3D-Hydrogen Analysis of Ferromagnetic Microstructures in Proton Irradiated Graphite ◇

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The recent discovery of a strong ferromagnetic phase of carbon induced by proton and helium broad- and microbeam irradiation in highly orientated pyrolytic graphite (HOPG) [2] rises many basic questions about the mechanism which leads to the enhanced ferromagnetism. Because the effects are much larger for proton than for helium ion irradiation and because theoretical models clearly indicate that hydrogen plays a major role [1], the precise knowledge of the 3D-distribution of hydrogen of virgin and irradiated HOPG samples is essential. Therefore, we used the sensitive 3D hydrogen microscopy system at the microprobe SNAKE [4] with its ability to image hydrogen down to 0.1 at-ppm with micrometer resolution [3]. We scanned a focused proton beam of 17 MeV over the samples and recorded the coincident proton-proton scattering events in a segmented annular down-stream detector.

The background hydrogen level in virgin HOPG was determined to be about 0.3 at-ppm which is much too low to be relevant for the induced ferromagnetism. About 5×10^{15} H-atoms/cm^2 were observed in the near-surface region with about 7 μm depth resolution.

The HOPG samples were implanted with 2.25 MeV protons at the Leipzig microprobe LIPSION. Extended areas and also μm-sized spots were exposed with various doses above the threshold where the strong enhancement of ferromagnetism occurs. The hydrogen depth profile of the extended area is shown in Fig. 1.

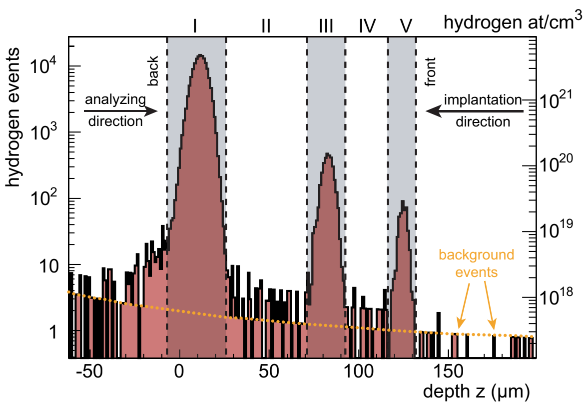

Fig. 1: Hydrogen depth profile of implanted region (160 μC on approx. 0.9 mm^2), recorded from a 200 μm by 200 μm area.

The large peak on the left side of the spectrum (I) is due to hydrogen contamination by the glue used for cutting the sample (4.5×10^{18} H-atoms/cm^2). The implanted hydrogen (region III) is located at the end of range in agreement with Monte Carlo simulations (TRIM), i.e. it is trapped there. The hydrogen concentration on the front at the near-surface region (V) was 1.4×10^{16} H/cm^2.

Fig. 2b shows a 2D hydrogen map of some implanted microspots. The hydrogen is well located at the implanted sites and could therefore be indeed responsible for the detected ferromagnetism. However, making up the hydrogen balance, we observed that up to 50% of the implanted hydrogen is not detected in microspots occasionally and might have escaped the damaged region.

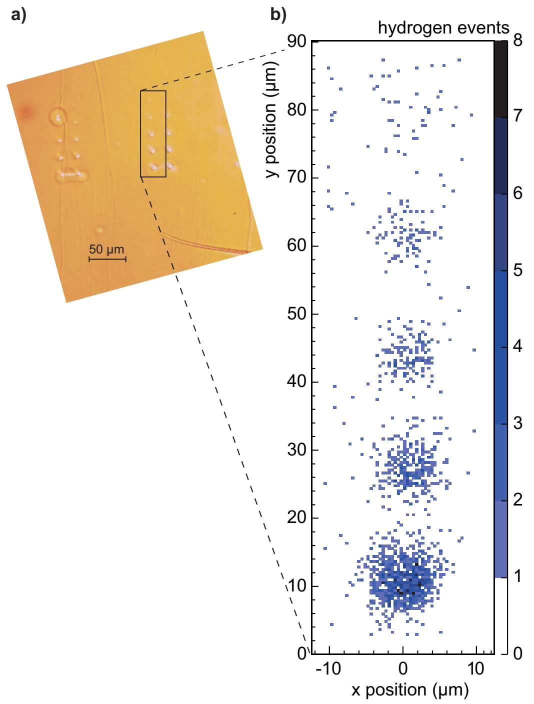

Fig. 2: a) Optical microscopy image of HOPG surface with the implanted microspots (2×2 rows with 85,34,17,8.5 and 3.4 nC H$^+$; 10% uncertainty) and b) hydrogen scan map of one row.

The surface hydrogen was not yet considered to influence the formation of ferromagnetic regions, but might play a major role. The differences between proton and helium ion irradiation would then be due to different stopping powers and related thermal effects. However, we note that the enhanced surface content at the implanted samples might be due to different sample treatment. A further systematic study will be necessary to proof this hypothesis.

References

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