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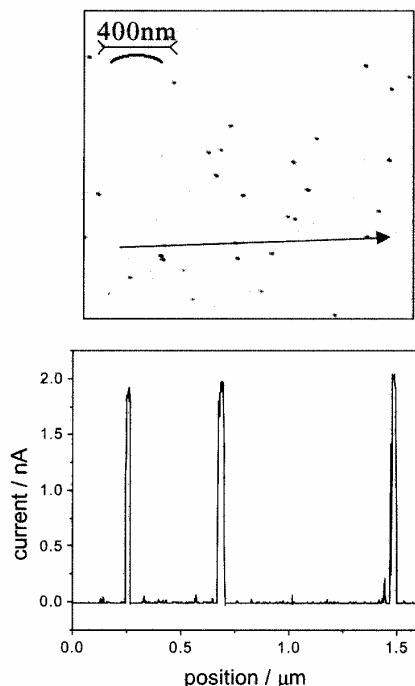


Fig. 3. (Top) SFM current mapping of an ion-irradiated DLC layer using a conducting PtIr tip. The image was recorded simultaneously with the topographic image in Fig. 2. (Bottom) Line scan through three conducting tracks.

hydrogen content. Good conducting tracks require hydrogen contents below a few percent, probably because hydrogen inhibits the formation of graphitic sp^2 bonding.

Fig. 4 shows the current–voltage curve of a well-

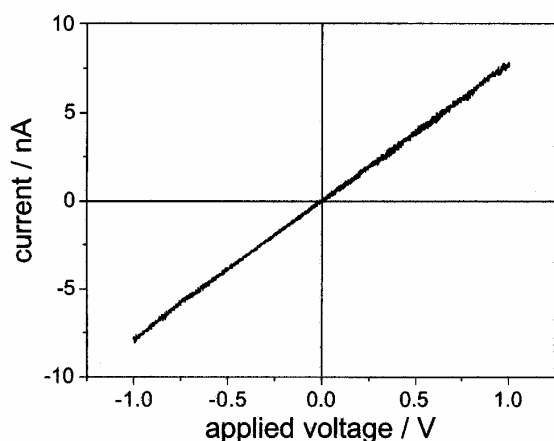


Fig. 4. Current–voltage curve of a single ion track selected from Fig. 3.

conducting single track with ohmic characteristics. Assuming a track diameter of 10 nm and a DLC film thickness of 700 nm, the conductance is in the order of 1 S/cm, which is approximately three orders of magnitude smaller than that of bulk graphite. This indicates that the material in the track is predominantly graphitic but not well ordered. The reduction of the conductance in the tracks compared to compact graphite might be due to some weak connections between the grains.

3.3. Field emission

Some preliminary field emission measurements were performed. In most cases, the emission started at fields in the order of 100 to 300 V/ μ m. If the emission current was kept at low values, e.g. 50 nA, the data would be reproducible. For higher emissions currents sparks occurred. Thereafter, the onset voltages were considerable lower due to the formation of craters.

The rather high onset voltages are consistent with a rough estimate of the enhancement factor.

Since the length of the filaments is e.g. 700 nm the aspect ratio is approximately 70. Taking into account the dielectric shielding of diamond ($\epsilon \approx 6$) a field enhancement factor of only 10 is expected.

4. Conclusion

The irradiation of insulating DLC films with energetic heavy ions leads to creation of cylindrical conducting tracks with a diameter of approximately 10 nm. They can be suitable for transport of electrical current from the substrate to the surface. Presently the field emission occurs only at high onset voltages consistent with the estimated field enhancement by the geometry of the tracks. Severe damage is often associated with these high fields. Attempts to lower the onset voltage by using thicker films or by modifying the surface structure of the channels are under way.

