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LETTER TO THE EDITOR

The oscillatory magnetoresistance of electrons in a square superlattice potential

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Abstract. The transverse magnetoresistance of a two-dimensional electron gas in an n-type GaAs/(AlGa)As heterostructure subjected to a square superlattice potential is investigated. Magneto-oscillations are observed at low field ($B \leq 0.4$ T) with period $\Delta(1/B) = ea/2\hbar k_F$, where $a = 145$ nm is the superlattice constant. At higher fields the magneto-resistance is dominated by Shubnikov–de Haas oscillations. A comparison is made with experiments on a one-dimensional superlattice.

The motion of conduction electrons under the combined influence of a two-dimensional periodic potential and a perpendicular magnetic field B has attracted considerable theoretical interest [1–3]. There are two fundamental length scales in the problem, the period a of the potential and the magnetic length $l_B = (\hbar/eB)^{1/2}$. The ratio $\alpha = a^2/2\pi l_B^2 = a^2B/\Phi_0$, where $\Phi_0 = h/e$ is the number of flux quanta passing through the unit cell. For an ordinary lattice of atoms, a magnetic field of $\sim 10^5$ T would be required to achieve $\alpha \simeq 1$. Such fields are at least two orders of magnitude larger than those available in the laboratory.

It has been suggested [3] that the case of $\alpha > 1$ could be investigated by preparing a synthetic superlattice with a much larger value of a. The periodic potential could be generated using the electrostatic field effect on which semiconductor transistor action is based. Recently, two groups have generated a one-dimensional superlattice potential in this way and have investigated its effect on the magnetoresistance of a two-dimensional electron gas (2DEG) at the interface of a GaAs/(AlGa)As heterostructure [4, 5]. Winkler and co-workers [5] produced a one-dimensional superlattice by depositing an array of parallel metallic stripes on the surface of the (AlGa)As layer. Weiss and co-workers [4] used a somewhat different method: their sample was illuminated for a brief interval of time at liquid-helium temperatures with a well-defined light-and-dark pattern of parallel fringes produced by two interfering laser beams. The light pulse ionises some of the DX centres in the (AlGa)As layer by means of the persistent photoconductivity effect [6]. The resulting stripe-shaped array of impurity space charge modulates the electrostatic potential of the adjacent 2DEG. Since Winkler and co-workers [4] also used an optical interference method to fabricate their metallic stripes, the superlattice period $a \simeq 0.5\ \mu m$, is limited by the wavelength of visible light in both cases.

Both groups observe a new oscillatory magnetoresistance effect when a magnetic field $\boldsymbol{B}(\| z)$ is applied perpendicular to the plane of the 2DEG (defined as the xy plane). The extrema in the magnetoresistance form a series periodic in $1/B$ at magnetic field values given by

$$2R_c = 2\hbar k_F/eB = (m + \varphi)a \qquad m = 1, 2, 3 \ldots \tag{1}$$

The minima in the resistance correspond to $\varphi = -0.25$ (maxima to $\varphi = 0.17$). The period $\Delta(1/B)$ is therefore given by $ea/2\hbar k_F$. Here R_c is the radius of a cylotron orbit at the Fermi energy, k_F is the Fermi wavenumber, and a is the period of the one-dimensional superlattice potential ($V(x) = V_0 \cos(2\pi x/a)$).

In this Letter, we extend this recent work in a natural direction, namely to investigate the magnetoresistance of a 2DEG in the presence of a *two-dimensional square* superlattice potential. Electron beam lithography (EBL) was used to fabricate the superlattice on a high mobility modulation-doped n-type (AlGa)As/GaAs heterostructure grown by molecular beam epitaxy. The heterostructure comprised the following layers, in order of growth from the semi-insulating substrate

(i) a 4 μm buffer layer of undoped GaAs
(ii) a 40 nm spacing layer of undoped (AlGa)As
(iii) a 40 nm (AlGa)As layer doped with Si to 2×10^{18} cm^{-3}
(iv) a 17 nm undoped GaAs cap.

The (AlGa)As layer had an Al fraction [Al] = 0.33. Hall effect measurements gave the following values of sheet density n_s and mobility μ at 4 K:

$n_s = 1.9 \times 10^{11}$ cm^{-2} $\quad \mu = 1.1 \times 10^5$ cm^2 V^{-1} s^{-1} (dark)

$n_s = 3.8 \times 10^{11}$ cm^{-2} $\quad \mu = 2.1 \times 10^6$ cm^2 V^{-1} s^{-1} (after illumination at 4 K).

