Coulomb blockade in low-mobility nanometer size Si MOSFET's

M. Sanquer, M. Specht, and L. Ghenim
CEA-DSM-DRFMC-SPSMS, 38054 Grenoble Cedex, France

S. Deleonibus and G. Guegan
CEA-DTA-LETI-DMEL CEA-Grenoble, 38054 Grenoble Cedex, France

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We investigate coherent transport in Si metal-oxide-semiconductor field-effect transistors with nominal gate lengths 50–100 nm and various widths at very low temperature. Independent of the geometry, localized states appear when $G \simeq e^2/h$ and transport is dominated by resonant tunnelling through a single quantum dot formed by an impurity potential. We find that the typical size of the relevant impurity quantum dot is comparable to the channel length and that the periodicity of the observed Coulomb blockade oscillations is roughly inversely proportional to the channel length. The spectrum of resonances and the nonlinear *I-V* curves allow us to measure the charging energy and the mean level energy spacing for electrons in the localized state. Furthermore, we find that in the dielectric regime the variance $var(lng)$ of the logarithmic conductance lng is proportional to its average value $\langle lng \rangle$ consistent with one-electron scaling models.

After the pioneering work of Scott-Thomas *et al.*,[1] Coulomb blockade in quantum dots formed by an impurity potential has been studied in quasi-one-dimensional (1D) wires or point-contact geometries.[2,3] In comparison with lithographically defined lateral quantum dots, impurity quantum dots (IQD) contain typically fewer electrons. Downscaling the size of the IQD allows us to operate a silicon based single electron quantum dot transistor even at room temperature.[4,5] In the opposite case of wires, i.e., in disordered thin and wide insulating barriers, no Coulomb blockade oscillations have been reported up to now. Resonant tunneling through single ionized donor potentials is responsible for electron transport in disordered thin insulating barriers. This has been studied in the deeply insulating regime of large thin barriers formed by depleting electrostatically a semiconductor under a gate,[6] or in thin amorphous silicon tunnel barriers.[7] Interaction between distant impurity states in the channel have been revealed by peculiarities of the nonlinear transport. However, a single ionized donor potential cannot accomodate many electrons without becoming screened.

We report Coulomb oscillations in very short metal-oxide-semiconductor field-effect transistors (MOSFET's) with gate length $L=0.05\ \mu$m and width W much larger than L. Contrarily to quasi-1D wires, where the size of the IQD is somewhat arbitrary, we will show that the diameter of the IQD is comparable to the source drain distance and that on resonance the conductance g in quantum units e^2/h is close to 1. Furthermore, we demonstrate that the fluctuations of the conductance characterized by $var(lng)$ are proportional to the mean value $\langle lng \rangle$, rather independent of geometry. Such an observation is consistent with one-parameter noninteracting scaling models of the metal-insulator transition (MIT). Our experimental findings suggest that interactions do not destroy this one-parameter description.

The devices are MOSFET's on the (100) surface of silicon doped to a level of 7×10^{12} B/cm^2 for the 100-nm series and of 3×10^{13} B/cm^2 for the 50-nm series. The gate oxyde thickness is only $d_{SiO_2}=3.8$ nm for the 100-nm series and $d_{SiO_2}=2.4$ nm for the 50-nm series. This screens strongly Coulomb interactions in the inversion layer. Source and drain consist of highly ion implanted regions (10^{15}As/cm^2). The polysilicon gate has a length L of 100 or 50 nm and the transverse dimension W varies between 300 nm and 25 μm. The effective channel length d_{SD} between source and drain is slightly smaller than the geometrical gate length L due to extension regions (2×10^{14} As/cm^2). d_{SD} is estimated to be of order 25 and 75 nm in the two cases considered in this paper. The room-temperature mobility is 242 cm^2 s^{-1} V^{-1} for the 100-nm series and 150 cm^2 s^{-1} V^{-1} for the 50-nm series. The source-drain current I_{SD} is measured for a source-drain voltage $V_{SD}=10\ \mu$V as a function of the gate voltage using a standard low-frequency lock-in technique. The $I_{SD}-V_{SD}$ characteristics is linear for this value of V_{SD} even at the lowest temperature, independent of V_g. The sample is inside a copper box thermally anchored to the mixing chamber of a dilution refrigerator. About 2 m of Thermocoax Philips[8] on each side of the sample provide the contact to the lock-in amplifier.

