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OSCILLATORY THERMOPOWER OF A QUANTUM POINT CONTACT

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We report the observation of a transverse voltage occurring on passing an electric current through a narrow, electrostatically defined wire in a two dimensional electron gas, at zero magnetic field. The voltage, which is measured using point contact voltage probes, is even in the current and shows strong oscillations as the number of subbands in either one of the point contacts is varied. Our observations can be explained by electron heating in the channel, which induces a thermoelectric voltage across the point contacts.

In spite of the strong recent activity in the field of quantum ballistic transport in one- and zero dimensional semiconductor nanostructures (for a review, see Ref. 1), very little has been reported on the thermoelectric properties of such devices. Gallagher *et al.*[2)], and Gusev *et al.*[3)] studied the thermopower fluctuations in the diffusive transport regime, which are the analogue of the well known universal conductance fluctuations. In the ballistic transport regime, one expects that such experiments reflect the discreteness of the electron density of states, analogous to the quantized conductance. Indeed Streda[4)], using a formalism due to Sivan and Imry[5)], showed that the thermopower of a quantum point contact should oscillate as a function of the Fermi energy, due to the depopulation of the 1D subbands.

We report on the first experimental study of the thermoelectric properties of nanostructures in the ballistic transport regime. More details are given elsewhere[6)]. The structures used are schematically depicted as the inset in Fig. 1. Using a split-gate technique we have defined a 18 μm long and 4 μm wide channel on a high mobility (Al,Ga)As heterostructure. Both sides of the channel contain two quantum point contacts, 3 μm apart. In this structure, we create a temperature difference between the electron gas in the channel and that outside (behind the point contacts) by passing a dc current through the channel, as indicated in the figure. A similar technique was used in Ref. 2. In this manner, one can easily generate a temperature difference of a few K across the point contacts. For example, for a current of 5 μA we estimate (from a simple heat balance argument[6]) an electron temperature T in the channel of about 4 K when the lattice temperature T_0 is 1.6 K. This temperature difference then induces a thermoelectric voltage across each point contact. The magnitude of these voltages depends on the voltage $V^i_{\rm gate}$ applied to the gates defining point contact i. Therefore, we can measure a non-zero transverse voltage (at zero magnetic field) resulting from the current in the channel, when we use unequally adjusted quantum point contacts as voltage probes.

The transverse voltage under the conditions of our experiment has been calculated in Ref. 6, following the method of Refs. 4 and 5. Physically, one expects that $V_{\rm trans} = V_1 - V_2$ depends, to first order, only on (a) the amount of electron heating ($T - T_0$) achieved for a given current level, and (b) the energy dependence of the transmission probability $t(E)$ through a quantum point contact. This is indeed borne out by our model calculation[6], and by the experimental results given below.

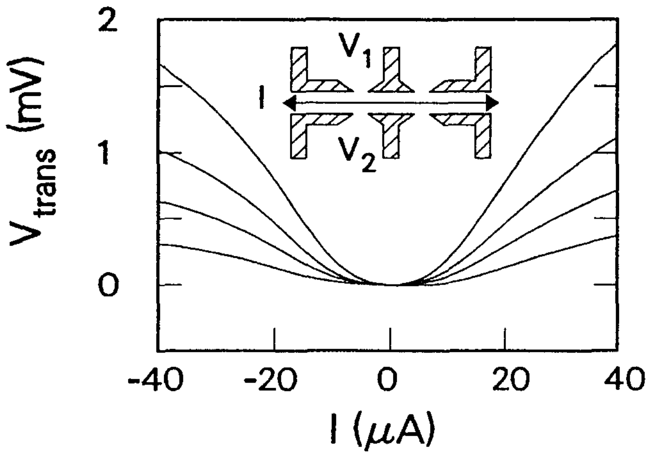

Figure 1. The dependence of $V_{\rm trans} = V_1 - V_2$ on the current I in the channel, using $V^2_{\rm gate} = -2.1$ (lowest curve), -2.3, -2.5, and -2.7 V; $V^1_{\rm gate} = -0.6$ V , $T_0 = 5.0$ K. The inset shows the experimental configuration.

