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Single-Electron Tunneling in Coupled Nanowire Systems

A.A. TAGER, M. LU, and J.M. XU

Electrical & Computer Engineering Dept., University of Toronto, 10 King's College Rd., Toronto, Ontario, Canada M5S 1A4

M. MOSKOVITS,

Chemistry Dept., University of Toronto, 80 St George St, Toronto, Ont., Canada M5S 1A4

Novel nonlithographic nanowire diode array devices reveal features resembling Coulomb staircase at room temperature. The devices can be thought as 2-D arrays of (vertical) double tunnel junction systems with strong interwire coupling. We investigate effect of such coupling on characteristics of single-electron tunneling (SET) and developed a two-coupled-wire model. Theoretical results show strong spontaneous polarization of the system due to SET. Both the average value and the dispersion of the polarization periodically depend on the applied voltage and decrease with temperature.

1. INTRODUCTION

Single-electron tunneling is a promising physical basis for future nanoscale electronic devices. Room temperature operation of such devices requires however extremely small capacitance tunnel junctions with dimensions near or beyond the limit of the modern and very expensive lithographic techniques. Recently, a new nonlithographic method of making nanowire structures by electrochemical deposition of materials of interest into porous aluminum oxide films has been developed[1)-4)]. The method allows us to make nanowires with diameter down to 10 nm or even less[3)], and packing density about 10^{12} $1/cm^2$. These nanowire templates, when sandwiched in-between metal/oxide layers, form 2D-arrays of double-junction systems with common "source" and "drain" contacts[4)], which at room temperature exhibited very complex behavior including both periodic and anomalous conductance oscillations and staircase I-V characteristics. The last ones strongly resembled the Coulomb staircase as predicted by the standard theory of single-electron tunneling (SET)[5),6)]. Simple estimation of junction capacitances for real arrays gives values in the order of 10^{-19} to 10^{-18} F[4)] that seems to support this explanation. These arrays however are essentially different from those considered previously[6)], where the tunneling occurs sequentially in the plane of the array of islands connected in matrix, and coupling capacitances are of the order of the junction capacitances. Adequate description of the novel system requires taking into account very strong electrostatic coupling between nanowires due to small interwire spacing (20...50 nm) as compared to the wire length (>1 μm typically).

2. MODEL

As a first approach to a good understanding, we investigated possible effects of interwire coupling on the single-electron tunneling in coupled double-junction systems on the basis of a two-wire model (Fig.1).

We analytically calculated the Fermy energy shifts due to wire charging by tunneling electrons, which govern the tunneling probabilities according to the "global rule" for SET[7)], and then performed Monte-Carlo simulations of the electron transport through the system assuming a low-impedance environment.

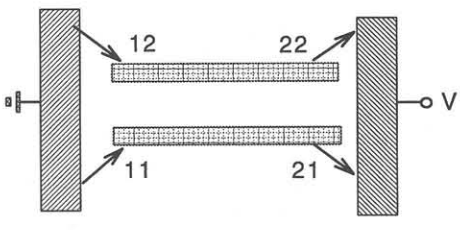

Fig. 1. Two-wire double-junction system. Arrows show the prevailing directions of tunneling for V>0.

Typical numerical values used in modeling were: junction capacitances $C_{ij} = (1.6 \pm .2) \cdot 10^{-19}$ F, coupling capacitance $C_0 = (0 \text{ to } 200) \cdot C_{ij}$, junction resistances $R_{11} = R_{12} = 50\text{k}\Omega$ (source), $R_{21} = 200 \cdot R_{11}$ and $R_{22} = (1 \text{ to } 100) \cdot R_{21}$ (drain). We thus consider the case of strong drain-source asymmetry, which is known to give a well-defined Coulomb staircase on the I-V characteristics of a single double-junction system. Conductance between wires was assumed to be zero.

3. RESULTS

Analysis shows that each tunneling event probes 1) the whole array as a single double-junction system with its junction capacitances equal to the total drain/source capacitances and charged with the total charge $eN = e(N_1 + N_2)$, and 2) the particular wire on (from) which the tunneling is actually happening. Relative contribution of the terms is governed by the ratio of junction and coupling capacitances, and the system behaves very differently for a weak and strong wire coupling. If the coupling is small ($C_0 << C_{1,2}$), an electron tunneling on a particular wire does not "feel" the presence of the other wire, and all tunneling events for both wires sum up independently, as do the currents. In this case the Coulomb repulsion at low temperatures keeps the numbers of excess electrons $N_{1,2}$ on each wire almost fixed for a given voltage

In the opposite and more interesting and relevant case of very strong coupling ($C_0 >> C_{ij}$) the whole array seems to respond as a single double-junction system wherever the electron actually tunnels, since the relative contribution of the particular wire charge is proportional to a small ratio C_{ij}/C_0. The apparent consequence is the reduction of the Coulomb-blockade region since it is determined now by the total source capacitance $C_{sr} = \sum C_{1j}$.

