Ballistic transport in nanoscale field effect transistors revealed by four-terminal DC characterization

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Ballistic transport in nanoscale field effect transistors revealed by four-terminal DC characterization

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Abstract

We show that four-terminal measurements of the differential conductance of field effect transistors (FETs) can provide important insights into the transport mechanism, and in particular can reveal the presence of ballistic transport. Measurements and simulations of purposely fabricated AlGaAs–GaAs heterostructure FETs show that ballistic transport results in a pronounced peak in the derivative of the differential conductance versus the gate voltage, which splits into two peaks with increasing drain-to-source voltage. Analyzing the four-probe conductance, ballistic electron transport through the channel is revealed as the origin of the observed peak splitting.

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One apparent effect of ballistic transport in field effect transistors is the enhanced current driving capability of the device, since electrons are able to traverse the channel without losing longitudinal momentum due to scattering. However, in order to determine whether

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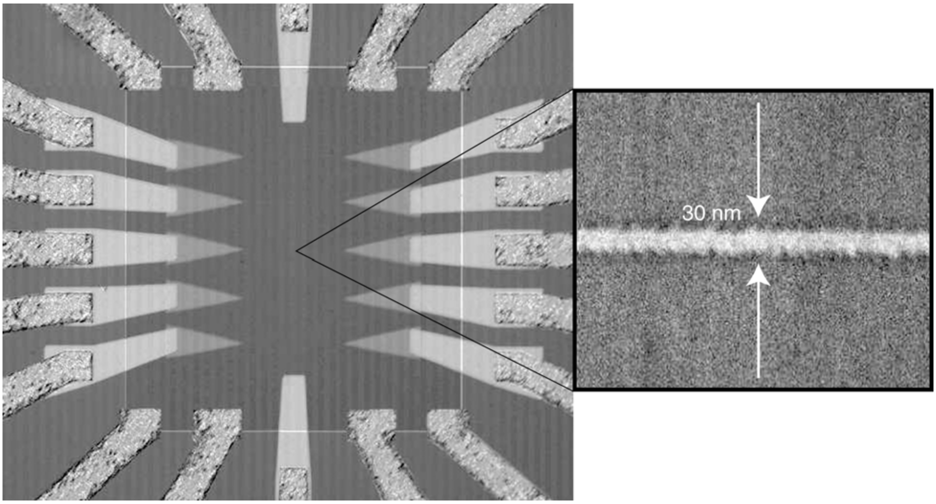

Fig. 1. Left part: an optical microscope image of the structure with the gate layout used for defining several field effect transistors. An FET is defined by activating only one gate. The top and bottom contacts serve as source and drain. Right part: an SEM micrograph of an ultrashort gate.

in a given multi-mode device electrons are ballistically transferred along the channel, one cannot rely on efficient current characteristics since many unknown parameters prevent an unambiguous classification of a given value of transconductance or current to ballistic transport.

In devices such as quantum point contacts [1, 2] or double-barrier (injector–spectrometer) systems [3–5] ballistic transport is revealed by peculiar electrical properties, e.g., conductance quantization, or transfer characteristics that allow one to reveal the energy distribution of electrons, respectively.

In the present paper, we will show that four-terminal measurements of the differential conductance of AlGaAs–GaAs heterostructure FETs (HFETs) may be used to determine whether transport is ballistic or dissipative.

We have fabricated HFETs with gate lengths L down to 25 nm and gate widths up to 100 μm. The mobility of the 2DEG at 4 K was 2.5×10^6 V s/cm^2. An optical microscope image of a structure containing several gates is shown in the left part of Fig. 1. One horizontal gate is activated at a time by the application of a negative voltage, separating two wide regions serving as the source and drain reservoirs. An SEM micrograph of one section of an ultrashort gate is shown in Fig. 1 (right-hand side).

When a voltage V_{DS} is applied between the drain and the source, a current I flows between the two terminals, which depends on V_{DS} and on the voltage V_{GS} applied to the gate. For the present set-up the source terminal was defined as grounded.

