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# Resistivity enhancement in quasiperiodic unidirectional lateral superlattices

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**Abstract**

Strong enhancement in the zero-magnetic-field resistivity, followed by negative magnetoresistance, has been observed for two-dimensional electron gases by introducing weak quasiperiodic (Fibonacci) potential modulation having a length scale close to the Fermi wavelength. The extra resistivity increases with decreasing length scale notwithstanding the concomitant decrease in the modulation amplitude, and also with decreasing temperature and increasing electron concentration. The enhancement is qualitatively explained by backscattering due to Bragg reflections from the quasiperiodic superlattices characterized by a dense set of reciprocal lattice vectors.
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Study of electronic transport properties in artificial quasiperiodic systems may possibly provide a pathway to access theoretically predicted exotic behaviors (see e.g. [1]), and can also supply useful knowledge toward the understanding of electronic transport properties in quasicrystals [2]. We have been studying transport properties of Fibonacci lateral superlattice (FLSL), a two-dimensional electron gas (2DEG) subjected to weak potential modulation arranged in a Fibonacci sequence, $LSLLSLSLLS\ldots$, with $L/S = \tau = (1+\sqrt{5})/2$. In a previous publication [3], we reported commensurability oscillation (CO) and the geometric resonance of open orbits, which are analogous to those observed in periodic LSLs [4,5], but display much more complex structure, reflecting the richness of Fourier components, or reciprocal lattice, of the Fibonacci potential. In the present paper, we report strong enhancement of the resistivity when the introduced length scales, $L$ and $S$, are made smaller and approach the Fermi wave length $\lambda_F$. No analogue is known for periodic LSLs.

Four FLSL samples, from A to D, with successively smaller $L$ and $S$ (keeping $L/S = \tau$) as tabulated in Table 1, are fabricated from a GaAs/AlGaAs wafer with 2DEG residing at the 90-nm-deep heterointerface. The electron concentration is $n_e = 1.7 - 3.1 \times 10^{15}\,\mathrm{m}^{-2}$ (varied by illumination) and the correspondent $\lambda_F = 45-60\,\mathrm{nm}$ is of the same order as $S$. Quasiperiodic potential modulation is introduced by placing negative electron-beam (EB) resist on the surface selectively on the $L$'s of the Fibonacci sequence and exploiting the stress-induced piezoelectric effect. Owing to the exponential decay along the depth of the effect exerted on the surface [6], FLSL with smaller $L$, $S$ inevitably has smaller modulation amplitude. As reported earlier [3] and can be seen in Fig. 1 for $|B| > \sim 0.1\,\mathrm{T}$, complicated CO is observed, which can be accounted for as superposition of a series of CO each arising from an average period, $S/f_j$ with $f_j = \tau^{2-j}/\sqrt{5} (j = 1, 2, 3, \ldots)$, belonging to one of the self-similar generations. In Table 1, modulation amplitude $V_3$ for the most dominant component $S/f_3$ corresponding to average distance between adjacent $S$'s, obtained from detailed Fourier analysis of CO [7], is tabulated. The amplitudes are roughly the

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Table 1
Sample parameters

| Sample | $L$ (nm) | $S$ (nm) | $S/f_3$ (nm) | $V_3$ (meV) |
|---|---|---|---|---|
| A | 104 | 64 | 231 | 0.36 |
| B | 81 | 50 | 180 | 0.20 |
| C | 69 | 43 | 154 | 0.16 |
| D | 58 | 36 | 129 | 0.07 |

