Electron Transport Properties of Composite Ferroelectrics

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In the past years, composite materials, consisting of conductive grains embedded into some insulating matrix, have attracted continuously increasing attention due to the possibility to combine different, and sometimes competing physical phenomena in a single material and observe new fundamental effects[1,2]. The possible range of observable behaviors is very broad and the following examples are by no means exhaustive: granular metals can show the insulator-superconductor transition[3] due to an interplay of superconductivity and Coulomb blockade, giant magnetoresistance effects appear in granular ferromagnets[4] because of the spin dependent tunneling of current carriers between grains, or the combination of ferroelectric and ferromagnetic materials allows to produce a strain mediated magnetoelectric coupling[5].

We investigated theoretically electron transport in granular ferroelectrics (GFE) consisting of metallic nano grains embedded into a ferroelectric matrix and show that depending on the external electric field and temperature three transport regimes are possible: 1) multiple electron cotunneling, 2) sequential tunneling, and 3) metallic transport[6,7,8]. We showed that the crossover between different regimes can be studied by changing the temperature or the external electric field leading to a strongly non-linear conductivity behavior and large conductivity jumps. The microscopic reason for the crossover between different regimes is the changing of the Coulomb gap due to the variation of dielectric permittivity of the ferroelectric (FE) matrix under the influence of temperature or electric field.

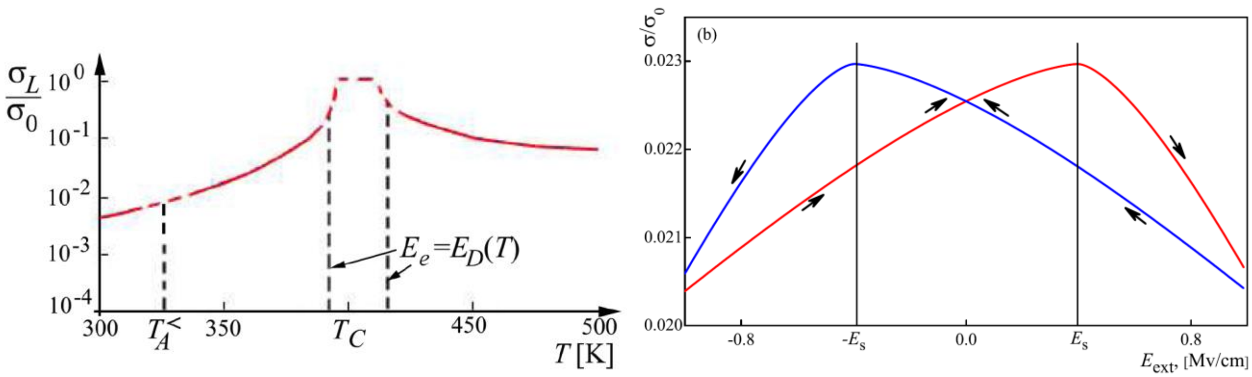
For temperatures approaching the paraelectric-ferroelectric transition point the dielectric permittivity of the FE matrix increases leading to a decrease of the Coulomb gap. This leads to occurrence of insulator-metal transition for temperatures close to the ferroelectric Curie temperature and weak applied electric fields (see Fig. 1(a)). The conductivity of GFE increases three orders of magnitude in a rather narrow temperature range. This is an unexpected result because usually conductivity decreases in the vicinity of a phase transition due to scattering of electrons on fluctuations of the order parameter. This behavior can be utilized to built a GFE thermometer for precise temperature measurements. It is worth to mention that this non-trivial behavior is a peculiarity of granular ferroelectrics and cannot be observed in the tunnel junctions with ferroelectric barrier.

Another peculiarity of electron transport in composite ferroelectrics occurs due to the hysteretic behavior of the ferroelectric matrix. The hysteresis leads to the existence of two different intermediate states with different average electrical polarization and correlation function of microscopic electric field and microscopic polarization. The conductivities in these states can be several order of magnitude different. This occurs since the two states of FE matrix corresponds to different transport regimes of the whole GFE, namely insulating and metal. The effect can be utilized in memory applications. It provides the reading mechanism based on the current measurement.

We calculated conductivity of granular metal film placed above FE substrate (see Fig. 1(b)). FE substrate state strongly influences the conductivity of granular film. The state of FE substrate can be controlled with a gate electrode placed below FE substrate. Due to above mentioned effect conductivity shows hysteresis behavior.

We showed that our theory is in qualitative agreement with recent experiments on transport properties of granular ferroelectrics.

In addition, we show that the main parameters determining the transport in composite ferroelectrics are: 1) the correlation function of intrinsic microscopic field and the local electric polarization and 2) the dielectric permittivity of the ferroelectric matrix.



(a) (b)

Figure 1. (a) Conductivity as a function of temperature for granular FE in which metal grains embedded into FE matrix. T_C is the FE Curie temperature. (b) Conductivity as a function of gate voltage for a field effect transistor with FE placed in between the channel and a gate electrode. Channel is made of granular metal film. E_s is the FE switching field.

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