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Spontaneous current generation in gated nanostructures

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Abstract. – We have observed an unusual dc current spontaneously generated in the conducting channel of a short-gated GaAs transistor. The magnitude and direction of this current critically depend upon the voltage applied to the gate. We propose that it is initiated by the injection of hot electrons from the gate that relax via phonon emission. The phonons then excite secondary electrons from asymmetrically distributed impurities in the channel, which leads to the observed current.

Gated semiconductor nanostructures have become the staple diet of modern condensed matter research and applications. Their small size has resulted in a wealth of new phenomena observed in electron transport, including universal conductance fluctuations [1] and the photogalvanic effect [2]. In such a structure, at low temperatures we observe a dc current through the conducting channel in the absence of any applied bias. This current is dependent upon the gate voltage V_g, which dictates its magnitude and direction through the channel. It was found that the observed current could not be produced by conventional sources of residual bias and stray interference coupling to the system [3].

We propose a model that eliminates this apparent "Maxwell's demon" required to support the voltage across the sample. A small gate leakage current is magnified in the source-drain circuit due to phonon-assisted excitation of localised electrons. While the leakage current itself has a smooth dependence on V_g, the "spontaneous" current changes its direction due to the V_g-dependent asymmetry of the channel. It transpires that the effect is greatest for channels of length $\sim 0.1\,\mu$m, which is the key size in contemporary devices. The observed phenomenon is of significant importance for both research and applications as it puts a limit on the small-signal performance of gated nanostructures.

The experiments were carried out on a GaAs-based transistor. The wafer consists of a $1 \cdot 10^{17}\,\mathrm{cm}^{-3}$ silicon doped layer 1450 Å thick on an undoped GaAs substrate. A metallic (Au) gate, of length $L = 0.15\,\mu$m in the current direction and width $9\,\mu$m across it, was

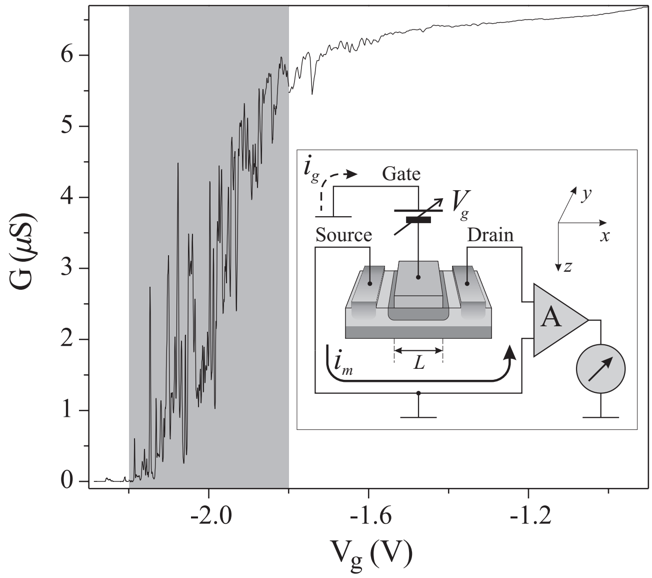

Fig. 1 – The two-terminal (differential) conductance as a function of the gate voltage. The shaded box delimits the range of V_g where the spontaneous current is resolved. Inset: circuit (simplified) used to measure the dc current i_m via the pre-amplifier (A). The transistor is depicted schematically: conductive regions are shown in light grey, and depleted regions in dark grey.

formed between the source and drain, see fig. 1 (inset). For large negative gate voltages the two-terminal conductance of the device is dominated by the region under the gate; this region defines the "channel", and regions outside the gate are the "contacts". Measurements were carried out in a dilution refrigerator at a base temperature of 30 mK using a low-noise pre-amplifier, all housed in a screen room.