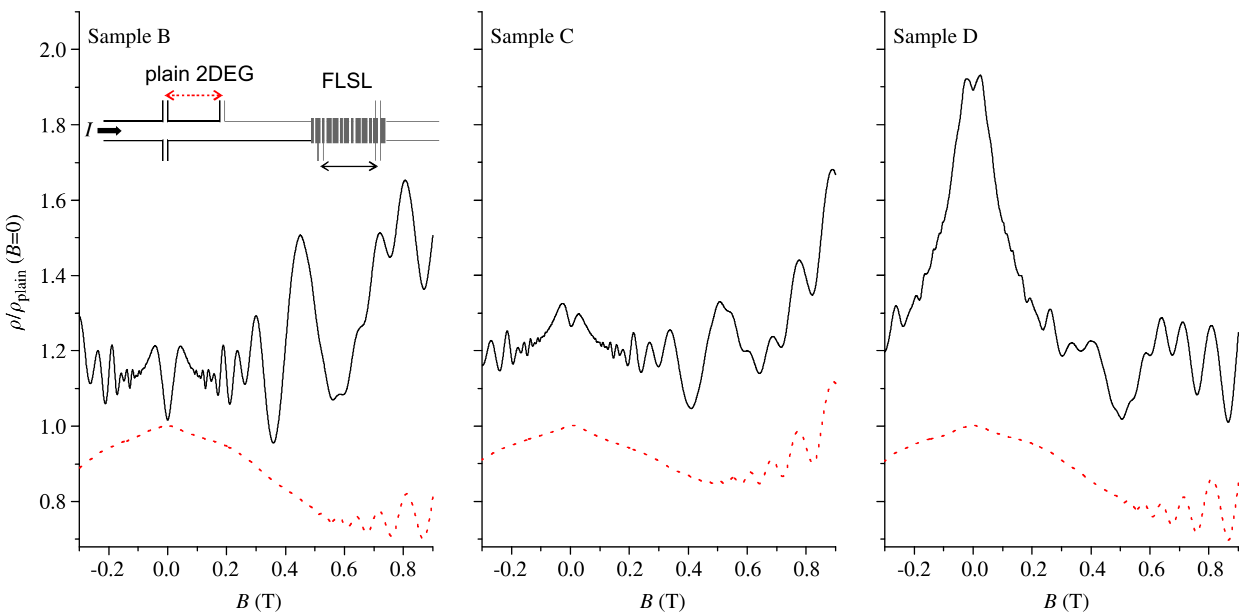


Fig. 1. MR traces for FLSL (solid) and the adjacent plain 2DEG (dotted), both normalized by the value for plain 2DEG at $B=0$, for samples B (left), C (center), and D (right). Inset: schematic configuration of the samples.

same as those of the periodic LSLs with period $a=S/f_3$ [6]. Note that the amplitudes are much smaller than the Fermi energy $E_F=7$–$11\,\mathrm{meV}$.

Enhancement of resistivity by the introduction of quasiperiodic modulation is clearly demonstrated in Fig. 1, which shows magnetoresistance (MR) of FLSL $\rho_{FLSL}(B)$ and of adjacent plain 2DEG $\rho_{plain}(B)$, both normalized by $\rho_{plain}(0)$. The ratio $\rho_{FLSL}(0)/\rho_{plain}(0)$ increases with decreasing $L$, $S$, despite the decrease in the modulation amplitude, and reaches ~2 for sample D. The negative MR (that appears following the low-field positive MR well know also for periodic LSLs [8]) signals that the enhancement is counteracted by a magnetic field.

By gradually increasing $n_e$ by successive LED illumination, the ratio $\rho_{FLSL}(0)/\rho_{plain}(0)$ is observed to slightly increase with $n_e$; it changes from 1.73 to 2.14 as $n_e$ increases from 1.7 to $3.1\times10^{15}\,\mathrm{m}^{-2}$ for sample D. Increase in the mean-free path $\Lambda_{mfp}$ by $n_e$ appears to be working favorably for the resistivity enhancement.

Temperature dependence of $\rho_{FLSL}(0)$ deviates from linear behavior characteristic of plain 2DEGs, as shown in Fig. 2.For sample A having largest $L$, $S$, hence largest modulation amplitude, the increment of the resistivity $\Delta\rho=\rho_{FLSL}-\rho_{plain}$ proportional to $T^2$ is attributable to the electron–electron interaction well established for periodic LSLs [9,10]. For samples with smaller $L$, $S$, $\Delta\rho$ shows negative temperature derivative at low temperatures, which becomes more prominent with the decrease of $L$, $S$ until $\rho_{FLSL}$ itself shows "insulating" behavior for sample D. Lower temperatures are advantageous for the resistivity enhancement probably through the increase in $\Lambda_{mfp}$.

