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Evidence of formation of an X_L miniband in short-period type-II GaAs/AlAs superlattices

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Abstract

The vertical magnetoresistance was explored in short-period doped GaAs/AlAs superlattices. The effect of the vertical longitudinal magnetoresistance expected to occur in the case of the open Fermi surface was found. The analysis of the possible position of the Fermi level allowed us to distinguish the type of the lowest miniband—between Γ and X origins. Our results indicate that the lowest miniband is formed by the X_L electron states of GaAs and AlAs. The result agrees with the theoretical predictions and shows that the residual stress does not significantly influence the miniband structure of the short-period superlattices studied.

Spatial localization results in different confinement energies corresponding to the Γ and X electron states in GaAs and AlAs. Therefore, two types of superlattice can be realized in the GaAs/AlAs heterosystem depending on the relative thicknesses of the layers. In long-period superlattices with periods larger than some tenths of an ångström, the lowest conduction miniband arises due to the superposition of the Γ electron states of GaAs and AlAs, while as the thicknesses are decreased the X states of GaAs and AlAs produce the miniband with the lowest energy [1, 2]. The first of the above structures corresponds to type I, while the second corresponds to type II. In the superlattice of type I the optical interband transitions are expected to be caused by direct electron transfer between the Γ valence and conduction band states localized in the wells, while the pseudo-direct optical transitions between the Γ states of the valence band and the X states of the conduction band occur in the superlattice of type II.

Furthermore, two types of X electron state can be involved in the miniband formation: those originate from X_L valleys oriented along the growth direction of a superlattice (z) and those derived from X_T valleys directed parallel to the x- and y-directions.

Two factors determine which type of superlattice structure will occur; they are: the already discussed confinement effects and the influence of the residual uniaxial stress related to the small lattice mismatch between GaAs and AlAs on the electron state energy which are different for the states of different origins.

The type (Γ or X) of the lowest miniband can dramatically change the optical and electronic properties of the devices based on the semiconductor superlattices. The effects of the stress depend on the superlattice structure and growth conditions and cannot be taken into account accurately in the calculation of the miniband structure. Therefore, experimental investigation of the origin of the superlattice minibands is of great importance.

Photoluminescence spectroscopy has been widely used to study the origins of the minibands and the effects of the Γ–X mixing in the superlattices (see [3] and references therein). However, the optical interband transitions involve the electron states of the valence band, which complicates the analysis. A separate contribution of the conduction band states to the formation of the electron minibands can be studied by means of transport measurements on the doped superlattices. The vertical transport through the Γ miniband was studied in [4]. Evidence of the X electron states was obtained from resonant tunnelling measurements on single-and double-well structures [5, 6]. However, to the best of our knowledge, no transport measurements associated with the conduction through the X miniband in superlattices have been reported.

This letter is devoted to the study of the miniband character in the short-period GaAs/AlAs superlattices where the lowest miniband is expected to be due to the X electron states. The data obtained do indeed indicate the formation of an X_L lowest miniband in accordance with the theoretical predictions.

The samples used were the $(GaAs)_5(AlAs)_5$ superlattices doped with Si, where the numbers denote the thicknesses of the corresponding layers expressed in monolayers. 40 periods were grown by molecular beam epitaxy on doped (001) GaAs substrates. Three superlattices with different electron concentrations ($N = 5.0 \times 10^{17}$, 2.0×10^{18} and 5.0×10^{18} cm^{-3}) were studied. The samples were patterned into mesa structures with diameter 1 mm by standard lithography and chemical etching procedures. The ohmic contacts were fabricated by depositing Au–Ge–Ni alloy. The measurements of the magnetoresistance were performed at $T = 1.6$ K with an Oxford Instruments helium cryostat with a superconducting magnet.

The energy structure of the superlattices was computed using the envelope-function approximation according to [7]. The effects of non-parabolicity were taken into account following the Kane model [8]. All the parameters for GaAs and AlAs were taken from [9], while the values of the conduction band discontinuity for the X valleys were taken from [10]. The resulting miniband structure is shown in figure 1 where the Γ–Γ, X_L–X_L and X_T–X_T electron transfers (the first Γ or X corresponds to the conduction band state of GaAs and the second one corresponds to the conduction band state of AlAs) are associated with the direct transfers, while the Γ–X_L process is caused by the pseudo-direct electron transfer [11]. As follows from the calculations, in the $(GaAs)_5(AlAs)_5$ superlattices the lowest narrow miniband is formed by the X_L electron states of GaAs and AlAs. The upper broad minibands resulting from the X_T and Γ states are separated by 53 and 91 meV respectively. The position of the Fermi energy E_{F1} in the doped superlattice was calculated with electron concentration $N = 5.0 \times 10^{18}$ cm^{-3} and it was found above the lowest X_L–X_L narrow miniband. In such a case, when the Fermi energy is located in the gap between the minibands, the Fermi surface has an open shape corresponding to an undulating cylinder. According to [12], in the superlattices with open Fermi surfaces, the Landau quantization results in a vertical longitudinal magnetoresistance (VLMR)—the magnetoresistance observed in the case when the magnetic field is directed along the vertical current direction (the current parallel to the growth direction). The value of the corresponding magnetoconductance can be calculated as follows [12]:

