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Effective Potential Calculation in a Two-Dimensional Electron Gas Containing Quasi One-Dimensional AlAs Submonolayer

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We report low-field magnetoresistance measurements of a two-dimensional electron gas in which half a monolayer of AlAs has been inserted into the centre of the GaAs quantum well. In these devices we observe a low file positive magnetoresistance on GaAs (001) substrates deliberately misoriented by 0.09 degrees toward the [110] direction in which a critical field causes magnetic breakdown. A large anisotropy is observed in both the mobility and the low field magnetoresistance in the orthogonal [$\bar{1}$10] and [110] directions. It is suggested that these effects arise from the quasi periodic effective one-dimensional potentials caused by the insertion of the AlAs submonolayer. We describe a method of using the anisotropic low field magnetoresistance to calculate the magnitude of the effective potential of the AlAs sub-monolayer at the GaAs/AlGaAs heterointerface.

I. INTRODUCTION

The ability to control and measure the electronic potential at a semiconductor heterostructure interface is important for understanding systems such as lateral superlattices, one-dimensional quantum wires, and single quantum wells [1] as well as a basic understanding of transport at heterointerfaces. An interesting route for the fabrication of one- [2–4] and zero- [5–8] dimensional nanostructures is by natural formation during the growth procedure. Whilst there are a few studies of the physics of such systems there is a notable dearth in the literature of detailed magnetotransport measurements of naturally formed submonolayer potential heterostructures. In this paper we present detailed magnetotransport studies of a two-dimensional electron gas (2DEG) in a GaAs quantum well in which half a monolayer of AlAs has been inserted into the centre of the well. Using a full surface Schottky gate it is possible to control the carrier density of the 2DEG in the well and observe the effect of the AlAs potential on the magnetoresistance in both the [110] and [$\bar{1}$10] directions. A strong positive magnetoresistance is observed at low-field in the [110] direction, with a corresponding magnetic breakdown at a critical field B_c. From the theory of magnetic breakdown we can calculate the effective potential height of the AlAs submonolayer as a function of carrier density. Our results demonstrate a method using electrical transport measurements to determine the potential barrier height formed at a heterointerface.

II. EXPERIMENTS

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A n-AlGaAs/GaAs heterojunction grown by molecular beam epitaxy on an undoped GaAs (001) substrate deliberately mis-oriented by 0.09 degrees. The structure consists of a 0.6 μm thick undoped GaAs buffer layer, followed by a 500 Å undoped $Al_{0.33}Ga_{0.67}As$ barrier, a 200 Å undoped GaAs quantum well, a 400 Å undoped $Al_{0.33}Ga_{0.67}As$ spacer layer, a 400 Å Si-doped (1×10^{18} cm^{-3}) $Al_{0.33}Ga_{0.67}As$ layer, and finally a 170 Å GaAs capping layer. Using a GaAs substrate with an intentional misorientation from the (001) plane, it is possible to form a periodic potential of AlAs islands along the [110] surface using migration enhanced epitaxy. [9] Knowing the misorientation angle and the monolayer thickness, it is possible to calculate the period of the effective corrugated potential using $d = a\cot\alpha \approx 180$ nm. The devices were processed into an orthogonal Hall bar structure, where the current flows in either the [110] and [$\bar{1}$10] direction. A Schottky barrier gate was constructed onto the top of the structure using NiCr/Au which allowed control of the carrier density n_s In the 2DEG channel.

III. RESULTS AND DISCUSSION

Figs. 1(a) and 1(b) show the low-field magnetoresistance of the 2DEG for the [110] and [$\bar{1}$10] directions, respectively. The measurements were taken at 1.5 K at a carrier density of 2.34×10^{11} cm^{-2} ($V_g = 0$) estimated from the slope of the Hall resistance for both directions. The zero-field resistance in the [110] direction is about one-and-a-half times higher than that in the [$\bar{1}$10] direction leading to a marked anisotropy in the mobility in the two orthogonal directions (with a peak mobility of 1.2×10^5 cm^2/Vs). A positive magnetoresistance is observed in both directions but which is much more pronounced in the [110] direction. The occurence of a strong magnetoresistance in the [110] direction is discussed in more detail below. At higher fields ($B > 0.15$ T) Shubnikov-de Haas oscillations corresponding to 2D transport are observed.

