Ion tracks – a new route to nanotechnology

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Ion tracks are created when high-energetic heavy ions with energy of about 1 MeV/nucleon (e.g. 140 MeV Xe ions) pass through matter. The extremely high local energy deposition along the path leads to a material transformation within a narrow cylinder of about 10 nm width. Unlike in the more conventional lithographic techniques based on ion or electron beam irradiation, a single heavy ion suffices to transform the material. Thus, problems like straggling or diffusively broadened features do not occur. Ion beams with the required properties are available e.g. at the national accelerator centres HMI Berlin, GSI Darmstadt and GANIL Caen. Some recent developments of this field are described in Ref. 1 and 2.

Ion tracks have a long tradition in science and technology. They play a role, e.g., in geology where the dating of geological formations is based in some cases on fission fragment tracks. Industrially, ion tracks are used for the production of porous media, e.g. for particle filters. Here, polymer foils are irradiated with heavy ions and subsequently etched to remove the material from the track region. A unique variant of this ion beam method is the single-hole filter which reaches an extremely high selectivity for particle filtering [3]. With modern microbeam facilities, the tracks can be placed in an ordered array [4] (see Fig.1). This is important for electronic applications since it facilitates the addressing, which is problematic for statistically distributed tracks.

Recently it became clear that heavy ion beams can also be used in nanotechnology [5,6] since ion tracks have just the right size for nanostructuring: the track diameter is of the order of 10 nm and the track length can be varied from a few nanometers up to several micrometers by choosing the appropriate sample thickness. In this way, quasi zero-dimensional nanodots or quasi one-dimensional nanowires can be created.

There are essentially two ways to use ion tracks for nanostructuring. The first is based on track etching as used in the filter production, i.e. one irradiates a polymer foil and etches the tracks to create thin pores in the foil. These pores are subsequently filled with an appropriate material to make nanostructures. In this process, the polymer foil serves as a template and can be removed (dissolved) if required.

The second method uses the ion tracks directly without additional etching and refill steps. This method is simpler than the template technique since no filling of the pores is required but it is of course strongly limited in the choice of materials and structures. The often occurring material transformation in the track from crystalline to amorphous is mostly not very useful for applications. Recently however, a dramatic increase of the electrical conductivity in ion irradiated diamond-like carbon (DLC) was found [6], the material changing from insulating (diamond-like) to conducting (graphite-like) carbon in the track. In this way, thin conducting wires in an insulating matrix are created.

Another material with a potentially useful ion irradiation effect is zinc-ferrite (ZnFe₂O₄) which is paramagnetic in its original state but converted to ferrimagnetic by ion irradiation [7]. A similar conversion can be induced in YCo₂ [8]. The number of such examples is certainly limited but two good ones, one for electronic and one for magnetic (spintronic) devices is in principle sufficient to further pursue this field.

In the following, some examples of already realized nanostructures will be presented and some proposed devices implementing ion track-induced structures will be discussed showing the great potential of this technique in nanotechnology.

### Template-grown nanostructures

The method of etching thin long pores along ion tracks in polymer foils is well developed [2] and, as mentioned above, is used in the production of filters for various applications. To give an idea of possible pore sizes and pore densities, table 1 of Ref. 2 is reproduced here. Other combinations of pore diameter, foil thickness and pore density are of course also possible.

These hollow channels in the solid material can be used as templates to grow nanostructures in them. The material deposition into the channels is usually performed by chemical or electrochemical methods from solutions. The track etched polymer foils have in some cases advantages over other template structures (e.g. porous alumina or lithographically prepared membranes) since they are more variable in the choice of parameters (radius, distance and length of the pores and the material to be used) and, compared to lithography, they reach a much larger aspect ratio (length to diameter) of the pores. Aspect ratios of 100 to 1000 are possible.

A large variety of nanostructures has been grown in polymer pores [5] in the form of compact cylinders of single or multi-layered material but it is also possible to create tubules [2], i.e. hollow cylinders, if the material deposition starts from the walls of the pores. In the following, two examples of compact structures will be discussed in more detail.

