Report on the project “Conducting ion tracks for field emission”

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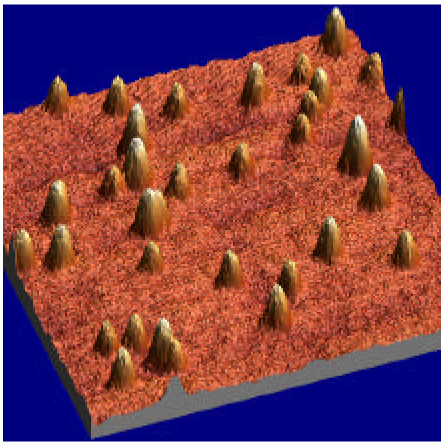
1. AFM/TEM Investigations

The atomic force microscopy (AFM) investigations were performed in air, using the contact mode. The AFM tip was coated with a conducting layer (doped diamond or Pt/Ir) in order to allow current measurements [1-3].

Figure 1 shows a typical topography picture of an irradiated sample. We always find small hills (hillocks) at the positions of the ion impact. Thus some material flows out of the track during the hot phase (several thousand degrees) after the ion impact. The height of the hills is one to a few nanometers and the apparent width is approximately 20 nm, mainly determined by the tips size and shape.

The transmission electron microscopy (TEM) measurements were performed at the TU Chemnitz [4] and the data were analyzed by Helga Schultrich from the TU Dresden [5]. Simulation calculations of the observed TEM features show that the density in the tracks (more precisely: the amount of carbon atoms in transmission direction) is reduced. It is also found that the sp^2 bonds are more abundant in the tracks than elsewhere. This information was derived by scanning the film with the electron energy loss set to the plasma energy of graphite or diamond, respectively.

Films with thickness’ from 40 nm to 700 nm, in one case (film from IKOS) even with 2500 nm, were investigated. They all show continuous tracks as seen from the current measurement (see below). Since it is impossible that material flows from the middle of thick films to the surface during the hot phase (too long way) the density reduction must be due to radial outflow of material. Thus, it is essential for conducting ion track formation that the DLC films do not have the (maximal) density of diamond, i.e. that they offer space for additional carbons (ρ(graphite) = 2.3 g/cm^3, ρ(DLC) = 3.0 g/cm^3, ρ(diamond) = 3.5 g/cm^3)


Area: 500 x 500 nm, z_{max} = 1.5 nm

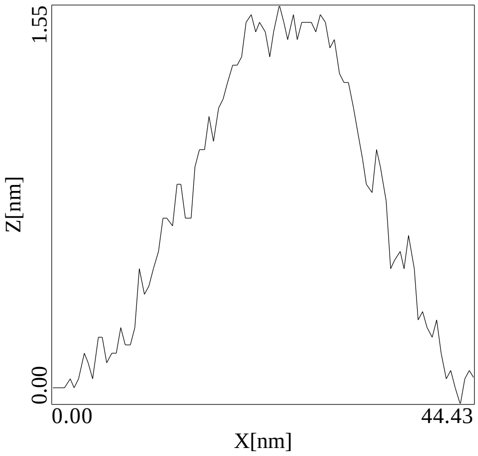


Fig. 1: *Left: three dimensional AFM-topography picture of a 150 nm thick DLC film (IWS A030801/3, shown area 500 x 500 nm) irradiated with* $2x10^{10}$ *U/cm*^{2}*. Right: cross-section through one ion track hill.*

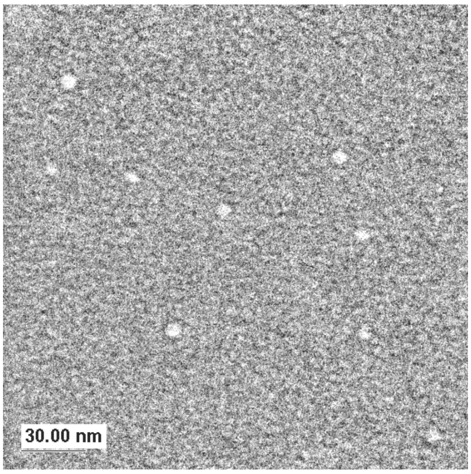


Fig. 2: *TEM image of a 50 nm thick DLC film (4-W00-02-28/I) irradiated with* 10^{10} *U/cm*^{2}*. The white spots correspond to the ion tracks. Contrast is due to reduced density (less material) in the tracks [5].*

Conclusions:

a) A **reduced density** in the channels is found by TEM, **diameter 8nm**.

