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SINGLE-ELECTRONICS

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Final Technical Report

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1. Summary

During the past decade, a new exciting field of physical and applied electronics has emerged. Its most common nickname is Single-Electronics. The physics of this field (for general reviews, see Refs. 1-3) is based on the effects of correlated single-electron tunneling. Their essence is that transfer of single electrons in systems of conducting (metallic, semiconductor, or molecular) "electrodes", connected by tunnel barriers of very small area, may be strongly correlated either in time, or in space, or both.

Since 1987, reliable evidence of correlated tunneling has been obtained in numerous experiments with normal-metal, superconductor, and semiconductor junctions and systems (for a recent collection of reviews, see Ref. 3). These experiments have shown, in particular, that the "orthodox" theory of correlated tunneling [2] gives a quantitatively correct description of the experimental data for systems in which each conducting "electrode" contains many free electrons. As a consequence, this theory can be used to analyze possible practical applications of correlated single-electron tunneling.

Preliminary studies of this type [1, 4, 5] have shown that single-electronics may yield a completely new generation of both digital and analog devices with unparalleled performance, most notably extremely dense digital circuits with up to 10^{11} active devices (logic gates and/or memory cells) per square centimeter. However, in order to bring single-electronics to practice, numerous problems must be solved.

In 1991, three research groups at SUNY - Stony Brook, headed by Professors Dmitri Averin, Konstantin Likharev and James Lukens, working in collaboration, began an AFOSR-supported project in the field of single-electronics. As a result of this effort, a solid technological, experimental and theoretical base for single-electronics was established at Stony Brook, and several important results have been obtained. Highlights of this work include:

- a reliable laboratory technology of fabrication of Al/AlOx/Al tunnel junctions of area down to ~40x40 nm^2, as well as systems of up to ~10 junctions, has been established;
- the long-lifetime trapping of a single electron (for at least 12 hours) in a specially designed multi-junction circuit has been demonstrated;
- the effects of electron parity in small superconducting samples on their transport properties have been predicted; these predictions have been confirmed in experiments performed by several groups;
- the simultaneous existence of the SET oscillations (with frequency proportional to current) and Bloch oscillations (with frequency proportional to energy change) has been predicted, though not yet observed.

Numerous problems of single-electronics should still be solved before practical introduction of this exciting new technology (some of the unsolved problems will be addressed in our new project with the same title). Nevertheless, we believe that our initial project has been an important step toward practical applications of single-electron devices.

2. Major Results

A. EXPERIMENT

A1. Fabrication Technology. We have established a reliable laboratory technology for fabrication of ultrasmall Al/AlOx/Al tunnel junctions with areas down to 40x40 nm^2, and of small systems of such junctions, including single-electron transistors and one-dimensional arrays. The technology uses angle evaporation of aluminum through suspended nanomasks formed by direct e-beam writing in bilayers of PMMA-type resists [6-8, 32]. This technology has allowed us to fabricate single junctions and single-electron transistors, as well as more complex systems including single-electron memory cells (see below).

A2. Signal and Noise Properties of Single-Electron Transistors. Using the technology described above, we have fabricated single-electron transistors on various configurations and have studied their low-frequency signal and noise properties. We have found the signal properties to be in quantitative agreement with results of the "orthodox" theory of single-electron tunneling, provided that experimental I-V curves of single junctions are used for calculations [6, 32]. On the other hand, the white noise of the transistor predicted by the theory is overshadowed at low frequencies by excess 1/f noise. Nevertheless, at low temperatures, charge resolution close to $10^{-4}/Hz^{1/2}$ at 100 Hz has been achieved, making the transistors suitable for unique experiments with single electrons.

A3. Single-Electron Trapping [7, 8, 32]. Using single-electron transistors as ultrasensitive electrometers, we have succeeded in demonstrating long-lifetime trapping of single electrons in solid-state devices. Such a device consists of a single aluminum thin-film island of area ~180x50 nm^2, connected to an external nanowire by a 1D array of 7 tunnel junctions of area ~ 50x50 nm^2 each. External voltage of a few millivolt applied to the nanowire leads to the injection of an additional electron into the trap through the array; the effective energy barrier (~0.5 meV) created by the array prevents the electron from leaving the trap even after the external voltage pulse is over. The electron can be removed from the cell by further reduction of the voltage. Several devices of this type were tested. At temperatures ~50 mK, single electron trapping for periods of more than 12 hours has been observed. This result is to be compared with previous experiments by Saclay and AT&T groups, where the trap time did not exceed fractions of a second. From a practical point of view, the device presents a prototype of a single-electron memory cell with nondestructive readout. However, before it could be used in practice, several problems must be solved, including eliminating the effects of random drift of the background charge.