The enhanced resistivity at $B=0$ results in reduced transport (momentum-relaxation) mobility $\mu$ calculated from it for FLSLs compared to plain 2DEGs. In marked contrast, the quantum mobility $\mu_Q$ deduced from the decay of Shubnikov–de Haas (SdH) oscillation [11] is found to remain virtually unchanged. For example, SdH traces in the range $B=0.1-0.25\,\mathrm{T}$ taken at 30 mK (not shown) leads to $\mu_Q=6.5\,\mathrm{m}^2/\mathrm{Vs}$ for both the FLSL and plain 2DEG for sample D at $n_e=2.0\times10^{15}\,\mathrm{m}^{-2}$. This, as well as unaltered $n_e$ double-checked by SdH frequency and the Hall resistance, rules out the disorder, introduced, e.g., by the EB processing,[1] as the origin of enhancement in $B=0$ resistivity and apparent insulating behavior.

[1]Possibility of EB-induced damage can be eliminated also by the fact that: (i) no sign of damage has ever been observed for periodic LSLs fabricated by the same process and (ii) EB-induced damage, if ever, should not depend on the length of $L$, $S$.

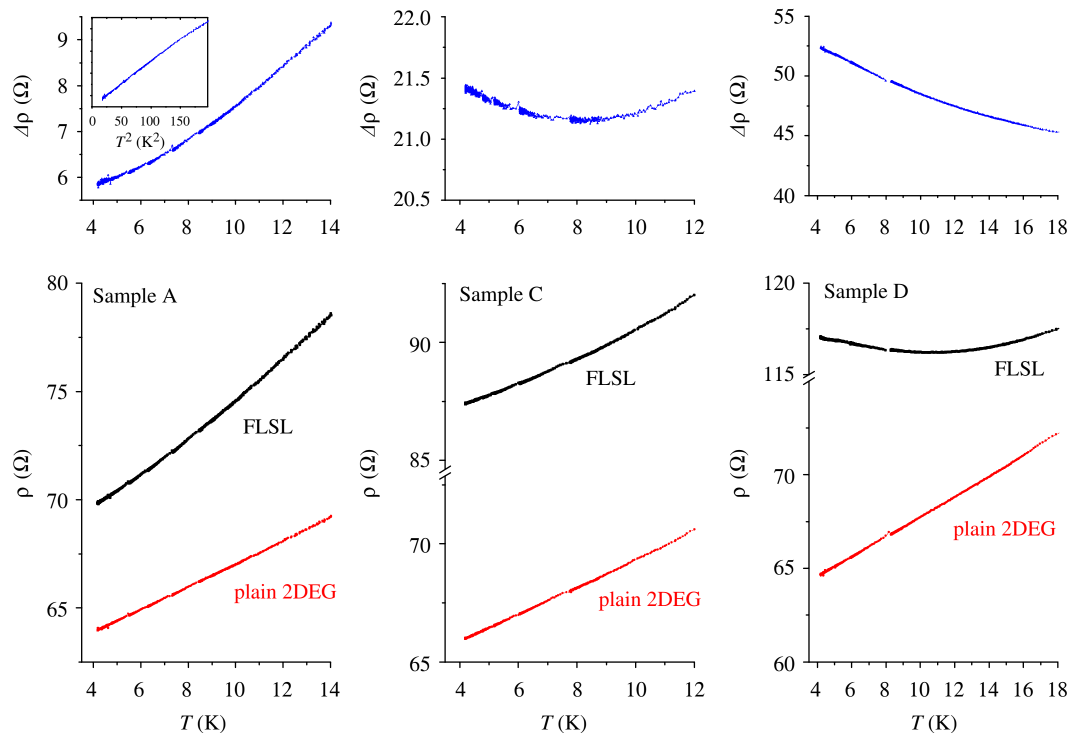


Fig. 2. Temperature dependence of resistivities at $B=0$ for FLSL and plain 2DEG (bottom) and their differences $\Delta\rho$ (top) for samples A (left), C (center) and D (right). Inset for sample A shows plot of $\Delta\rho$ against $T^2$.

