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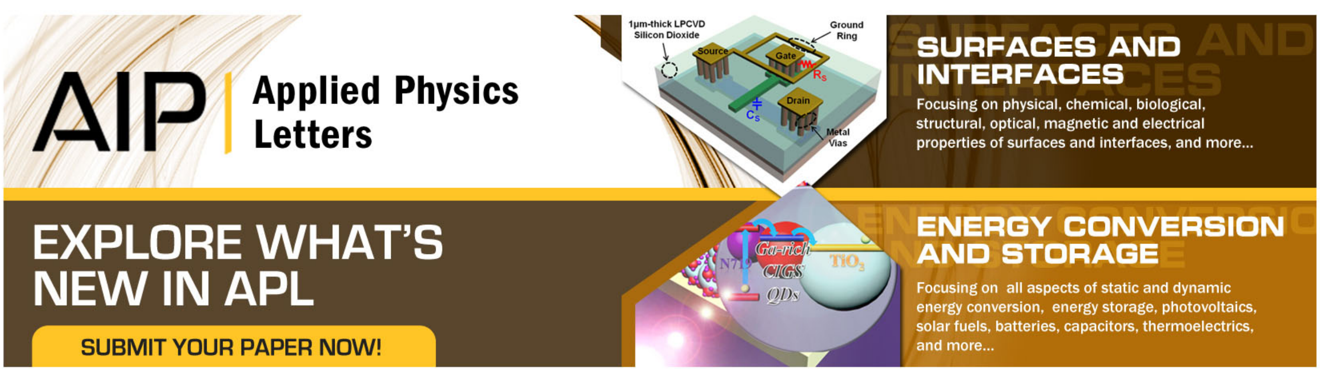

Anisotropic piezoelectric effect in lateral surface superlattices

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We have studied the potential induced by lateral surface superlattices deposited on a GaAs/AlGaAs heterostructure as a function of bias and orientation of the gates. By using the gates to null the total potential, we extracted the contribution to this potential in the absence of gate bias. Its angular dependence shows that it is dominated by strain from the gates coupled to the electrons by the piezoelectric effect. [S0003-6951(97)02507-2]

A periodic modulation of the two-dimensional electron gas (2DEG) in a heterostructure induces magnetoresistance oscillations[1] periodic in $1/B$. These commensurability oscillations (CO) are driven by the ratio of the diameter of the cyclotron orbit to the period of the modulation. Their amplitude and phase were calculated by Beenakker[2] using a semiclassical model which allows one to deduce the magnitude of the potential.

There are several ways of inducing a periodic potential in a 2DEG. The most common method is to apply a bias to a periodic metal grating on the surface, known as a lateral surface superlattice (LSSL). The resulting potential in the 2DEG is usually close to a sinusoid. However, experiments on a shallow 2DEG by Cuscó *et al.*[3] revealed a strong second harmonic. Theoretical analysis[4] was unable to explain this from electrostatic modulation alone. Instead it was postulated that the modulation arose from strain generated by differential contraction between the metal gate and the underlying semiconductor. This explanation is now widely accepted.[5]

The original analysis gave both the harmonic content and the absolute magnitude of the modulation in reasonable agreement with the experiment. Unfortunately, the sample was complicated by a layer of free carriers around the donors which provided additional screening. Inclusion of this parasitic layer reduces the predicted modulation by a factor of 4.

Also, the calculation was for a LSSL oriented along ⟨010⟩, in which case the deformation potential provides the only coupling between strain and the 2DEG. In fact the gates were oriented along ⟨011⟩ (as is usually the case). GaAs has symmetry 43m and is therefore piezoelectric for certain stresses. This provides further modulation of the 2DEG[6] if the orientation of the gates differs from ⟨010⟩. We estimate that the piezoelectric effect is about an order of magnitude larger than the deformation potential, and this restores agreement between experiment and theory.

In this letter we describe experiments which confirm that the piezoelectric effect provides the dominant modulation in LSSLs by exploiting its anisotropy. It can readily be shown by using the method of Nye[7] that the piezoelectric modulation under a LSSL on a (100) surface is proportional to sin 2θ, where θ is the orientation of the current flow measured from the [010] direction towards [001]. The effect is maximized along the [011] and [011] directions with opposite signs.[6] We distinguish the sign of the modulation by biasing the gates to null the modulation in the 2DEG. Equal but opposite voltages are needed for the two cases.

