Spontaneous current generation in gated nanostructures

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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.

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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, 2] and the photogalvanic effect [3, 4]. 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 [5, 6]. 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 localized 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 nanostructures.

The experiments were carried out on a GaAs based transistor. The wafer consists of a $1 \cdot 10^{17}\,\text{cm}^{-3}$ silicon doped layer 1450 Å thick on an undoped GaAs substrate. A metallic (Au) gate, of length $0.15\,\mu$m in the current direction and width $9\,\mu$m, was 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, housed in a screen room to suppress external interference. Both the ac and dc currents were measured via a battery-powered EG&G 181 low-noise pre-amplifier within the room.

Figure 1 shows the conductance ($\mathrm{d}i/\mathrm{d}V$) through the channel as a function of the applied gate voltage. Strong, reproducible structure can be seen to occur near the

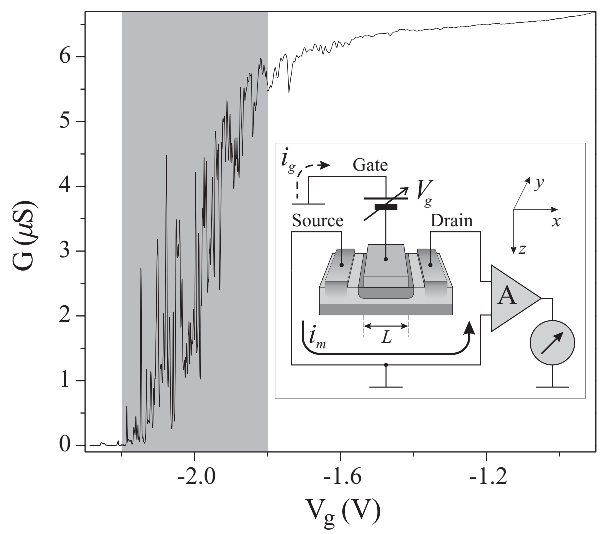

FIG. 1: The two-terminal (differential) conductance as a function of the gate voltage. The shaded box delimits the range of V_g where the spontaneous current is resolved. Inset: Circuit (simplified) used to measure the dc current i_m via the pre-amplifier (A). The transistor is depicted schematically: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

pinch-off, associated with mesoscopic hopping and tunnelling processes [7]. 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 at any gate voltage. Contrarily, Fig. 2(a) shows that a large current occurs that changes direction and magnitude 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 (drift) dc bias V_d can produce a "drift" current i_d. Second, rectification of stray interference of frequency ω and magnitude V_ω can produce a rectified current i_r. Third,

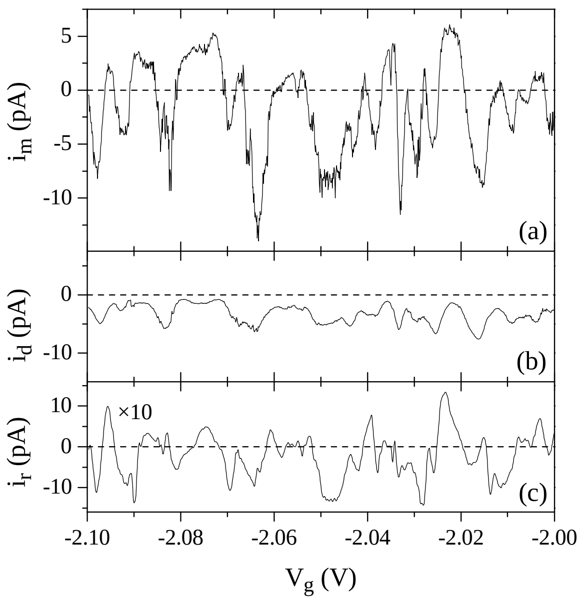

FIG. 2: (a) The measured dc current i_m in the source–drain circuit with no applied bias within the range of V_g highlighted in Fig. 1. (b,c) The contribution to i_m from the drift current i_d due to the presence of unintentional dc biases in the circuit (b), and from the rectified current i_r due to the rectification of stray interference (c).

there is a small leakage current from the gate i_g, which splits into $(1-\alpha)i_g$ in the gate–source and αi_g in the gate–drain 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:

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

where the first two terms on the right define i_d 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. In order to investigate the nature of i_0, we first compare it to i_d, i_r and i_g; then we propose a new mechanism of current generation that accounts for its existence.

