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Shubnikov–de Haas effect in submicron-width $GaAs/Ga_{1-x}Al_xAs$ heterojunction wires

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Shubnikov–de Haas oscillations have been measured in 0.4-μm-wide $GaAs/Ga_{1-x}Al_xAs$ wires and compared to the oscillations from adjacent wide areas of material. The amplitudes of the oscillations from each area have been analyzed in terms of existing theory. The results show a higher scattering rate in the narrow wires, which we suggest is due to the influence of the sample walls.

Lateral confinement of a two-dimensional electron gas (2DEG) has been mainly studied using narrow silicon metal-oxide-semiconductor field-effect transistors (MOSFET's).[1-8] Recently, however, a number of studies have been made using narrow samples of $GaAs/Ga_{1-x}Al_xAs$ single heterojunctions.[9-15] This system has the advantage that the length scales involved are somewhat larger, and therefore quasi-one-dimensional effects may be expected at larger physical size.

Narrow conducting pathways have been fabricated in both materials by two main methods: physical confinement by etching narrow mesas,[1-5,12-15] and electrostatic confinement using split-gate geometries.[6-11] In both types of sample the conducting width is an unknown parameter. In narrow-mesa geometries the depth of surface depletion is unknown, and in split-gate geometries the dependence of conducting width on gate voltage is unknown since it is controlled by complicated fringing effects at the edges of the gate contacts.

Studies of the transport behavior of narrow samples of $GaAs/Ga_{1-x}Al_xAs$ heterojunctions may be very briefly summarized as follows. Hall-bar-geometry samples, etched into a $GaAs/Ga_{1-x}Al_xAs$ heterojunction, have shown size effects in the low-field magnetoresistance when the width of sample was reduced below the inelastic scattering length of the electrons.[14,15] These effects were attributed to changes in the electron-electron interactions occurring in the narrow samples. Similar etched samples with widths of 1.0 μm have been studied at higher magnetic field, and have shown a variety of size effects in the quantum Hall effect and the Shubnikov–de Haas (SdH) effect; however, the effects were not analyzed quantitatively.[13] Split-gate geometries have been used to confine the 2DEG of the $GaAs/Ga_{1-x}Al_xAs$ system to submicron widths. Thornton *et al.*[10] fitted the low-field magnetoresistance data from one such device to one-dimensional localization theory using the width as a fitting parameter. They found a good fit to the theory for a width of 400 Å. The same method was used by Zheng, Wei, Tsui, and Weimann[11] to calculate the width of slightly wider split-gate devices, and by Choi, Tsui, and Alavi[12] to calculate the width of narrow mesas. Also using slightly wider split-gate geometries, Berggren, Thornton, Newson, and Pepper[9] suggested that the aperiodic nature of their low-field Shubnikov–de Haas oscillations was linked with the influence of confinement effects on quantum magnetic effects.

We undertook the present work to obtain information concerning the onset of quantum-confinement effects in a narrow, exposed mesa fabricated in a $GaAs/Ga_{1-x}Al_xAs$ heterojunctions, where surface effects were expected to be important. Quantitative analysis of the SdH effect can provide additional information to that derived from weak localization and one-dimensional subband effects, which have been observed in narrow channels of 2DEG.

We have studied the SdH effect in high-mobility $GaAs/Ga_{1-x}Al_xAs$ heterojunction material wet etched to a width of approximately 0.4 μm (estimated by electron microscopy of samples fabricated alongside the test device, which was not measured to avoid damage by the scanning electron microscope). By using uv lithography we avoided the possibility of damage by high-energy electrons in *e*-beam lithography. By using isotropic wet etchants we have minimized surface damage, which could occur in ion-beam milling or reactive-ion etching and have also produced exceptionally smooth etch surfaces. Figure 1 shows the device geometry, together with the epitaxial structure of the material, which was grown by molecular-beam epitaxy at Philips Research Laboratories, Redhill. Details of the growth procedure have been published elsewhere.[16] In addition to experiments performed with nine narrow wires in parallel (as shown), some have been performed with just one narrow wire, the others having been broken using a microprobe. Figure 1 also shows the mobilities and carrier densities in the light and dark measured at Philips Research Laboratories, Redhill, using conventional samples. Similar values were also obtained at the University of Sussex using Hall bars, which were fabricated alongside the devices used in the present work.

