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Anisotropic magnetotransport in two-dimensional electron gases on (311)B GaAs substrates

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Abstract. Interest in electron transport on high-index GaAs surfaces is increasing, especially since the advent of patterned substrate regrowth, in which high index surfaces are revealed on (001) GaAs after etching. In this paper we observe anisotropic mobility in orthogonal directions in two-dimensional electron gases grown on (311)B GaAs substrates. The mobility in the $[\bar{2}33]$ direction is found to be up to 50in the $[01\bar{1}]$ direction. The lower mobility is accompanied by a large anomalous negative magnetoresistance. These effects are studied as a function of temperature and carrier density. It is suggested that interface roughness scattering could be a cause for the large anisotropies in mobility and a simple calculation is performed to demonstrate this hypothesis.

Despite the formation of very high-mobility two-dimensional electron gases (2DEGs) at heterojunctions of AlGaAs/GaAs grown on GaAs(001) substrates [1–3], little study has been made of 2DEGs grown on other substrate orientations. The advent of regrowth on patterned substrates has opened up the possibility of 2DEGs on a variety of substrate orientations [4]. In a conventional 2DEG on GaAs(001), Si is used to modulation dope part of the AlGaAs region as n type. In the case of growth on (311) GaAs substrates, the two equivalent surfaces (311)A and (311)B allow the Si to dope, under special conditions, either n or p type. With a (311)A substrate and growth surface, Si incorporation gives rise to Si-doped p type doped material, allowing two dimensional hole gases to be formed. Such systems have been studied quite extensively [5–9]. However, there is a notable dearth of literature for transport properties of 2D electrons on the (311)B surface.

In this paper we investigate some properties of the electron gases formed on (311)B substrates. We have studied transport properties in two orthogonal directions, namely the $[01\bar{1}]$ and directions. We find that there is a marked difference between the resistivities and hence mobilities in these two directions. Conduction in the $[\bar{2}33]$ direction has a higher mobility than conduction in the $[0\bar{1}1]$ direction. We also observe negative magnetoresistance which is different in the two directions and the effects are found to be temperature and carrier density dependent. We present a study of the anisotropy and present some possible explanations for it.

It is known that for certain growth conditions, the (311) GaAs surfaces can show surface relaxation giving rise to undulations or regular corrugations. Nötzel *et al* [10–11] together with Däweritz [12] have observed RHEED patterns during growth that can be interpreted to arise from regular corrugations running along the $[\bar{2}33]$ direction. Such corrugations

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can be explained by an energetically favourable surface relaxation, which is found to be temperature dependent. At typical growth temperatures they find the surface relaxes into a periodic superlattice of 32 Å period and 10.4 Å height. Indeed, Nötzel *et al* [10–11] have presented evidence that under certain growth conditions such corrugations can be grown into GaAs/AlGaAs structures. The corrugations have been observed in high resolution electron microscopy and can explain energies and line shapes in photoluminescence spectra. However, unfortunately few layers have been designed and grown for transport studies.

The 2DEGs were formed by growing on undoped (311)B GaAs substrates. The samples consisted of the following layers; 1.1 μm of GaAs followed by either 200 Å or 400 Å of undoped AlGaAs spacer, then 400 Å AlGaAs doped by 10^{18} cm^{-3} Si and finally a 170 Å GaAs cap. The Al content in the AlGaAs was 33% and the growth temperature was 650 °C as measured by an optical pyrometer. The specific layer dimensions seem to have little relevance to the observed effects. Hall bars were fabricated using a wet chemical-etched mesa with AuNiGe alloy ohmic contacts annealed at about 430 °C, a 500 Å thick semitransparent NiCr/Au Schottky barrier gate was put over the conducting regions on some of the Hall bars to control the carrier density. Hall measurements were carried out in either a 4.2–300 K continuous flow cryostat with magnetic fields up to 1 T or a 1.5 K 8 T Oxford cryomagnet system. Resistances were measured using lock-in techniques with a typical frequency of 30 Hz and a constant current of 100 nA. The Schottky barrier gate voltage was controlled by a Keithley 230 SMU and leakage currents were kept below 10 nA.

