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Measurement of Anisotropic Transport Using Unidirectional Lateral Superlattice with Square Geometry

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Anisotropy in resistivity is often measured conveniently using a square sample. A very recent example is on ultrahigh mobility ($\mu \geqslant 1000\,\mathrm{m^2/Vs}$) two-dimensional electron gas (2DEG), which showed strongly anisotropic transport near half-filling of high ($N \geqslant 2$) Landau levels.[1)] Ratio of the resistance close to 100 was reported between two different current configurations. It was soon pointed out, however, that the resistance ratio measured on a square sample does not correctly represent the intrinsic resistivity ratio of the material, but gives a greatly enhanced value of anisotropy as a result of anisotropic spread of the current flow.[2)] The purpose of the present notes is to experimentally verify the theoretically calculated formula for square geometry [eq. (1) below], employing unidirectional lateral superlattice (ULSL) samples with well defined transport anisotropy.[3–5)]

Top panels of Fig. 1 show the schematic and an SEM image of our square sample. Square mesa ($40 \times 40\,\mu\mathrm{m}^2$) with eight arms ($\sim 4\,\mu$m wide) for electric contact is lithographically defined from conventional GaAs/AlGaAs 2DEG. Unidirectional periodic potential modulation is introduced by placing a grating of electron-beam resist on the surface as done in our previous work.[5)] It can readily be seen that resistance R_{xx} measured using arms 3, 7 as source/drain and 2, 8 as voltage probes (I_{37}–V_{28}) mainly represents resistivity perpendicular to the grating. Likewise, R_{yy} measured by I_{15}–V_{24} mainly picks up the parallel component. According to the theory,[2)] R_{xx} thus measured is related to resistivity tensor components ρ_{xx} and ρ_{yy} as,

$$R_{xx} = \frac{4}{\pi}\sqrt{\rho_{yy}\rho_{xx}} \times \sum_{m=1}^{\infty}\left[(2m-1)\sinh\left(\frac{2m-1}{2}\pi\sqrt{\frac{\rho_{yy}}{\rho_{xx}}}\right)\right]^{-1}, \quad (1)$$

assuming the uniformity of ρ_{xx} and ρ_{yy}. R_{yy} is obtained by interchanging every x and y in eq. (1). The main panel of Fig. 1 shows experimentally measured R_{xx} and R_{yy} for our square ULSL with period $a = 184$ nm. R_{xx} qualitatively displays well-known features expected for ρ_{xx} in ULSL: low-field ($|B| \leqslant 0.06$ T) positive magnetoresistance[4)] and commensurability oscillation in higher fields with minima occurring at expected positions ($2R_c/a = n - 1/4$, $n = 2, 3, \ldots, 9$ with $R_c = \hbar k_F/eB$ the cyclotron radius, $k_F = \sqrt{2\pi n_e}$ the Fermi wavenumber, and n_e the electron density).[3)] R_{yy} shows anti-phase oscillations with smaller amplitude.

In order to compare observed traces with eq. (1), we *experimentally* obtain ρ_{xx} and ρ_{yy} by measuring a Hall bar sample ($37\,\mu$m wide, $64\,\mu$m long) of ULSL identically prepared from the same 2DEG wafer. Figure 2(a) shows traces for ULSL and adjacent plain 2DEG reduced to sheet resistivity using the geometric factors. We take the former and the latter as ρ_{xx} and ρ_{yy} respectively. Strictly speaking, ρ_{yy} is reported to contain small oscillatory part, $\Delta\rho_{yy}^{\mathrm{osc}}$, anti-phase to that of ρ_{xx}, $\Delta\rho_{xx}^{\mathrm{osc}}$,[3)] resulting from collisional contribution expected to present for both ρ_{xx} and ρ_{yy}, as opposed to diffusion contribution present only for ρ_{xx}.[6)] However, since $|\Delta\rho_{yy}^{\mathrm{osc}}| \ll |\Delta\rho_{xx}^{\mathrm{osc}}|$, especially for smaller a because roughly $|\Delta\rho_{yy}^{\mathrm{osc}}| \propto (ak_F)^2|\Delta\rho_{xx}^{\mathrm{osc}}|$, we neglect $\Delta\rho_{yy}^{\mathrm{osc}}$ for a moment. (Small oscillations seen in the plain-2DEG trace for $B \geqslant 0.4$ T are the Shubnikov–de Haas effect.) Inserting these ρ_{xx} and ρ_{yy} into eq. (1), the calculated R_{xx} and R_{yy} are shown in Fig. 2(b) as dotted traces. As can be seen, they show very good agreement with the measured (solid) traces, attesting to the validity of eq. (1). It is important to point out that the anti-phase oscillation in R_{yy} is reproduced even *without* oscillatory part in ρ_{yy}. Meticulous care should be taken of the sample geometry, therefore, if one really wants to measure small $\Delta\rho_{yy}^{\mathrm{osc}}$ in the presence of large $\Delta\rho_{xx}^{\mathrm{osc}}$.

