

CONDUCTING ION TRACKS IN DIAMOND-LIKE CARBON FILMS

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ABSTRACT

Electrically conducting thin filaments were produced in diamond-like carbon (DLC) films by heavy ion irradiation. For this purpose, 1 GeV uranium ions were chosen since they provide the largest electronic stopping power (dE/dx) possible and therefore lead to the highest temperature in the tracks. Due to the high temperature a transformation of the insulating, diamond-like form of carbon (sp^3 -bonding) into the conducting, graphitic configuration (sp^2 -bonding) occurs. The separation of the tracks from one another is determined by the ion beam fluence while their length is determined by the thickness of the film. Atomic force microscopy (AFM) was used to measure the topography and current mapping of the irradiated films. Hillocks of approximately 4 nm height and conducting channels with a current enhancement of 3 to 4 orders of magnitude were found at the ion impact sites. The resistivity of the ion tracks is in the range of 40 to 250 Ω cm.

Keywords: Diamond-like carbon, ion tracks, field emission.

INTRODUCTION

Amorphous diamond-like carbon (DLC) films have been studied extensively with respect to electron field emission and application as cold cathodes in field emission displays (FEDs) (ref. 1 to 4). It was found that pure diamond is less suitable for this purpose than defect-rich materials; the latter have lower threshold voltages for electron emission (ref. 5). For field enhancement due to a large aspect ratio (length to diameter), long and thin conducting filaments embedded in an insulating film and reaching from the substrate to the surface are expected to be optimum. However, no satisfying realization has been found yet. Carbon nanotubes, with their extremely large aspect ratio, have been applied for field emission showing very low threshold fields and high emission currents (ref. 6 to 7). Nevertheless, long-term stability of the emission sites is limited due to continuous burning-off (ref. 8). In this paper we present studies on conducting ion tracks in DLC films which might be useful for field emission applications.

SAMPLE PREPARATION

The DLC films were produced by either ion beam techniques (Univ. Göttingen) or by plasma deposition with magnetic filtering (filtered arc method, FhG Dresden) on highly doped silicon substrates. In both cases, the C ions were implanted into the growing film with an energy in the order of 100 eV. This is the optimum ion energy to create diamond-like carbon by "subplantation". Such films are amorphous, contain 70 - 80 % sp^3 bonds and have a high resistivity. In the present case the films are 50 nm (FhG Dresden) and 100 nm (Univ. Göttingen) thick.

ION TRACK FORMATION

The ion irradiation of the DLC films was performed at the heavy ion accelerator facility UNILAC of GSI Darmstadt with uranium projectiles moderated down from 2.7 GeV by an aluminum foil to an energy of ~ 1 GeV or 4.2 MeV/amu (amu = atomic mass unit). The irradiation dose for the data presented here was 1×10^{10} ions/cm². Figure 1 illustrates the evolution stages of the track formation process (ref. 9). The high energetic U ions hit the sample which is at room temperature under a normal incidence (fig. 1a). They pass the DLC film and are stopped deep inside the Si substrate ($\sim 55 \mu\text{m}$). The first step in the ion track formation is the energy transfer from the high energetic ion to the electrons present along its path through the DLC layer (electronic stopping). The energy deposition is uniform and amounts to approximately 28 keV/nm. It occurs within a diameter of a few nanometers forcing the atoms to move and to rearrange again (fig. 1b). Due to the high energy deposition the temperature along the ion trajectories increases up to several thousand degrees. As a result the material melts and is transformed from insulating diamond-like (sp^3 -bonding) to conducting graphite-like carbon (sp^2 -bonding) leading to thin electrically conducting channels embedded in an insulating matrix (fig. 1c). The hillocks are formed since material flows out of the region of the ion track during the hot stage of the track formation process. The outflow is driven by the density reduction during the transformation from the diamond-like ($\rho \sim 3 \text{ g/cm}^3$) to the graphitic ($\rho \sim 2.3 \text{ g/cm}^3$) phase.

