well. At the same time, the proximity of the QW to the metal results in a reduction of screening that causes an increase in both scattering rates. The DP interaction is altered only by the change in screening. The metal-induced modification of the PA interaction originates not only from the reduction of the piezoelectric potential but from the reduction of screening as well. For $T \ll T_0$, the change in electron

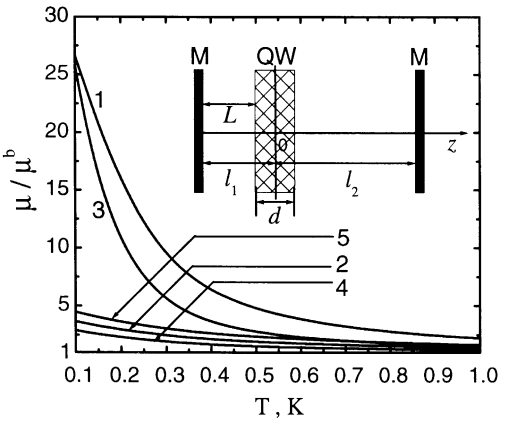

Fig. 1. Ratio of mobility calculated for QW with metal layers to that of bare QW versus the temperature. The electron sheet density is $n_s = 10^{11}$ cm^{-2}, width of well d: (1,2) 40 Å, (3,4) 100 Å. Curves 1 and 3 correspond to the symmetrical structure with two metal layers separated by a spacing of $L = 50$ Å from walls of rectangular well; curves 2 and 4 correspond to structure with one metal layer. Curve 5 represents results for triangular well with a spacing $L = 50$ Å. The structure under consideration is represented schematically in the inset: the metal layers are at the distances l_1 and l_2 from a center of QW of width d. For triangular QW, only one metal layer is placed at the distance L from the interface ($l_2 \to \infty$).

energy due to scattering with phonons is of the order of $k_B T$ and a typical value of the phonon wave vector q can be estimated as $q \simeq k_B T/\hbar s \ll k_F$. If a metal surface is at a distance l from the QW center, the suppression of the bare PA potential and the reduction of screening factor are substantial when $ql \lesssim 1$, i.e. for the temperatures $T \lesssim \hbar s/k_B l$. For $l = 100$ Å and $s = 3\times10^5$ cm/s, we obtain the estimate of $T \sim 2$ K for the upper limit of the temperature range where the effect may exist.

Incorporation of metal–semiconductor junctions have been proposed earlier [11] in order to reduce the optical phonon scattering by tailoring the interface optical modes. Nanostructures containing metal–semiconductor heterojunctions can be fabricated with highly uniform interfaces [12]. In our paper, we assume that the presence of metal layers does not modify the acoustic phonon modes, in contrast to the case of optical phonons. This assumption can be justified if discontinuity in elastic properties of host material and foreign layers is small enough. For example, Al metal provides good acoustic matching

to GaAs [13]. For Al–GaAs interface, the transmission coefficient used to estimate mismatch is almost the same as for AlGaAs–GaAs system, where the common accepted approach is to use bulk phonon modes.

We will also neglect a change of mobility caused by Coulomb coupling between electrons of QW and electrons in the metal layers. The measurements on Coulomb drag [14,15] showed that the current driven through 2DEG induced a current in three-dimensional electron gas (with concentration higher than $10^{18}\,\mathrm{cm}^{-3}$) about 10^5 times smaller. In Ref. [16], it was found that due to screening in the passive layer, the influence of this layer on the mobility in the active layer decreases as the temperature decreases and/or the concentration of carriers in the passive layer increases.

The inset of Fig. 1 shows schematically a quantum well placed between thin metal layers which are inserted in the potential barriers. Due to rapid decay of a quasistatic electrical potential in a metal (the scale is set by the Thomas–Fermi screening length), a few atomic layers are enough to render the potential at the metal–semiconductor interface equal zero. We assume that the spacing between the 2DEG channel and the metal layer is large enough so that the stationary electron distribution is unaffected by the presence of the metal.

