First-order metal-insulator transition induced by electric field: physics and applications

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First-order metal-insulator phase transitions (MIT) in thin films can be controlled by an applied electric field. The effect can be employed for the implementation of useful devices, such as a three-terminal ultra-fast switch. Unlike field-effect transistors, the speed of such a switch is not limited by carrier drift time under the gate. Two field-controlled phase transition switches can be arranged in a CMOS-like inverter circuit in which no significant current flows in either of its steady states.

We shall discuss the basic physics of the field-induced transition and make estimates of the expected magnitude of the effect in the instance of vanadium oxides. Being able to combine with oxygen in 2-, 3-, 4-, and 5-valent states, vanadium forms a long series of oxides of which at least 8 exhibit MIT. Phase transition in V_2O_3 occurs at T_{cr} = 150 K and in VO_2 at T_{cr} = 340 K (with the electrical conductivity changing by up to 10 and 5 orders of magnitude, respectively). The MIT in vanadium oxides is also accompanied by a discontinuous variation of other than electrical properties, such as optical, magnetic, etc. Vanadium dioxide, VO_2, is of particular interest for technology because its transition occurs near room temperature and furthermore its T_{cr} is tunable over a wide range by doping with impurities such as tungsten.

One of the origins of the electric field influence on the metal-insulator phase transition may be connected with the difference between the electric field energy in the metal and in the insulator, a difference that manifests itself in the expulsion of the field from the metal. The metal-insulator transition alters the spatial distribution of electrostatic field and therefore alters the part of the free energy of the system associated with this field. This effect is very transparent thermodynamically, although its microscopic picture may be not so clear. Using the specific heat data to estimate the electrostatic effect on the transition temperature we find that the effect may be sufficiently significant to offer an efficient control of the transition. The basic symmetry of the electrostatic effect, namely the invariance of the field energy $F^2/8\pi$ under the change of the field direction, may offer special opportunities for logic applications. In particular, it offers the possibility of implementing non-dissipating circuits in which a significant current is flowing only during the switching process.

In a 3-terminal MIT switch, the switching time is *not* limited by the propagation of electrons from the source to the drain, as it is the case for a field-effect transistor. Indeed, the FET transit time limitation arises from the fact that the entire channel charge variation is induced by the field effect, which implies that the input circuit must place on the gate a charge of opposite polarity of at least the same magnitude. In contrast, the surface density of charge carriers released in a dielectric film upon a field induced MIT can exceed the gate charge density by orders of magnitude. Hence the switching delay is only limited by the phase transition kinetics. Kinetics of the inhomogeneous transition is not well understood theoretically at this time. It appears reasonable, however, that the phase boundary should propagate at a rate determined by the Fermi velocity of electrons in the metallic phase.