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NOISE RECTIFIER BASED ON THE TWO-DIMENSIONAL ELECTRON GAS

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The dc voltage observed at low temperatures in a 2D electron sample in the absence of noticeable external excitations [1] is accounted by the Schottky contact rectification of the noise generated in the measuring circuit. The rectified voltage is shown to depend on the asymmetry of the contact pair. The dependence of the rectified voltage on the noise amplitude first follows the trivial quadratic law, then exhibits a nearly linear behavior, and finally, levels off.

We examine the experimental setup well known for routine low-T transport measurements. Let a two-dimensional electron gas (2DEG) sample be placed (Fig. 1) in a sample chamber kept at liquid helium temperature. The coaxial current leads are attached to the sample and then connected to an external measuring terminal kept at room temperature. The dc voltmeter coaxial input leads can be connected to arbitrary 2DEG sample contacts. Unexpectedly, the voltmeter demonstrates [1–5] a puzzling nonzero voltage (NV) of the order of about μV. The value and the sign of the dc potential depend on the actual contact pair.

In the presence of a magnetic field, the measured dc potential demonstrates strong (∼mV) oscillations named "zero" oscillations (ZO), which exhibit a $1/B$-periodicity similar to the well-known Shubnikov–de Haas (SdH) oscillations. The ZO period allows extracting the two-dimensional carrier density. The temperature dependence of the ZO amplitude is similar to that for SdH oscillations and gives the correct value of the carrier effective mass. In contrast to SdH oscillations, ZO are skew symmetric. The amplitude and the phase shift of the ZO depend on a chosen contact pair. Moreover, for a certain contact pair, the ZO shape is strongly affected if other sample leads are connected to (disconnected from) the measuring circuit [6]. We emphasize that NV and ZO effects are in general universal and observed in various 2DEG systems and for arbitrary sample configuration.

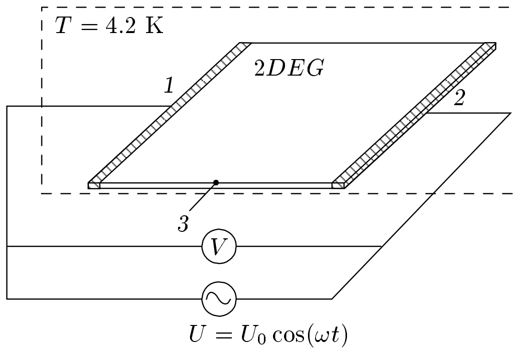

Fig. 1. Setup configuration. The noise is simulated by the ac generator

The basic idea put forward in Refs. [3, 5] in order to explain these effects concerns the possible rectification of the input noise by 2D–3D Schottky diodes formed at the sample contacts. An extra screening of the circuit is shown to diminish the amplitude of the rectified voltage [3, 5]. Then, shunting of the sample contacts by a capacitance also suppresses the dc potential [5]. To quantitatively examine the influence of the noise, both the voltmeter and the ac generator playing the role of a noise source were attached to same sample contacts [3, 5] (see Fig. 1). However, the amplitude of the rectified voltage is reported to be proportional to the ac input voltage. Until now, this finding remained unresolved within the rectification concept [3, 5]. In this paper, we propose a phenomenological analysis and explain the important features of the effect.

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We use the simplest model of a current–voltage characteristic of the 3D–2D Schottky contact [7, 8]. In the thermionic diode approximation at finite temperatures, the current is given by

$$I = I_0 \left(\exp\left(\frac{eV}{kT}\right) - 1 \right), \qquad (1)$$

where

$$I_0 = 5.36A(kT)^2 w \exp\left(\frac{\epsilon_F - eV_0}{kT}\right)$$

is the backward saturation current, V_0 is the equilibrium contact potential, and V is the voltage drop across the contact. Then

$$A = \frac{em*}{2\pi^2\hbar^3}$$

is the Richardson constant for the thermionic emission and w is the quantum well width.