All the superlattices described in this work were deposited on a shallow delta-doped GaAs/AlGaAs structure with a 21-nm-thick spacer layer and with the electrons confined against an interface 38 nm from the surface. This material is a compromise between the GaAs/AlAs layers used in the earlier work,[3,8] whose behavior is complicated by a parasitic layer of mobile electrons around the donor layer, and our shallowest GaAs/AlGaAs materials with an 11 nm spacer, which have mobilities too low for the current studies.[9] The dark mobility of the layer used was generally about 40 $m^2 V^{-1} s^{-1}$, for a carrier concentration of typically 3×10^{15} m^{-2}. This value corresponds to a bulk transport mean free path of around 4 μm, comfortably greater than the periods of the superlattices studied. These were fabricated by electron beam lithography, using positive resist and lift-off, across Hall bars of a typical width of 20 μm. Superlattice periods of 200 and 300 nm were studied, with a typical device having 80–100 periods. The length of the gates was as close as possible to half the period of the superlattice, so as not to introduce a high second harmonic component with the applied potential.[8] The magnetoresistance was measured 4-terminally for a range of fixed gate voltages, and generally at 4.2 K. This relatively high temperature was chosen to reduce the degree of interference between the Shubnikov–de Haas oscillations and the CO.

Two methods were used to deduce the periodic potentials seen by the electrons underneath the superlattice. The first was to determine the magnitude of the CO from the magnetoresistance trace. The nth harmonic of the potential V_n was then deduced from the semiclassical Beenakker formula[2] for the fractional change in the magnetoresistance

$$\frac{\delta\rho_n}{\rho} = \left(\frac{eV_n}{E_f}\right)^2 \left(\frac{n\ell^2}{aR_c}\right) \cos^2\left(\frac{2\pi n R_c}{a} - \frac{\pi}{4}\right). \tag{1}$$

Here E_F is the Fermi energy, ℓ is the electron mean free path, a the fundamental period of the superlattice, and R_c is the cyclotron radius. The carrier concentration (which is required to deduce the cyclotron radius) and the mean free path employed in this analysis were mean values for the appro-

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TABLE I. Details of the samples studied.

Sample	Period	Alignment θ	V_1 ($V_g=0$)	V_2 ($V_g=0$)
	nm ($\pm 2\%$)	Degrees ($\pm 2°$)	mV ($\pm 15\%$)	mV ($\pm 25\%$)
1A	300	$+45°$	$+0.34$	⋯
1B	300	$-45°$	-0.29	⋯
2	200	$-75°$	-0.10	0
3A	200	$75°$	$+0.18$	± 0.09
3B	200	$+15°$	$+0.11$	± 0.13

priate gate voltages determined from the Shubnikov–de Haas frequencies and the zero field resistances. The required amplitudes of the CO were deduced from *one particular commensurability oscillation* at all gate bias values. This was generally chosen to be the one at the highest magnetic field which could be completely distinguished from the Shubnikov–de Haas structure (most frequently the second highest oscillation). Although the Beenakker formula is known not to account accurately for scattering effects, particular for large cyclotron radii (small B),[10] and this is reflected in large absolute errors in the potential components (see Table I), we believe that the *relative* values for the potential components at different gate voltages are comparable to an accuracy of about 5%.

The second method used was to analyse the positive magnetoresistance step at low fields, resulting from open electron orbits. The model of Beton *et al.*[11] may readily be used to derive the fundamental potential amplitudes. Values for the potential deduced by the two methods generally agree to within experimental error provided that the harmonic content is correctly treated. The values used in this letter are those deduced from Eq. (1). The harmonic content of the data was studied by interpolating it in uniform intervals of $1/B$ and Fourier transforming using a square window. Because of uncertainties introduced by the restricted number of oscillations necessarily included in this process, these amplitudes are used for qualitative comparisons only.

The important details of the samples investigated in this study are summarized in Table I. Samples prepared on the same chip and measured in the same cooling cycle are given the same identification number. In Fig. 1, we show the amplitudes of the fundamental Fourier component of the potentials V_1 deduced using Eq. (1) for one of the samples as a function of gate voltage V_g. As expected, the magnitude of V_1 increases at positive and negative gate voltages. However, the points where the potential passes through zero are displaced from the origin, and a finite potential is observed at zero bias. We interpret these finite zero bias potentials as resulting from the strain which is present even when no gate voltage is applied. Only when a gate voltage of the correct sign is applied is the strain contribution cancelled by an electrostatic effect.

