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Field effect in thin granulated metal films

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Abstract. In this work we analyze the field effect in granulated metal films and propose the current-switching device utilizing this effect. It is shown as a result of numerical modeling that efficient current modulation can be achieved in thin granulated films if the charging energy of metallic granules is at least several times higher than the thermal energy kT .

1. Introduction

Last time considerable effort has been made to develop single-electron transistor (SET) in which the current path between source and drain is controlled by the charge state of the central metallic island having extremely low capacity. Due to Coulomb blockade the current through SET can be modulated by the gate electrode potential. Successful operation of SET made by conventional technique is possible at temperatures below 1 K because of limitations of lithography resolution [1]. The extension of operating temperature range requires the implementation of sophisticated technologies [2] based on manipulation with ultra-small metallic granules. These particles are fabricated by nanoparticle source, selected and then placed precisely in the source-drain gap. However in this approach the parameters of SET are critically dependent on island size and position which can hardly be controlled with desired accuracy.

The proposed way to avoid this critical dependence is to use the structures containing large number of metallic granules statistically distributed in the gap. In this case the characteristics of inter-granular tunnel junctions are averaged over the volume and, under certain conditions, the performance of the whole system is independent on individual grain positions. The current in such granulated film can still be controlled by external electric field due to modulation of charge distribution. In this work we consider the possibility of efficient current modulation in thin granulated films incorporated in the gap of current switch device shown schematically in Fig. 1. This consideration is based on the newly developed Monte-Carlo model of granulated film conductivity.

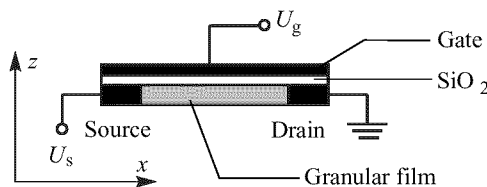


Fig. 1. Schematic diagram of current switching device.

2. Monte-Carlo model

In the model the granulated film is represented by the set of metallic balls randomly distributed in the given volume. At each step the system state is characterized by the electric charge of each ball expressed in terms of unit charge. For a given state the probabilities of electron tunneling from one ball to another are calculated taking into account the Coulomb

interaction of charged balls and the presence of the external electric field. One tunneling event is realized according to its relative probability by means of Monte-Carlo technique and this procedure is repeated many times. The macroscopic electric current could be calculated as time averaged number of electron hops across the selected cross-section. Since the number of granules involved in calculations was limited (to about 250 balls), the results were also averaged over different realizations to avoid the mesoscopic current fluctuations originating from the randomness of granules distribution.

This model has been tested by calculating the I–V curves and temperature dependencies of granular films conductivity and comparing the results with experimental data obtained on composite Cu:SiO₂ films [3].

3. Discussion

Simulating the behavior of the structure shown in Fig. 1 the potential distribution was first calculated by solving the 2-dimensional Poisson equation with given potentials at the electrodes. Then the obtained solution was used as an external potential in calculation of source-drain current according to the procedure described above. In calculations the parameters of granulated film were taken similar to those of composite Cu:SiO₂ films studied in our previous works [4]: granules diameter is 3 nm, the volume fraction of metal is 25% and the dielectric constant of the media is equal to 4. The thickness of SiO₂ layer isolating the gate from the film was taken to be 5 nm and the distance between source and drain — 30 nm.

It was found that the main effect of the gate is the generation of the excess charges at the granules adjacent to the gate if the gate potential is about or higher than the single-electron charging energy of granules (which is about 50 meV with regard to screening effects). Figure 2 shows the average charge distribution in 12 nm thick film simulated at gate voltage +1 V. As it seen from the figure, the field penetration depth, i.e. the area where the averaged charge density deviates from zero, is rather small (about 2–3 nm). In the rest part of the film the concentrations of negative and positive charges are controlled by the temperature and are equal to each other. This is the layer carrying excess charge which is responsible for the conductivity modulation, while the conductivity of the rest

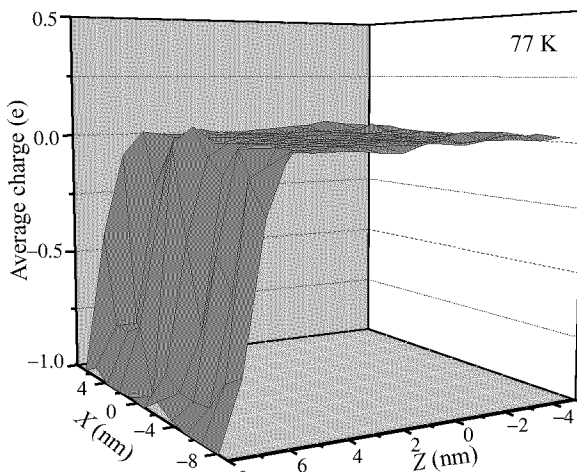


Fig. 2. Charge distribution in 12 nm thick granulated film under gate voltage +1 V ($z = 8$ nm is the film top interface).

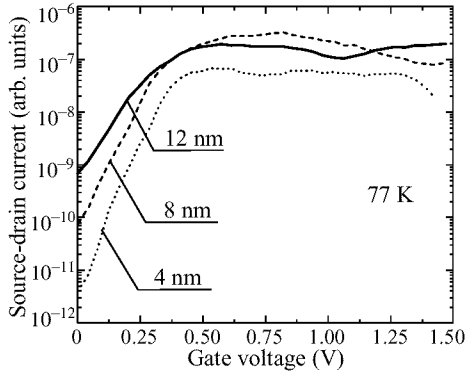


Fig. 3. Modulation characteristics for granulated films having different thickness.

$U_{\text{source-drain}} = 0.014$ V.

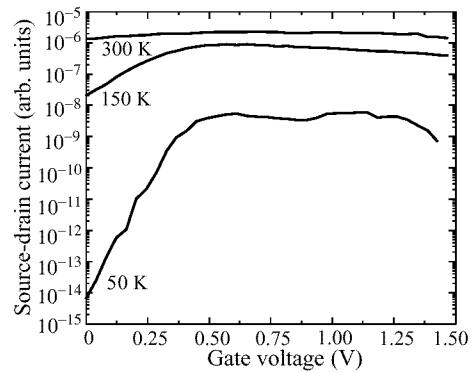


Fig. 4. Modulation characteristics for 4 nm thick granulated films at different temperatures.

$U_{\text{source-drain}} = 0.01$ V.

part is unaffected by gate potential. This means that the efficiency of current modulation is highest in case of extremely thin films. This is illustrated in Fig. 3, where the modulation characteristics are shown for films having different thickness.

The other important parameter influencing the efficiency of current modulation is the temperature. The higher the temperature is, the more charges exist in the film in the absence of gate potential and the higher is initial conductivity. At the same time the upper limit of conductivity (reached at high gate voltage) is roughly defined by the granules concentration and does not depend on temperature. The dependence of modulation characteristics on temperature is shown in Fig. 4. This dependence manifests that the efficient modulation can be achieved if the charging energy of granules is at least several times higher than the thermal energy kT .

4. Summary

We have proposed the field-effect current switching device based on granulated metal film. The origin of current modulation is shown to be the charge generation in thin layer adjacent to the gate. The dependencies of the current modulation depth on film thickness and temperature were analyzed. The current modulation depth may amount to as much as four orders of magnitude at 77 K in the 5 nm thick films with charging energy of granules about 50 meV. The route to increase the operation temperature is to find the granulated structures in which the charging energy is higher. One of the promising candidates could be the structures recently fabricated by laser ablation technique [6].

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