### Magnetic multilayered nanowires

Magnetic multilayered materials are of great interest because of the so-called giant magnetoresistance (GMR) effect which occurs in some materials if magnetic and non-magnetic layers are stacked. The current through these layers depends on the relative orientation of the magnetisation. If this orientation is anti-parallel in zero external field – this can be achieved by choosing the appropriate spacing – it can be switched to parallel orientation by applying a magnetic field, thereby lowering the resistance by some percent. This effect can be used in reading devices for magnetic recording media.
has to be insulated either by oxidation or by under-etching, before metal are etched away. Then the metal adjacent to the channel in the polymer sheets and afterwards the exposed part of the is the third contact, the gate. Here the ion track method allows an with the current perpendicular to the plane. Such a structure was grown in an ion track template and the magnetoresistance was measured [5]. The arrangement of the layers, i.e. their spacing and thickness, can be adjusted to obtain the optimum effect (high GMR and reasonable switching field and switching time).

**Nanotransistor**

Because of its central role in electronic devices, the realisation of a transistor is usually the primary goal of a new research field in this area. The progressing miniaturisation in electronics requires structure dimensions in the nanometer range. Here the perpendicular-to-plane orientation is advantageous for close packing. In some cases a flexible transistor which does not break upon bending is desirable. A device with these specifications, a vertical nanotransistor in a flexible polymer matrix, was recently realised [9]. The principal concept is shown in Fig.2.

A two-terminal device, i.e. a semiconductor structure with source and drain contacts, is usually easy to fabricate, the problem is the third contact, the gate. Here the ion track method allows an elegant solution: A polymer foil is metallized on one side and glued together and irradiated with heavy ions (upper part). After ion irradiation, the material in the track, first in the polymer sheets and afterwards the exposed part of the metal are etched away. Then the metal adjacent to the channel has to be insulated either by oxidation or by under-etching, before finally the semiconductor material is introduced and contacts are deposited. The principal operation of such a device has been demonstrated [9].

**Direct use of ion tracks**

**Conducting ion tracks in diamond-like carbon**

Diamond-like carbon (DLC) is a well developed material and, e.g., used in industry for protective coating. The structure of DLC is amorphous and the bonding is primarily sp3 (tetrahedral)-like as in crystalline diamond and therefore the material is insulating. Hydrogen-free DLC, as necessary for the present application, is produced in thin sheets on substrates (e.g. Si) by plasma deposition. The energy of the deposited particles has to be about 100 eV in order to form the compact tetrahedral (sp3) structure.

High energy heavy ions, e.g. 1 GeV uranium ions, convert the material along their path from insulating diamond-like to conducting graphite-like carbon [6]. The large change in the conductivity is easily seen with a scanning probe microscope. Fig. 4 shows the topography and current image of an irradiated film. Each ion track is characterized by a small hillock at the impact site of a single ion and by a huge increase of the current through the film.

The electrical resistivity of the tracks is on the order of 1-10 S/cm and is approximately four orders of magnitude larger than outside of the tracks, depending on the properties of the original DLC layer. Transmission electron microscopy (TEM) measurements have shown that the diameter of this converted region is approximately 8 nm [6]. Thus, by this ion irradiation, a thin straight wire in an inert matrix has been created. It can be used as a building block in nanoelectronics, as is discussed below.

**Ferrimagnetic filaments in a paramagnetic matrix**

It was found [7] that ZnFe2O4 converts along the ion track from a paramagnetic to a ferrimagnetically ordered material. This effect is due to a randomization of the Fe atoms on the Zn and Fe sites. Thus the effective magnetic interaction becomes stronger and leads to magnetic ordering up to temperatures well above room temperature (about 500 K). The nm-sized converted region can be used in spintronic applications.

A similar magnetic conversion of ZnFe2O4 is known for nanostructured material obtained by mechnochemical milling. That this conversion can be induced also by ion tracks was clearly demonstrated [2]. The pore diameter is determined by the etching time, the pore density corresponds to the fluence of the ions (number of ions per cm²) and the thickness of the foil determines the pore length.