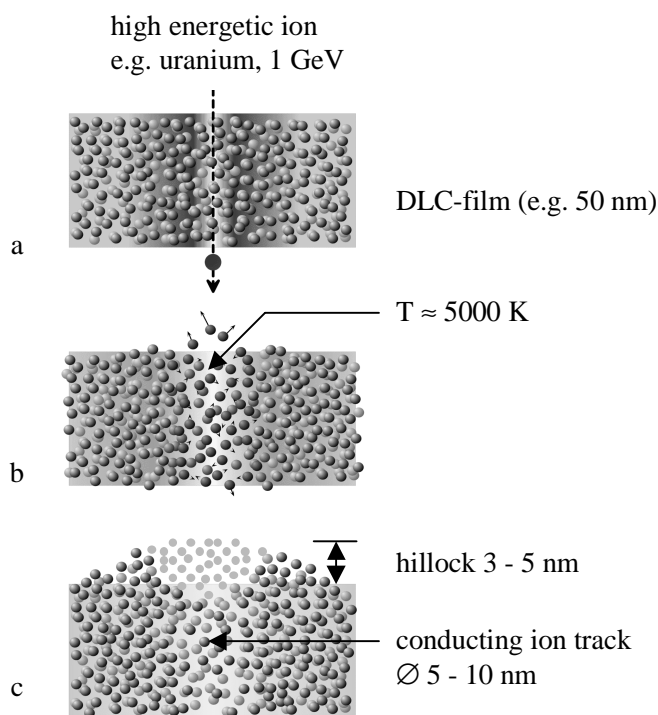


Figure 1: Evolution of conducting ion track formation (ref. 9).

Experimentally it is found (ref. 10 to 12) that continuous tracks are only formed if the energy deposition along the ion path exceeds a critical value, which depends on the target material. Since the energy loss per path length or stopping power dE/dx increases with the ion mass and has its maximum around 1 to 5 MeV/amu, only high energetic heavy ions form continuous ion tracks. This is demonstrated in fig. 2a, where a TRIM (ref. 13) calculation of dE/dx for different heavy ions is shown as a function of the beam energy. It can be seen that the stopping power dE/dx falls off rather steeply below 1 MeV/amu. Thus low-energy heavy ions are not suited for the formation of continuous ion tracks.

Figure 2b shows the evolution of the damage morphology in dependence of the stopping power as it is proposed by Toulemonde et al. (ref. 12). Actually this work is done for oxide materials like e.g. $Y_3Fe_5O_{12}$, but we assume that these results can also be adopted to the DLC films under investigation here. This is also supported by the work of Pawlak (ref. 14), where the ion track formation in amorphous carbon is studied. At low values of dE/dx , small spherical defects appear which are separated from each other (regime II). With increasing dE/dx the damaged regions start to overlap forming somewhat extended cylindrical defects (regime III). But these cylinders still do not form a continuous track. For still higher values of dE/dx , these cylindrical defects grow further (regime IV) and finally build a long cylinder where the damage is homogeneous (regime V). For most materials investigated by Toulemonde et al. continuous track formation starts at dE/dx values greater than 20 keV/nm. Therefore, from fig. 2a it is clear that heavy ion bombardment of the DLC film with Au or U at a specific energy between 2 and 5 MeV/amu is the best choice to create continuous ion tracks in this material. In (ref. 15) conducting ion tracks in DLC were found in spite of irradiation with relatively light Xe ions (1.1 MeV/amu), but the conductivity of the tracks was much poorer than in the present case in agreement with the argumentation shown in fig. 2.