Strong coupling also leads to *spontaneous polarization* of neighboring wires, when an accumulation of excessive electrons on one wire is partly compensated by the hole accumulation on another one, yielding very low-energetic "excitonic excitation" of the system. The polarization is conveniently described by the charge difference $P = N_2 - N_1$ (in units of electron charge e). It can considerably exceed the total charge $N = N_1 + N_2$ on both wires, which at low enough temperature remains rather strictly determined by the applied voltage.

Computer simulations show that for identical wires this spontaneous polarization stochastically oscillates in time, with zero time average $\langle P \rangle$ and dispersion $D_P = \sqrt{\langle (\Delta P)^2 \rangle}$ which increases with increasing coupling. The polarization becomes however quite regular in the case of *asymmetrical wires*, when either the source or drain junction resistances R_{ij} differ for different wires. If e.g. the second wire drain junction resistance is larger than that of the first wire, electrons will leave the first wire faster yielding thus a positive charge ("holes") accumulation on this wire and electron accumulation on the "slower" wire. Fig.2 shows

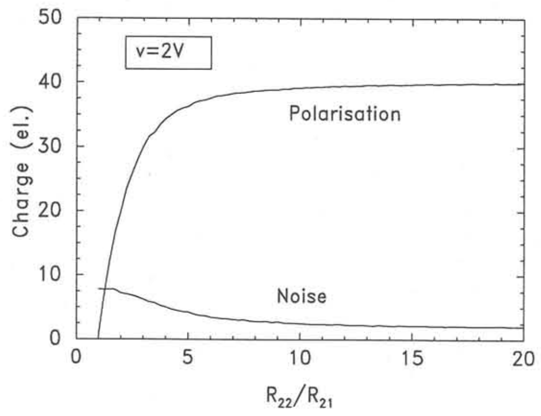

Fig. 2. Average polarization and polarization dispersion vs. drain resistance asymmetry; $C_0/C_{ij} \cong 100$, T=0.

that $\langle P \rangle$ rapidly increases with increasing wire asymmetry, with a maximum saturation level in the order of $C_0/(C_{11}+C_{21})$ (determined by the "faster" wire).

The saturation level however depends on the voltage, since the wire charges, $\langle P \rangle$ and D_P periodically oscillate with increasing voltage (Fig.3). They reach local minimums every time when the maximum total charge number on both wires N increases by one (yielding steps on the N-V and I-V curves). For these critical voltages the energy shift associated with a tunneling event reduces to almost zero, and the Coulomb blockade ceases to exist. The average wire charges are then determined approximately by the Kirhhoff's lows and almost independent on the system temperature.

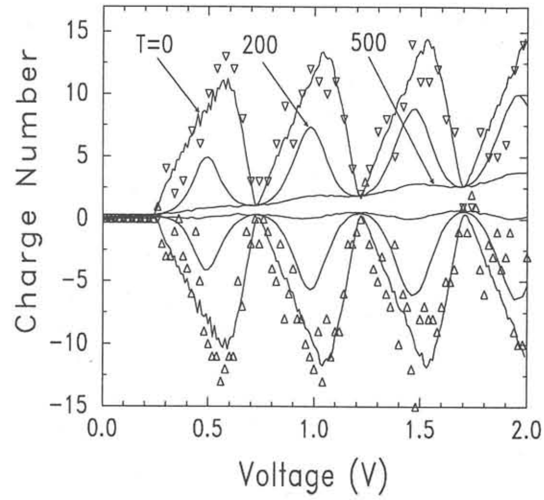

Fig. 3. Average wire charges $\langle N_j \rangle$ vs. voltage at three different temperatures. Top 3 curves represent the upper (slower) wire, other 3 - the faster one. "Δ" and "∇" show the "faster" and "slower" wire charges at a particular time instant for T=0 K

The strong system polarization in-between these critical voltages is the consequence of the Coulomb blockade effect and the single electron tunneling. It does not exist for high temperatures when $kT \geq e^2/2C_j$ and the thermal fluctuations control the charge statistics. For higher temperatures the average wire charges approach the Kirhhoff's values for all voltages and vary almost linearly with the voltage (500K- curves on Fig.3).