Figure 1 shows the source-drain conductance in quantum units versus V_g in three samples of gate length $L=100$ nm differing only by the width W. At a temperature of $T=35$ mK, we observe reproducible conductance fluctuations as a function of gate voltage which persist up to $T=20$ K at small V_g. Depending on the value of the conductance these fluctuations evolve differently with temperature: If $G>e^2/h$ the fluctuations are Gaussian around their mean value and poorly sensitive to temperature below $T=4.2$ K. This characterizes universal conductance fluctuations in the diffusive regime not further considered here. If $G<e^2/h$, fluctuations evolve into sharp resonances at very low temperature (dielectric regime). In the diffusive regime, the linear increase of the conductance with the gate voltage permits to evaluate the mobility μ: $G_{square}=n_s e\mu=C_g V_g \mu \propto V_g$ if μ and C_g do not depend on V_g. We find $\mu=25$ cm^2 V^{-1} s^{-1} for $0.135\leqslant V_g\leqslant0.2$ V in the W

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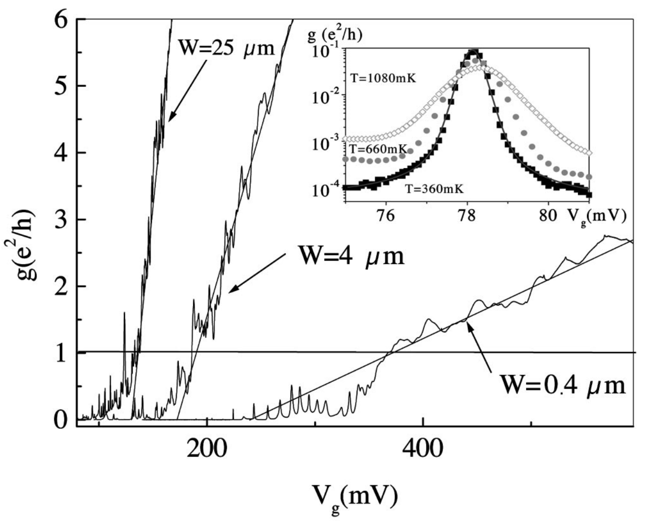

FIG. 1. Source-drain conductance versus gate voltage of samples with gate length $L=100$ nm and various widths W at $T=35$ mK. The horizontal line corresponds to $G=e^2/h$ where independent of geometry diffusive transport sets in. A linear dependence of g with V_g is expected if one supposes a constant mobility, a constant density of states, and a constant gate capacitance. Inset: Source-drain conductance versus gate voltage at various temperatures for a resonance in the dielectric regime of the $W=4$ μm sample. The solid lines is the fit associated to thermally broadened resonant tunnelling (see text) (Ref. 11). The intrinsic linewidth inferred from the fit is $\Gamma_e/k_B=60$ mK.

