Time-Irreversible Random Telegraph Signal Due to Current along a Single Hopping Chain

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We have directly observed individual hopping events in the flow of current along a single chain of localized states. These events modulate the conductance of a ballistic constriction formed in a $GaAs/Al_xGa_{1-x}As$ split-gate transistor, resulting in a time-irreversible random telegraph signal. The hopping chain, carrying approximately one electron per second, is situated between the gate and the two-dimensional electron gas, and can be altered by varying the gate voltage.

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In the last decade considerable attention has been paid to mesoscopic effects in the hopping regime of conduction [1-5]. Usually the conductance averaged over time is measured, and reproducible fluctuations are observed as a function of gate voltage or magnetic field. The analysis of these fluctuations is based on the Miller-Abrahams approach [6], where the hopping between each pair of localized states is associated with a definite resistance. Changes in the critical hop, whose resistance dominates the total conductance, are then responsible for the fluctuations in the averaged conductance [7,8]. However, this approach deals only with the time-averaged energy levels and mean occupations of the localized states. A direct monitoring of hopping *in time* is desirable as the next step towards the understanding of elementary hopping events, and the correlations [6,9] between them.

To investigate the dynamics of hopping current, we employ a ballistic constriction formed in a highly conductive two-dimensional electron gas (2DEG) using the split-gate technique [10]. The conductance of the constriction acts as a sensitive probe of the defect charges in a very small region surrounding it, and allows one to follow the electron configuration on a single hopping chain as a function of time. The hopping gives rise to a random telegraph signal (RTS) in the conductance of the constriction, each level of which corresponds to a particular electron configuration. The key feature of this signal is that its characteristics are asymmetric under reversal of the time axis.

Any noise signal caused by processes in equilibrium should be reversible, by the principle of detailed balance. No time-irreversible RTS has been seen previously in a semiconductor structure [11] (to our knowledge the only one reported in any system was in a submicron Josephson junction [12]). In our experiment the observed irreversibility is a direct consequence of the current flow through localized states between the gate and the 2DEG in a strong electric field. At low electric field the hopping current between a pair of localized states arises from a small imbalance between hopping rates up and down the field [6], while at high electric field most hops occur down the field.

Our system is a split-gate $GaAs/Al_{0.3}Ga_{0.7}As$ high-electron-mobility transistor, and all measurements were made at a temperature of $T=1.2$ K. The density of the 2DEG at the heterojunction is 3×10^{11} cm^{-2} and the mobility is 1.0×10^6 $cm^2V^{-1}s^{-1}$. The palladium-on-gold Schottky split gate was patterned on the surface by electron-beam lithography, and the gate leakage current was always too small to measure down to a resolution of 10 pA. The two-terminal conductance was measured using an ac source-drain voltage of 100 μV at 3 kHz, with a blocking capacitor to prevent any dc voltage appearing along the channel. When a negative potential is applied to the gate relative to the 2DEG, lateral depletion away from the edges of the 0.5 μm$\times$0.5 μm gap in the split gate produces a very short and narrow constriction of controllable width in the 2DEG, and plateaus appear in the conductance as a function of gate voltage as a result of one-dimensional quantization effects [13,14].

Figure 1 shows the result of sampling the conductance with a bandwidth of 1 kHz while sweeping gate voltage V_g at the indicated rate, from pinch-off to the edge of the first quantized conductance plateau. The visible noise is due to a complex RTS. The curve labeled *O* follows the highest conductance level of the RTS, and the dotted

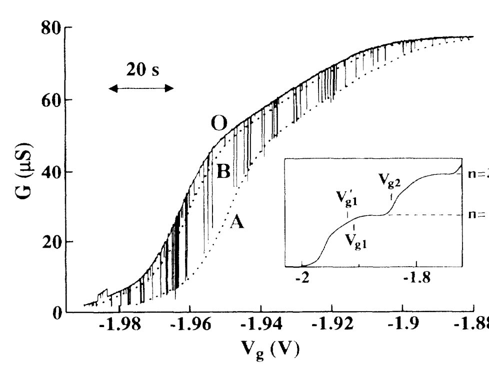

FIG. 1. Main trace: Gate-voltage sweep between pinch-off and the first one-dimensional quantized plateau, at the rate indicated, with conductance sampled at 1 kHz. Inset: Sweep over the first two plateaus with noise filtered out.