Figure 1 shows the conductance of the channel as a function of the gate voltage. Strong, reproducible structure can be seen to occur near the pinch-off, associated with mesoscopic hopping and tunnelling processes [4]. In the absence of a voltage source in the source-drain circuit, shown in fig. 1 (inset), one would expect the measured dc current i_m to be zero. Contrarily, fig. 2(a) shows that a fluctuating (reproducible to within 10%) dc current occurs that changes its direction as a function of V_g. This current is only resolved in a small range of gate voltages, highlighted in fig. 1, where fluctuations of the conductance are large.

Three conventional sources of dc current exist in the circuit and can contribute to i_m. First, an unintentional dc bias V_b results in an induced "bias" current i_b. Second, rectification of stray interference of frequency ω and magnitude V_ω can produce a rectified current i_r. Third, there is a small leakage current from the gate i_g, which splits into αi_g in the gate-drain and $(1-\alpha)i_g$ in the gate-source branches of the circuit. If we include an additional, unknown current i_0 as a fourth contribution, the total measured current i_m can be written as

$$i_m = \frac{\mathrm{d}i}{\mathrm{d}V} V_b + \frac{1}{4}\frac{\mathrm{d}^2 i}{\mathrm{d}V^2} \sum_{\omega\in\Omega} V_\omega^2 + \alpha i_g + i_0 \,, \tag{1}$$

where the first two terms on the right define i_b and i_r, respectively. We have found that the conventional contributions do not constitute the primary element of the measured current i_m, either in the magnitude or fine structure, and instead i_0 dominates i_m.

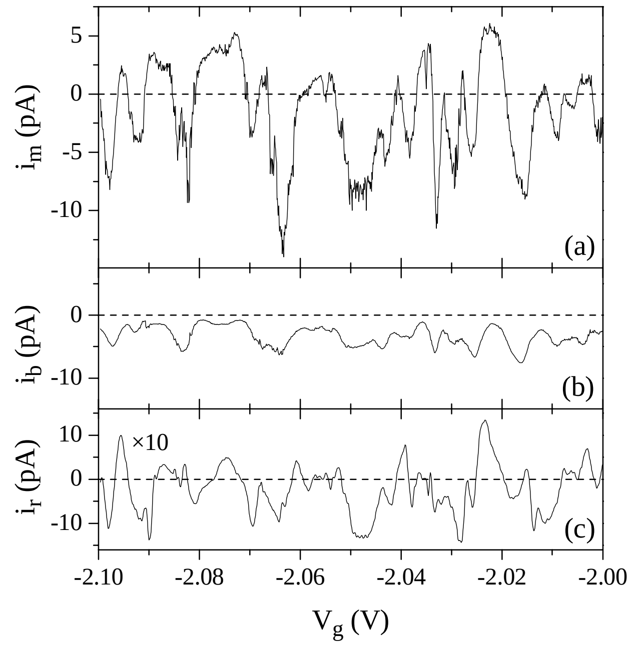

Fig. 2 – (a) The measured dc current i_m in the source-drain circuit with no applied bias within the range of V_g highlighted in fig. 1. (b), (c) The contribution to i_m from the bias current i_b due to the presence of unintentional dc biases in the circuit (b), and from the rectified current i_r, multiplied by ten, due to the rectification of noise (c).

The first contribution to i_m is derived from an unintentional dc voltage in the source-drain circuit. This bias was found to be predominantly caused by the pre-amplifier (yet encompasses all possible contributions such as thermocouples in the circuit), and, although minimised, changed monotonically over the course of an experiment (1–2 hours) by $\sim 200\,\text{nV/hour}$. Figure 2(b) shows the resultant bias current $i_b = (\mathrm{d}i/\mathrm{d}V)V_b$ that can be ascribed to the average measured value of this voltage. From this we see that the amplitude of i_b is much smaller than the measured current, and it is only driven in one direction. We also look at the mesoscopicity of i_b and i_0. We calculated the correlation coefficient $C(i_b, i_m) = \langle \delta i_b \delta i_m \rangle / \langle \delta i_b^2 \rangle^{1/2} \langle \delta i_m^2 \rangle^{1/2}$, where $\delta i = i - \langle i \rangle$ and $\langle \cdots \rangle$ is an average over the gate voltage range shown in the figure. When the conventional contributions in eq. (1) are subtracted from i_m (see below) we find that $C(i_b, i_m) = C(i_b, i_0) = -0.28$. The small and negative correlation of i_0 with the bias current thus substantiates our conclusion above that the latter is not the source of the observed effect.