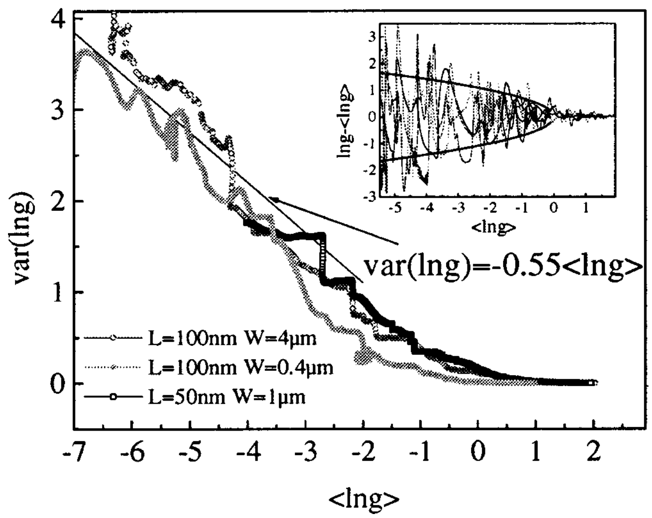

FIG. 2. The variance $var(lng)$ of the logarithmic conductance lng versus its average $\langle lng\rangle$ for four samples with different geometries. For $\langle lng\rangle\leqslant 0$, lng fluctuates strongly roughly corresponding to $var(lng)\simeq -0.55\langle lng\rangle$ over orders of magnitude in the insulating regime. Inset: Fluctuations of the logarithmic conductance versus $\langle lng\rangle$ of four samples with various geometries. The solid lines correspond to $\pm\sqrt{-0.55\langle lng\rangle}$. For $\langle ln(g)\rangle\geqslant 0$, the log-normal fluctuations of the dielectric regime disappear independent of geometry.

$=25$ μm sample, $\mu=53$ cm^2 V^{-1} s^{-1} for $0.2\leqslant V_g\leqslant 0.3$ V in the $W=4$ μm sample and $\mu=73$ cm^2 V^{-1} s^{-1} for $0.375\leqslant V_g\leqslant 0.6$ V in the $W=0.4$ μm sample (at low temperature). These mobilities are weak reflecting a strong short-range disorder and a mean free path of order 4 nm. The measured capacitance to gate coincides with the theoretical estimations: $C_g/S=\epsilon_0\epsilon_{SiO_2}/d_{SiO_2}=10^{-14}$ F/μm^2 (for $d_{SiO_2}=3.8$ nm). A variation of $\delta V_g=1$ V induces $\delta n_s=6.25\times 10^{12}$ cm^{-2} for the 100-nm series ($\delta n_s=1.0\times 10^{13}$ cm^{-2} for the 50-nm series).[9]

Typical conductance resonances in the dielectric regime are well fitted over three orders of magnitude (see inset of Fig. 1) by the standard relation for the thermally broadened resonant tunneling regime:

$$G(V_g,T)=\frac{e^2}{h}A\int_{-\infty}^{\infty}\mathcal{L}(V)\times\frac{\partial f(e\alpha(V-V_g),T)}{\partial V}dV,$$

$$\mathcal{L}(V)=\frac{\Gamma_e^2}{e^2\alpha^2(V_0-V)^2+\Gamma_e^2}$$

with $f(x,T)=[1+\exp(x/k_BT)]^{-1}$, $\alpha=0.252$, and $A=0.8\pm 0.2$. $\Gamma_e/k_B=60$ mK is the intrinsic linewidth and V_0 is the gate voltage at the resonance. $\delta E_F=e\alpha\delta V_g$ is the variation of the Fermi energy. $T=360$ mK± 15 mK is the effective electron temperature which is larger than the phonon temperature. $A\simeq 1$ means that the localized state is equally connected to the source and the drain. If not, the resonant conductance would be exponentially smaller.[10] From $\alpha=C_g/e^2g_{2D}$, we estimate an approximately constant density of states in the channel $g_{2D}\simeq 0.25\times 10^{14}$ cm^{-2} eV^{-1}, which is reduced by a factor 4 compared to the metallic 2D density of states. This is due to Lifshitz tails induced by disorder at the bottom of the conduction band.

The central result in Fig. 1 is that the onset of diffusive transport is essentially independent of the width of the sample. It always occurs when the total conductance $G\simeq e^2/h$. This is also illustrated in a scaled representation of the fluctuations with respect to the average conductance $\langle lng\rangle$ in the inset of Fig. 2: Independent of geometry the log-normal fluctuations of lng disappear when $\langle lng\rangle\geqslant 0$.