The remnant discrepancy between measured and calculated traces seems to be resulting from difference in not-well-understood slowly varying background, and also from slight uncontrollable difference in the amplitude V_0 of the potential modulation between the two samples. In pursuit of further verification of eq. (1) circumventing these obstacles, we next compare the oscillatory part ΔR, whose behavior is quantitatively well understood. The comparison is shown in

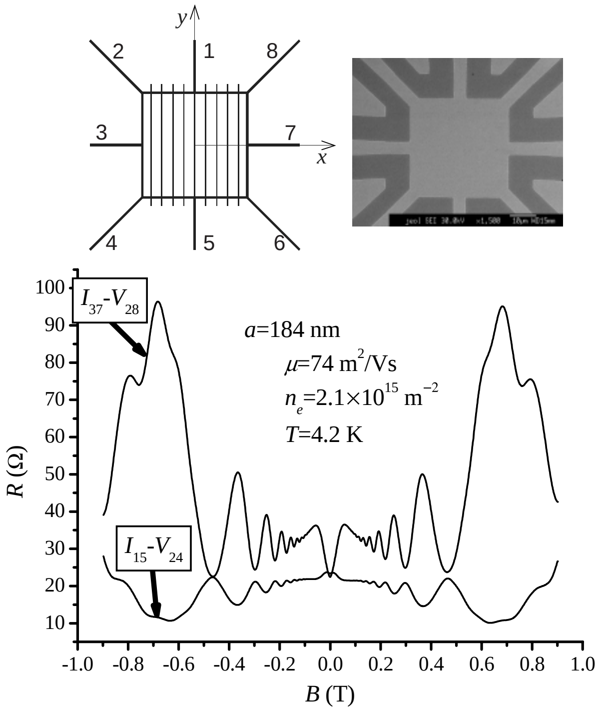

Fig. 1. Top: schematic illustration and SEM image of square ULSL sample. Main: magnetoresistance traces R_{xx} and R_{yy} measured by current- and voltage-probe configuration I_{37}–V_{28} and I_{15}–V_{24}, respectively.

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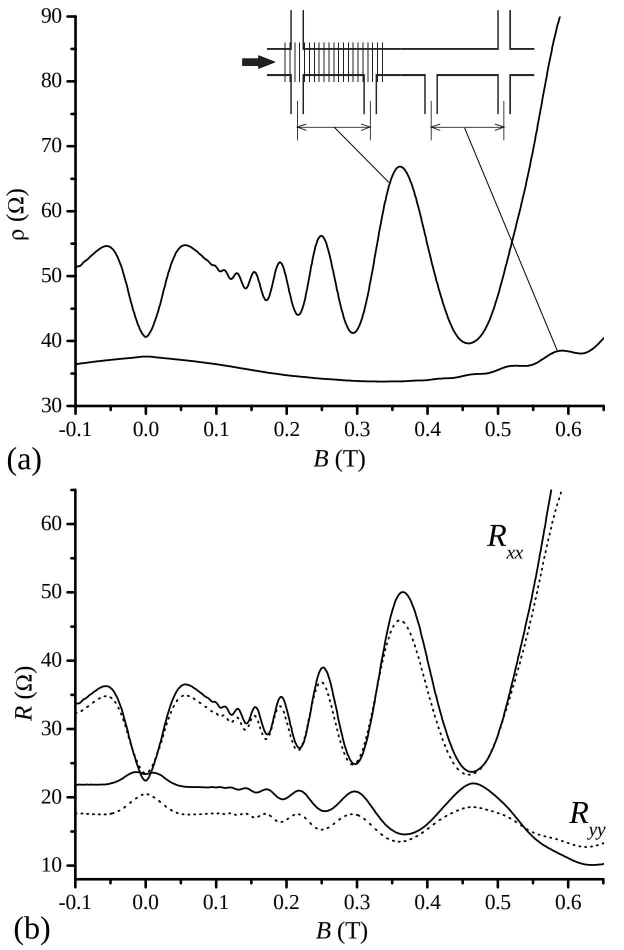

Fig. 2. (a) Magneto-resistivity measured for a Hall bar with ULSL and adjacent plain 2DEG. They are taken as ρ_{xx} and ρ_{yy}, respectively. (b) Solid traces: measured R_{xx} and R_{yy} (reproduction from Fig. 1). Dotted traces: calculated R_{xx} and R_{yy} using ρ_{xx}, ρ_{yy} from (a) and eq. (1).