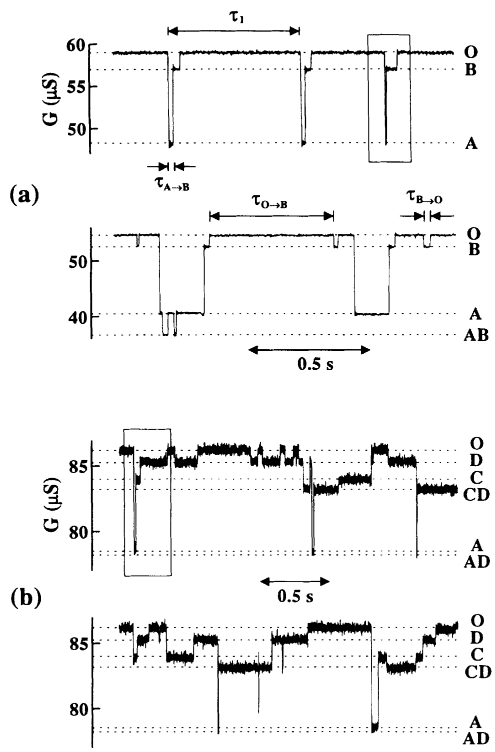

FIG. 2. Samples of the noise at fixed gate voltages. (a) Four-level irreversible RTS at $V_{g1} = -1.91$ V (upper trace) and $V'_{g1} = -1.92$ V (lower trace). (b) More complex irreversible RTS at $V_{g2} = -1.85$ V.

curves labeled A and B are identical in shape to curve O but have been shifted along the V_g axis by $\Delta V_{OA} = 14$ mV and $\Delta V_{OB} = 2.7$ mV, respectively. The accuracy with which these curves coincide with the other levels of the RTS implies that the conductance modulation is brought about by a fairly uniform shift in the potential at the constriction [15], equivalent to that resulting from a change of V_g by ΔV_{OA} or ΔV_{OB}.

The inset in Fig. 1 shows the filtered gate-voltage dependence of the conductance on which three particular gate voltages are marked. Figure 2(a) shows samples of the four-level RTS seen at nearby voltages V_{g1} and V'_{g1}. At V_{g2} the RTS evolved into the more complex form shown in Fig. 2(b). The important feature of the data which is apparent in these traces is the time irreversibility. In Fig. 2(a) the transition between levels O and A occurs in the direction $O \rightarrow A$, while the reverse, $A \rightarrow O$, is never seen. Meanwhile, all other transitions occur in both directions. In Fig. 2(b), the situation is similar but more complicated, with several irreversible transitions.

As there was no dc electric field along the channel, and the ac signal level was not larger than $k_B T/e$, the lack of equilibrium must be related to some finite current flow along the high electric field between the gate and the 2DEG. The properties of the RTSs are fully consistent with a microscopic model in which this current passes

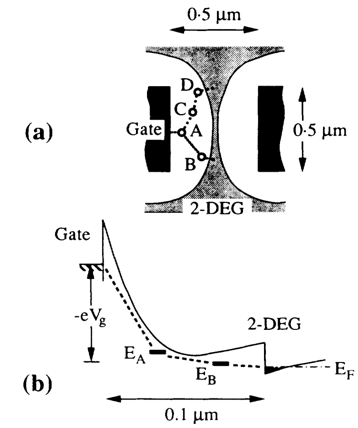

FIG. 3. (a) Sketch of the geometry of the ballistic constriction in plan view, showing locations of the defects and the hopping paths linking them with the gate and the 2DEG. (b) Schematic band diagram along a line connecting the gate and the 2DEG, indicating energies of defects A and B.