Acknowledgments

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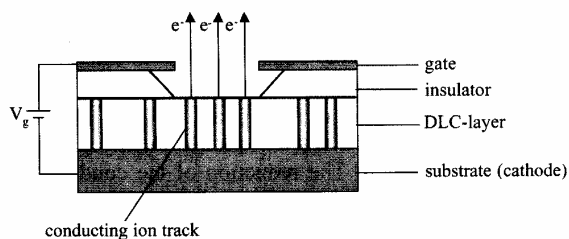


Fig. 1. Schematics of proposed field emission cathode. Electrons are extracted by an insulated gate electrode from the conducting ion tracks embedded in insulating DLC film.

mode. To allow current measurements, the sensor tip was coated with a conductive layer of PtIr.

Field emission experiments were performed in vacuum ($p \leq 1 \times 10^{-4}$ Pa) using a tip anode of a mechanically sharpened tungsten wire with an effective tip diameter of approximately 20 μm . The sample was mounted on a three dimensional piezo-drive which allows nanometer-resolution.

3. Experimental results and discussion

3.1. Topography

In the topographic SFM image ($2\mu\text{m} \times 2\mu\text{m}$), the impact sites of the projectiles appear as dark spots corresponding to small hillocks protruding from the flat sample surface (Fig. 2, top)

The height of the hillocks in Fig. 2 varies between 0.5 and 1 nm and the mean diameter (FWHM) is approximately 16 nm (Fig. 2, bottom). Due to the convolution of the hillock with the finite size of the sensor tip, it is reasonable to assume that the true diameter of the tracks is smaller. According to literature, a realistic value for tracks inside the DLC layer is approximately 10 nm [5].

With our SFM tip, we are not able to identify any microstructure of the hillocks. However, we expect some structural surface roughness, which possibly influences the field emission behavior. The phenomenon of hillock formation has been observed for many other track recording materials [6] and is linked to stress relaxation processes at the surface. Since the mass density in the tracks is general smaller than in the surrounding unirradiated matrix, the increased track volume may lead to pronounced stress [7]. For our DLC samples, where the density of tracks can be approximated by $\rho = 2.3 \text{ g/cm}^3$ of graphite, in comparison to that of amorphous diamond which has a much higher density of $\sim 3 \text{ g/cm}^3$. Evidence that the ion tracks in DLC consist of less dense material has also been found by transmission electron microscopy where tracks appear as light objects due to increased electron-beam transparency [8]. It

should be mentioned that the track regions did not exhibit any crystalline order, i.e. the matter in the tracks remains amorphous or microcrystalline.

3.2. Conductivity

A virgin DLC layer is almost a perfect insulator, exhibiting extremely low currents when scanned by a conducting SFM tip in contact mode. The situation is quite different in the track region where the current rises by several orders of magnitude (Fig. 3) reaching values typical for graphite. The absolute value of the conductivity along the tracks was found to depend strongly on the ion species and energy. Highest conductivities are only produced with very heavy projectiles (such as Au or U ions) with energies of several hundred MeV. We assume that for lighter ions or ions with lower energies ($E < 1 \text{ MeV/u}$), discontinuous tracks are created. If the conversion from sp^3 to sp^2 bonding does not occur on the entire track cylinder, the conductance along the track channels is interrupted.

Differences in the conductivity were also found for DLC layers produced with different techniques. The concentration of hydrogen in the films seems to play a major role. Recent concentration measurements [9] show an inverse correlation of the conductivity with the

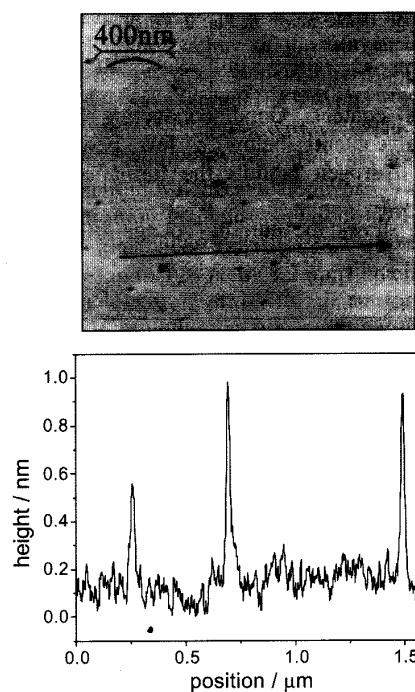


Fig. 2. (Top) SFM image of a DLC film irradiated with uranium ions of 1 GeV energy and a fluence $2 \times 10^8 \text{ ions/cm}^2$. The layer was produced by mass-separated ion deposition and had a thickness of 700 nm. (Bottom) Line scan through three hillock-shaped tracks.