$$\sigma_{zz} = C\frac{2\pi Ze^2 N_{imp}}{\varkappa^2} a_{\alpha\alpha'}(k_{zF})\frac{\tau}{1+\omega_c^2\tau^2}\tanh\frac{\hbar\omega_c}{2kT} \qquad (1)$$

where C is a constant, Ze^2 is the impurity charge, N_{imp} is the doping concentration, $\varkappa$ is the reciprocal screening length, $a_{\alpha\alpha'}(k_{zF})$ is the matrix element of the electron transitions between

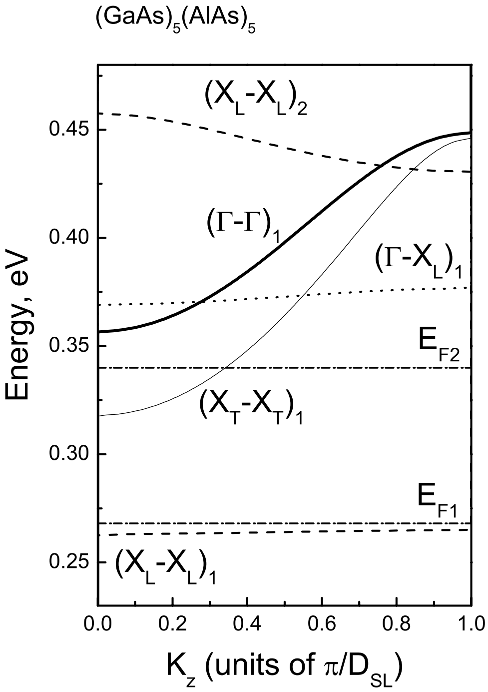

Figure 1. The calculated miniband structure of the $(GaAs)_5(AlAs)_5$ superlattice. The dash–dot lines show the Fermi energies E_{F1} and E_{F2} calculated for the electron concentration $N = 5.0 \times 10^{18}$ cm^{-3} in the case of the lowest X_L–X_L or X_T–X_T miniband respectively. D_{SL} is the superlattice period.

the different Landau levels, ω_c is the cyclotron frequency and τ is the characteristic time of the Landau level broadening.

However, if for some reason the broad X_T–X_T or Γ–Γ miniband is located at a lower energy than the X_L–X_L miniband then, for the same electron concentration, the Fermi level E_{F2} will be disposed inside this broad miniband (in figure 1 the occupation of the X_T–X_T miniband is shown). As was reported in [13, 14], such an interchange of the energies of the electron states can occur in the GaAs/AlAs heterostructures due to the residual stress. In this case the Fermi surface is closed and no VLMR effect is predicted [12].

Thus, the VLMR effect can serve as an indicator of the Fermi surface shape in the relevant superlattice and, therefore, it can be used to specify the origin of the miniband involved in the magnetotransport: the presence of the VLMR manifests itself in the open shape of the Fermi surface and, thus, shows the X_L origin of the lowest miniband. Moreover, the observation of this effect testifies to the formation of a dispersive miniband.

The vertical magnetoresistance measured in one of the $(GaAs)_5(AlAs)_5$ superlattices studied is shown in figure 2. As in [12], no effect was observed for the magnetic field perpendicular to the current, while a positive magnetoresistance was found for the magnetic field parallel to the current. This result indicates an open Fermi surface which, according to our calculations, can occur if the lowest miniband is formed by the X_L electron states. The dashed curve in figure 2 shows the result of the calculation of the VLMR according to equation (1) with $\hbar/\tau \simeq 14$ meV being the energy broadening of the Landau levels. Similar results were obtained for all three samples. The Landau level broadenings obtained in the $(GaAs)_5(AlAs)_5$ superlattices with the different electron concentrations are depicted in the inset of figure 2.