The second contribution to the measured current is rectification of noise as a result of the non-linear nature of the system, *e.g.* [4–6]. For small ac voltages the rectified current is given by eq. (1) (second term). To justify this relation in our case we measured the response of the system to an intentionally applied ac voltage V_ω. Below $V_\omega \sim 150\,\mu\text{V}$ the rectified current caused by this ac voltage was proportional to V_ω^2; therefore, in this voltage range distortion by higher harmonics can be neglected and eq. (1) be used. To calculate the rectified current resulting from any residual stray interference coupling to the circuit (predominantly through the part outside the screen room) both $\mathrm{d}^2i/\mathrm{d}V^2$ and the integrated unintentional ac voltage across the sample have to be determined. The second derivative was found from the second harmonic response $i_{2\omega}$ using the relation $\mathrm{d}^2i/\mathrm{d}V^2 = 4i_{2\omega}/V_\omega^2$. The latter was verified by the

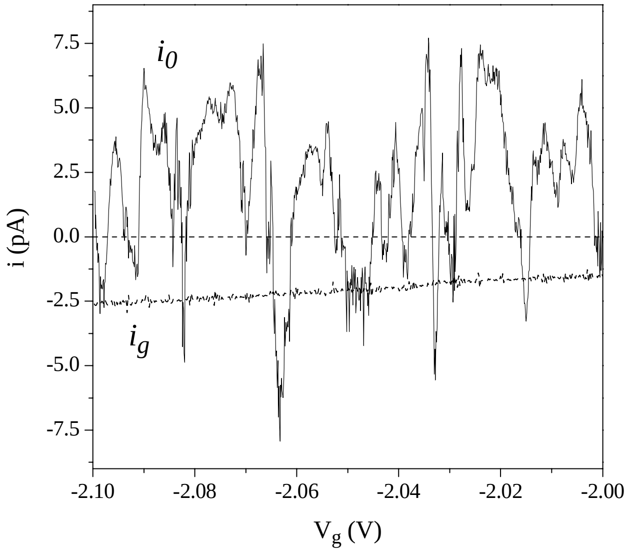

Fig. 3 – The spontaneous current i_0, after subtracting the contributions of the bias and rectified currents from the measured current i_m in fig. 2. Also shown is the gate leakage current i_g in the same range of gate voltage.

agreement with direct differentiation of the $i(V)$ characteristic at a fixed V_g. The current i_r as a function of V_g is then reconstructed from measurements of the second derivative and the integral of the voltage noise. The frequency range Ω of the noise was found experimentally to be $0 < \omega < 20\,\mathrm{kHz}$, with negligible contribution at higher frequencies. The total integrated voltage noise was $\sim 30\,\mu\mathrm{V}$ (which, being much smaller than the $V_\omega \sim 150\,\mu\mathrm{V}$ limit determined above, vindicates our use of the second term in eq. (1)).

The calculated rectified current is shown in fig. 2(c), where it can be seen that it is approximately an order of magnitude smaller than i_m; thus we conclude that i_0 cannot be related to the rectification of stray interference. This is further proved by comparison of the small correlation $C(i_r, i_0) = 0.14$ with that obtained when a strong ac bias ($V_\omega \gtrsim 100\,\mu\mathrm{V}$) is intentionally applied to the channel, $C(i_r, i_m) \sim 1$. We confirmed the absence of the relation between i_0 and rectified noise in additional experiments where all the measurement apparatus outside the screen room was replaced by analogue meters and batteries (to control V_g) mounted directly upon the refrigerator inside the room. The measurements of $i_0(V_g)$ by discrete points yielded the same results as those presented here with the meters outside.