along a chain of localized states whose arrangement is shown in Figs. 3(a) and 3(b). The RTS in Fig. 2(a) can be explained in terms of two defects, A and B. The four levels of the RTS are identified with the corresponding charge configurations of these defects as illustrated in Fig. 4(a). In configuration O both defects are empty, while in configuration AB both are occupied. All observed transitions between configurations are shown, and irreversible ones are indicated by one-way arrows. The sequence appropriate to the typical cyclic pattern $O \rightarrow A \rightarrow B \rightarrow O$, as enclosed in the box on the upper trace of Fig. 2(a), is emphasized by thick solid arrows. The ir-

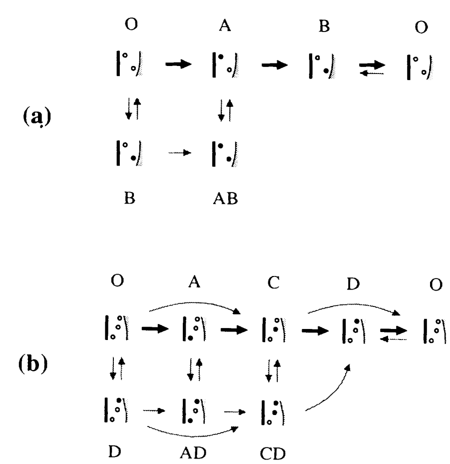

FIG. 4. (a),(b) Transitions between electron configurations on the hopping chains between the gate and the 2DEG, appropriate to the RTSs in Figs. 2(a) and 2(b), respectively. One-way arrows correspond to irreversible transitions. Horizontal sequences connected by thick solid arrows correspond to the portions of the RTS contained within the boxes on the RTSs shown in Fig. 2, while shaded arrows indicate all other observed transitions.

reversibility of the transitions $O \rightarrow A$ and $B \rightarrow AB$ between RTS levels is connected with the transfer of an electron from the gate to defect A, which occurs in only one direction.

The distance between the defects and the critical central region of the constriction in our scheme is of the order of 1000 Å. This is large enough for there to be a fairly uniform electrostatic shift of the potential in this region (whose size is around 200 Å, the separation of the classical turning points of the lowest 1D subband) when the defect charge configuration changes. The rate of increase of the barrier height in the constriction with more negative V_g is about 15 meV/V in such devices [15]; thus the effective modulation amplitudes ΔV_{OA} and ΔV_{OB} correspond to potential shifts at the constriction of about 210 and 40 μeV, respectively. These values are smaller than the unscreened Coulomb potential of one electron at a distance of 1000 Å (about 1 meV), because of the screening effect of the 2DEG. The smaller potential shift associated with defect B is consistent with it being located closer to the 2DEG.

The characteristic times of the four-level signal, whose definitions are indicated in Fig. 2(a), were measured at the two gate voltages $V'_{g1} = -1.92$ V and $V''_{g1} = -1.96$ V, averaging over at least fifty events for each time. The current through the chain is given by $I_{\text{ch}} = e/\tau_I$, where τ_I is the mean time between $O \rightarrow A$ transitions, corresponding to the frequency at which electrons transfer from the gate to defect A. At both gate voltages τ_I is equal to 1.2 s, giving $I_{\text{ch}} = 1.3 \times 10^{-19}$ A—less than one electron per second. The times $\tau_{B \rightarrow O} = 10$ ms and $\tau_{O \rightarrow B} = 2.0$ s, which are the reciprocals of the tunneling rates between defect B and the 2DEG, are also constant. In contrast, $\tau_{A \rightarrow B}$, the time an electron waits before hopping from defect A to defect B, increases from 30 ms at V'_{g1} to 80 ms at V''_{g1}.

These values are consistent with the energetic positions of defects A and B indicated in Fig. 3, which is a schematic band diagram following the hopping path from the gate to the 2DEG. The observed constancy of the transition rate τ_I^{-1} is as expected. The transitions from the gate to state A involve either direct hopping, or tunneling through the Schottky barrier followed by energetic relaxation through the conduction band and subsequent capture by defect A. In neither case should the transition probability be sensitive to a small change in gate voltage, $V'_{g1} - V''_{g1} \ll |V_g|$. The current between the gate and defect A is also proportional to the density of occupied states in the gate, which is independent of V_g, and to the probability, $1 - \tau_{A \rightarrow B}/\tau_I$, for state A to be empty, which remains close to unity.

