Ballistic thermopower of suspended semiconductor Hall bars with two dimensional electron gas

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Abstract. We study ballistic electron transport in suspended semiconductor nanostructures containing high mobility two dimensional electron gas structured with periodical square lattice of artificial scatters — antidots. Thermopower demonstrates magnetic field commensurability oscillations resulting from geometrical resonances similar to those earlier observed in magnetoresistance, thus indicating the retaining of the ballistic regime in thermopower measurement on suspended structures and the validity of the Mott rule in this case. In spite of peculiarities of the heat transport in suspended structures leading to the observed anomalies in non-linear effects, the amplitude of thermopower oscillations remains unchanged after the suspension. This can be explained by short Thouless time compared to the time of electron-phonon interaction.

1. Introduction
Recently there has been growing interest in nanoelectromechanical systems. Conducting nanostructures with two-dimensional electron gas (2DEG) detached from the substrate are one of the examples of such systems. The study of these structures showed them to demonstrate a series of interesting peculiarities [1,2]. It was found that additional mechanical degrees of freedom drastically influence electron-transport properties of suspended membranes [3,4]. Moreover, it was shown that the heat transport in suspended structures essentially differs from that in non-suspended ones [5-7]. However electron transport in ballistic regime in suspended structures still remains poorly investigated [8].

In the present work we investigate ballistic electron transport, measuring conductance and thermopower in suspended 2DEG structured with periodical square lattice of artificial scatters — antidots.
2. Experimental details

Experimental samples were fabricated from AlAs/GaAs heterostructures containing high-mobility 2DEG grown by molecular beam epitaxy. The 2DEG density and electron mobility measured at liquid helium temperature were \( n_s = 5 \times 10^{11} \) cm\(^{-2} \) and \( \mu = 2 \times 10^6 \) cm\(^2\)/Vs correspondingly. The described heterostructures were grown over a 400 nm-thick Al\(_{0.7}\)Ga\(_{0.3}\)As sacrificial layer (see Figure 1). After photolithography the obtained samples represented themselves Hall bars with typical length of \( L = 15 \) \( \mu \)m, and typical width of 3 \( \mu \)m. A periodical square lattice of antidots was created on these Hall bars by means of electron-beam lithography followed by anisotropic plasmachemical etching. The antidots diameter varied from 100 to 200 nm while the lattice period varied from 500 to 800 nm for different samples (see Figure 2). The sacrificial layer was removed from-under the Hall bars by means of selective wet etching in HF water solution (see Figure 1). Magnetotransport measurements were performed at low temperatures (0.5÷4.2 K) by standard low-frequency lock-in technique in linear regime. Non-linear effects were studied by passing low-amplitude ac current together with dc current through the sample and measuring their resistance on the ac signal. We performed identical measurements on the same samples before and after the suspension.

![Figure 1](image1.png)

**Figure 1** The GaAs/AlGaAs heterostructure with sacrificial layer.

3. Experimental results

Solid lines in Figures 3(a) and 3(b) show magnetoresistance of non-suspended and suspended samples correspondingly (the antidots diameter is \( a = 200 \) nm, the lattice period is \( d = 600 \) nm). We found that the magnetoresistance of the samples with antidots lattice demonstrates commensurability oscillations in both cases. Earlier it was shown that, in the case of non-suspended samples, these oscillations originate from geometrical resonances [9]. We demonstrate that detaching of the samples from the substrate has almost no influence on the magnitude of the commensurability oscillations which means that electron mean free path remains practically unchanged (\( l > 2 \) \( \mu \)m) after the suspension. The suppression of commensurability oscillations by dc current demonstrates different behavior for suspended and non-suspended samples (see Figure 3 (a) and 3 (b)) which can be explained by poor heat coupling of suspended Hall bars to the substrate. More comprehensive understanding of non-linear effects requires further theoretical and experimental studies.
Figure 3. The influence of applied dc current (values are shown in the Figure) on the magnetoresistance of the Hall bar with antidots lattice (the antidots diameter is $a = 200$ nm, the lattice period is $d = 600$ nm). (a) Non-suspended sample; (b) suspended sample.

Figure 4 shows well pronounced “S-shaped” peculiarities of ballistic thermopower measured on non-suspended and suspended samples. They are observed at magnetic fields corresponding to commensurability oscillations of magnetoresistance. The characteristic form of the peculiarities is explained by the fact that, according to the Mott rule, thermopower is proportional to the logarithmic derivative of conductivity on the Fermi energy [10]. This makes thermopower measurements more sensitive compared to magnetoresistance and explain earlier beginning Shubnikov – de Haas oscillations. One could expect some additional features in thermopower caused by modified phonon spectrum in thin suspended sample. However, the commensurability oscillations in thermopower are quite similar for suspended and non-suspended Hall bars. In our case, we measure the diffusion thermopower without the contribution of phonon drag because the electron-electron interaction time is much less than electron-phonon interaction time ($\tau_{ee} < \ll \tau_{e-ph}$). Hence, the thermopower signal is determined by electron temperature gradient. The observed similarity of the thermopower curves shows that electron-phonon relaxation time $\tau_{e-ph}$ is much greater than the Thouless time $\tau_{Th}$, i.e. the time an electron spends in the sample. The described behavior is the same for all the periods of the investigated lattices, except the number of commensurability peaks varies. For example, in Figure 5 and Figure 6 one can see four peaks of commensurability oscillations of magnetoresistance and corresponding four “S-shaped” features in thermopower of the suspended sample with 800 nm period of the antidot lattice.

Figure 4 Ballistic thermopower of non-suspended and suspended Hall bars with antidot lattice (diameter of antidots $a = 200$ nm, period of the lattice $d = 600$ nm).
Figure 5 Magnetoresistance of the suspended Hall bar with antidots lattice (diameter of antidots \(a = 200\text{nm}\), period of the lattice \(d = 800\text{ nm}\)).

Figure 6 Ballistic thermopower of the suspended Hall bar with antidots lattice (diameter of antidots \(a = 200\text{nm}\), period of the lattice \(d = 800\text{ nm}\)).

4. Conclusions
Magnetic field dependence of thermopower in suspended 2DEG with square lattice of antidots demonstrate commensurability oscillations originating from geometrical resonances similar to those observed in magnetoresistance. This indicates that the suspension of the 2DEG does not suppress ballistic regime in thermopower measurements. While the non-linear effects in suspended and non-suspended structures demonstrate difference, caused by the peculiarities of the heat transfer in suspended samples, the thermopower does not demonstrate any additional features related to the suspension. This can be explained by short Thouless time in our samples compared to electron-phonon relaxation time \(\tau_{\text{Th}}\ll\tau_{\text{e-ph}}\).

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