Qualitative explanation of the phenomena is given by the backscattering due to Bragg reflections from the quasiperiodic superlattice. Electrons can gain momentum $\mathbf{\Delta k} = (\Delta k_x, \Delta k_y)$ by reciprocal vector $\mathbf{g} = (g, 0)$ of the superlattice. Here, the direction of the current hence of the modulation is defined as $x$ direction. In periodic systems, only $g = 2\pi/a$ and its harmonics are allowed. In the Fibonacci superlattices $g = g_{m,n} = 2\pi f_{m,n}/S$ with $f_{m,n} = (m\tau + n)/(\tau + 2)$ ($m$, $n$ integers) [12] fills up the $k_x$ axis of the reciprocal space, although in reality only a small fraction of them with small $|m|$, $|n|$ are effective, the detail of which depending on the profile of the potential modulation. Such Bragg reflections actually manifest themselves as geometric resonance of (diffraction-induced) open orbits [3,7]. Therefore, in quasiperiodic superlattices, chances for the electrons to fulfill the Bragg conditions are boosted, leading to an increased probability of the backscattering. The scattering angle for each reflection increases with decreasing $S$, accounting for the dependence on the introduced length scale. The effect of the Bragg reflection is naturally more pronounced for cleaner sample, namely, for sample with larger $\Lambda_{\mathrm{mfp}}$.

A magnetic field acts against the Bragg reflections through the magnetic breakdown effect [13]. The probability of breakdown for the reflection $(m,n)$ with potential component $V_{m,n}$ is given by $p_{m,n} = \exp(-B_{m,n}/B)$, with

$$B_{m,n} = \frac{\pi}{16}\frac{2m^*}{e\hbar}\frac{V_{m,n}^2}{E_F}\left[\frac{g_{m,n}}{2k_F}\sqrt{1-\left(\frac{g_{m,n}}{2k_F}\right)^2}\right]^{-1}.$$

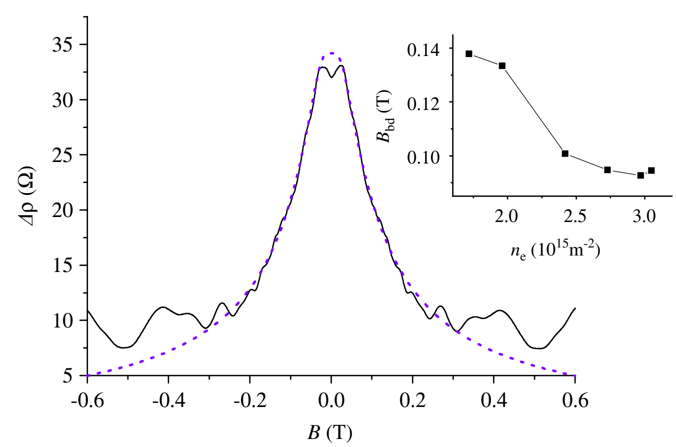


Fig. 3. Extra resistivity $\Delta\rho(B)$ introduced by the quasiperiodic modulation (solid trace) for sample D ($n_e = 3.1\times10^{15}\,\mathrm{m}^{-2}$) and the fit to Eq. (1) (dotted trace; $\rho_{\mathrm{bd}} = 34\,\Omega$ and $B_{\mathrm{bd}} = 0.094\,\mathrm{T}$). Inset: $n_e$ dependence of $B_{\mathrm{bd}}$ obtained by similar fittings.

Thus, the probability for an electron to survive all the breakdown is given by $q = 1 - \prod_{m,n} p_{m,n} = 1 - \exp(B_{\mathrm{bd}}/B)$, where we defined $B_{\mathrm{bd}} \equiv \sum_{m,n} B_{m,n}$. Assuming that the increment of resistivity by the modulation $\Delta\rho(B) = \rho_{\mathrm{FLSL}}(B) - \rho_{\mathrm{plain}}(B)$ is proportional to the probability $q$, one obtains

$$\Delta\rho(B) = \rho_{\mathrm{bd}}\left[1 - \exp\left(-\frac{B_{\mathrm{bd}}}{B}\right)\right]. \quad (1)$$

Fig. 3 shows that the negative MR can actually be described by the formula of Eq. (1) very well. More quantitative account of the phenomena that relates operative $V_{m,n}$'s with $B_{bd}$ requires further studies.

To summarize, we have reported drastic enhancement in the resistivity of 2DEGs by quasiperiodic modulation having a length scale close to the Fermi wavelength and amplitude of the order of percent of the Fermi energy. The enhancement is found to diminish by the application of a magnetic field.

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