Electrons occupy the lowest QW subband with the energy spectrum $\varepsilon = p^2/2m^*$ and the density distribution $\psi^2(z)$. Let the z-axis be oriented along the (0 0 1) direction in a cubic crystal. For the sake of simplicity, we assume the same elastic and piezoelectric properties, densities, and dielectric constants for the semiconductor materials composing heterostructure. We assume that electrons interact with conventional bulk acoustic phonons, which are found in the isotropic continuum approximation. The energy of the electron–acoustic phonon interaction is $V = D\,\mathrm{div}\,\mathbf{u} + \mathrm{e}\phi$ where D is the deformation potential constant, $\mathbf{u}$ is the acoustic displacement, and ϕ is the total electric potential; that is, it is the sum of the piezoelectric potential and potential induced by redistribution of the electron density. The acoustic displacement, $\mathbf{u}(\mathbf{r},t)$, and potential, $\phi(\mathbf{r},t)$, are taken to be proportional $\exp(\mathrm{i}\mathbf{qr} - \mathrm{i}\omega t)$, where $\mathbf{q}$ is the phonon in-plane wave vector, and ω is the angular frequency. The dependence of the potential on z-coordinate is determined by Poisson's equation

$$\frac{\partial^2\phi}{\partial z^2} - q^2\phi = \frac{4}{\mathrm{e}a_\mathrm{B}}\langle V\rangle\psi^2 + \beta\left(\mathrm{i}q_x\frac{\partial u_y}{\partial z} + \mathrm{i}q_y\frac{\partial u_x}{\partial z} - q_xq_yu_z\right) \tag{1}$$

and the boundary conditions

$$\phi(z = -l_1) = \phi(z = l_2) = 0. \tag{2}$$

Here, $a_\mathrm{B} = \varepsilon_0\hbar^2/m^*\mathrm{e}^2$ is effective Bohr radius, ε_0 is the lattice dielectric permittivity, $\beta = 8\pi e_{14}/\varepsilon_0$, and e_{14} is the component of the piezoelectric tensor which relates the strength of an electric field to the strain tensor. In Eq. (1) we have used the definition

$$\langle f\rangle = \int_{-l_1}^{l_2}\mathrm{d}z\,\psi^2(z)f(z). \tag{3}$$

In Eq. (1) the screening is taken into account within the Thomas–Fermi approximation.

We present results for a mobility that is defined as in several papers [3,5–8,17]: $\mu = \mathrm{e}\tau/m^*$, where τ is the mean momentum relaxation time due to intrasubband transitions. For degenerate electrons

$$\frac{1}{\tau} = \frac{m^*}{8\pi^2\hbar\rho k_\mathrm{F}^3k_\mathrm{B}T}\sum_j\int_0^\infty\mathrm{d}\omega\int_0^{2k_\mathrm{F}}\mathrm{d}q \times\frac{\omega q^2|M_j|^2|J_j|^2}{|\varepsilon|^2s_j^2q_j(1-(q/2k_\mathrm{F})^2)^{1/2}\sinh^2(\hbar\omega/2k_\mathrm{B}T)}. \tag{4}$$

Here, the summation is over the phonon modes involved in the scattering. The variables ω and q are expressed through the energy and momentum transfer of the electrons: $\omega = |\varepsilon - \varepsilon'|/\hbar$, $q = |\mathbf{p} - \mathbf{p}'|/\hbar$, $q_j = (\omega^2/s_j^2 - q^2)^{1/2}$, where $\mathbf{p}$ and $\mathbf{p}'$ are the initial and final 2D momenta of electrons, s_j is sound velocity, $j = l(t)$ labels longitudinal (transverse) waves. M_j is the matrix element for a strictly 2D electron gas in the absence of metal layers and the electron form factor J_j takes into account the finite thickness of the electron density distribution and depends on the distance from the QW to the metal layers. For the dielectric function ε we get $\varepsilon = 1 + (2/a_\mathrm{B}q)H(q)$,

where $H = H_b - H_m$:

$$H_b = \int_{-l_1}^{l_2} dz \int_{-l_1}^{l_2} dz' \psi^2(z)\psi^2(z') e^{-q|z-z'|}, \quad (5)$$

$$H_m = \frac{1}{e^{2q(l_1+l_2)} - 1} \times [e^{2ql_1}\langle e^{qz}\rangle^2 + e^{2ql_2}\langle e^{-qz}\rangle^2 - 2\langle e^{-qz}\rangle\langle e^{qz}\rangle]. \quad (6)$$