Figure 3 shows the spontaneous current $i_0 \approx i_m - i_d - i_r$. Also shown is the total gate leakage current i_g, see fig. 1. Its contribution to the measured current in eq. (1) is determined by the fraction α, which is expected to be close to 0.5. (Indeed, we show below that the leakage electrons relax within the contacts far away from the channel region. Thus any mesoscopicity of the channel is not important for the leakage current which flows equally to the source and drain contacts.) Therefore, the small contribution of the leakage current cannot produce the large, direction-changing fluctuations that constitute the spontaneous current i_0. Nevertheless, in the model we propose below i_g plays a key role in the generation of i_0. Although the leakage current is small, the power it supplies, $i_g V_g \sim 4 \cdot 10^{-12}\,\mathrm{W}$, is enough to support the current i_0 in the source-drain circuit (in fact, it is significantly larger than the dissipated power $i_0^2 R \sim 10^{-17}\,\mathrm{W}$, where R is the circuit resistance). Thus we do not have a situation of *perpetuum mobile*.

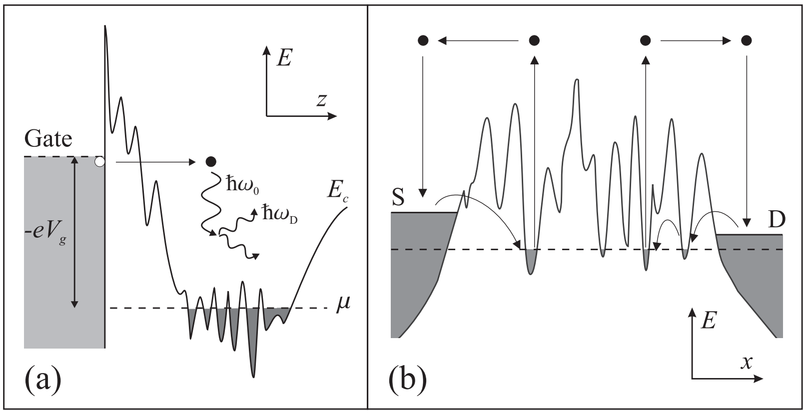

Fig. 4 – The physical mechanism to explain the spontaneous current as a process of relaxation and excitation. (a) The relaxation of hot electrons from the gate into the channel (stages a-b, described in the text). (b) Diffusion and neutralisation of secondary electrons from the channel (stages c-d). The equilibrium Fermi level is shown as a dotted line.

The observed current i_0 is described in terms of two main processes: phonon-mediated magnification of electrons tunnelling from the gate into the channel by a factor $\sim eV_g/2\hbar\omega_D$ (where ω_D is the Debye frequency); and the propagation of these electrons around the external circuit driven by the mesoscopicity of the disordered channel. To elucidate the description of these processes we break them into a sequence of four events, fig. 4: a) emission of optical phonons by the tunnelling electrons; b) conversion of optical into acoustic phonons; c) excitation of "secondary" electrons by these acoustic phonons; d) diffusion of secondary electrons into the contacts, and their subsequent return to the channel.

a) Electrons from the gate are injected into the channel with energy $\simeq e|V_g| \approx 2\,\mathrm{eV}$ (fig. 3), which is large compared with the sample temperature. These electrons relax rapidly, predominantly by the emission of a cascade of $N_p = eV_g/\hbar\omega_0 \gg 1$ *optical* phonons with energy $\hbar\omega_0$, either inside the channel or in the contacts close to the channel, fig. 4(a). The hot electrons mostly reside in the side valleys of GaAs with small mobility and large effective mass $0.35 \cdot 10^{-27}$ g [7], so their initial velocity can be roughly estimated as $v \sim 10^8\,\mathrm{cm/s}$ (from the condition $mv^2/2 \approx 1\,\mathrm{eV}$). Consequently, in a short channel (in our case $\sim 10^{-5}\,\mathrm{cm}$) only a few optical phonons are emitted before the hot electron reaches a contact, where it continues to emit optical phonons. (The contacts are made of heavily doped GaAs with Fermi energy $\sim 10\,\mathrm{meV}$, and in such material the emission of optical phonons remains the most efficient mechanism of electron energy relaxation [8].) The typical size of the contact region where the phonons are emitted is $L_{\mathrm{dif}} = (DN_p\tau_{\text{e-ph}})^{1/2}$, where $D = v^2\tau_p/3$ and τ_p (estimated below) is the elastic electron mean free time, while $\tau_{\text{e-ph}} \sim 10^{-13}\,\mathrm{s}$ is the relaxation time due to emission of an optical phonon.