EBL allows us to fabricate a superlattice with a considerably shorter period than is possible using optical techniques. The arrangement is shown schematically in figure 1. A nichrome metallic gate is evaporated onto a film of poly(methyl methacrylate) (PMMA) in which a rectangular array of circles (of diameter ~60 nm) is exposed. The 'superlattice' constant a of the array was measured to be 145 nm. This patterned gate overlaps a Hall bar of dimensions $15 \times 5\ \mu$m. The current-carrying axis of the device was parallel to one side of the square unit cell. The metallic gate produces a periodic modulation of the electron potential energy in the 2DEG, for which the lowest frequency Fourier component can be written

$$V(x, y) = V_0[\cos(2\pi x/a) + \cos(2\pi y/a)]. \tag{2}$$

As a control sample, we also prepared and investigated a one-dimensional superlattice (a = 106nm) in which the parallel metallic gate stripes were perpendicular to the current direction. As was the case in the devices in [4, 5] the unbiased gates produce only weak modulation of the potential ($V_0 \ll \varepsilon_F = \hbar^2 k_F^2/2m^*$). Figure 2 shows the low-field magnetoresistance plots of the two structures at zero gate voltage, measured using a standard four-terminal technique. At fields below about 0.4 T, a series of oscillations, periodic in $1/B$, is observed in both structures, and is indicated by the arrows in figure 2. The amplitude of the oscillations for the two structures is comparable. For fields $\geqslant$0.4 T the magnetoresistance is dominated by the standard Shubnikov-de Haas (SDH) oscillations

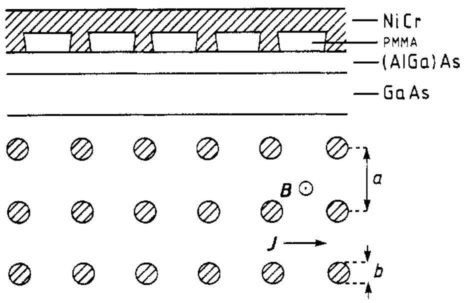

Figure 1. A schematic diagram of the process used to fabricate the two-dimensional superlattice.

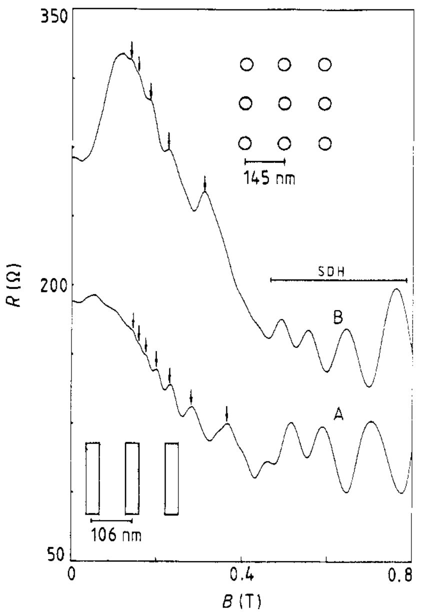

Figure 2. Resistance versus magnetic field for a two-dimensional electron gas subjected to a weak one-dimensional superlattice potential (curve A), and a weak two-dimensional superlattice curve (curve B).

which are also periodic in $1/B$. From our measurements we are able to deduce the period of the oscillations in $1/B$ for both the low-field and high-field SDH oscillations. The inverse of these periods are denoted by B_f and B_s, respectively. The value of B_s is related to the density of the 2DEG by $n_s = 2eB_s/h$. By illuminating the sample with bursts of light from a LED we are able to exploit the persistent photoconductivity effect to vary the electron density n_s. Figure 3 shows the relationship between n_s and B_f deduced from the low-field magnetoresistance, for samples with a 2D superlattice (full circles) and a 1D superlattice (open circles). The curves plotted are the expression

$$B_f = 2(2\pi n_s)^{1/2}\hbar e/a \qquad (3)$$

which is obtained from equation (1), with the superlattice constant a set to 106 nm (curve A) and 145 nm (curve B). These values of a correspond to the periods of the 1D and 2D superlattices, respectively. Clearly, within the experimental error in B_f ($\sim 8\%$ for the 2D superlattice and $\sim 5\%$ for the 1D superlattice), the relationship between B_f and n_s is the same for 1D and 2D superlattices. This is because the origin of the low-field series for