The differential conductance of the device is defined as $G = \mathrm{d}I/\mathrm{d}V_{\mathrm{DS}}$. When the voltage V_{DS} is a few millivolts, the derivative of G with respect to V_{GS} plotted versus V_{GS} exhibits the behavior shown in Fig. 2. Two peaks are clearly visible at low temperatures. With increasing temperature, the peaks widen and at the same time get closer as well as

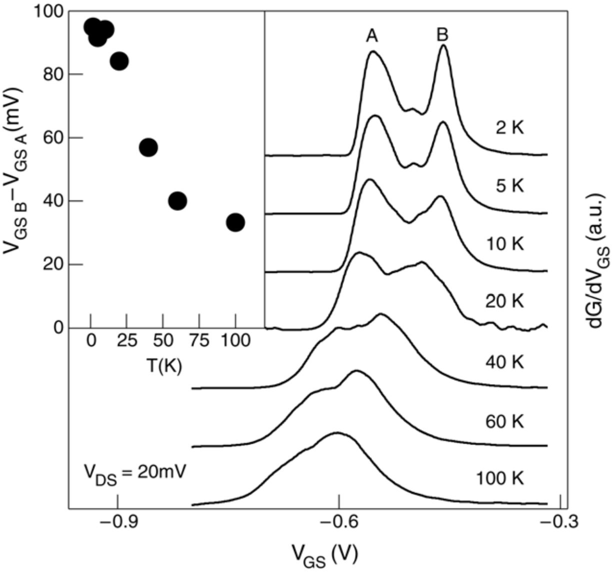

Fig. 2. The derivative of the differential conductance with respect to the gate voltage plotted versus the gate voltage for different temperatures measured for a 50 nm gate length HFET. The curves are shifted for clarity of presentation. Inset: peak splitting as a function of the operating temperature.

shifting towards lower values of V_{GS}. In the inset of Fig. 2 the peak splitting is plotted as a function of temperature. The measurements performed confirm that the peak splitting increases almost linearly with V_{DS}. The splitting is larger for devices with smaller gate length L.

We interpret the observed peak splitting as a fingerprint of ballistic electron transport in multi-mode devices. For a better discussion we compare our experiments to models, with one based on ballistic transport and the other describing a dissipative transport regime. In the ballistic model, we assume that in the channel two separate populations of electrons exist: those injected from the source, which are in thermal equilibrium with the source reservoir, and those injected from the drain, which are in thermal equilibrium with the drain. In this case the left (right) peak occurs when the maximum potential energy seen by electrons in the channel aligns with the source (drain) electrochemical potential.

In the drift-diffusion regime, we have a unique quasi-Fermi level in the channel, that is slowly varying, and coincides with the source electrochemical potential at the source and with the drain electrochemical potential at the drain. A double-peak feature can be obtained only if we include the effect of contact resistances at the source and at the drain. In such a case the first peak of dG/dV_{GS} versus V_{GS} occurs when the FET passes from the cut-off to saturation, and the second peak is associated with the FET transition from saturation to the ohmic region.

In Fig. 3 the results of analytical calculations using for the ballistic FET the well known model by Natori [6] and for the dissipative FET the EKV model [7] are shown. As can be seen both models reproduce the qualitative features of the experiment. However, since