One point should be noted about these graphs. From the LSSL amplitudes, one can only determine the *modulus* of the potential. To assist in the interpretation, we have allotted a negative sign to the potentials at more negative gate voltages than the point at which the potential is zero, in agreement with our expectation that when the contribution from the charged gates is dominant, the potential in the channel will follow that at the gates.

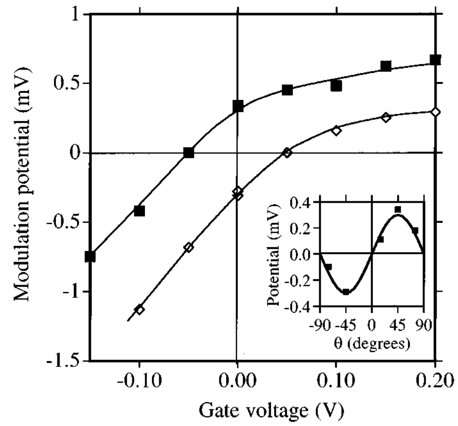

FIG. 1. Amplitudes of fundamental potential component for sample 1 plotted against gate voltage. Squares - sample 1A, diamonds - sample 1B. The lines drawn are to guide the eye. Inset - amplitudes plotted against orientation angle. The solid line is the predicted fit with an amplitude of 0.3 mV.

The key result is evident from Fig. 1, showing data for sample 1. For this sample two superlattices were studied with current flowing in the [011] and [011] directions ($\theta=\pm 45°$). For these two samples the offset of the zero point is equal in magnitude but of opposite sign, showing that the strain effect was reversed. This is exactly what is predicted for the piezoelectric coupling.

In the inset to Fig. 1, we plot the fundamental potential components observed at zero gate bias against the orientation angle of the superlattice. The curve shows the predicted angular dependence of $\sin 2\theta$. The fit is very good, confirming that the origin of the perturbation is the piezoelectric effect, and that the angular dependence dominates any variation with the period of the superlattice.

Further evidence arises from an analysis of the harmonic content of the modulation. In Fig. 2, we plot the amplitudes versus gate bias for each of the first two Fourier components of the CO (which are a measure of the equivalent components of the potential, provided the modulation is small) for sample 3A. The amplitude of the first harmonic, which is dominated by the electrostatic term, increases in rough proportion to the gate voltage (taking into account the offset). However, the electrostatic contribution to the second harmonic is small for samples of equal mark/space ratio,[4] and

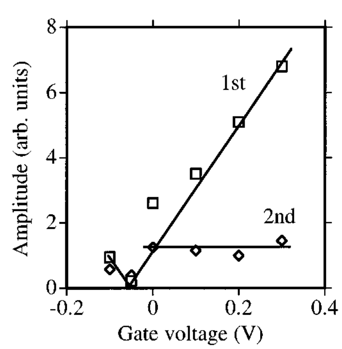

FIG. 2. Harmonic content of CO for sample 3A in forward bias. Squares - 1st harmonic, diamonds - 2nd harmonic. Lines are drawn to guide the eye.

hence this is expected to be dominated by the strain. The amplitude of the second harmonic reflects this, in that it is almost independent of gate voltage. This harmonic data confirms the hypothesis that piezoelectric coupling of the strain dominates the behavior at zero bias.

The last two columns in Table I, showing the first and second harmonics at zero gate bias, give a measure of the strength of the piezoelectric potential. We have extended our previous calculation[4] to include the piezoelectric coupling. Assuming a strain under the gates of 0.001 (derived from estimates of differential thermal contraction as discussed in Ref. 4), we obtain values in reasonable agreement with experiment, although there are significant uncertainties associated with the elastic behavior of the gate. These calculations will be discussed in detail in a future paper.

We have demonstrated that the modulation of a 2DEG under an unbiased LSSL is dominated by strain from the gates, coupled by the piezoelectric interaction. Although strain has long been used for restricting excitons to wires,[12] the piezoelectric effect has only a weak influence there. In contrast it offers a valuable tool for modulating a 2DEG in both one and two dimensions. If this modulation is not wanted it can be eliminated by orienting the LSSL along $\langle 010 \rangle$.

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