Although our growth conditions were very similar to Nötzel *et al* we have not observed RHEED patterns with satellites commensurate with a surface superlattice structure. This is perhaps because we use a lower-energy RHEED gun 12 kV as opposed to 30 kV and thus have lower resolution. It remains unclear why we did not observe RHEED patterns similar to those of Nötzel *et al*. However, if the corrugations do exist they will undoubtedly affect the transport properties of the electron gas. The transport properties are also dependent on the electron effective mass and the shape of the electron potential. We note that the conduction band for sheet carrier concentrations of between 2 and 5 × 10^{11} cm^{-2} is isotropic and thus the electron effective mass has little anisotropy in the $[01\bar{1}]$ and $[\bar{2}33]$ directions [13]. This is contrary to the case of hole gases on (311) substrates [14], where it is thought that band mixing causes anisotropy in effective mass resulting in differences in mobilities for certain directions. As far as the electronic potential is concerned, it is thought that the valence band offsets for (311) surfaces are essentially identical to the (001) case [15–18] and thus the electron potential well will be very similar in size and shape to the (001) case. Thus the fundamental properties of a 2DEG on (311)B will be very similar to a 2DEG on (001)GaAs.

Initial resistivity measurements in our samples suggest a marked anisotropy in the mobility in the two orthogonal directions. Figure 1 shows a typical result of magnetoresistance in two directions for one sample measured at 1.7 K. In this case the carrier concentration is 3.2×10^{11} cm^{-2}. It can be seen that at high fields ($\mu B > 1$) Schubnikov–de Haas (SDH) oscillations are observed and are essentially identical in the two orthogonal directions. However, at low fields a negative magnetoresistance is observed which is directional dependent and is very pronounced in the $[01\bar{1}]$ direction leading to a reduction in mobility in the so called *slow* direction. There is some negative magnetoresistance in the $[\bar{2}33]$ direction but it is negligible compared to that of the $[(01\bar{1}]$ direction.

We have studied the mobility anisotropy as a function of carrier density. To change the carrier density in the 2DEG we have used a surface Schottky gate. Using the mobility values and analysis of SDH oscillation amplitudes, we have determined both transport, τ_t, and quantum lifetimes, τ_q, as a function of carrier density within the 2DEGs. The analysis for quantum lifetimes is similar to that of Coleridge *et al* [19] in which we remove the

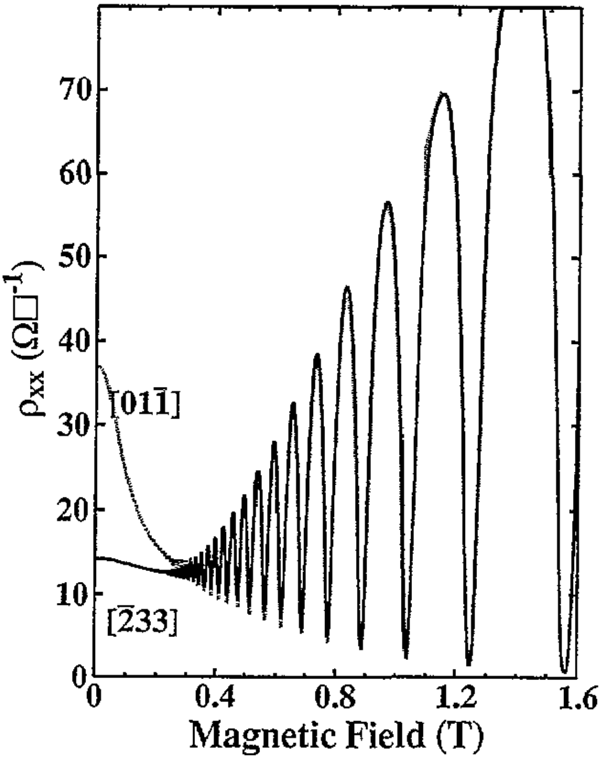

Figure 1. ρ_{xx} for a 2DEG on (311)B GaAs measured in two orthogonal directions, namely [$\bar{2}$33] and [01$\bar{1}$]. Note the large magnetoresistance in the [01$\bar{1}$] direction. The measurement tempertaure was 1.7 K.