The explanation of this striking result lies in the very broad distribution of conductances in the dielectric regime. Theories of log-normal distributions of conductances[12] indicate that an anomalously large conductance, a rare event, dominates the total conductance. This is only valid at very low temperature, when parallel thermally activated conducting channels are exponentially small. According to the scaling theory of localization, at the metal-insulator transition, this event is the last conducting channel with conductance $G\simeq e^2/h$.[13] In samples consisting of many squares in parallel and since the conductance distribution is log-normal, this last conducting channel carries almost the total current.

Deep in the insulating regime, we find that the conductance fluctuations obey roughly: $var(lng)\simeq -0.55\langle lng\rangle$, independent of geometry for widths up to $W=4$ μm (Ref. 14) (see Fig. 2). Here $var(lng)=\langle[lng-\langle lng\rangle]^2\rangle_{V_g}$ is the variance of the average conductance $\langle lng\rangle$ where the average is taken over V_g. The proportionality between the variance and the mean of lng is expected in disordered insulators at zero temperature and described by non-interacting scaling models.[15] However, since interactions are crucial to explain the details of the fluctuations as shown below, our

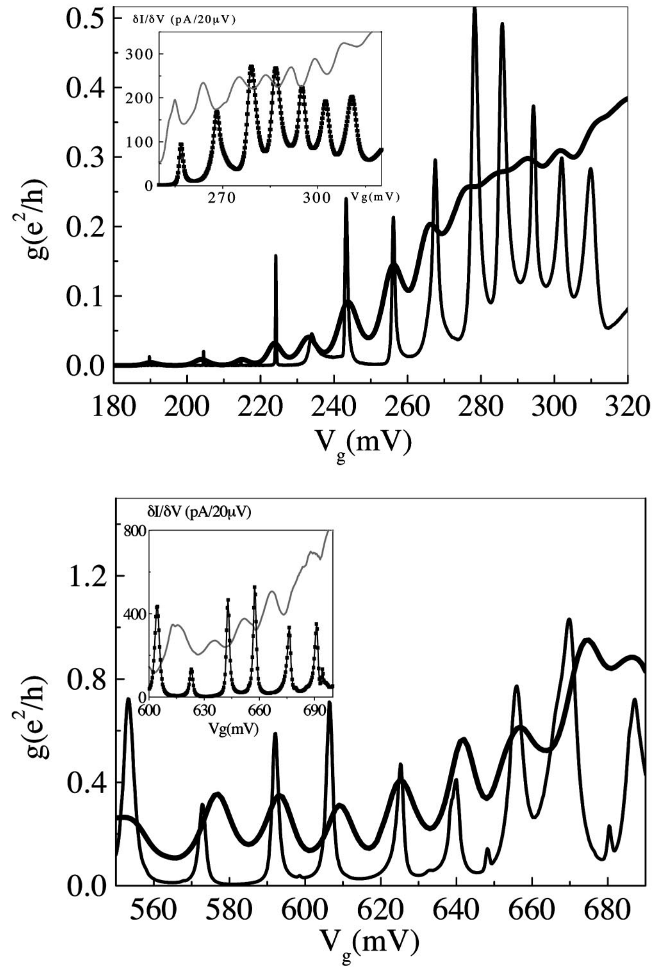

FIG. 3. Periodic oscillations of the conductance versus gate voltage in two different samples (Top: $L=100$ nm, $W=400$ nm. Bottom: $L=50$ nm, $W=1000$ nm). Thick lines are at $T=4.2$ K and thin lines at $T=35$ mK. The oscillations are periodic at $T=4$ K but not strictly periodic at lower temperature. Top inset: differential conductance oscillations for $V_{SD}=0$ and $V_{SD}=-2$ mV in the 100-nm sample at $T=35$ mK. Bottom inset: differential conductance oscillations for $V_{SD}=0$ and $V_{SD}=-3.5$ mV in the 50-nm sample at $T=35$ mK. Note the alternance of conductance maxima, predicted in the classical Coulomb blockade model.