The first contribution to i_m is derived from an unintentional dc voltage in the source–drain circuit, which is due to the pre-amplifier. This voltage was found to change monotonically over the course of an experiment ($1-2$ hours) by $\sim 200\,\mathrm{nV/hour}$. In Fig. 2(b) the resultant drift current i_d that can be ascribed to the average of this voltage, V_d, is shown (Eqn. 1). From this we see that the amplitude of i_d is much smaller than the measured current, and more importantly, it is only driven in one direction. To quantify this difference, we calculate the correlation coefficient $C(i_d,i_m) = \langle\delta i_d \delta i_m\rangle/\langle\delta i_d^2\rangle^{1/2}\langle\delta i_m^2\rangle^{1/2}$, where $\delta i = i - \langle i\rangle$ and $\langle\cdots\rangle$ is an average over the gate voltage range shown in the figure. We find $C(i_d,i_m) = 0.61$, which increases to > 0.9 when an intentional bias voltage ($\sim 1\,\mathrm{mV}$) is applied such that i_d dominates i_m. However, if all the conventional contributions are first subtracted from i_m (see below) we find that $C(i_d,i_0)$ is only -0.28. This low correlation, together with the small magnitude and singular direction shows conclusively that the mechanism associated with a dc bias voltage cannot account for the observed effect.

The second contribution to the measured current is rectification as a result of the non-linear nature of the system (as evinced in Fig. 1). The non-linearity of nanostructures has been observed previously, e.g. [7, 8, 9]. For such a system, the rectified current i_r is related, through the second derivative $\mathrm{d}^2 i/\mathrm{d}V^2(V_g)$, to the second harmonic response at frequency 2ω to an applied ac bias at ω. In the absence of an applied ac bias, a rectified current is still present due to residual stray interference coupling to the circuit, predominantly the part outside the screen room. Therefore i_r as a function of V_g can be reconstructed from measurements of the second harmonic and the integral of the voltage noise across the channel. In Eqn. 1, the frequency range Ω for which $V_\omega \neq 0$ was found experimentally to have an upper limit of 20 kHz. 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. If we also compare the correlation $C(i_r,i_0) = 0.14$ with that obtained when a strong ac bias ($V_\omega > 100\,\mu\mathrm{V}$) is intentionally applied to the channel, $C(i_r,i_m) \sim 1$, we conclude that i_0 cannot be related to the rectification of stray interference. We confirmed this in additional experiments where 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 measurement of $i_0(V_g)$ by discrete points (the meters being read by candlelight) yielded the same result as that presented.

Figure 3 shows the spontaneous current $i_0 \approx i_m - i_d - i_r$. Also shown is the gate leakage current i_g. This is roughly constant ($\sim 2\,\mathrm{pA}$) and its contribution to the measured current, determined by $\alpha \sim 0.5$, is small compared to i_0. In addition, it is important to note that i_0 flows around the source–drain circuit, whereas i_g flows down each branch in the same direction, see Fig. 1(inset). The absence of fine structure in i_g also shows that it cannot directly account for i_0, although in the model we propose it plays a key role in its generation.

It is interesting to note that samples defined by longer gate lengths, up to $2.0\,\mu$m, have shown no evidence in our experiments for producing spontaneous current. This suggests a critical dependence of its magnitude on the length of the channel. The model discussed below shows that indeed there can be an optimal channel length for the observation of the effect, which is close to that of our experiment.

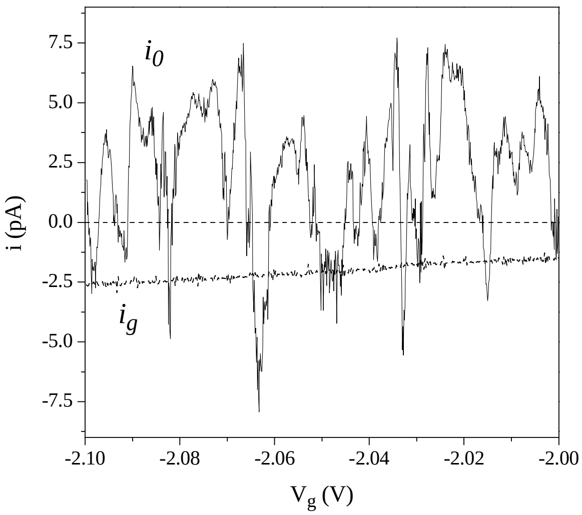

FIG. 3: The spontaneous current i_0, after subtracting the contributions of the drift and rectified currents from the measured current i_m in Fig. 2. Also shown is the gate leakage current i_g in the same range of gate voltage.