temperature dependence from the SDH oscillations and then fit the peak to peak values of normalized resistivity to an exponential function to retrieve a quantum or Dingle lifetime. We assume the SDH oscillations in $1/B$ only have one major sinusoidal component; this assumption seems to hold in most of the 2DEG samples analysed in this way and does not seem to effect the calculated lifetimes. The measurement temperature was 1.7 K. Figure 2 shows lifetimes plotted against carrier denisty, where the carrier densities were determined by low-field Hall measurements. It can be seen that the quantum lifetime has virtually no dependence on carrier density or direction of current, and is between 50 and 100 times smaller than the transport lifetime. Such ratios of quantum to transport lifetimes are quite typical of high mobility 2DEGs, where the dominant scattering is due to remote ionized impurities separated from the 2DEG by a spacer layer [20]. Importantly we also observe that as carrier density is increased there is anisotropy in τ_t which also increases. However, the transport lifetimes at low carrier densities are almost independent of direction.

The effect of anisotropy in transport lifetime but not quantum lifetime is striking and could be explained by the presence of some form of anisotropic scatterers. The quantum lifetimes are derived from SDH oscillations, which presuppose that the electrons are moving in cyclotron orbits. Thus the electron experiences scattering in all directions as it travels on its circular path and hence τ_q has no directional dependence. At low fields in the region where τ_t is measured, the electron predominantly moves in one direction and thus anisotropic scattering will affect the value of τ_t.

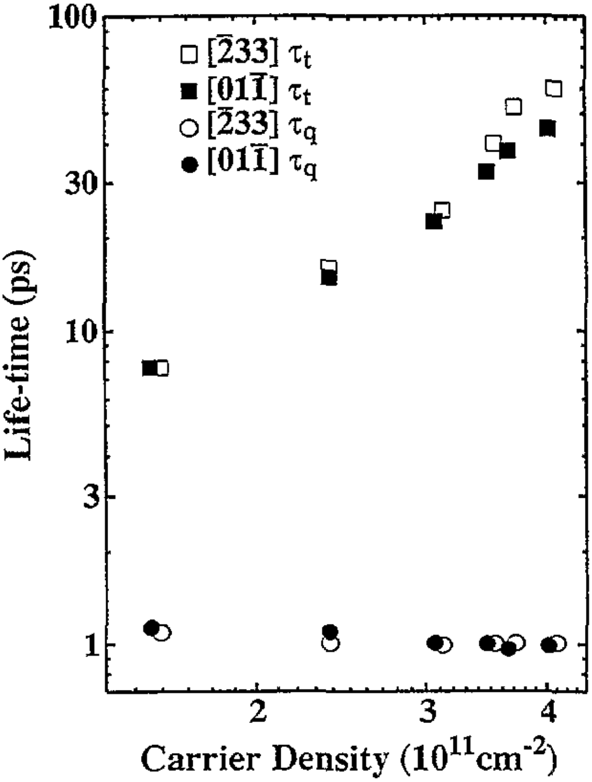

Figure 2. Transport, τ_t and quantum, τ_q lifetimes for a (311)B 2DEG with Schottky barrier surface gate for a range of carrier densities. The lifetimes were derived from zero-magnetic-field mobility values and SDH data. Note the small anisotropy in quantum lifetimes but a large anisotropy in transport lifetimes as carrier density increases.

This result can be compared with measurements on 2DEGs where a scatterer has been deliberately inserted in the 2DEG region; see, for example [21–24]. In these papers the authors have investigated 2DEGs grown in vicinal (001) GaAs substrates misorientated between 0.5 and 2°. Scatterers are placed near to the 2DEG by inserting sub-monolayers of AlAs in the 2DEG region. In one case, islands of AlAs are inserted at the AlGaAs/GaAs heterojunction interface, in the other cases a lateral superlattice is formed with 0.5 monolayers of AlAs placed at the edge of the terraces on the vicinal substrates. In both cases anisotropic mobilities are observed. In the case of scattering from AlAs islands, anisotropy in the transport lifetime increases monotonically with carrier density in a similar fashion to that which we observe. With the periodic array of scatterers at the interface, the anisotropy has a maximum when the electron wavelength has the same order as the periodicity, i.e. $\lambda_{\mathrm{Fermi}} = a$. Unfortunately no magnetic field data were presented with [21] or [24] so a comparison with our SDH data cannot be made. The sample reported in [23] is measured to 8 T but shows no significant magnetoresistance. Noda *et al* [21] have shown that this type of scattering can be modelled fairly well by using a form of interface roughness scattering, in which two parameters in orthogonal directions describe a coherence length for the scattering.