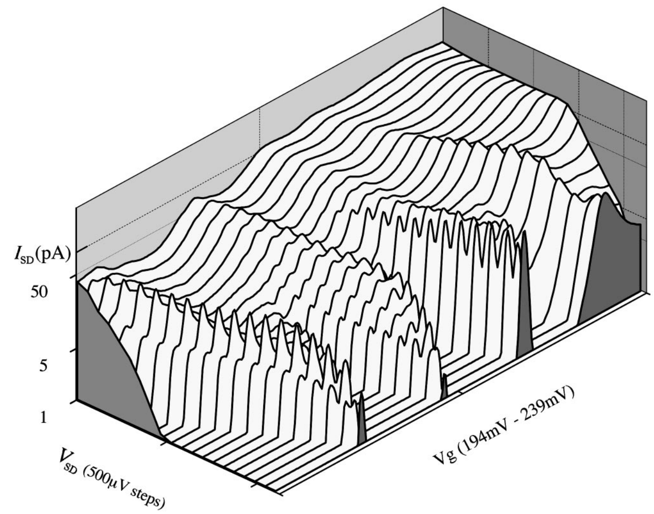

FIG. 4. Source-drain current (ac excitation voltage: 20 μV) versus gate voltage at various dc-bias V_{SD} (0–9.5 mV by steps 0.5 mV) for the sample ($W=0.4$ μm, $L=0.1$ μm) at $T=35$ mK. Several excited states appear at finite V_{SD}.

experiment suggests that the relation $var(lng)-\langle lng\rangle$ is more general and not affected by electron interactions.

Figure 3 shows Coulomb oscillations in our shortest samples with gate lengths L of 100 and 50 nm. In both samples each conductance peak at $T=4.2$ K corresponds to one peak at the lowest temperature. No additional peaks appear upon cooling and we only observe small shifts in gate voltage. This is consistent with *single* dot resonances and rules out multiple dot tunnelling as previously reported in quasi-1D wires.[2,16] Actually, several dots acting in parallel explain qualitatively the complicated pattern observed in samples with widths larger than typically $1\,\mu$m. We also note that the oscillations in Fig. 3 are essentially insensitive to thermal cycling.

We first consider the series of resonances at relatively high gate voltage when the dot is filled with several electrons. Taking a simple Coulomb blockade model periodic conductance resonances occur if the temperature is lower than the charging energy $E_C \gg k_B T$. At zero source-drain voltage V_{SD} and V_g such that $C_g V_g = Ne + e/2$ where N is the number of electrons in the dot, charge is transfered; if on the other hand $V_{SD}=e/C$, resonances occur at V_g such that $C_g V_g = Ne$. This is demonstrated in the insets of Fig. 3. We suppose here that the capacitances to source and drain $C_S = C_D = C/2$ are equal. Within this classical model, we find $C=8\times10^{-17}$ F and $C_g=2\times10^{-17}$ F for the 100-nm sample, and $C=4.6\times10^{-17}$ F and $C_g=1\times10^{-17}$ F for the 50-nm sample. The charging energy is $e^2/C \simeq 2$ meV and 3.5 meV, respectively, for the 100-nm and the 50-nm samples. In the simplest model, $\alpha=\delta E_F/e\,\delta V_g = C_g/(C_g+C)\simeq 0.2$, in agreement with the value deduced from the temperature dependence of the resonances (see inset of Fig. 1).