Figure 2(a) shows the mobility μ versus the carrier density n_s at 1.5 K in the [110] and [$\bar{1}$10] directions for sample A. At low densities (0.7×10^{11} cm^{-2}) the mobility is independent of direction as the electrons are mainly scattered by isotropic impurity scattering. At higher densities anisotropic interface scattering due to the quasi-periodic 1D potential dominates and the mobility becomes anisotropic. In order to provide further insight as to what is happening at the different carrier densities (marked I-V) we present the corresponding magnetoresistance traces along the [110] direction in Fig. 2(b).

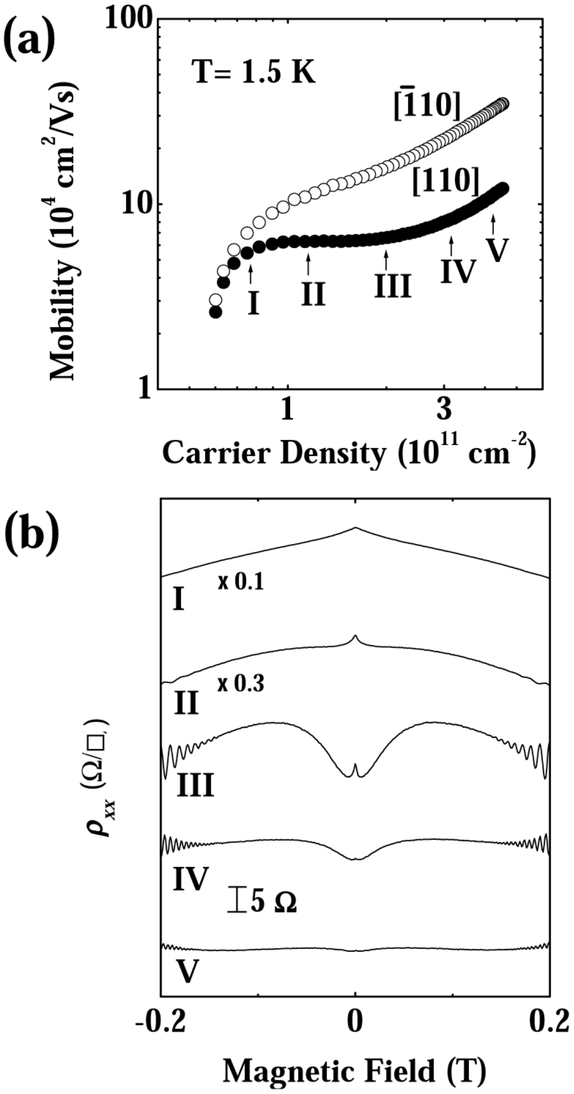

Fig. 2. (a) The mobility along the [110] and [$\bar{1}$10] directions as a function of carrier density n_s at T = 1.5 K. Arrows with Roman numerals indicate the points at which the magnetoresistance data in figure 3 (b) were taken. (b) Magnetoresistance in the [110] direction are measured at gate voltages -0.20 (top), -0.15, -0.05, 0.10, and 0.25 V (bottom), respectively.

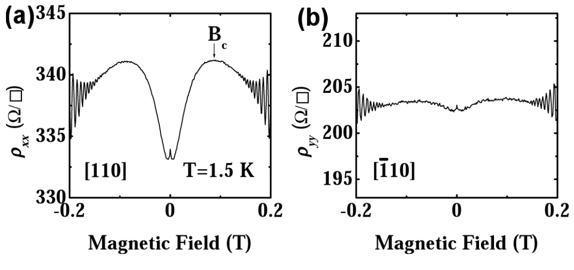

Fig. 1. Low-field magnetoresistivity traces at a carrier density of 2.3×10^{11} cm^{-2} in the (a) [110] and (b) [$\bar{1}$10] directions at a carrier density of 2.6×10^{11} cm^{-2} in both orthogonal directions. All traces are at 1.5 K.

At low carrier densities ($< 0.68 \times 10^{11}$ cm^{-2}) where the mobility is isotropic, a large negative magnetoresistance is observed [see Fig. 2(b) at $V_g = -0.20$ V]. As the

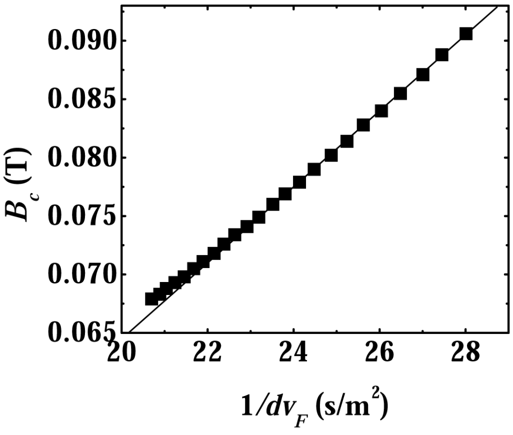

Fig. 3. B_c as a function of $1/dv_F$.