We emphasize that the Schottky diodes at the left (Fig. 1, index 1) and right (index 2) contacts have the opposite polarity and are different from each other in general. Therefore, the relation between the total voltage drop U across the sample and the current I is given by

$$u = ir + \ln\left(\frac{1+i}{1-ia}\right), \qquad (2)$$

where $u = eU/kT$ is the dimensionless voltage, $i = I/I_{01}$ is the current scaled with respect to the reverse saturation current (I_{01}) of the left-contact diode, and $a = I_{01}/I_{02}$ is the asymmetry parameter of the contacts. Then $r = I_{01}Re/kT$ is the dimensionless resistance of the 2DEG and R is the 2DEG resistance.

We are primarily interested in the low-current case $i \ll 1$, and we therefore linearize Eq. (2) with respect to the current as

$$u = (1+a+r)i - \frac{1-a^2}{2}i^2 + \frac{1+a^3}{3}i^3 + \ldots \qquad (3)$$

As expected, the current–voltage characteristic exhibits the Ohmic behavior $u = (1+a+r)i$ or $U = IR_{tot}$, where $R_{tot} = R_1 + R_2 + R$ is the zero-field total resistance of the sample and $R_{1,2} = kT/eI_{01,2}$ are the Schottky resistances of contacts 1 and 2. In the opposite case of a high applied voltage, the current–voltage characteristic is strongly nonlinear. Indeed, in that case, the forward and reverse currents are limited (see Fig. 2*a*) by the respective Schottky diode saturation currents I_{02} and I_{01}.

We first seek the response of the 3D/2DEG/3D system to the applied ac voltage $u = u_0\cos(\omega t)$. The ac voltage is provided by the generator shown in Fig. 1. At low voltages $u \ll 1$, Eq. (3) allows extracting the current as

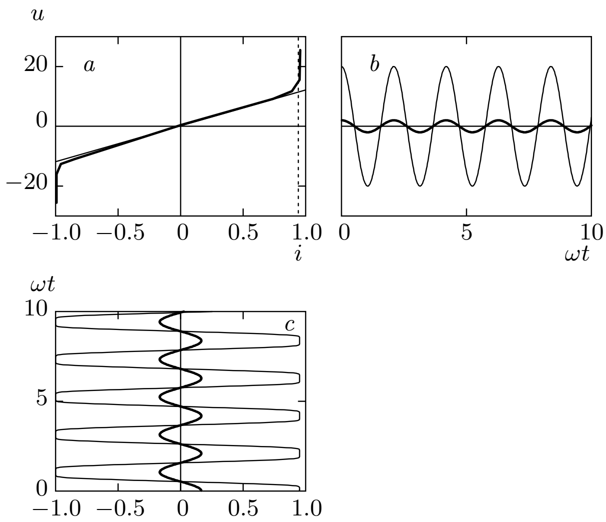

Fig. 2. Panel a: Current–voltage characteristics of the circuit (Fig. 1) specified by Eq. (2) for the contact asymmetry parameter $a = 1.05$ and the 2DEG resistance $r = 10$. The dashed line represents the low-field Ohmic dependence. The low-voltage (bold line) and high-voltage (thin line) ac input signals are represented in panel b. The respective responses are shown in panel c

$$i = \frac{u}{1+a+r} + \frac{1-a^2}{2(1+a+r)^3}u^2 + \beta u^3 + \ldots, \qquad (4)$$

where

$$\beta = \frac{(1-a^2)^2}{2(1+a+r)^5} - \frac{1+a^3}{3(1+a+r)^4}.$$

It's worth noting that the in-phase response to the applied ac voltage, $i = (u_0/(1+a+r) + 3/4\beta u_0^3)\cos(\omega t)$, consists of the Ohmic contribution and an additional part associated with the cubic term in Eq. (4). We therefore conclude that the widely used lock-in ac measurement method could give a systematic error in the sample resistance [3] compared to dc measurements.