We propose that the perturbation on $\sigma_{xx}(B = 0)$ seen in our samples could be due to a similar anisotropic scattering at the 2DEG AlGaAs/GaAs interface, possibly due to corrugated

AlGaAs/GaAs interfaces. This type of scattering can explain the carrier density dependence, in which the amount of scattering increases as the electron wavelength, λFermi, reduces with increasing carrier density. We have performed a simple calculation to obtain τ_t in orthogonal directions, similar to that of Noda *et al* [21]. A Fang–Howard wavefunction is assumed [25], the lifetimes are calculated at $T = 0$ K assuming contributions from (i) remote ionized impurities and (ii) interface roughness. The interface roughness is defined by three parameters, (i) an amplitude of the roughness Δ and (ii) a correlation lengths in the $[\bar{2}33]$ and $[01\bar{1}]$ directions, using a Gaussian form of correlation of the interface roughness in both directions [26]. The anisotropy of the scattering rate was incorporated in the calculation using a method described in [25]. In figure 3(a) we show a typical calculation which is comparable to our experimental results. The values of lifetime at low carrier densities are determined by the number of remote ionized impurities in the AlGaAs region. Since this is an unknown parameter a minor discrepancy can exist between the calculated and measured lifetimes. We have marked on the individual contributions due to remote ionized impurities and interface roughness scattering and the total scattering times. Figure 3(b) shows detail of experiment transport lifetimes of a typical (311)B 2DEG, where the carrier density is changed with a front gate. In comparing the experimental and theoretical results we see that there is some discrepancy in lifetimes for carrier densities in the region of 3-4 $\times 10^{11}$ cm^{-2}. We think this may be due to some of the remote ionized donors becoming neutralized as the gate voltage is varied to increase the carrier density and thus the experimental lifetime increases in this region more rapidly than the theory predicts. We have tried various sizes for the scattering correlation, including one corresponding to a corrugated surface reported by Nötzel *et al* [11]. In figure 3(b) the experimental case, we have assumed that at high carrier density ($\sim 5 \times 10^{11}$ cm^{-2}) the lifetimes are dominated by interface roughness scattering. Using the ratio of experimental lifetimes at high carrier density, we have obtained a best fit for the anisotropy and we find the parameters of lengths 13 Å in the $[01\bar{1}]$ direction and 61 Å in the $[\bar{2}33]$ direction with an amplitude of 2.6 Å. Ignoring the discrepancy where remote ionized scattering dominates, the fit is quite reasonable. If we compare these dimensions with the corrugations that Nötzel *et al* observed, then our amplitude is about 1/4 of their observation, and so, roughly, is our period of 13 Å. We could surmise that instead of scattering from corrugations of height 10 Å and period 32 Å, the corrugated surfaces have been terraced and we scatter from the terraces with step size of one monolayer (2.Å) and length a quarter of 32 Å (of the order 10 Å). The correlation length of 61 Å in the $[\bar{2}33]$ direction would not seem unreasonable for the length of a linear part of a terrace on the substrate surface. It is clear from our fits, however, that the scattering has not arisen from corrugated surfaces of height 10 Å and period 32 Å.

Whilst interface roughness scattering describes the effect of mobility anisotropy as a function of carrier density fairly well, it should be noted that in the momentum relaxation time approximation, in which our calculations are performed, the theory simply produces two different scattering times for the two orthogonal directions, namely $[01\bar{1}]$ and $[\bar{2}33]$. These determine the mobility through the empirical relation $\mu = e\tau/m^*$. However, when the lifetimes are included into the conductivity tensor, both σ_{xx} and σ_{xy} are changed and no magnetoresistance is predicted. So interface roughness scattering can, at least within the relaxation time approximation, explain mobility anisotropy but not the observed negative magnetoresistance. We have studied the anomalous negative magnetoresistance in both directions as a function of temperature. Figure 4 summarizes the results and we see that the magnetoresistance in the $[01\bar{1}]$ direction exists up to 35 K, whilst in the $[\bar{2}33]$ direction it is almost extinct at 8 K. We find the magnetoresistance has a B^2 dependence at fields below 0.1 T. Small negative magnetoresistance can be associated with the suppression of weak