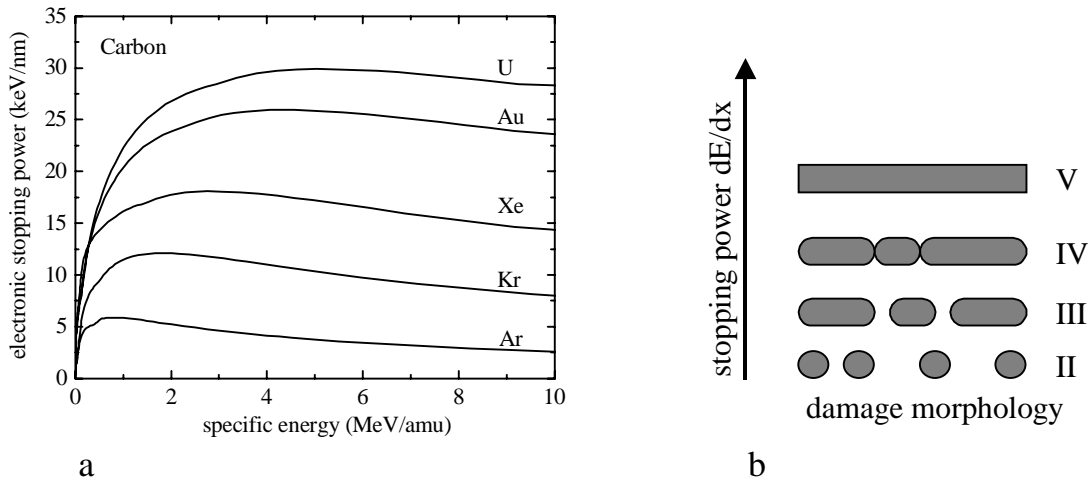


Figure 2: TRIM (ref. 13) calculation of the electronic stopping power dE/dx versus specific beam energy for different ions in a carbon target with $\rho = 2.9 \text{ g/cm}^3$ (a). The corresponding damage morphology is illustrated in (b): The classification in regimes from II to V is based on the work of Toulemonde et al. (ref. 12) and links the defect creation process to the deposited energy in the film (see text).

AFM-MEASUREMENTS

With regard to resolution and the possibility to measure the topography and the conductivity of the sample simultaneously, atomic force microscopy with a conducting tip is the best choice for visualization of the ion tracks. In the following we present AFM measurements recorded in contact mode with an air AFM using a highly doped (0.01 – 0.025 Ωcm) silicon cantilever with a tip coated with polycrystalline conducting diamond. The current mapping was done with a fixed voltage of 2.5 V between the tip and the substrate in case of the 50 nm thick films and 5 V for the 100 nm thick films.

Topography

Figure 3 shows the two- and three-dimensional image of the surface topography ($1 \times 1 \mu\text{m}^2$) of a 50 nm thick DLC film irradiated with 1×10^{10} ions/ cm^2 uranium ions at ~ 1 GeV. Within experimental uncertainties the number of bright spots in the left picture corresponds to the applied ion fluence (100 ions per μm^2). Hillocks with a few nm

in height which are the result of the track forming process described above are seen at the ion impact sites. The apparent width (FWHM) of the hillocks is 17 nm as shown in Figure 4b. Essentially this reflects not the true dimension of the material throw-off but reflects the convolution of the AFM tip and the hillock.

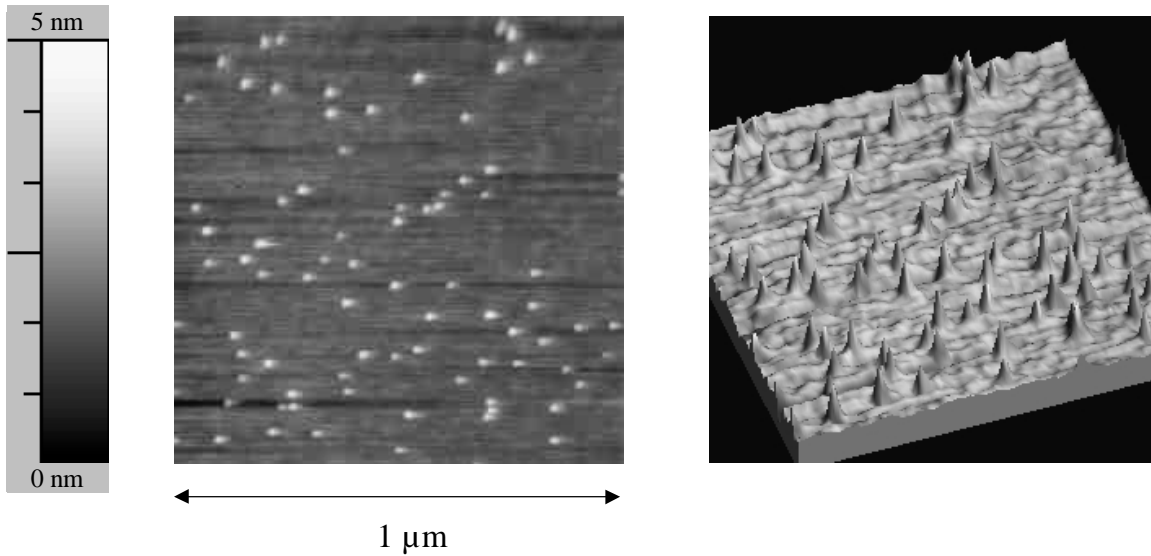


Figure 3: Topography of a 50 nm thick DLC film ($1 \times 1 \mu\text{m}^2$) irradiated with uranium ions of 1 GeV and a dose of 1×10^{10} ions/cm² in two-dimensional and three-dimensional view. The hillocks have a height of 2 to 5 nm and are due to the outflow of material from the ion tracks during the hot stage of the track formation process.