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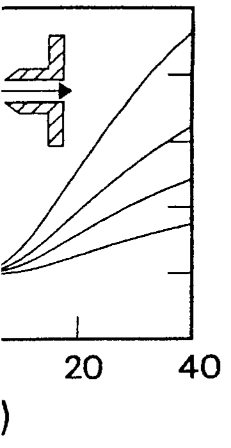

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Fig.1 shows the dependence of V_{trans} on the current I in the channel for several different values of V^2_{gate} (V^1_{gate} is kept constant at −0.6 V, corresponding to a point contact resistance of ca. 1 kΩ). The lattice temperature T_0 is 5.0 K. Several features emerge from these data. Firstly, V_{trans} exhibits a quadratic dependence on the current in the channel. This is a direct consequence of Joule heating being the driving force of the effect. The quadratic response constitutes a novel means for second harmonic generation in nanostructures, fundamentally different from the small quantum-interference driven harmonic generation observed in the quantum-diffusive regime[7], at very low temperatures and current levels.

For $I \gtrsim 20$ μA, the current dependence of V_{trans} saturates, presumably due to lattice heating and the temperature dependence of the heat capacity of the 2D EG. Also evident from Fig.1 is the increase in V_{trans} on decreasing $t(E)$ of point contact 2 (by applying a more negative V^2_{gate}). At this temperature of 5 K no quantum size effects are observed, and the transverse voltage generation is essentially a classical ballistic phenomenon.

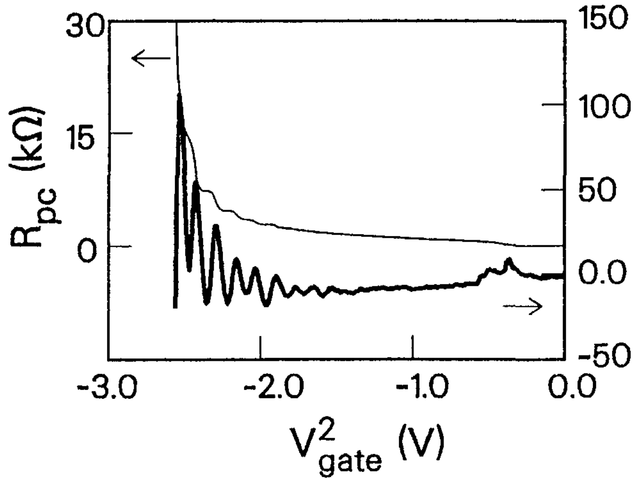

Figure 2. The dependence of V_{trans} on V^2_{gate} using a constant $V^1_{gate} = -2.0$ V and I = 5 μA. The thin line gives the resistance of point contact 2 as a function of V^2_{gate}.

In Fig.2 we show experimental traces obtained at $T_0 = 1.65$ K, and from a second device. The measurement configuration is the same as in Fig.1; note however, that in these experiments I is kept constant at 5 μA and V_{gate}^2 is scanned. The experimental data for V_{trans} (thick line) show strong oscillations, with maxima occurring at values of V_{gate}^2 where the resistance of point contact 2 (thin line) changes abruptly due to the depopulation of a 1D subband in the point contact. We have also observed this effect at moderate magnetic fields, where magnetic depopulation of subbands occurs (not shown here). The oscillations in V_{trans} are clearly a quantum-size effect. As is well known[1)], the resistance of the point contact is given by $R_{\mathrm{pc}} = h/2e^2 t(E_F)$. The maxima in V_{trans} are due to the strong energy dependence of $t(E)$ at the depopulation treshold of a 1D subband. As long as $k_B(T - T_0)$ remains small compared to the 1D subband splitting, the number of channels in the point contact accessible for hot electrons differs significantly from that for cold electrons, whenever E_F is close to the bottom energy of a subband.

In conclusion, we have shown that electron heating is a powerful method for studying thermoelectric effects in nanostructured devices in the ballistic regime. We have found a novel mechanism for second harmonic generation, and have observed the quantum oscillations in the thermopower of a quantum point contact[4)] for the first time.

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