With decreasing number of electrons on the dot, the mean level spacing Δ increases and the barrier resistance between source and drain and the impurity quantum dot increases. If the temperature is below the mean level spacing we can estimate Δ by the $I_{SD}-V_{SD}$ nonlinearities revealing the excited states of the dot. In our samples this is shown in Fig. 4. Upon rising V_{SD}, the differential conductance $\delta I_{SD}/\delta V_{SD}$ exhibits a peak each time an excited state E_i enters or exits the energy window $\mu_S + \alpha e V_g > E_i > \alpha e V_g + \mu_D$. Up to three excited states (six peaks in $\delta I_{SD}/\delta V_{SD}$) are distinguishable for resonances at low gate voltage for $V_{SD} \simeq 3$ meV, such that $\Delta \simeq 1$ meV. At higher gate voltage Δ becomes smaller and the contrast between excited states is washed out (classical Coulomb blockade regime). Since Δ is smaller but non-negligible compared to E_C, the periodicity of the Coulomb oscillations is not strictly obeyed.

The values for the mean spacing and charging energy are typical for all the measured samples. $\Delta \simeq 1$ meV corresponds to what is expected for single electron levels in a 2D box of 65×65 nm taking into account the reduced density of states in the Lifshitz tail. Alternatively it corresponds also to a parabolic potential confinement of radius 50 nm, comparable to the source-drain distance, and height 10 meV, comparable to the Fermi energy at the MIT. The capacitance to gate $C_g = 2\times10^{-17}$ F ($L=100$ nm) (respectively, $C_g = 1\times10^{-17}$ F for $L=50$ nm) corresponds to a 2D dot of size 45×45 nm (respectively 25×25 nm).

A main feature of our samples is the very thin gate oxide which makes the gate very efficient to screen the Coulomb interaction in the IQD. For instance, a simple estimation of the repulsion between two *bare* electrons at a mean distance of $r=20$ nm in the channel gives $V=(1/4\pi\epsilon_0)2\epsilon_{Si}(d^2/\epsilon^2_{SiO_2})(e^2/r^3)\simeq 3.9$ meV where $\epsilon_{Si}=11.4$ and $\epsilon_{SiO_2}\simeq 4$ are the relative dielectric constants of Si and SiO_2. Since the oxyde thickness ($d_{SiO_2}=3.8$ nm) is much smaller than the distance between two electrons, the Coulomb interaction is a dipole interaction.

The various above estimations confirm that the sequence of resonances reflects the interaction between electrons sharing the same (barely) localized site whose extension is comparable to the source-drain distance independent of the width of the channel or the dopand concentration. Furthermore, we have demonstrated in this way that in order to observe Coulomb blockade in nanostructures it is not necessary to constrict the current through a quasi-1D segment such as point contacts or wires. The domination of a rare event in a short two-dimensional electron gas (2DEG) intrinsically favors a channel through a single IQD in not too wide geometries. In this way one has a better estimate of the relevant length and energy scales of the dot than in quasi-1D geometries. Also, downscaling the gate length L from 100 to 50 nm increases the Coulomb energy, as expected when the dot size of the charge transmitting IQD decreases with channel length.

In summary, we have studied standard Si MOSFET's of gate length $L=50$ nm and $L=100$ nm and various widths without any intentional confinement. Close to the MIT, characterized by $G\simeq e^2/h$ at low temperature, conductance resonances as a function of the gate voltage are due to tunneling through a single disordered quantum dot, whose extension is comparable to the source-drain distance and which accomodates several electrons. In contrast to many previous studies on quasi-1D wires, our geometry allows us to isolate single dot tunnelling in an impurity potential and quench multiple dot tunnelling. If the transverse dimension is increased too much, several IQD conduct for the same gate voltage ranges, causing eventually a complex structure of conductance resonances. Furthermore, we find that in the dielectric regime the variance of lng systematically scales with the average of lng. Such an observation is consistent with a one-parameter description of the metal-insulator transition. Finally, our results strongly suggest that reducing the channel length even further should imply the observation of Coulomb oscillations with a charging energy comparable to room temperature.

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