The function H_b describes the screening in a bare QW and H_m reflects the influence of the metal. For the piezoelectric interaction, the form factor is $J_j = J_j^{(b)} + J_j^{(m)}$ where $J_j^{(b)} = \langle e^{iq_j z}\rangle$ is the form factor for a bare QW, and $J_j^{(m)}$ provides the effect of the metal layers

$$J_j^{(m)} = \frac{1}{\sinh q(l_1 + l_2)} \times [e^{-iq_j l_1}\langle \sinh q(z - l_2)\rangle - e^{iq_j l_2}\langle \sinh q(z + l_1)\rangle]. \quad (7)$$

The scattering via the deformation potential is determined by the interaction with longitudinal phonons; the form factor coincides with that of a bare QW and the influence of the metal is described only by the screening function of Eq. (6).

In the limit of temperatures much smaller than the transition temperature of Bloch–Grüneisen regime, the scattering is described by the low-angle approximation which is expressed by the inequalities $qd, q_j d \ll 1$, where d is an effective width of the QW. For a bare QW as $l_{1,2} \to \infty$, $H_m = J_j^{(m)} = 0$; under these conditions, one can set $H_b = J_j^{(b)} = 1$, and $\varepsilon \simeq 2(a_B q)^{-1}$ to obtain, as in Refs. [5–8], that $\mu_{PA} \sim T^{-5}$ and $\mu_{DP} \sim T^{-7}$. As stated previously, the PA scattering determines the mobility at low temperatures. When the 2D channel is placed between two metal layers and the distances l_1 and l_2 are comparable to d, then in the same temperature limit, the inequalities $ql_{1,2} \ll 1$ and $q_j l_{1,2} \ll 1$ are also valid. In this case, we get $|J_j|^2 \sim C(\omega/s_j)^4$, where C is a constant which depends on l_1 and l_2 and the parameters which specify the electron density $\psi^2(z)$. In the small-q limit, the function H is a linear function of q, and the dielectric permittivity ε does not depend on q. Such a change of the form factor and the screening gives rise to a dramatic change in the temperature dependence of the mobility in comparison to that of a bare QW. From Eq. (4) we find $\mu_{PA} \sim T^{-7}$ and $\mu_{DP} \sim T^{-5}$; thus, the PA scattering loses its dominant role at low temperatures.

For a heterostructure that has only one metal layer, in the small-q limit we get $|J_j|^2 \sim (\omega/s_j)^2$. In this case, the screening function ε also does not depend on q, and as a result we obtain the identical power laws: $\mu_{PA}, \mu_{DP} \sim T^{-5}$. So for this structure, both mechanisms under consideration contribute to mobility at the lowest temperatures. The last mentioned, T^{-5}, power laws coincide with the results obtained in Ref. [18] for a QW that is placed near a semiconductor surface covered with a thin high-conducting film, where the scattering from acoustic modes of semi-infinite medium has been considered. This fact justifies the bulk acoustic-phonon approximation used in the present paper to demonstrate the role of metal films.

