Comment on "Conductance Oscillations Periodic in the Density of a One-Dimensional Electron Gas"

In a recent Letter, Scott-Thomas *et al.*[1] announced the experimental discovery of conductance oscillations periodic in the density of a narrow Si inversion layer. An interpretation in terms of pinned charge-density waves was suggested.[1,2] We propose an alternative *single-electron* explanation of this remarkable effect, based upon the concept of the Coulomb blockade of tunneling (arising from the charging energy associated with the tunneling of a single electron). Likharev[3] and Amman, Mullen, and Ben-Jacob[4] have studied theoretically the possibility of removing the Coulomb blockade by capacitive charging (by means of a gate terminal) of the region between two tunnel junctions in series. They found that the zero-bias conductance of such a device exhibits periodic peaks as a function of gate voltage, due to the modulation of the charging energy. We propose that the current through the channel in Ref. 1 is limited by tunneling through potential barriers constituted by two dominant scattering centers which delimit a segment of the one-dimensional channel (see Fig. 1). We describe the two tunnel barriers by capacitances C_1 and C_2. Because the number of electrons localized in the region between the two barriers is necessarily an integer, a charge imbalance, and hence an electrostatic potential difference, arises between this region and the adjacent regions connected to wide-electron-gas reservoirs. As the gate voltage is varied, the resulting Fermi-level difference ΔE_F oscillates in a sawtooth pattern between $\pm e\Delta$, where $\Delta = e/2C$ is the voltage drop over the effective capacitance $C = C_1 + C_2$ with charge $e/2$. The single-electron charging energy $e^2/2C$ maintains the Fermi-level difference, until $\Delta E_F = \pm\Delta$. Then the energy for the transfer of a single electron to (or from) the region between the two barriers vanishes, so that the Coulomb blockade is removed, and the conductance shows an unactivated maximum at low temperatures T and source-drain voltages V ($k_B T/e$, $V \lesssim \Delta$).[3,4,5] The oscillation of the Fermi energy as the gate voltage is varied thus leads to a sequence of conductance peaks. The periodicity of the oscillations corresponds to the addition of a single electron to the region between the two scattering centers forming the tunnel barriers, so that the oscillations are periodic in the density—as in the experiment. This single-electron tunneling mechanism also explains the observed activation of the conductance minima, and the insensitivity to a magnetic field.[1,2] The capacitance

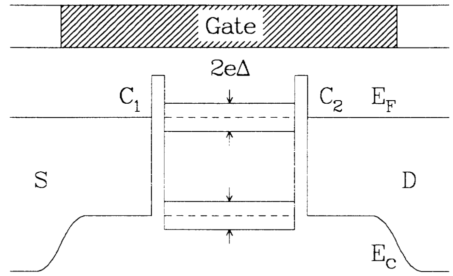

FIG. 1 Schematic representation of the bottom of the conduction band E_c and Fermi energy E_F in the device of Ref. 1 along the channel. The band bending at the connections of the narrow channel to the wide source S and drain D regions arises from the higher threshold for the electrostatic creation of an inversion layer by a narrow gate (shaded part). Tunnel barriers associated with two scattering centers are shown. The maximum Fermi-energy difference $\Delta E_F = \pm e\Delta$ [with $\Delta = e/2(C_1+C_2)$] sustainable by the Coulomb blockade is indicated.

associated with the scattering centers is hard to ascertain, but the experimental value of the activation energy, $\Delta E \approx 50$ μeV, yields $C \approx e^2/2\Delta E \approx 10^{-15}$ F—a value typical for observations of the Coulomb blockade.[3,4] To our knowledge, the idea that a Coulomb blockade may be associated with scattering centers in a one-dimensional electron gas, acting as tunnel barriers with a small capacitance, has not been suggested before.

H. van Houten and C. W. J. Beenakker
Philips Research Laboratories
5600 JA Eindhoven, The Netherlands

Received 26 June 1989
PACS numbers: 73.20.Dx, 71.45.Lr, 72.15.Nj

[1] J. H. F. Scott-Thomas, S. B. Field, M. A. Kastner, H. I. Smith, and D. A. Antoniadis, Phys. Rev. Lett. **62**, 583 (1989).

[2] The same interpretation has been given to a similar effect in GaAs by U. Meirav, M. A. Kastner, M. Heiblum, and S. J. Wind, Phys. Rev. B **40**, 5871 (1989).

[3] K. K. Likharev, I.B.M. J. Res. Dev. **32**, 144 (1988), and references therein.

[4] M. Amman, K. Mullen, and E. Ben-Jacob, J. Appl. Phys. **65**, 339 (1989); see also L. I. Glazman and R. I. Shekhter (unpublished).

[5] In the case of very different tunneling rates through the two barriers, one would expect steps in the current as a function of source-drain voltage, which are not observed in Ref. 1. For two similar barriers this "Coulomb staircase" is suppressed (see, e.g., Fig. 3 in Ref. 4).