The topography image in fig. 4a is taken from the same film as in fig.3 just recorded with a higher measurement resolution.

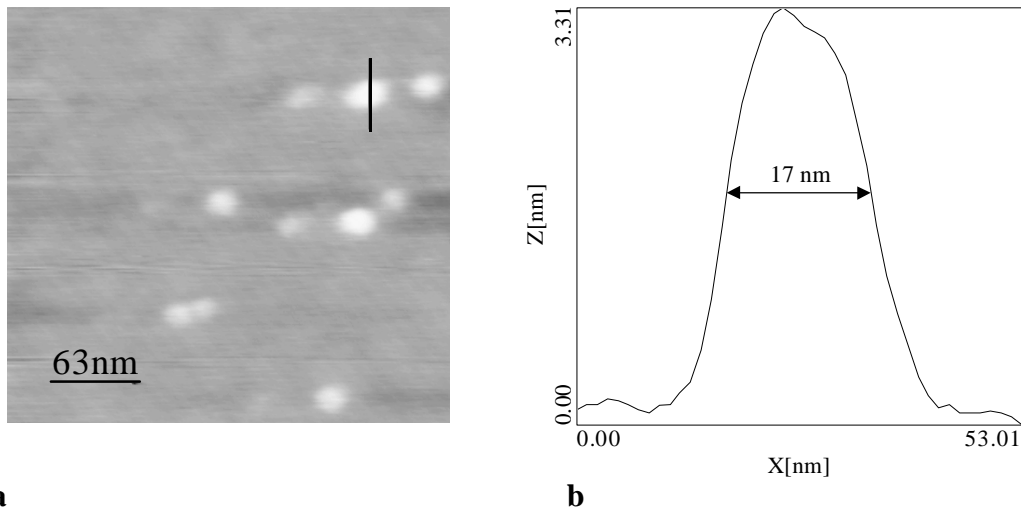


Figure 4: AFM image of the topography (a) of a 50 nm thick DLC film irradiated with uranium, 1×10^{10} ions/cm² at 1 GeV. A topographical profile (b) is made through one of the impact sites (black line in (a)) showing a width of 17 nm (FWHM) and a maximum height of approximately 3.3 nm.

The current from the tip to the substrate through the DLC film was measured in the contact AFM mode together with the topography. Figure 5 shows clearly that for each hillock seen in the topography (fig. 5a) a bright spot appears in the current mapping (fig. 5b). The width of the current peak is 16 nm, i.e. in the same range as the width found for the hillocks. However, note that the apparent width again is a convolution of the width of the track and the AFM tip curvature. The real diameter of the ion tracks is estimated to be approximately 10 nm (ref. 12).

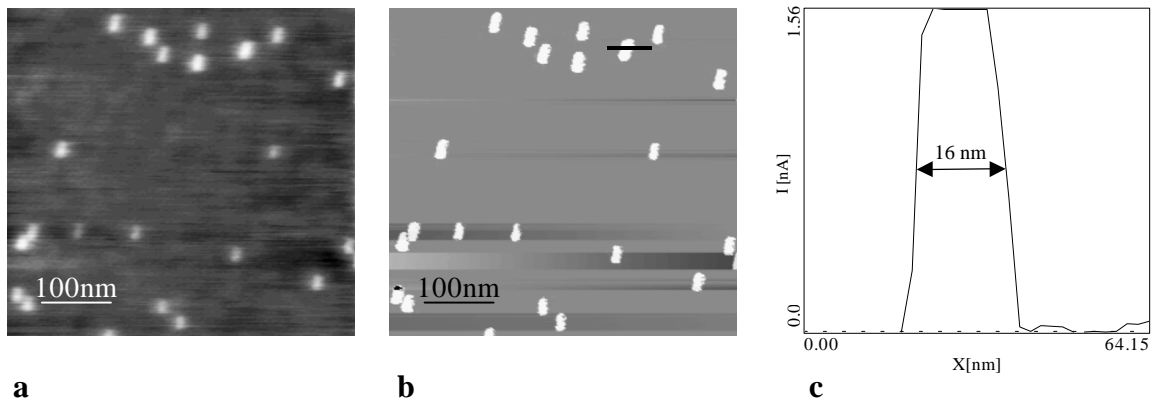


Figure 5: AFM images of the topography (a) and the current mapping (b) of a 50 nm thick DLC film irradiated with uranium, 1×10^{10} ions/cm² at 1 GeV. A current profile (c) is made through one of the hillocks (black line in (b)) showing a width of 16 nm (FWHM) and a maximum current of 1.56 nA flowing from the AFM tip to the substrate (tip-substrate voltage = 2.5 V).