Measurements were performed with the sample immersed in liquid helium in the temperature range 4.2–1.7 K. Magnetic fields up to 5.5 T were applied, and the carrier concentration of the sample was increased by photoexcitation. The resistances were measured using an EG&G Brookdeal lock-in amplifier for low-frequency, constant rms current. dc measurements were made using

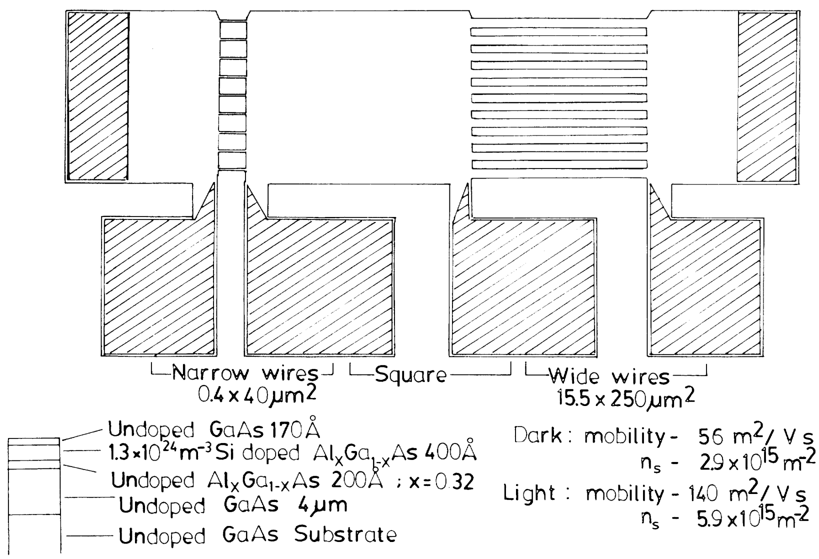

FIG. 1. Sample geometry, the epitaxial structure of the material and its transport parameters measured at 4.2 K.

a Keithley 195A digital multimeter and a Keithley 220 current source. Applied voltages never exceeded $3kT/e$, in order to minimize heating effects, and this inevitably required the use of very low currents due to the high resistance of the narrow wires.

Between 300–1.7 K the narrow wires had resistances in excess of 10 MΩ when in the dark with no persistently photoexcited carriers. However, on exposure to light, the resistances dropped to values which, if one used the carrier density calculated from the SdH data and assumed that the mobility was the same as that in the wide wires, suggested that the conducting width of each wire was 0.12 μm. An alternative conclusion is that the whole wire conducted but the mobility of the electrons was reduced. The resistance of the array of narrow wires was inversely proportional to the number of intact wires, suggesting a high degree of uniformity. The photoconductivity effect was persistent at low temperatures, hence, all measurements of the SdH effect were made with some persistently photoexcited carriers.

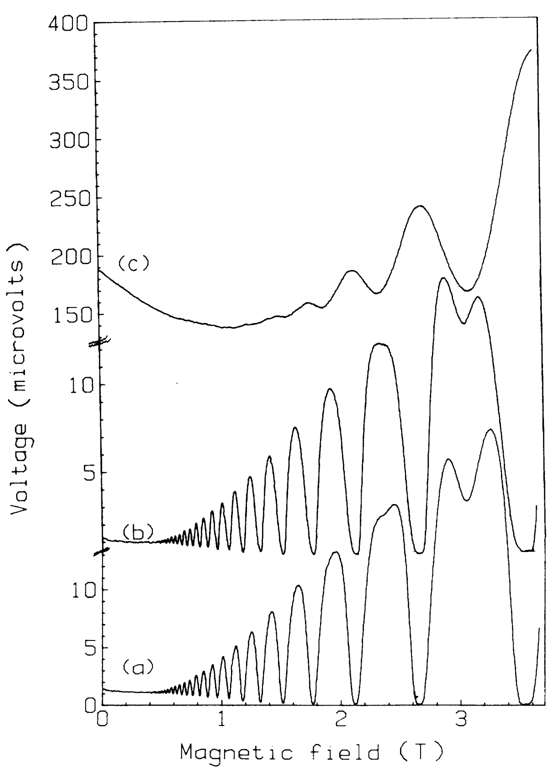

FIG. 2. Shubnikov–de Haas oscillations obtained from the sample with one narrow wire intact. $T=1.7$ K, current 7.8 nA. (a) Square, (b) wide wires, (c) narrow wire.

SdH oscillations obtained from the sample with one narrow wire intact at a temperature of 1.7 K are shown in Fig. 2. The amplitudes of the oscillations from each part of the sample, expressed as a fraction of the zero-field resistance $\Delta\rho(B)/\rho(0)$, were compared at various values of magnetic field. The amplitude of oscillation, expressed in this manner, was always smaller in the narrow wires than in the wide regions, irrespective of carrier density or temperature. Similar effects were observed in 1.0-μm samples in Ref. 13.