carrier density is increased interface roughness scattering starts to dominate and a large positive magnetoresistance develops, with a maxima at $B = B_c$ (see III). In order to understand the occurence of a large positive magnetoresistance observed in the [110] direction for the intermediate field range (0.02 to 0.2 Tesla) we turn to an earlier study of 1D surface superlattices by Beton *et al.* [10,11] They observed a positive magnetoresistance in a periodically modulated 2DEG when the direction of the current flow is orthogonal to the superlattice axis. The magnetoresistance shows a maxima at a critical field B_c, where B_c is given by:

$$B_c = 2\pi V_{eff}/dv_F, \tag{1}$$

where V_{eff} is the amplitude of the effective potential, d is the period, and v_F is Fermi velocity. The positive magnetoresistance arises from electron orbits "streaming" along the 1D superlattice potential. When the force due to the magnetic field is greater than that due to the electric field (B> B_c) a form of magnetic breakdown occurs and the streaming orbits are suppressed. This is a purely classical effect which ignores the effect of tunneling through the AlAs potential barriers. Increasing the carrier density even further (traces IV and V) causes the magnitude of the positive magnetoresistance to decrease. This is because the Fermi energy increases with increasing carrier density, so the relative height of the fixed potential due to the periodic 1D AlAs superlattice decreases.

Using Eq. (1), the effective 1D periodic potential energy of the AlAs submonolayer, V_{eff} can be determined from B_c and n_s. The experimentally determined B_c is plotted in Fig. 3 as a function of calculated value $1/(dv_F)$, where Fermi velocity v_F is obtained from n_s. From the linear fit we obtain the effective potential V_{eff} of the AlAs submonolayer to be $\approx$ 0.512 meV. It can be seen that the effective potential V_{eff} is almost constant over all this range of densities but at low electron densities, V_{eff} is observed to increase and deviate from 0.512 meV. This increase in V_{eff} at low densities can be understood as a consequence of the electron drift in the [110] direction.

IV. CONCLUSIONS

In summary, we have incorporated half a monolayer of AlAs into a GaAs quantum well to induce an imperfectly periodic 1D potential in a 2DEG. A strong low-field positive magnetoresistance is observed in the [110] direction, with a corresponding critical magnetic breakdown field. From the theory of magnetic breakdown we can calculate the effective potential of the AlAs submonolayer as a function of carrier density and found that the potential is fixed at 0.512 meV. The results demonstrate a method of inducing a fixed periodic potential at a heterostructure interface and using electrical transport measurements to determine the effective height of potential.

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REFERENCES

[1] T. W. Lee, H. Hwang, Y. Moon and E. Yoon, J. Korean Phys. Soc. **34**, S25 (1999).

[2] J. Motohisa, M. Tanaka and H. Sakaki, Appl. Phys. Lett. **55**, 1214 (1989).

[3] Y. Nakamura, S. Koshiba and H. Sakaki, Appl. Phys. Lett. **69**, 4093 (1996).

[4] B. R. Shim, S. Torii, T. Ota, K. Kobayashi, K. Maehashi and H. Nakashima, J. Korean Phys. Soc. **35**, S599 (1999).

[5] C. K. Hahn, E. K. Kim, I. S. Jeun, K. M. Kim, M.-S. Kim and S. K. Min, J. Korean Phys. Soc. **29**, 624 (1996).

[6] B. D. Min, Y. Kim, E. K. Kim, S. Min and M. J. Park, Phys. Rev. B **57**, 11879 (1998).

[7] G. D. Lian, J. Yuan, L. M. Brown, G. H. Kim and D. A. Ritchie, Appl. Phys. Lett. **73**, 49 (1998).

[8] G. H. Kim, D. A. Ritchie, M. Pepper, G. D. Lian, J. Yuan and L. M. Brown, Appl. Phys. Lett. **73**, 2468 (1998).

[9] M. Tanaka and H. Sakaki, Appl. Phys. Lett. **54**, 1326 (1989).

[10] P. H. Beton, E. S. Alves, P. C. Main, L. Eaves, M. W. Dellow, M. Henini, O. H. Hughes, S. P. Beaumont and C. D. W. Wilkinson, Phys. Rev. B **42**, 9229 (1990).

[11] P. H. Beton, M. W. Dellow, P. C. Main, E. S. Alves, L. Eaves, S. P. Beaumont and C. D. W. Wilkinson, Phys. Rev. B **43**, 9980 (1991).