A Field-Effect-Transistor from Graphite: No Effect of Low Gate Fields

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Received: date / Revised version: date

Abstract. Inspired by the striking similarities between the metal-insulator transitions in graphite and Si-MOSFET’s and the recent attention to charge doping in carbon-based materials, we have made attempts to fabricate a field-effect transistor based on graphite. A relatively thick layer of boron nitride turned out to be able to serve as a gate dielectric. This, however, limits the achievable electric gate field, which might be the reason for our observation of no charge-doping effect.

PACS. 71.27.+a Strongly correlated electron systems; heavy fermions — 71.30.+h Metal-insulator transitions and other electronic transitions — 73.40.Rw Metal-insulator-metal structures

The striking similarities between Si-MOSFET’s and highly ordered graphite have been pointed out in a number of recent publications [1,2,3,4]. Namely, the essentially two-dimensional character of the electron system and the basically equal charge carrier density manifest themselves in metal-insulator transitions in both systems with remarkable similar properties. The main difference remains that the transition in Si-MOSFET’s can be driven by the charge carrier density, which is tuned through charge doping in the field-effect transistor configuration [5], while in graphite the transition is driven only by a magnetic field applied perpendicular to the graphite layers [3]. In Si-MOSFET’s, however, it has been demonstrated that a parallel field can drive the transition [5].

Recent reports on charge-doping effects in carbon-based materials [7,8] have attracted great attention but so far any attempts to reproduce the results failed (see e.g. [9]), supporting the revelation that a major part of those results was pure invention [10]. Nevertheless it has been pointed out, that it’s not unlikely to observe such effects and some ways have been proposed [11].

Clearly, it is desirable to fabricate a field-effect transistor based on graphite, like any research that is potentially able to deepen the similarities between graphite and Si-MOSFET’s and thus shed light on both of the systems. In this letter we report on our attempts to do so.

Our sample is highly oriented pyrolytic graphite (HOPG) produced by the research institute "Graphite" in Moscow with dimensions $4.7 \times 2.6 \times 0.72$ mm$^3$. X-ray diffraction measurements give the crystal lattice parameters $a = 2.48$ Å and $c = 6.71$ Å, the density is $2.26$ g · cm$^{-3}$. The high degree of orientation of the crystallites’ hexagonal c-axes was confirmed by X-ray rocking curve FWHM of 0.6°. Consequently, the anisotropy of the resistivity is large with a ratio of the resistivities measured along and normal to the c-axis of $5 \times 10^3$ at room temperature.

On top of the surface normal to the c-axis of the graphite lattice four line contacts were made by sputtering of gold through a shadow mask with a thickness of 200 nm (see Fig. 1). They were used to determine the resistance of the sample in a four-point DC-measurement. The current has been inverted for each point and the average of the resulting two voltages has been taken to exclude thermo-electrical effects.

Fig. 1. Scheme of the experimental setup. The vertical dimensions in the enlarged frame are not to scale.
from a mechanical and electrical point of view. A solution of BN [12] received in a spray can was sprayed between the two center gold contacts through a shadow mask and then covered by silver paint as the gate electrode, because the dielectric does not withstand the process of gold sputtering. A tunable gate voltage $U$ between -100 V and +100 V was applied between this electrode and the negative current electrode (positive voltage corresponds to the negative pole connected to the negative current electrode, see Fig. 1). Additionally, we have applied magnetic fields normal to the sample surface.

As the BN-layer is mechanically soft, the standard methods for determining the thickness fail. Therefore we estimated the thickness by weighting the sample before and after the deposition of the layer. The resulting thickness is $d = (20 \pm 10) \mu m$. In the case of Si-MOSFET’s the dielectric layer is thinner by a factor of about 100, allowing the change of the charge carrier density within a factor of 2 or more [13].

Assuming a charge carrier density in graphite of $2 \times 10^{18} cm^{-3}$ [14] and with the spacing of the graphite layers $c/2 = 3.36 \times 10^{-8} cm$ one gets the carrier density of a single layer $n = 6.72 \times 10^{10} cm^{-2}$. In contrast, the effect of the gate field can be estimated by $\Delta n \approx \epsilon_0 U/d = 2.8 \times 10^{10} cm^{-2}$ at the maximum $U$. Taking into account that probably more than one layer is active, the carrier density changes by a factor below 0.4. Therefore the expected effect is very small, if at all observable by our means.

The dependence of the resistance on the gate voltage for two different currents at different magnetic fields and at a temperature of 2 K is shown in Fig. 2. Obviously there is no visible effect of the gate field for none of the currents. However, in the case of low current it could be masked by the large scattering of the data.

In Fig. 3 we present the temperature dependence of the resistance at different magnetic fields. The metal-insulator transition is clearly seen. The resistance remains independent on the gate field in all regimes.

By the arguments given above, the absence of an effect of the gate field does not imply that there is none. It is highly desirable to increase the range for changing the charge carrier density. A favorable way to do so is the fabrication of a thinner insulating layer serving as the gate dielectric in a field-effect transistor configuration based on graphite. This remains a challenge for the future.

We thank Y. Kopelevich for fruitful discussions and H. Hochmuth for technical support. This work is supported by the Deutsche Forschungsgemeinschaft under DFG ES 86/6-3.

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