The expression for $\Delta\rho(B)/\rho(0)$ [Eq. (1)] has been given by Choi, Tsui, and Palmateer[14] who inverted the conductivity tensor using Ando's formula for $\sigma_{xx}(B)$ (Ref. 17) and the classical form of $\sigma_{xy}(B)$. This expression was predicted to be valid where $\omega_c\tau < 2$. For simplicity, we have omitted any contribution from electron-electron interaction and weak localization,

$$\frac{\Delta\rho(B)}{\rho(0)} = \frac{2(\omega_c\tau)^2}{1+(\omega_c\tau)^2}\cos\left[\frac{2\pi E_F}{\hbar\omega_c}\right] \times\exp\left[\frac{-\pi}{\omega_c\tau}\right]\frac{2\pi^2 k_B T/\hbar\omega_c}{\sinh(2\pi^2 k_B T/\hbar\omega_c)} . \quad (1)$$

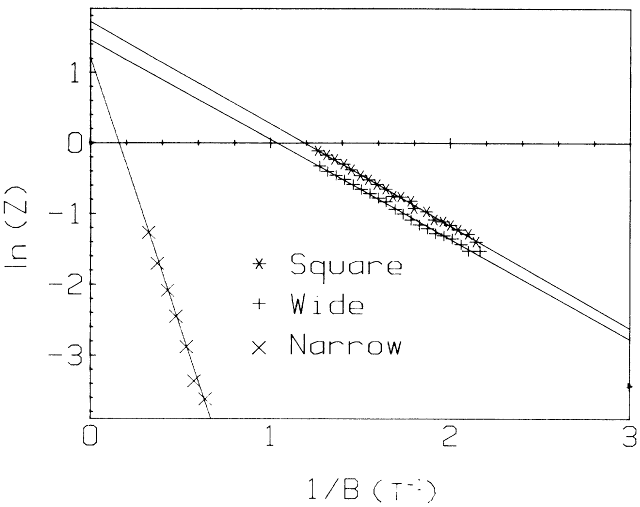

FIG. 3. Dingle plots for the data given in Fig. 2.

Here, τ is a scattering time relevant to the orbital motion and not directly comparable to the conductivity scattering time, unless the zero-field scattering mechanism is known.[18,19]

By iterating a Dingle plot of $\ln(Z)$ against $1/B$, where

$$Z=\frac{\Delta\rho(B)}{\rho(0)}\left[\frac{1+(\omega_c\tau)^2}{2(\omega_c\tau)^2}\right]\frac{\sinh(2\pi^2k_BT/\hbar\omega_c)}{2\pi^2k_BT/\hbar\omega_c},$$

evaluated at the maxima and minima of the oscillations, we obtained a straight line of slope $(-\pi m^*/e\tau)$. The final iterations of the plots for the data given in Fig. 2 are shown in Fig. 3.

Although the excellent straight-line plots, such as those of Fig. 3, suggest that the effects of temperature and magnetic field have been well accounted for, the results show a nonzero intercept on the y axis, which is inconsistent with Eq. (1). The value of the intercept was smaller in the narrow wires than in the wide regions. This suggests that the form of the SdH oscillations is accurately represented by Eq. (1), if there is an additional preexponential factor A, which is independent of B and T but dependent on sample size ($\ln A$ is the intercept). The inclusion of contributions from electron-electron interaction or weak localization would increase the value of A. Analysis of data published in Ref. 13 has also shown the existence of a preexponential factor.

Typical values of τ obtained by this method are shown in Table I, together with values of A. The values of τ for both the wide wires and the square region increased as the temperature decreased, as expected. However, the value of τ in the narrow wires was insensitive to temperature. We believe that this reflects the destruction of phase coherence in the cyclotron orbit by collision with the walls of the wire in a narrow sample, rather than collision with phonons in a wide sample.

TABLE I. Values of τ and A for the narrow, wide, and square regions of the sample, measured at 4.2 and 1.7 K.

Temp (K)	N_s (10^{15} m^2)	Area measured	τ (10^{-13} s)	A
4.2	4.88	Square	5.9	6.1
1.7	5.15	Square	8.3	5.5
4.2	4.87	Wide	6.3	4.9
1.7	5.15	Wide	8.4	4.5
4.2	4.36	Narrow	1.8	2.6
1.7	4.56	Narrow	1.6	3.4

We have calculated the scattering time relevant to the zero-field conductivity τ_c using the following expression:

$$R_\square-\frac{m^*}{N_se^2\tau_c}.$$

Under the conditions used to obtain the data in Fig. 2 $R_\square=9\,\Omega$ and, therefore, $\tau_c=5.1\times10^{-11}$ s. The ratio between the two scattering times τ_c/τ in the wide regions is, therefore, 62. This value is somewhat higher than the theoretical prediction for our material.[19] At present we have no explanation for this. There is no theoretical expression for the ratio τ_c/τ in narrow samples, but in the analogous experiment, where a magnetic field is applied parallel to a 2DEG, no SdH oscillations are observed, so $\tau=0$, but τ_c is finite and so the ratio is infinite. We would, therefore, expect the ratio to increase smoothly as the width of our samples is decreased.

To conclude, we have shown that the SdH oscillations from high-mobility GaAs/$Ga_{1-x}Al_xAs$ heterojunctions fit the equation given by Choi *et al.*,[14] provided that an additional preexponential factor is included. This factor was independent of temperature and magnetic field. The values of τ obtained from the wide and narrow samples indicate that there exists a different mechanism for the destruction of phase coherence in the narrow samples, which we suggest is probably due to the influence of the sample walls.

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