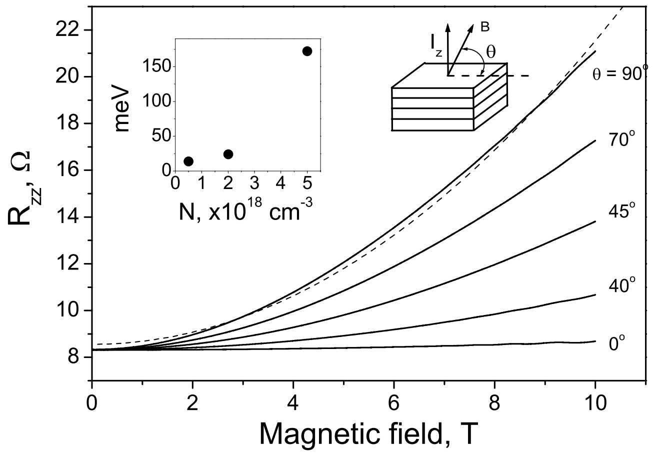

Figure 2. Dependences of the vertical magnetoresistance on the angle between the current and the magnetic field measured in the doped $(GaAs)_5(AlAs)_5$ superlattice with $N = 5.0 \times 10^{17}$ cm^{-3}. The dashed curve was calculated as explained in the text. The insets show the values of the Landau level broadening $\hbar/\tau$ obtained in the superlattices with different electron concentrations and the configuration of the measurements.

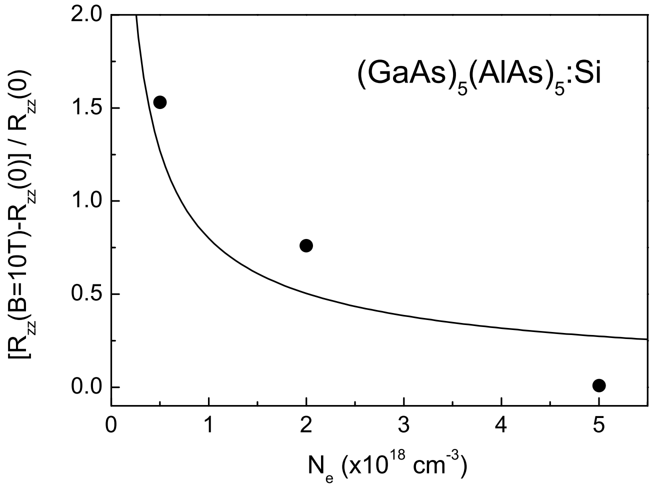

Figure 3. The relative VLMR measured (points) and calculated (full curve) for the $(GaAs)_5(AlAs)_5$ superlattices with different doping concentrations.

In accordance with equation (1), the increases of the Landau level broadening, the impurity concentration and the screening length favour electron transitions between the Landau levels, thus resulting in the decrease of the VLMR. Therefore, the accumulated effect of the doping is to decrease the VLMR. The relative VLMR measured in the superlattices with different doping concentrations is shown in figure 3, where the qualitative agreement between the experimental results and the VLMR calculated from equation (1) is demonstrated.

It is worth mentioning that the above-discussed VLMR results from the destruction of the miniband dispersion caused by the quantization of the electron motion parallel to the layers in the magnetic field and it occurs in relatively highly doped superlattices with open Fermi surfaces. In contrast, a narrow miniband can be destroyed also due to electron scattering processes if the electron energy broadening exceeds the miniband width. In this case, VLMR is expected even for low electron concentrations corresponding to the closed Fermi surface. Such a VLMR was observed in superlattices where the miniband dispersion was broken due to imperfections [15]. This kind of VLMR may occur in the $(GaAs)_5(AlAs)_5$ superlattice for the X_L–X_L miniband with width equal to 2 meV. However, this is definitely not the case for the broad Γ–Γ and X_T–X_T minibands. Therefore, in any case—in highly doped $(GaAs)_5(AlAs)_5$ superlattices with open Fermi surfaces or in low-doped superlattices with closed Fermi surfaces—the observation of VLMR manifests an X_L origin of the lowest miniband. However, the VLMR should not be observed in the case where the lowest miniband is of X_T or Γ origin. This is because these broad minibands have widths much higher than the broadening $\hbar/\tau$ and the Fermi energy is definitely located inside the miniband even at the highest doping, which results in a closed Fermi surface.

We can conclude that in the $(GaAs)_5(AlAs)_5$ superlattices studied here, the lowest miniband is indeed formed by the X_L electron states of GaAs and AlAs and the residual stress does not result in a significant alteration of the energies corresponding to the Γ, X_T and X_L states relative to those calculated without stress effects. It is worth adding that although, as was mentioned in the introduction, the presence of the miniband formed by the X states was already detected by means of photoluminescence in [3], our results add some important complementary information: namely, the observation of the VLMR effect indicates the presence of a superlattice miniband resulting from extended X_L electron states, while the photoluminescence study does not reveal the nature of the origin of the electron states involved (extended or localized).

Acknowledgments

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