**Table 1:** Typical parameters of ion track-etched polymer templates [2]. The pore diameter is determined by the etching time, the pore density corresponds to the fluence of the ions (number of ions per cm²) and the thickness of the foil determines the pore length.

<table>
<thead>
<tr>
<th>Pore diameter (nm)</th>
<th>Pore density (cm²)</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4.0 x 10⁸</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>2.0 x 10⁹</td>
<td>10</td>
</tr>
<tr>
<td>80</td>
<td>2.0 x 10⁹</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>6.0 x 10⁹</td>
<td>10</td>
</tr>
<tr>
<td>200</td>
<td>5.0 x 10⁹</td>
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<td>10</td>
</tr>
<tr>
<td>600</td>
<td>4.0 x 10⁷</td>
<td>19</td>
</tr>
<tr>
<td>1000</td>
<td>2.2 x 10⁷</td>
<td>19</td>
</tr>
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</table>
demonstrated by Mössbauer measurements that exhibit the well known six line splitting after irradiation [7]. Since this effect is present also for widely separated tracks (low dose irradiation), it is demonstrated that the conversion takes place in the individual tracks. Thus magnetic filaments in a non-magnetic environment are produced by ion irradiation.

**Self-aligned contacts**

Contacting nanostructures is usually a considerable problem since the contacts must be small (nm sized) themselves and must be aligned with the structures for which the contacts are made. The situation is even worse for statistically distributed ion tracks since a safe distance between the structures has to be maintained in order to avoid overlapping. A partial solution, which regulates at least the immediate environment of the track, is a lithographic process initiated by the track itself. In this procedure, one applies a resist (polymer) on top of the sample. After passage of the ion, the resist is developed giving access to the track in a well aligned manner. Through this open space, the contact can be applied, e.g. by metal deposition. The continuation of the contact to the outside can be achieved with less precise but well-established methods like electron-beam lithography.

A further development of this technique would be to align complete electronic circuits to the tracks. This can be achieved by using multilayer systems and multiple etching and deposition processes as in conventional device fabrication. A proposed simple example is shown in Fig. 4. Here, a multilayer stack with a resist on top is irradiated with heavy ions. After etching with different solutions, the final structure of an aligned gate electrode (heavily doped poly-Si) is obtained. A similar structure as shown in Fig. 4 has been realized by the Livermore-Candescent group for field emission applications [10].

**Outlook**

Presently, there exist research collaborations on a European level to realize some of the basic structures with this new technique. The national research centres, GANIL in France, GSI Darmstadt and HMI Berlin in Germany are involved in this research. In the following, three proposed devices will be discussed, one from electronics, one from magnetism and one from field emission.

**i) Quantum dot and Coulomb blockade**

The basic concept for making a small dot is to interrupt the conducting track at two points by insulating intersects. This can be achieved by inserting insulating layers which do not convert to conductors by the ion passage. In this way, one obtains pieces of nano-wires connected by tunnel junctions. The multilayer samples, consisting of DLC layers and insulating layers (e.g. SiO2), are prepared by conventional deposition techniques and irradiated after preparation.
Figure 5 shows a proposed design of this structure. The ion track (upper part of Fig.5) is embedded in an insulating matrix and connected with two leads (conducting substrate and conducting AFM tip) to the outside. For a solid-state device, the AFM tip can be ultimately replaced by a self-aligned metal contact as indicated in Fig.4.

An enlargement of the track region is shown in the lower part of the figure. The approximately 8 nm wide cylinder corresponds to the ion track region. The insulating layers serve as tunneling barriers. As indicated in Fig. 4, an efficient emission can ultimately be replaced by a self-aligned magnetic metal contact. The structure in the lower part of Fig.5 represents a two-terminal device (diode), the two terminals serving as source and drain, respectively. The addition of a third terminal, the gate, in order to complete the transistor may be achieved by the self-alignment as shown in Fig.4, an efficient emission structure could be realized.

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References