Figure 6 shows a three-dimensional view of the current (fig. 6a) and a current versus voltage curve (fig. 6b) for a single ion track of a 100 nm thick DLC film irradiated with uranium, 1×10^{10} ions/cm² at 1 GeV .

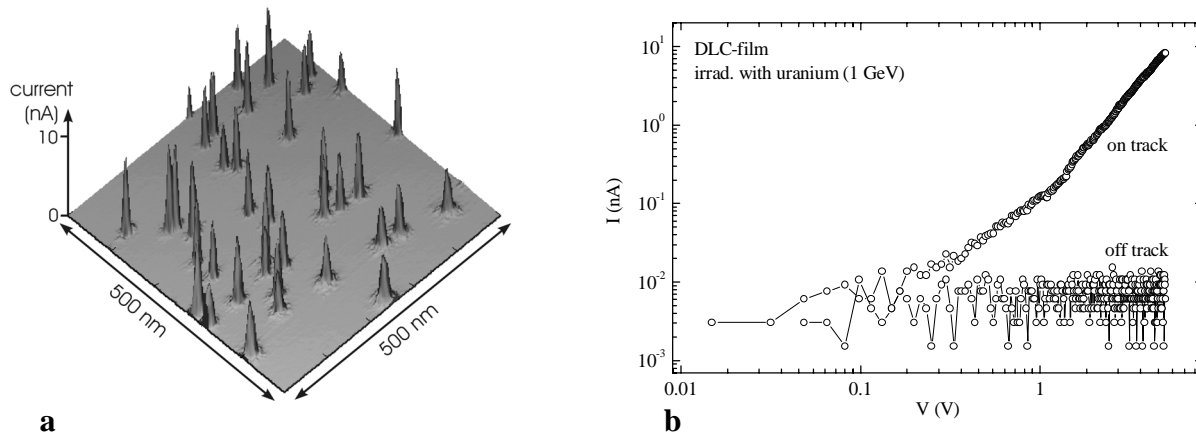


Figure 6: Three-dimensional current image (a) (tip-substrate voltage = 5 V) of a 100 nm thick DLC film irradiated with uranium, 1×10^{10} ions/cm² at 1 GeV, and current/voltage curve (b) for a single track (AFM tip on top of the track). For comparison the current/voltage curve in the off track position is also shown.

Again each of the current spikes corresponds to an ion track. If the AFM tip does not contact a track the measured current is practically zero, indicating the overall noise level of the unirradiated parts of the sample. For a spot on the ion track the current through the track is a function of the applied voltage. In fig. 6b these two cases are

termed as “off track” and “on track”, respectively. The difference in the current between this two tip positions exceeds 3 orders of magnitude. Assuming an ion track cross section of 100 nm^2 , the measured current at 5 V gives a current density of $8 \times 10^3 \text{ A/cm}^2$ and thus with 100 nm as the length of the track the resistivity ρ at this selected point is $62.5 \text{ }\Omega\text{cm}$. The different ρ values found for this kind of samples is in the range of $40 \text{ }\Omega\text{cm}$ to $250 \text{ }\Omega\text{cm}$.

CONCLUSION

With heavy ion irradiation it is possible to form electrically conducting ion tracks in an insulating diamond-like matrix. This was demonstrated in this work for 50 nm and 100 nm thick DLC films which were bombarded with 1 GeV uranium ions. AFM measurements with a conducting tip show that there is a clear correlation between the topographic surface image and the current mapping confirming that the current only flows at the impact positions of the ions. From theoretical considerations and from experiments in other systems it can be assumed that the tracks go straight through the film and have a diameter of several nanometers. The length of the tracks is determined by the film thickness and can be extended up to several micrometers. The energy of the ions can be chosen such that the electronic energy loss per unit length along their path through the film remains approximately constant even for micrometer-thick films. The average separation of the ion tracks from one another is determined by the ion fluence and can be adjusted in such a way that the emission sites in field emission applications have the required density. The field enhancement factor for a conductor with 10 nm in diameter and a length of 100 nm embedded in a dielectric medium is still fairly low. For a significant improvement of the field emission properties, thicker DLC films, which then yield a larger aspect ratio of the tracks, should be used. We are presently extending our work in this direction.

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