Fig. 3. For measured (solid) traces, the oscillatory parts ΔR_{xx}, ΔR_{yy} are extracted from Fig. 2(b), using spline envelope curves as described in our previous publication.[5] For calculated (dotted) traces, we follow the following prescription. First, the oscillatory part $\Delta\rho_{xx}^{\mathrm{osc}}$ is extracted in the same manner from ρ_{xx} in Fig. 2(a). The oscillatory part has been shown by the present authors to be well delineated by,

$$\frac{\Delta\rho_{xx}^{\mathrm{osc}}}{\rho_0} = A\left(\frac{\pi}{\mu_{\mathrm{W}} B}\right)\frac{\eta^2}{2}\frac{L}{a}B\mu A\left(\frac{T}{T_a}\right)\sin\left(\frac{4\pi R_{\mathrm{c}}}{a}\right), \qquad (2)$$

with $A(x) \equiv x/\sinh x$ and $\eta = V_0/E_{\mathrm{F}}$ (see ref. 5 for other detailed parameters). The inset in Fig. 3 shows the extracted $\Delta\rho_{xx}^{\mathrm{osc}}$ and simulated curve using eq. (2) with $\eta = 0.0336$, showing excellent agreement confirming our previous result.

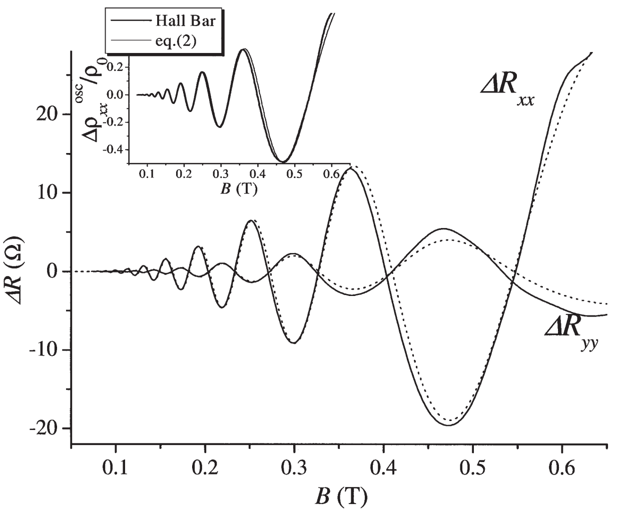

Fig. 3. Inset: oscillatory part of ρ_{xx} extracted from Fig. 2(a) and simulated curve eq. (2) with $\eta = 0.0336$ and $\mu_{\mathrm{W}} = 9.6\,\mathrm{m^2/Vs}$. Main: oscillatory part of R_{xx} and R_{yy} extracted from the measurement (solid traces) and calculated (dotted traces) by the procedure detailed in the text.

After replacing the oscillatory part in ρ_{xx} from the extracted $\Delta\rho_{xx}^{\mathrm{osc}}$ to eq. (2) with slight modification, i.e., 2% and 8% increase in n_e and η, respectively, to account for slight difference between the samples, R_{xx} and R_{yy} is calculated using eq. (1). Finally, oscillatory part of the calculated R_{xx}, R_{yy} is extracted and plotted as dotted traces in Fig. 3. Again agreement between measured and calculated ΔR is excellent. The procedure described here allows accurate determination of η from the measurement on square sample. The oscillation amplitude of calculated ΔR_{yy} is slightly smaller above $\sim$0.35 T, which may be resulting from ignoring $\Delta\rho_{yy}^{\mathrm{osc}}$. Another possible source of disagreement is imperfectness of the sample geometry: current path may be perturbed also in the Hall bar by the presence of voltage probes, and probes are not infinitely small points as assumed in eq. (1) but possess finite width in the square sample. Given these factors, the agreement between measured and calculated traces is quite satisfactory.

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