We now intend to resolve the primary problem formulated in this paper. We investigate the dc response of the circuit (see Fig. 1) to an applied ac voltage. We emphasize that term in Eq. (4) of the second order in voltage describes the rectification properties of the 2DEG sample at $a \neq 1$. Equation (4) yields the time-averaged current

$$\overline{i} = \frac{\omega}{2\pi} \int\limits_0^{\frac{2\pi}{\omega}} i\, dt \ll 1$$

and then the voltage drop measured by dc voltmeter is given by

$$\overline{u} = \frac{1-a^2}{4(1+a+r)^2} u_0^2, \qquad (5)$$

The polarity of the measured dc voltage is determined by the contact asymmetry. As expected, the transmission characteristic $\overline{u}(u_0)$ is a quadratic law at $u_0 \ll 1$. In the opposite case of a strong ac excitation $u_0 \gg 1$, the dc response can be found qualitatively with the help of Fig. 2c. Indeed, the rectified current can be regarded as a rectangular meander sequence with linear fronts. The higher the applied ac voltage is, the sharper the front of the current pulse. After simple averaging, we obtain the dc current and, finally, the rectified voltage as

$$\overline{u} = \frac{(1-a)(1+a+r)}{2a} \left[1 - \frac{(1+a+r)(1+a)}{\pi u_0 a} \right]. \qquad (6)$$

For a high input ac signal $u_0 \gg 1$, the measured voltage saturates, $\overline{u}_{sat} = (1/a - 1)(1+a+r)/2$. We could expect that, at a moderate ac signal level $u_0 = i(1+a+r), i \sim 1$, the low and high ac input cases merge, and, consequently, there could exist a certain part of the transmission characteristic that could be associated with a linear dependence [3, 5].

To confirm our qualitative predictions, we present the result of our numerical calculations in Fig. 3. We use current–voltage characteristic specified by Eq. (2). Solving this equation for the current, we find the dependence $i(u)$ numerically. The successive averaging of the current caused by the input ac signal gives the related dc voltage drop across the sample and, hence, the transmission characteristic. At low excitations, as expected, the transmission characteristic follows the asymptote given by Eq. (5). At a high-level ac input $u_0 \gg 1$, the dependence $\overline{u}(u_0)$ can be approximated by Eq. (6), and then levels off. For intermediate voltages $u_0 \sim r = 10$, the transmission characteristic exhibits a nearly linear behavior $\overline{u} = -A + Bu_0$ in accordance with the experimental findings [5].

We estimate the actual parameters of the 3D/2DEG/3D system [5]. For an n-AlGaAs/GaAs sample (the 2DEG density $n = 3.46 \cdot 10^{11}$ cm^{-1}, the dielectric constant $\epsilon = 12.7$, and the effective mass $m = 0.068 m_e$), we find the Fermi energy $\epsilon_F = 80$ meV, whereas the Bohr energy is $\epsilon_B = me^4/2\kappa^2\hbar^2 = 6.7$ meV. As was demonstrated in Ref. [9], the