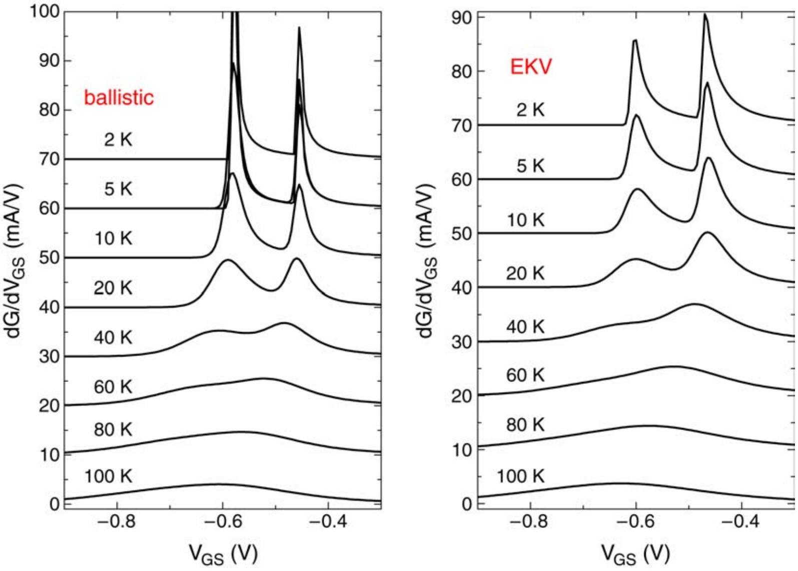

Fig. 3. The derivative of the differential conductance with respect to the gate voltage plotted versus the gate voltage for different temperatures for a 50 nm gate length HFET. Curves are shifted for clarity of presentation. Left part: theoretical results obtained with a ballistic transport model. Right part: theoretical results obtained with the EKV model.

in the case of a dissipative FET the double-peak feature is only due to the presence of contact resistances, we have performed four-terminal measurements with two additional voltage probes separated from the source and drain electrodes. In such a way it is possible to measure the intrinsic drain-to-source voltage, excluding the voltage drop on the contact resistances. Therefore, we were able to obtain the current I as a function of V_G and of the intrinsic V_{DS}, and derive numerically G and dG/dV_{GS}.

Results for an HFET with a gate length of 50 nm are shown in Fig. 4 (thick solid line). In addition calculated curves obtained using the ballistic model (thin solid line) and the EKV model (dotted line) are plotted. In all cases the model parameters have been chosen in order to provide the best fit with experiments. It is clear that only the ballistic model is able to reproduce the double-peak behavior observed in experiments. In contrast, the dissipative model provides a double-step behavior, which qualitatively differs from the experimental traces.

In conclusion, we have shown that four-terminal measurements of the differential transconductance provide a unique way to recognize ballistic transport in a field effect transistor. In particular, the double-peak shape of the plot of the derivative of the differential conductance with respect to the gate voltage versus the gate voltage is a clear indication of ballistic transport.

From our theoretical calculation we predict that the reported peak splitting could be observed at much higher temperatures for nanoscale devices with sufficiently low scattering. At high temperatures, due to thermal broadening of the electron distribution, the two peaks

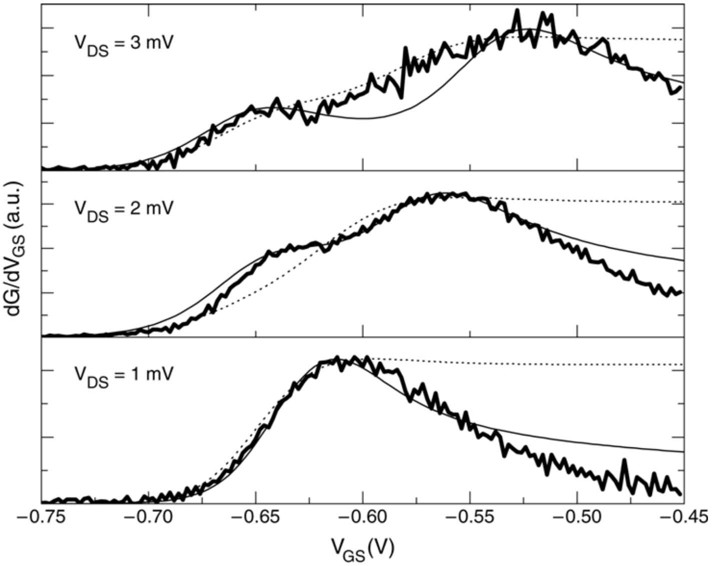

Fig. 4. dG/dV_{GS} as a function of V_{GS} obtained with a four-probe measurement for V_{DS} ranging from 1 to 3 mV (thick solid line). Theoretical best fitting curves with the analytic model for ballistic transport (thin solid line) and with the EKV model (dashed line) are shown.

would become wider and merge into a single peak. However, diffusive transport would provide a single plateau, and not a peak, still allowing the identification of ballistic transport.

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