The room temperature electron mobility in the side valley is known to be $\sim 150\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$, from which one estimates for an electron energy of $k_BT \sim 30\,\mathrm{meV}$ that $\tau_p \approx 3 \cdot 10^{-14}\,\mathrm{s}$. The scattering of hot electrons is mostly due to polar scattering by optical phonons [8] for which $\tau_p \propto \varepsilon^{-1/2}$. Thus, for a typical energy $\sim 1\,\mathrm{eV}$ the value of τ_p is about an order of magnitude larger than its equilibrium, room temperature value. Taking into account an additional factor $\ln(\varepsilon/\hbar\omega_0)$ in the relaxation rate [8] we estimate $\tau_p \sim 10^{-13}\,\mathrm{s}$. Consequently, an estimate for the penetration depth of a hot electron into the contact is $L_{\mathrm{dif}} \approx 1\,\mu\mathrm{m}$.

b) Each optical phonon quickly decays into two high-energy acoustic phonons over the characteristic time $\tau_{\rm op} \sim 10^{-11}$ s [9]. However, the decay of acoustic phonons is much weaker. The transverse modes practically do not decay, and their relaxation is mostly due to their conversion to longitudinal modes in the course of phonon-impurity scattering. One expects that the cross-section for the scattering of transverse acoustic phonons with $\hbar\omega_D \sim 15\,\mathrm{meV}$ by impurities is of the order of the atomic one, $\sigma \sim 10^{-15}\,\mathrm{cm}^2$. The mean free path for such phonons within the contacts at impurity concentration $N_i \sim 10^{17}\,\mathrm{cm}^{-3}$ is $l = (\sigma N_i)^{-1} \sim 10^{-2}\,\mathrm{cm}$, and so the majority of the phonons created over the distance of $L_{\rm dif}$ can easily (ballistically) reach the channel region. Thus, the number of acoustic phonons in the channel produced by one tunnelling electron is $\sim eV_g/2\hbar\omega_D$.

c) These phonons ionise donors in the channel creating "secondary" electrons, fig. 4(b). The probability for them to do so can be estimated using Fermi's golden rule, the squared matrix element being

$$\frac{\lambda^2\hbar q}{M\omega_q}\left|\left\langle \frac{e^{-r/a}}{a^{3/2}}\left|\frac{e^{i\boldsymbol{qr}}}{\mathcal{V}^{1/2}}\right|\frac{e^{i\boldsymbol{kr}}}{\mathcal{V}^{1/2}}\right\rangle\right|^2 \approx \frac{\lambda^2\hbar a}{M\omega_q q\mathcal{V}}\,.$$

Here a is the localisation length, $\boldsymbol{q}$ and $\boldsymbol{k}$ are the wave vectors of the phonon and excited electron respectively, λ is the deformation potential, M is the atomic mass, and $\mathcal{V}$ is the normalisation volume. The phonon scattering rate due to the ionisation processes is

$$\frac{1}{\tau_{\rm ph,i}} \sim \frac{\omega_q\, N_i a^3}{(qa)^2}\,\frac{\lambda^2}{E_b^2}\left(\frac{\hbar\omega_q - E_i}{E_b}\right)^{1/2},$$

where E_i is the donor ionisation energy and E_b is of the order of the atomic energy. Since $\lambda \sim E_b$, $qa \sim 10$, $\hbar\omega_q - E_i \sim 10^{-2}E_b$ and $N_i a^3 \sim 1$, one has $\tau_{\rm ph,i}^{-1} \sim 10^{-3}\omega_q$. Correspondingly, the mean free path with respect to ionisation is about $3\cdot 10^{-5}$ cm.