Conductivity of ion tracks in diamond-like carbon films

J.-H. Zollondz^{a,*}, J. Krauser^b, A. Weidinger^a, C. Trautmann^c, D. Schwen^d, C. Ronning^d,
H. Hofsaess^d, B. Schultrich^e

^aHahn-Meitner-Institute Berlin, Glienicke Str. 100, Berlin 14109, Germany

^bHochschule Harz, Friedrichstrasse 57–59, Werningerode 38855, Germany

^cGesellschaft für Schwerionenforschung, Darmstadt, Germany

^dUniversity Göttingen, Bunsenstrasse 13, Göttingen 37073, Germany

^eFraunhofer-Institute IWS, Winterbergstrasse 28, Dresden 01277, Germany

Abstract

High-energy heavy ions (e.g. 1 GeV uranium ions) passing through a diamond-like carbon (DLC) film create conducting tracks along their path. The conductivity of these channels is due to a conversion of diamond sp^3 bonds to graphite sp^2 bonds caused by the large energy deposited along the ion track. The tracks have a diameter of approximately 10 nm and represent conducting filaments embedded in the insulating diamond-like matrix. They might be used as electron field emitters in vacuum electronic devices.

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1. Introduction

Fig. 1 shows the concept of a field emission cathode based on ion tracks in diamond-like carbon films. The electron-emitting layer consists of an amorphous diamond-like carbon (DLC) film containing cylindrical ion tracks as conductive filaments. These tracks are created when energetic heavy ions pass through the DLC layer [1,2]. The large energy deposition along the ion path leads to graphitization of the material within a cylindrical zone of a few nanometers in diameter. These conducting channels facilitate the electron transport from the back contact to the surface. Due to their large aspect ratio, field emission of electrons is expected and has to be investigated.

In this paper, we report the characterization of these ion tracks by means of scanning force microscopy (SFM). Some preliminary measurements on the field emission behavior were performed.

2. Experimental details

The DLC films were produced by ion deposition on heavily doped Si substrates. Two different methods, the

filtered arc technique (at FhG Dresden, [3]) and the mass selected direct ion deposition (at Univ. Göttingen, [4]) were applied. In both cases, the carbon ions are implanted into the growing film using energies between 50 and 100 eV. Such films are amorphous and contain 70–80% sp^3 bonds. An important parameter is the hydrogen content, which was approximately 0.1 at% for the Göttingen samples and in the 1 at% region for the Dresden samples. We found that a hydrogen content beyond several at% inhibits the formation of conducting tracks. The thickness of the films was usually in the 50 nm to 100 nm range but in a few cases films with 500 nm to 700 nm were used.

The irradiation of the DLC films with heavy ions was performed either at the GSI Darmstadt with U ions of approximately 1 GeV or at the HMI Berlin with Au ions of 340 MeV. In both cases, the specific energy corresponds to the maximum energy loss region forming a broad plateau above approximately 1 to 2 MeV/u projectile energy. The exact energy is not important as long as the energy loss is above a certain threshold value. Due to the high energy deposition along the ions trajectory, the material is transformed from insulating diamond-like to conducting-graphite-like carbon [1,2].

The electrical property of the narrow conducting channels was studied by means of SFM in the contact

*Corresponding author. Tel.: +49 30 8062 3234; fax: +49 30 8062 3199.

E-mail address: zollondz@hmi.de (J.-H. Zollondz).