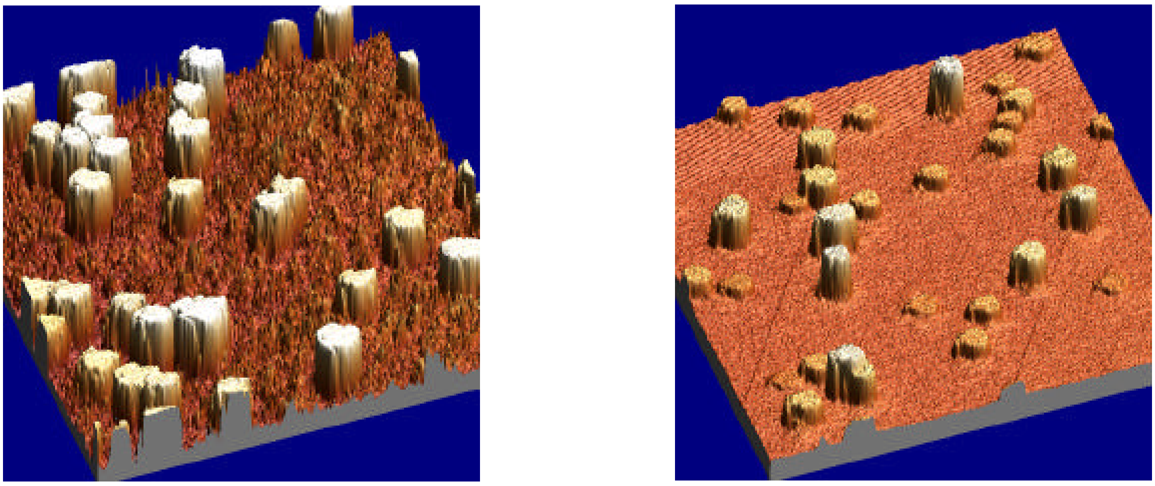
b) Material outflow from the channel must be **radial**, since material transport from the middle of thick films to the surface is impossible (too long way).

c) Plasmon-EELS indicates more **sp**^{2} **bonds** in the channels than outside the channels.

d) The crystal structure in the channels remains (effectively) amorphous, i.e. **no nanotubes** or long range graphitic structures are seen in TEM.

2. Conductivity of the channels

This is the most successful part of the project so far. Impressive pictures of current mapping were obtained (see picture gallery in appendix A). Fig. 3 shows two extreme examples, one with high conductivity and one with low conductivity channels. In Fig.3a (high conductivity), all channels have approximately the same current value, whereas in Fig.3b (low conductivity), these values are different and they even seem to be “quantized” (current values in steps). We think that the “quantization” is due to weak links in the conducting channels like small insulating interruptions. This may be an interesting “spin off” but is not essential for the field emission issue (actually has to be avoided).



Area: 500 x 500 nm,
I_{max} = 1.6 nA at 100 mV

Area: 500 x 500 nm,
I_{max} = 0.05 nA at 500 mV

Fig. 3: *Three-dimensional current-mapping of DLC films irradiated with* $2x10^{10}$ *U/cm*^{2}*. Left: 500 nm thick film (Nr. 609, Göttingen), right: 150 nm thick film (IWS A030801/3).*

Fig. 4 shows typical I/V curves (AFM tip on top of a conducting channel) for the same samples as in Fig. 3. For the good conducting tracks the I/V-curves are almost linear, whereas they are clearly bent in the other case. This is again an indication that the poorly conducting channels have weak sections where the track is partly interrupted.