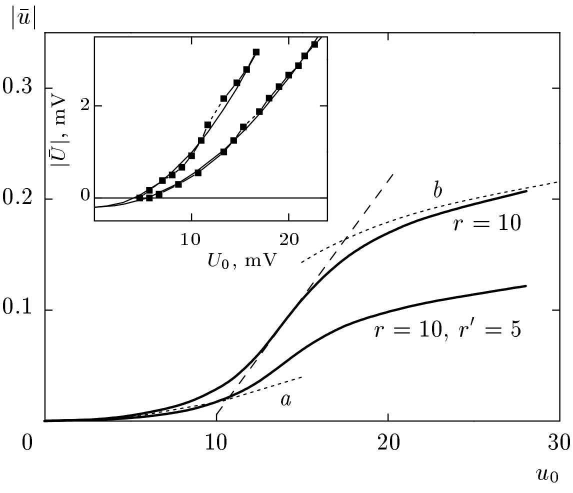

Fig. 3. Transmission characteristic for the contact asymmetry $a = 1.05$ and the 2DEG resistance $r = 10$ (upper curve). Dotted lines a and b represent the low- and high-voltage approximations respectively specified by Eq. (5) and Eq. (6). The dashed line demonstrates a nearly linear dependence reported in [5]. The lower curve corresponds to the case of a voltmeter connected to 1-3 contacts (see Fig. 1) with $r = 10$ and $r' = 5$. Inset: The observed [5] transmission characteristics

thermionic diode approximation is justified well when $T > T_0$, where

$$T_0 = \frac{\epsilon_F}{k} \sqrt{\frac{\epsilon_B}{e(V_0 - V)}}.$$

At $T < T_0$, the tunneling current across the Schottky diode becomes higher than the thermionic current. For the typical equilibrium contact potential $V_0 = 1$ eV and Schottky diode bias $V = 0$, we obtain $T_0 = 73$ K, and, hence, the observed low-T (about 4 K) data [5] cannot be analyzed directly in terms of the thermionic mechanism [7]. Nevertheless, even at low temperatures, the current–voltage characteristic of the 2D–3D contact behaves similarly to that described by Eq. (1). Therefore, the main assumption of NV originated from rectification of ac noise remains justified.

We now estimate the resistance of the Schottky diode. This becomes possible due to the improved arrangement suggested in Ref. [5]. For the same ac input (1-2 contacts in Fig. 1), the dc voltmeter leads are connected to 1-3 contacts. Contact 3 was placed in the middle of a 2DEG sample. In this case, the transmission characteristic is given by Eq. (5) multiplied by the geometry factor $(1 + a' + r')/(1 + a + r)$, where $a' = I_{01}/I_{03}$ is the asymmetry of the intermediate contact with respect to the first contact, and

$r' = r/2$. In the inset in Fig. 3, we reproduce the transmission characteristic data [5] for the dc output measured across 1-2 (upper curve) and 1-3 (lower curve) contacts. Both curves demonstrate a threshold behavior, which can be attributed to the possible voltmeter zero-point shift. The low-voltage part of these curves can be approximated by the respective equations $\overline{U}_{12}[V] = -0.0002+12U_0^2[V]$ and $\overline{U}_{13} = -0.0002+7U_0^2$. Neglecting a spurious zero-point shift, these curves differ by the ratio $7/12$ which is equal to the geometry factor $(R_1+R_3+R/2)/(R_1+R_2+R)$. The estimate of the 2DEG sample resistance in [5] yields $R_{tot} = 13k\Omega$. Finally, under the reasonable assumption of small contact asymmetry, i.e., $R_1 \sim R_2 \sim R_3$, we find the Schottky contact resistance $R_1 = 1.05k\Omega$.

Finally, we argue that the zero oscillations observed in a 2DEG in strong magnetic fields also originate from noise rectification. Indeed, at a fixed magnetic field, the transmission characteristic observed for the ZO amplitude in [5] is analogous to that reported for $B = 0$. We recall that the sign of the rectified voltage depends on the asymmetry of the Schottky diode contact pair. If the reverse current I_0 of the Schottky contact oscillates in the magnetic field, then the rectified dc voltage (ZO) oscillates as well.

To conclude, we have demonstrated that the dc voltage observed at low temperatures in a 2D electron sample without noticeable external excitation is caused by the noise rectification by Schottky diodes formed at the sample contacts. At a low noise level, the rectified voltage as a function of the noise amplitude follows the usual quadratic law. At higher noise magnitudes, the rectified voltage exhibits a nearly linear behavior and finally saturates. The rectified voltage is shown to depend on the contact pair asymmetry. We suggest that the shunting of the sample contacts by a capacitance is a powerful tool for suppressing the rectified voltage.

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