3. Numerical results

Numerical calculations were carried out for an infinitely deep rectangular QW and a triangular QW with the Fang–Howard wave function for the following parameters of GaAs: $e_{14} = 0.16$ C/m^2 and $D = 8$ eV. To show the metal-induced effect more clearly, we calculated the ratio μ/μ^b, where μ^b is the mobility in bare channel. Dependences of normalized mobility on temperature are shown in Fig. 1. We see that influence of two metal layers (curves 1 and 3) is much stronger than that of one layer (curves 2, 4 and 5) and the effect is noticeable for $T \lesssim 1$ K. The mobility enhancement practically does not depend on the electron sheet density n_s. As seen from Fig. 2, metal layers placed even at large distances increase the mobility, and the influence of the metal layers is more pronounced for narrow QWs. In Fig. 3 we represent the acoustic-phonon limited mobility of a 2DEG in the structure with two (curve 1) and one (curve 3) ideal metal layers and in the absence of metal layers (curve 5). We emphasize that the acoustic-phonon limited mobility obtained in Ref. [3] corresponds to curve 5. The theoretical limit of mobility decreases when the metal is replaced by a highly doped semiconductor with a non-zero screening length, l_s. (The generalized expressions for screening function and form factor are not included in this paper.) Comparing curve 3 ($l_s = 0$ Å) and curve 4 ($l_s = 30$ Å) with curve 5, we see that the enhancement of mobility may remain substantial even when

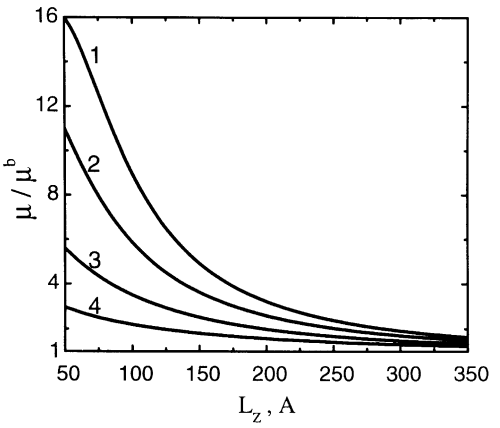

Fig. 2. Ratio of mobility calculated for a rectangular QW with metal layers to that of a bare QW as a function of a distance L from interface to metal layer: $n_s = 3\times10^{11}$ cm^{-2}, $T = 0.2$ K, width d for symmetrical structure: (1) 40 Å, (2) 100 Å, (3) 200 Å, (4) 40 Å for structure with one metal layer.

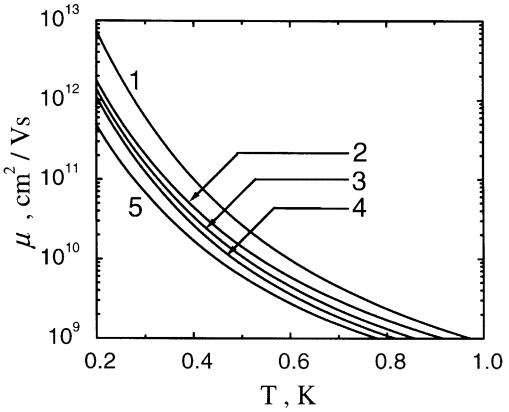

Fig. 3. Acoustic-phonon limited mobility of 2DEG in (0 0 1) GaAs rectangular quantum well structure with $L = 50$ Å, $d = 40$ Å (curves 1, 3, and 4) and triangular well (curves 2 and 5) versus temperature; $n_s = 10^{11}$ cm^{-2}. Curves 3 and 4 are calculated for a structure having screening lengths in inserted layers: 0 and 30 Å, respectively.

the 2DEG is in the proximity to highly doped semiconductor. Let us note that the same screening function H_m and form factor $J_j^{(m)}$ of Eqs. (6) and (7), respectively, are used to describe the electron energy losses in the presence of inserted metal layers. The influence of metal layers on the electron energy relaxation rate is similar to the results demonstrated in Figs. 1 and 2.

4. Conclusion

In conclusion, we have found that establishing metal–semiconductor interfaces can significantly increase the mobility of the electrons in 2D channels due to the suppression of the piezoacoustic coupling. For GaAs-based heterostructures, this effect is well pronounced at temperatures less than or about 1 K. The temperature range of the effect under consideration can be larger for semiconductor materials having larger piezoelectric moduli. The metal layers can be replaced by highly doped semiconductor layers having thicknesses enough to screen the piezoelectric potential.

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