Table 1 summarizes the conductivity σ of samples measured with the same kind of AFM-tips (PtIr-coated). It can be seen that one category of samples (the earlier thin ones from Dresden and those of Göttingen) have conductivities in the order of 1 S/cm (note: $\sigma_{graphite}$ = 250 S/cm) whereas the others have conductivities approximately three orders of magnitude lower. The reason for this difference must be related to the preparation process of the films and might be connected to the hydrogen content of the DLC films.

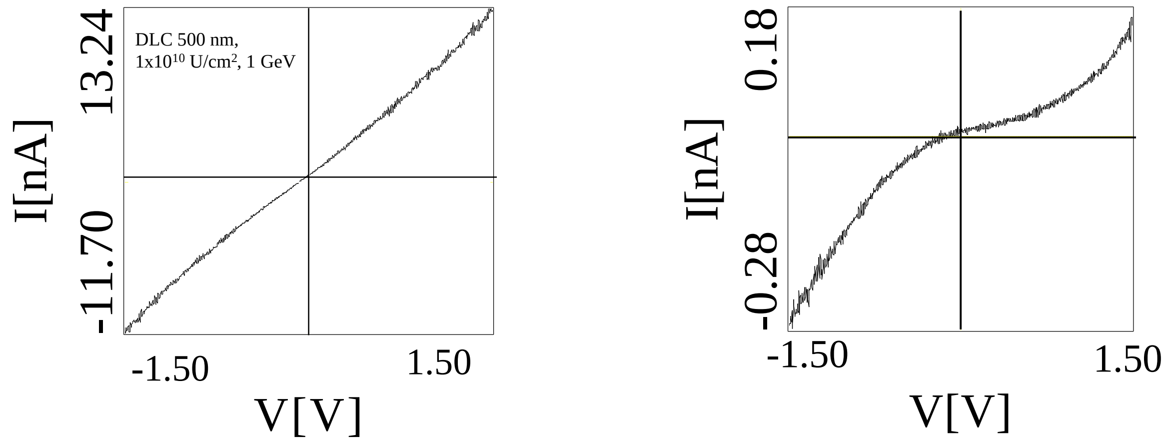


Fig. 4: *Current/voltage curve through an ion track. Left: 500 nm thick film (Nr. 609, Göttingen), right:150 nm thick film (IWS A030801/3).*

Table 1: *Conductivity s of the ion tracks in different samples. For the calculation a track diameter of 10 nm was assumed and in case of non-linear I/V-curves, a reasonable voltage between the tip and the substrate was chosen.*

Sample		**d (nm)**	s **(S/cm)**
IWS Dresden	(#365)	50	2.0
	(#367)	50	2.5
	(#369)	50	0.7
Kalish		70	0.5
Göttingen	(#609)	500	0.55
IWS Dresden	(A030801/3)	150	0.002
IKOS		2500	0.0004

3. Field emission

3.1. Flat anode

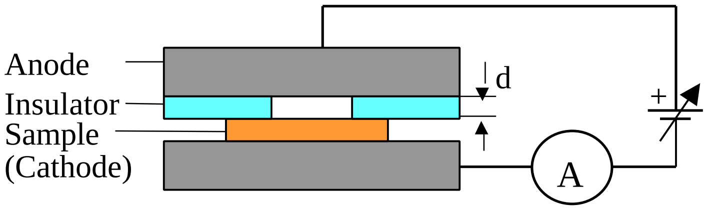


Fig. 3: Principle of flat geometry arrangement for field emission measurement.

One sees emission (Fig. 4), but this is due to dust particles or defects on the sample and is not caused by the ion tracks.