A4. Scanning Tunneling Microscopy with New Piezoelectric Engine. For our single-electron microspectroscopy work we would like to have a scanning tunneling microscope (STM) which could operate at helium and millikelvin temperatures without any mechanical links to the ambient temperature environment. (Commercially available low-temperature STMs are not applicable in our experimental conditions). This is why we have designed and implemented a preliminary version of such an STM using a new type of piezoelectric engine for the tip position adjustment [10]. Our engine operated reliably at room temperatures, and was applied to studies of several systems which seemed most promising from the point of view of single-electron tunneling. In particular, we have studied Moire pattern on graphite surfaces, monolayers of stearic acid on graphite, atomically-smooth gold thin films on mica, monolayers of C_{60} buckyballs on atomically-smooth gold surfaces, including modification of these monolayers by extremely thin gold overlayers [10], and metal-doped diamond-like carbon [9]. While some of the studies gave interesting results, we have not yet been able to find sufficiently stable objects which would exhibit correlated single-electron tunneling at room temperature Also, the low-temperature operation of the STM has not been made reliable enough.

B. MODELING AND SIMULATION

B1. Geometrical Modeling. The first step toward automation of layout design of single-electron devices and systems is automated calculation of the mutual capacitance matrix of an arbitrary system of conducting electrodes. We have adjusted the software package FASTCAP (kindly provided by its author, Prof. J. White of MIT) to this task. For that, the package was supplemented by our program Cmat which directly transfers the geometrical information from AutoCAD files (used for controlling our nanofabrication process) into the input files for FASTCAP. The capacitance matrix generated by the latter package is picked up by our simulation programs MOSES and SENECA (see below).

B2. MOSES Simulator. We have completed the first version of a numerical simulator (presently called MOSES, standing for Monte-Carlo Single Electron Simulator) of the single electron dynamics in arbitrary systems of ultrasmall tunnel junctions, capacitances and voltage sources. This program uses equations of the "orthodox" theory of the correlated tunneling, ignoring more rare processes of macroscopic quantum tunneling of charge (q-MQT). We have successfully used the FASTCAP-MOSES package for simulation of our experimental systems, including the single-electron trap described above. Reasonable agreement between results of modeling and experimental data was obtained (deviations range from ~10% to ~30% for various parameters, and are believed to be due to imperfect control of the fabrication processes and random background charges). The simulator has been also used for modeling of gates of C-SET family (see below).

B3. SENECA Program. We are going to have the MOSES package complemented by calculation of q-MQT event rate. At this stage, a stand-alone program SENECA (standing for Single Electron Nano-Electronic Circuit Analyzer) has been developed. The program is based on numerical solving the basic master equation of the system under analysis using an original algorithm for iterative screening of most important charge states. SENECA has already been successfully used for analysis of single-electron traps (see below).

C. THEORY

C1. Single-Electron Transistors. We have calculated [12, 13] white noise in single-electron transistors, taking into account thermal, shot-noise, and quantum effects (but not the excess 1/f noise). The white noise is essentially dependent on the effective capacitance of the signal source, so that this device can be effectively used for ultrasensitive electrometry of compact objects. In this case, the white noise of the device can be as low as $\sim 10^{-5} e/Hz^{1/2}$, some 7 orders of magnitude better than that of commercially available solid-state electrometers. In another work [14] it was shown that a further improvement of the sensitivity is possible if the transistor uses a very small middle electrode with only a few electrons and hence has discrete energy spectrum. In one more work, possible effects of overheating of the single-electron transistors have been estimated [15]; for present-day devices the effects may be important only at very low temperatures (below ~0.1 K). The effect of macroscopic quantum tunneling of charge on the Coulomb staircase oscillations has been analyzed in detail [16].