For lower temperatures the polarization statistics is governed instead by the shot noise in combination with the Coulomb-blockade effect, which suppresses the fluctuations of the total charge on both wires but increases the anticorrelated fluctuations of the individual wire charges. This behavior is illustrated on Fig.4 which shows how $\langle P \rangle$ and D_P depend on temperature for two different voltages: one that correspond to a local $\langle P \rangle$ minimum (the top graph) and another that gives a peak value of $\langle P \rangle$ for low temperature (the lower graph). In the first case the almost constant average polarization is accompanied by the increasing noise as temperature increases.

On the contrary, not only the average polarization, but also *the polarization noise* decrease at first as the temperature rises, and only at higher temperatures the polarization noise start rising again due to the thermal contribution and eventually gets on the same level as in the

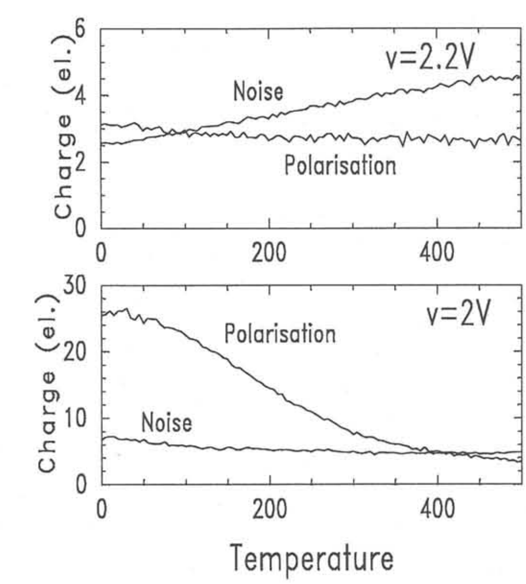

Fig. 4. Average polarization and polarization noise vs. temperature for different voltages.

first case.

This anomalous temperature dependence of the polarization fluctuations is even more evident if the noise spectral characteristics are considered (Fig.5). Our calculations have shown that the spectral bandwidth of the SET-induced polarization noise is much smaller than that of the pure shot noise and increases with temperature. As the

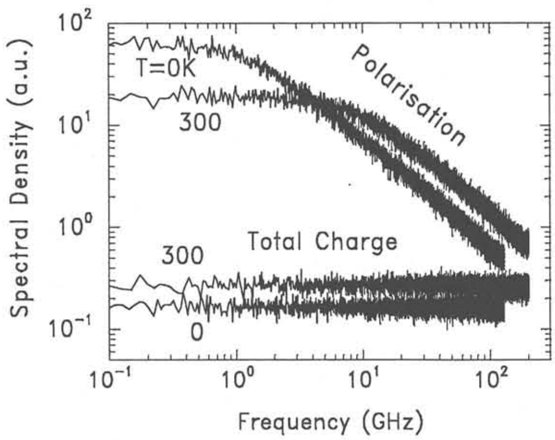

Fig. 5. Spectral density of fluctuations for the wire charge polarization and the total wire charge at two temperatures.

result, the low-frequency polarization noise decreases much faster than the polarization dispersion as the temperature is increasing - in our case by a factor of 3 when the temperature increases from 0 K to 300 K.

Similarly, relatively low fluctuation bandwidth of the SET-induced polarization noise makes the difference between the noise intensity of the total charge number N and that of the charge polarization P much more striking - at low frequencies $\langle \Delta P^2 \rangle(\omega)$ exceeds $\langle \Delta N^2 \rangle(\omega)$ by more than 3 order of magnitude.

4. SUMMARY

We theoretically investigated possible effects of strong interwire coupling for a two-coupled-wire double-junction system, which is a building block of novel devices based on 2D-arrays of vertical nonlithographic nanowires. Under the conditions of the SET, the coupling leads to strong interwire polarization of charges, which oscillates both in time and as function of the applied voltage. Anomalous temperature dependence of the large polarization noise associated with this SET-induced effect has been found.

In the much more complex case of multi-wire systems and nanowire arrays, this SET-induced spontaneous self-polarization may lead to a number of (quasi)static and dynamic phenomena. Among others, the prospect of "phase transition" between random polarization and ordering with changing of system parameters or an applied field, and the possibility of the self-sustained "polarization waves" are under consideration.

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