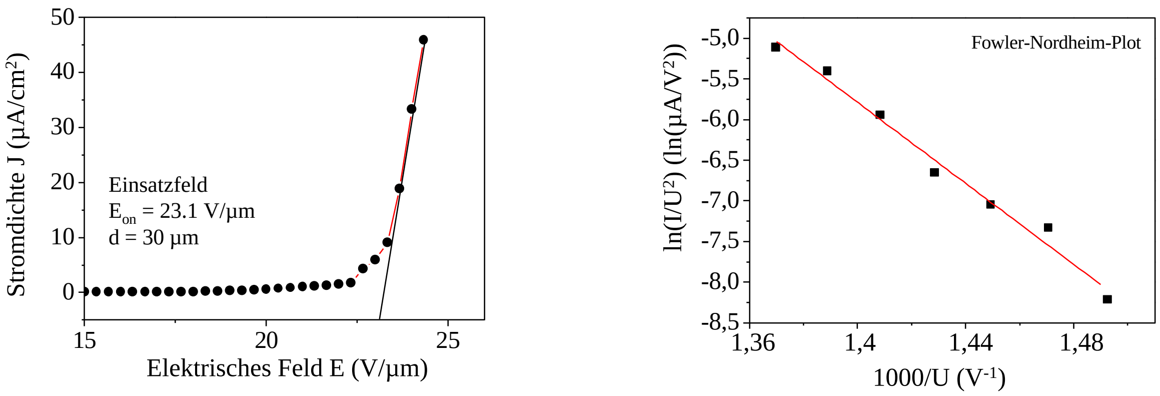


Fig. 4: *Field emission as observed in the flat geometry. Emission is due to dust particles or graters on the sample.*

Conclusion: **Flat geometry is not good!**

3.2. Tip Anode (Wuppertal)

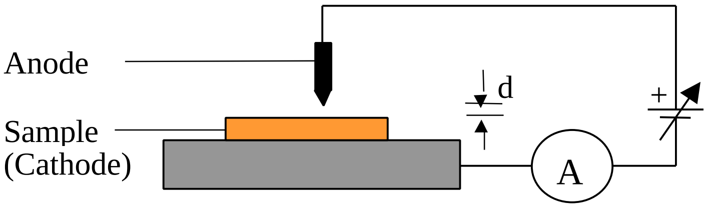


Fig. 5: Principle of tip anode geometry

First experiments (with preliminary equipment) were started in Wuppertal on a 700 nm tick DLC film (from Göttingen), irradiated with 10^8 U/cm². After an initialization, stable emission was observed (Fig.6).