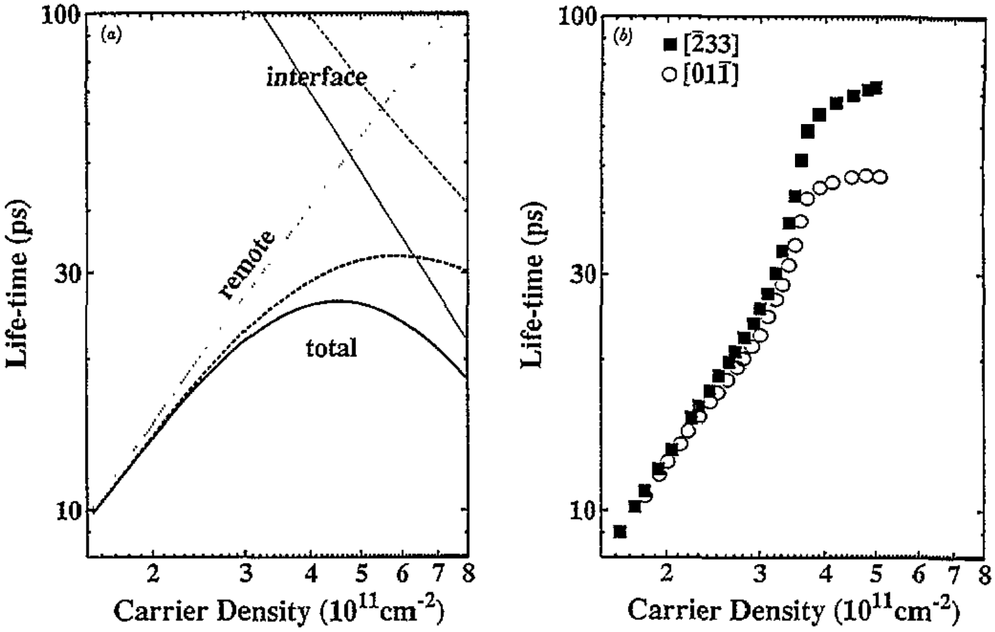

Figure 3. (a) Calculated values of transport lifetimes as a function of carrier density. (b) Detail of the experimental transport lifetimes for a (311)B 2DEG in the [$\bar{2}$33] and [01$\bar{1}$] directions. We have assumed a form of interface roughness scattering that enables an anisotropy to be observed which increases with carrier density. The parameters that we use for this calculation are scattering correlation lengths of 13 × 61 Å and height 2.6Å.

localization, however, at fields of less than 50 mT, weak localization is normally observed in low mobility 2DEGs and at low temperature where the elastic mean free path is large [27]. In our case the 2DEG mobility is very high ($> 1 \times 10^6$ cm^2 V^{-1}s^{-1}), the negative magnetoresistance extends to above 0.1 T and is observed up to temperatures of 35 K. High-field magnetoresistance has been seen in 2DEGs in the past and has been explained by electron–electron interactions [28–30].

It is well known that any small perturbation on the conductivity tensor component σ_{xx} will give rise to a parabolic perturbation in $\rho_{xx}(B)$. The exact form for small $\delta\sigma_{xx}$ with $\delta\sigma_{xy} = 0$ is given by :

$$\rho_{xx}(B) = \rho_{xx}(0) + \rho_{xx}(0)^2\,\delta\sigma_{xx} + \rho_{xx}(0)^2\mu^2B^2\,\delta\sigma_{xx} \tag{1}$$

which is simply derived from inverting the conductivity tensor but including the perturbation $\delta\sigma_{xx}$, where we take $\mu B = \omega_c\tau_0$, ω_c is the cyclotron frequency, τ_0 the transport scattering time and $\rho_{xy} = \omega_c\tau_0\rho_{xx}$ is assumed. The B^2 dependence can be obtained as a function of temperature and direction by fitting a parabola to our results and using equation (1). Figure 5 shows $\delta\sigma_{xx}$ as a function of temperature, derived from the magnetoresistance for a typical sample. Here we have used $\omega_c\tau$, with τ as a function of T and not τ_0, for μB, so we include effects from the electron–phonon interaction. It can be seen that for both directions $\delta\sigma_{xx}$ has a logarithmic dependence in temperature, $\delta\sigma_{xx} \propto \beta\log(T)$. However, there is a difference in proportionality, β depending on the direction. Al'tshuler and Aronov [30] have shown that $\delta\sigma$ has a logarithmic dependence on temperature for electron–electron interactions. However, the magnitude of the electron–electron interaction