The model explains the experimental observations in terms of magnification of the gate leakage current. First we note that, 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*.

We suggest the following sequence of events (detailed below), shown in Fig. 4: (a) emission of optical phonons by electrons tunnelling from the gate; (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.

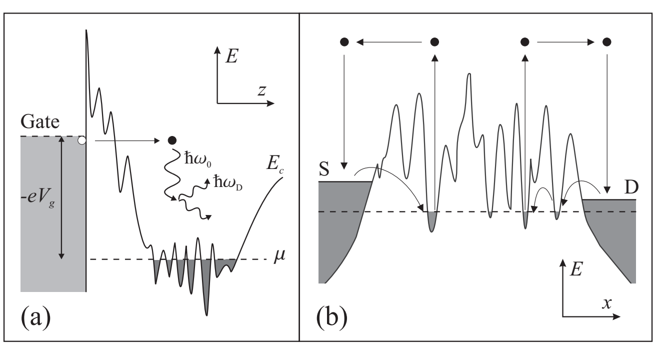

FIG. 4: The physical mechanism to explain the spontaneous current as a multistage process of relaxation and excitation. (a) The relaxation of hot electrons from the gate into the channel (Stages a–b, described in the text). (b) Diffusion and neutralization of secondary electrons from the channel (Stages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

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. So 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. The hot electrons mostly reside in the side valleys of GaAs with small mobility and large effective mass $0.35 \cdot 10^{-27}$ g [10], so their initial velocity can be roughly estimated as $v \sim 10^8$ cm/s (from the condition $mv^2/2 \approx 1\,\mathrm{eV}$). Consequently, in a short channel (in our case $\sim 10^{-5}$ 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 [11].) 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.

It is known that the room-temperature electron mobility in the side valley is $\sim 150\,\mathrm{cm^2V^{-1}s^{-1}}$, from which one estimates for an electron energy of $k_BT \sim 30\,\mathrm{meV}$ that $\tau_p \approx 3 \cdot 10^{-14}\,\mathrm{s}$. It is expected that scattering of hot electrons is mostly due to polar scattering by optical phonons [11] 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 [11] 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 $\tau_{\mathrm{op}} \sim 10^{-11}\,\mathrm{s}$ [12]. 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_{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 ionize donors in the channel creating "secondary" electrons. The probability for them to do so can be estimated using Fermi's golden rule, the squared matrix element being

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

Here a is the localization length, $\mathbf{q}$ and $\mathbf{k}$ are the wave vectors of the phonon and excited electron, respectively; λ is the deformation potential, M the atomic mass, and $\mathcal{V}$ is the normalization volume. One calculates the phonon scattering rate due to the ionization processes as

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

where E_i is the donor ionization 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 $\tau_{\mathrm{ph,i}}^{-1} \sim 10^{-3}\omega_q$. Correspondingly, the mean free path with respect to ionization 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 ionization 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, $\sim (2{-}4)\cdot 10^7$ 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 $\sim (2-4)\cdot 10^{-5}$ 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 ionized 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 spatial position of donors in the channel. Thus the magnitude and direction of i_0 is critically dependent upon its value, Fig. 3.

Our estimations above show that the proposed mechanism is indeed realized in systems with channel length $0.1\,\mu$m; moreover this length appears to be an optimal one for its realization. Upon increasing the length the effect is significantly suppressed, both due to the increased probability for secondary electrons to relax directly back to the ionized donors in the channel (Stage d), and due to the decrease in the asymmetry of the channel. Contrarily, in shorter channels the process of ionization (Stage c) will be less efficient.

In conclusion we have observed a novel "phonon–electric" effect in a gated nanostructure, which is seen as a spontaneous generation of a dc current with no driving voltage applied. Our explanation is 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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