From the above estimates it follows that the non-equilibrium acoustic phonons effectively relax within the channel via ionisation of the donors. The net current of secondary electrons is thus $\sim (eV_g/2\hbar\omega_D)i_g$. The term in parentheses, which is ~ 100, can be regarded as an amplification factor for the gate leakage current. Experimentally, it was shown above that the required magnification is $\lesssim 10$, which is well within the theoretical limit.

d) Since $\hbar\omega_D \sim 15\,\mathrm{meV} > E_i$, the secondary electrons have a large characteristic energy and a correspondingly large velocity, $\sim (2\text{–}4)\cdot 10^7$ cm/s, to escape from the initial donor. The energy of these electrons is well above the conduction band edge, thus they are only weakly sensitive to the potential landscape of the channel. This fact ensures that only a small difference exists in the flow of secondary electrons towards the two contacts. For a characteristic electron energy around 10 meV and mean free time 10^{-12} s (estimated for the Coulomb scattering by charged impurities with concentration N_i) the mean free path is $\sim (2\text{–}4)\cdot 10^{-5}$ cm, which is of the order of the length of the channel. Hence most of the secondary electrons reach the contacts ballistically where they relax by electron-electron interaction.

The system now needs to restore quasi-neutrality, and the only way to do so is for electrons to hop back to the channel and be captured by the ionised donors. Although the secondary electrons diffuse equally to both contacts, their return to the donors is *asymmetric*. This is due to the fact that the channel is mesoscopic, and the hopping paths from the two contacts are different, fig. 4(b). As a result, the electrochemical potentials in the contacts are increased differently with respect to the equilibrium Fermi level. It is this potential difference that drives the current i_0 in the external circuit. In experiment the degree of asymmetry is controlled by the gate voltage which determines the hopping paths in the channel. Thus the magnitude and direction of i_0 is critically dependent upon its value, fig. 3.

The experiment bears out qualitatively the salient features of our model. *Firstly*, the leakage current was found to be the only source capable of sustaining the spontaneous current in the circuit. As the magnitude of i_0 is expected to be proportional to i_g, we attempted to change i_g in the experiment, both by changing the samples and by varying i_g in the same sample by use of a back gate. For two other samples with negligible gate leakage ($< 0.1\,\mathrm{pA}$) the current i_0 was undetectable. In the other extreme, samples with high leakage currents were unfortunately too unstable to be studied. We expected that with a negative voltage applied to a back gate, one can reach the regime of fluctuations highlighted in fig. 1 at smaller $|V_g|$, and hence at a smaller leakage current. However, it transpired that the back gate voltage affected the leakage current as well, which made this experiment ambiguous. *Secondly*, the structure of i_0 is expected to be a unique function of the gate voltage. This was seen experimentally in the low correlation of i_0 with the currents driven by the bias along the channel, i_b, and by the nonlinearity of the channel, i_r. *Thirdly*, in a sample of significantly larger gate length ($2.0\,\mu\mathrm{m}$) spontaneous current was not measurable. This is in agreement with our estimations above showing that in the proposed mechanism a channel length of $0.1\,\mu\mathrm{m}$ is optimal for its realisation. Upon increasing the length the effect is significantly suppressed, both due to the increased probability for secondary electrons to relax directly back to the ionised donors in the channel (stage d), and due to the decrease in the asymmetry of the channel. Contrarily, in shorter channels the process of ionisation (stage c) will be less efficient.

In conclusion we have observed the generation of a spontaneous dc current by a gated nanostructure in the absence of an applied driving voltage. This is explained by a novel "phonon-electric" effect based on the combination of leakage current magnification mediated by phonons and asymmetry in the channel controlled by the gate voltage.

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