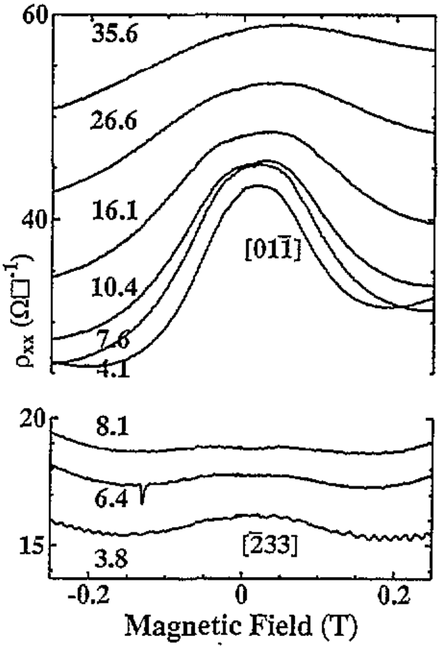

Figure 4. The magnetoresistance observed in figure 1 as a function of temperature, between 4 and 35 K in both [$\bar{2}$33] and [01$\bar{1}$] directions.

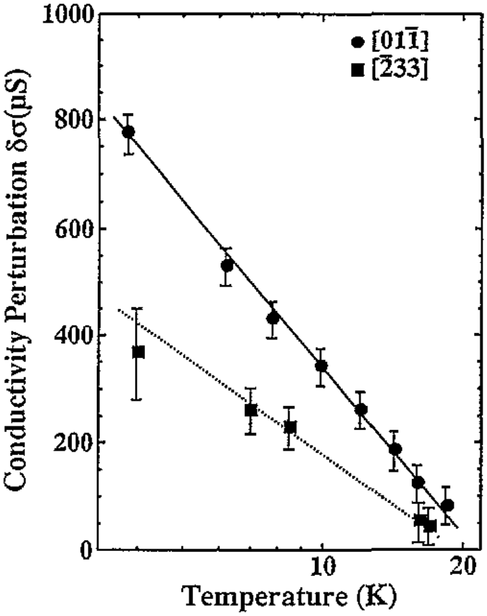

Figure 5. The conductivity perturbation $\delta\sigma$ derived from the magnetoresistance as a function of temperature. Note that $\delta\sigma$ is proportional to $\log(T)$, however, the magnitude of proportionality depends on direction of current flow.

is very small [28] and it only causes a small perturbation on the resistivity. Our results show very large magnetoresistance, which not only puts into question the validity of equation (1) but suggests that it is unlikely that the observed magnetoresistance is due to electron–electron interactions. The magnetoresistance is more likely due to some kind of interference rather than an interacton effect. For example, Smith *et al* [31] have reported a logarithmic dependence in conductivity perturbation for a one-dimensional superlattice imposed on a 2DEG. They explain this phenomenon as a form of localization caused by Bragg reflections within the superlattice, where electron half-wavelengths fit in to the superlattice period. This subsequently gives rise to a logarithamic temperature dependence in $\delta\sigma$. It is possible that the large temperature-dependent magnetoresistance which we observe is due to a similar effect and we are observing the manifestation of a periodic interface roughness which is imposing a superlattice potential on the 2DEG.

In summary we have observed anisotropic mobility and magnetoresistance that seems to be universal for electron gases grown on (311)B-orientated GaAs substrates. The anisotropy depends on the 2DEG carrier density but mobilities are always higher in the [$\bar{2}$33] direction. We propose that interface roughness scattering is a possible cause of the mobility anisotropy, although magnetoresistance associated with the anisotropy cannot as yet be explained within this framework. The magnetoresistance has a log dependence on temperature and is also dependent on current direction. However, due to its inherent size it is unlikely to be due to weak localization or an electron–electron interaction effect. It is more likely an interference effect, possibly caused by a weak superlattice induced by periodic interface roughness or corrugations.

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