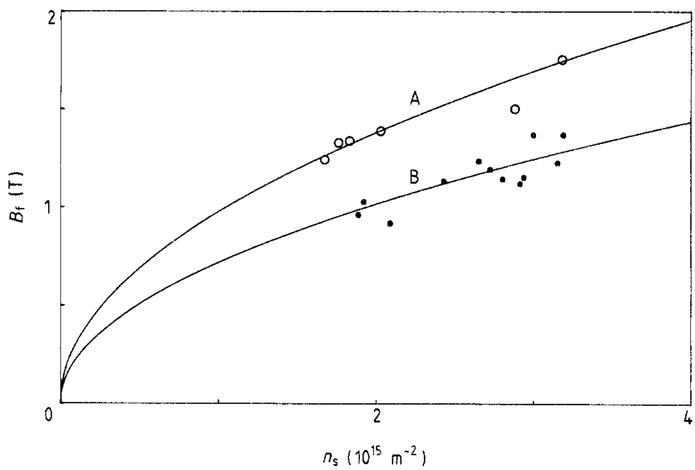

Figure 3. Inverse period of the low field $1/B$ series, plotted against electron density n_s, for the one-dimensional superlattice (open circles) and the two-dimensional superlattice (full circles). Also shown are the curves $B_f = 2(2\pi n_s)^{1/2}\hbar e/a$ with $a = 106$ nm (curve A) and $a = 145$ nm (curve B).

both the 1D and 2D superlattices is determined by the commensurability of the cyclotron orbit diameter and the period of the superlattice.

This result may be understood within the semi-classical model in [5] in which it is argued that the first-order perturbation of the energy of the Nth Landau level can, for large N, be approximated as the average of the perturbing potential around a classical cyclotron orbit. Thus the energy of the nth Landau level $E_N(k_y)$ is given by

$$E_N(k_y) = (N + \tfrac{1}{2})\hbar\omega_0 + \langle V \rangle \tag{4}$$

where

$$\langle V \rangle = \frac{1}{2\pi}\int_0^{2\pi} V(x, y)\, \mathrm{d}\theta \tag{5}$$

with $x = R_c \cos\theta$ and $y = R_c \sin\theta$, and $R_c = (2N + 1)^{1/2}(\hbar/eB)^{1/2}$. Note that, for a 1D periodic potential, $\langle V \rangle$ is the same for a potential varying along the x or the y direction. Thus the perturbation from a two-dimensional superlattice within this approximation will simply be a sum of the perturbations from the potentials which are periodic along the x and y directions. We therefore anticipate that the perturbation of energy eigenvalues and the corresponding effect on conductance will have the same dependence on magnetic field for 1D and 2D perturbing potentials, as is observed.

In references [4] and [5] the phase of the oscillations was measured to be $\varphi = 0.18$ (-0.25) for maxima (minima). The predicted values are $\varphi = 0.25$ (-0.25) for maxima (minima). We are unable to identify a consistent value for φ over the experimental range of values for n_s. This is due in part to the onset of the SDH oscillations for $m \sim 4$ (m is defined in equation (1)), compared with $m = 1$ in [4, 5]. Errors in estimates of φ are thus proportionally higher.

In similar samples, we have observed that by varying the gate voltage we may control the strength of the perturbation which may suppress the formation of Landau levels at low field, shifting the onset of the SDH oscillations to higher fields. We anticipate that the phase of the low-field oscillations may be extracted under these circumstances, and intend to extend this work to a systematic study of the effects of the variation of gate voltage on the magnetoresistance.

In conclusion, we have measured the low-field magnetoresistance of a 2DEG with a weak 2D superlattice perturbing potential. A low-field series of oscillations periodic in $1/B$ is found whose origin is closely related to those due to a 1D superlattice perturbing potential. Very recently, Weiss and von Klitzing [7] communicated to us the result of an experiment in which they investigate a square superlattice produced by partial photoionisation of DX centres. They also find magneto-oscillation with a period given by equation (3).

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References

[1] Harper P G 1955 *Proc. Phys. Soc.* A **68** 874
[2] Azbel M Ya 1964 *Sov. Phys.–JETP* **19** 634
[3] Hofstadter D R 1979 *Phys. Rev.* B **14** 2239. References to earlier work on this topic can be found in this article
[4] Weiss D, von Klitzing K, Ploog K and Weimann G 1989 *Springer Series in Solid State Sciences* vol 87 p 357; 1989 Europhys. Lett. **8** 179
Gerhardts R R, Weiss D and von Klitzing K 1989 *Phys. Rev. Lett.* **62** 1173–6
[5] Winkler R W, Kotthaus J P and Ploog K 1989 *Phys. Rev. Lett.* **62** 1177–80
[6] Lang D V and Logan R A 1977 *Phys. Rev. Lett.* **39** 635
[7] Weiss D and von Klitzing K 1989 private communication