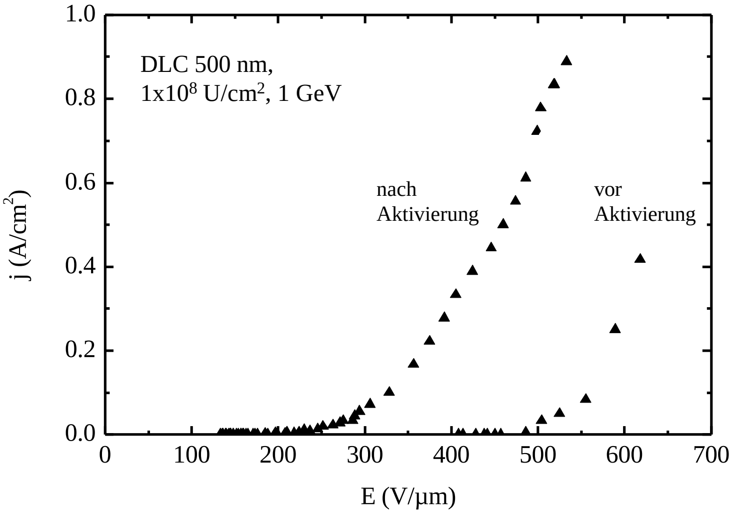


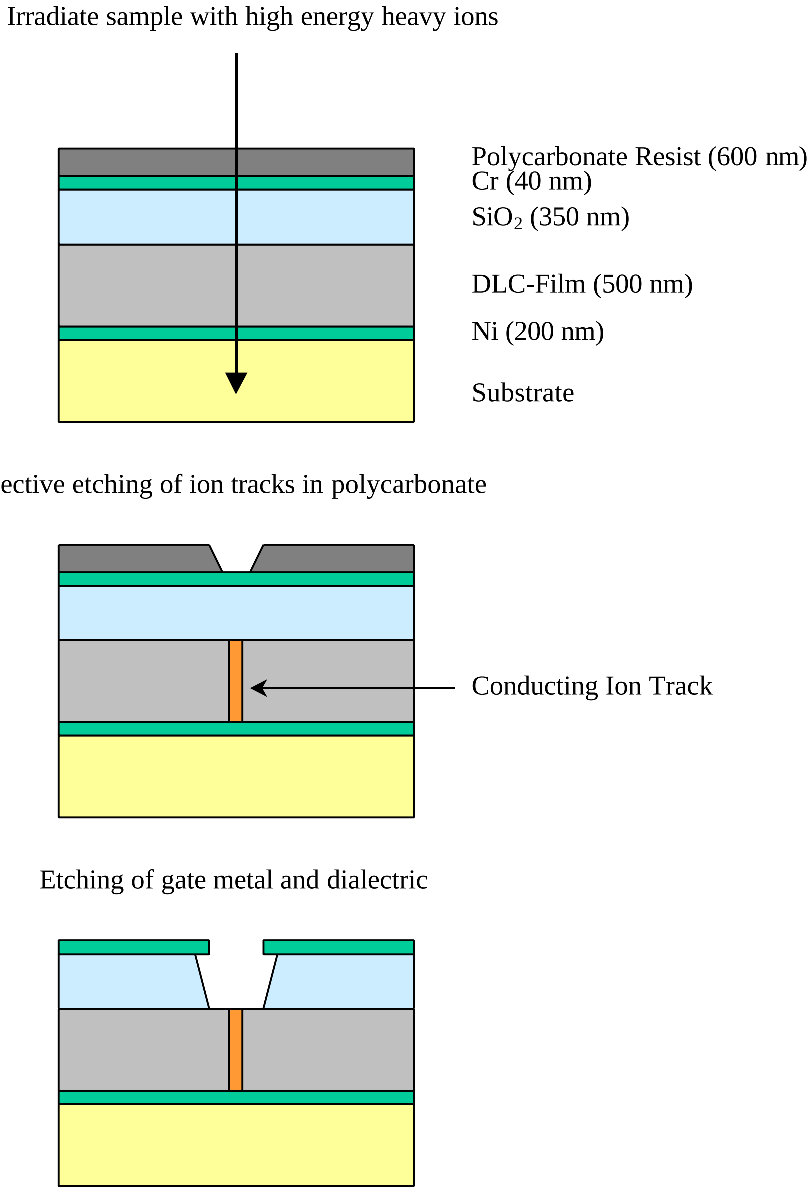
***Fig. 6:** Emission current density as a function of field strength, before and after activation (preliminary data)*

Conclusion: More measurement with the final equipment should be performed.

4. Proposal for a new cathode structure

Recently we became aware of a publication of a new fabrication process of Spindt-typ field emitters [6] where heavy ion irradiation was used for creating structures with sub-300 nm gates. Their procedure except the Spindt-tips can be applied directly for our case. The Spindt-tips would be replaced by our conducting ion tracks. The preparation steps for this device are shown in Fig. 7.

The DLC film is deposited as usual in Dresden and Göttingen onto a metal-coated (fine strips) substrate. After that a thin SiO_2 insulator and the Cr micro strips are evaporated. Finally, a polycarbonate resist is deposited onto the device. The two metal contacts (Ni and Cr in Fig. 7) are crossed micro strips which allow single pixel addressing. After irradiation, the resist in the track region is etch, opening areas for etching the metal and the SiO_2 insulator. The dimensions of the openings are in the range of 300 nm. Using metal strip sizes of 50 µm and an irradiation dose of $1x10^8$ U/cm^2 a pixel would contain 2500 emitters (ion tracks).



Irradiate sample with high energy heavy ions

Selective etching of ion tracks in polycarbonate

Etching of gate metal and dialectric

Fig. 7: *Preparation steps for a field emission cathode.*

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