The energy difference between E_B and the Fermi energy E_F in the 2DEG should be given by the detailed-balance requirement $\exp[-(E_B - E_F)/k_B T] = \tau_{B \rightarrow O}/\tau_{O \rightarrow B}$, yielding $E_B - E_F = 550$ μeV. The lack of measurable changes in $\tau_{B \rightarrow O}$ and $\tau_{O \rightarrow B}$, and therefore in E_B, in the range from V'_{g1} to V''_{g1} is consistent with the proximity of defect B to 2DEG, which is also required to explain the stronger screening of its Coulomb potential. On the other hand, defect A is considerably closer to the gate, so E_A moves upwards faster than E_B as V_g is made more negative. Thus the decrease in the transition rate $1/\tau_{A \rightarrow B}$ is likely to result from a decreasing matrix element for spontaneous phonon emission [6]. We may then roughly estimate the separation r_{AB} of the defects from the expression $1/\tau_{A \rightarrow B} \approx \gamma^0 \exp(-2r_{AB}/a)$, where $a \approx 100$ Å is the Bohr radius of the donor states and $\gamma^0 \sim 10^{13}$ Hz. For $\tau_{A \rightarrow B} \approx 50$ ms this gives $r_{AB} \sim 1300$ Å, in agreement with the preceding arguments.

As a result of the proximity of defects A and B there should be a Coulomb interaction between them such that an electron in state A increases the energy of B by an amount ε, and vice versa. This could result in reduced probabilities for the level transitions $A \rightarrow AB$ and $B \rightarrow AB$ if $\varepsilon > k_B T$. However, level AB occurred sufficiently often in experiment to imply that this effect is not large. This is consistent with ε being of the order of the interaction energy between each defect and the constriction, i.e., between 40 and 200 μeV, which is not much larger than $k_B T$ (≈ 100 μeV). Also, even a larger value of ε would not influence the high-field transition $B \rightarrow AB$ as long as $\varepsilon \ll E_A - E_B$.

At more positive V_g the defect energies are sufficiently altered for a new chain of three defects, A, C, and D, to become visible, producing the altered RTS of Fig. 2(b). As in Fig. 2(a), the levels are labeled in accordance with the occupation of these defects. We established that for the RTSs of both Figs. 2(a) and 2(b) the levels O and A correspond to the same configurations of the defect charges. The value of ΔV_{OA} is the same at V_{g2} and V_{g1}, in spite of the variation in the conductance levels O and A resulting from the stepwise dependence of the conductance on V_g.

In Fig. 4(b) are indicated all level transitions observed in the RTS at V_{g2}. The simple staircaselike sequence of transitions surrounded by the box on the upper trace in Fig. 2(b) is explained by the transfer of an electron directly along the following path: gate $\rightarrow A \rightarrow C \rightarrow D \rightarrow$ 2DEG. The level transitions $O \leftrightarrow C$ and $D \leftrightarrow CD$ can be related to the direct motion of an electron along a path through only one intermediate defect, gate $\rightarrow C \rightarrow$ 2DEG, with defect D remaining either empty or full, respectively.

In conclusion, we have demonstrated the possibility of monitoring the single hopping events along a current-carrying chain by measuring the conductance of a nearby ballistic constriction as a function of time. Under high-field conditions the hopping current results in a random telegraph signal which is irreversible in time. The same principle could be used to follow single-electronic processes in other systems.

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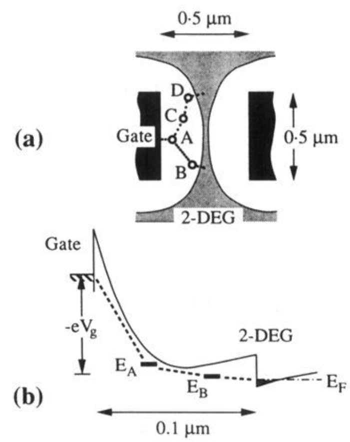

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