C2. Single-Electron Transistor Circuits. We have carried a detailed analysis of digital circuits using single-electron transistors [33, 34]. The analysis has shown that a slight modification of the basic principles accepted in C-MOS technology can give a functionally complete family of logic gates using single-electron transistors of a single type, while using similar logic and voltage supply levels. Maximum operation temperature, switching speed, power consumption, reliability, and critical parameter margins of the basic gates of this "C-SET" family have been calculated.

An important drawback of the C-SET logic devices is a relatively high power dissipation. This drawback may be avoided in single-electron logic ("SEL") devices processing digital bits in the form of single electrons. We have suggested [37] a new logic family of this type, which can work without wire connections to the environment (the necessary power and clock information in provided by ac electric field). Unfortunately, parameter margins of these devices are narrow, and we are working on their further modification.

In a separate work, a single-electron transistor with resistive input circuit was considered in view of its possible applications as a multistable element [17]. However, ways of experimental implementation of appropriate resistors for circuits like this one are still to be developed.

C3. Other Single-Electron Devices. We have carried out extensive calculations of the macroscopic quantum tunneling of charge in various structures which may be used as fundamental standards of dc current, including multi-junction single-electron "turnstile" and "pump" [18]. The results show that using existing fabrication technology, q-MQT processes allow the implementation of standards with accuracy certainly much higher than the figure ~1 ppm demonstrated recently by the NIST-Boulder group.

Most single-electron devices are based on one-dimensional arrays of conducting islands separated by small tunnel junctions. Using the geometrical modeling and a simple analytical model, we have shown that electron-electron interactions in such arrays is substantially different from the approximation which had been universally accepted in previous works. A new simple but adequate analytical expression for the interaction has been suggested [36].

In another work [19], photoresponse and photosensitivity of several single-electron systems has been analyzed. Some of the predictions have been confirmed in a recent work by the Berkeley group.

C4. Electron Parity Effects. We have predicted [20] that single-electron tunneling to/from small superconducting particles can depend on the parity of the total number of electrons in the particle, because adding one more electron to an even number of electrons forming the superconducting condensate requires an additional energy contribution equal to $\Delta(T)$. This theoretical work has triggered a burst of experiments, and reliable evidence of the predicted parity effects was obtained in Harvard, NIST-Boulder, and Saclay.

C5. Domain Quantization and Combined SET/Bloch Oscillations in "Slim" Superlattices. We have shown [21] that single-electron quantization of charge of high-field domain walls in semiconductor superlattices can lead to a noticeable periodic structure in their dc I-V curves. This effect should be observable in structures with cross-section about $1\mu m^2$ (or less) at temperatures about 1 K (or lower). Using the same model, we have examined the relationship between single-electron-tunneling (SET) oscillation with frequency $f_S=I/e$, and so-called Bloch oscillations with frequency $f_B=\Delta E/h$ (where ΔE is the change of the system energy due to a single tunneling effect). Surprisingly enough, we have found that these two types of fundamental oscillations may exist simultaneously [22]. We believe that this result is of general physical importance, because it gives an example of coexistence of particle behavior of electrons (SET oscillations) with their quantum behavior (Bloch oscillations), in a single experiment with the same system, without any violation of Heisenberg's uncertainty relation.

C6. Control of Single Electrons on Atomic Level. Another important result was a constructive proof [23] that the Coulomb interaction in principle allows logic functions in atomic structures to be performed with high reliability (e.g. error rate below 10-20 in 1D structures of ~50 atomic sites) even in the absence of inelastic interactions of electrons with the environment. Though practical implementation of such a system would certainly require a large-scale multi-disciplinary effort, the very possibility of extending the general ideas of Single-Electron Logic to atomic structures seems very important conceptually.

C7. Single Electron Dynamics in One-Dimensional Ballistic Channels. We have analyzed [24] the dynamics of single electrons in very narrow and shallow but uniform one-dimensional channels, and have shown that if the channel is uniform enough the electrons may exhibit considerable correlation of motion despite the fact that no tunneling takes place in the system. In particular, a finite dc current I should lead to fundamental "SET" oscillations with frequency f=I/e. In separate works [25, 26] we have considered a similar channel, but with substantial ingomogeneities creating energy barriers for the electron motion, and have calculated the dc I-V curves of the channels for this case.

We have also published several review papers on various aspects of single-electronics [28-31].

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