Application of the ATOMKI-ECRIS for materials research

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Abstract ***In the ATOMKI ECRIS Laboratory long-term projects were initiated to investigate basic properties of high charged ions and use heavy ion beams and plasmas for materials research, including the nanotechnology as well as to explore the possibility of industrial or medical applications of such ion treatments. In this paper a brief review of some new experimental possibilities and applications is presented. The ECR ion source was further developed towards irradiation of solid surfaces with highly charged ions or even fullerenes. Experiments on interaction of such plasma with titanium surface were performed with an aim of its bio-functionalization. The modification of functional amorphous chalcogenide layer surfaces by highly charged argon and xenon ions was also investigated with aim to establish basic mechanism of such processes and to develop new possibilities of nanofabrication.***

***Keywords*: high charged ion, fullerene, surface modofiation**

I. INTRODUCTION

Nowadays a continuously increasing demand is detected for the application of heavy ion beams in scientific R&D, industry and medicine. The application of plasmas and ion beams produced by Electron Cyclotron Resonance ion sources attracts increasing interest connected to the basic problems of ion physics and to the application of wide variety of ions with comparatively low energies (usually up to 200 keV). The known publications usually do not show the details of the ion sources or the "beam-making" itself. However, a specific application of a heavy ion beam frequently requires the modification of the ion source itself or, at least, unusual plasma formation or ion extraction. In this paper we show a few possible, promising applications of heavy ion beams. Each of these projects just started at the ATOMKI ECRIS Laboratory, some of them in collaboration with University of Debrecen and other institutes. The first results already appeared, but the major achievements are expected within the next 1-5 years.

11. EXPERIMENTAL TECHNICS

At the ATOMKI-ECRIS fullerene plasmas have been produced since 2000 by using filament ovens to evaporate fullerene. One of our goals has been the production of high intensity singly and multiply charged fullerene ion beams. Another research topic is the investigation of mixture plasmas (C_{60} + X, where X is N, O, Fe or other atoms). In C_{60}+N mixture plasmas endohedral N@C_{60} was observed in the beam spectra and in macroscopic quantity in the soot deposited on the wall of the plasma chamber [2].

The fullerene encapsulated iron would be another promising new material if one could produce it first in a beam then in bulk quantity. In the past years we made some efforts in this direction. The composition of C_{60}+Fe mixture plasmas was studied by extracting ions from it. The iron component of the plasma was obtained from ferrocene powder or using high-temperature filament ovens to melt pure iron rods [3,4]. These and other results and demands led us to a major modification of the ATOMKI-ECRIS. Since 2006 it has been operating in two modes ("A" and "B") [5]. In "B"-mode the ion source is equipped with a large plasma chamber and a weak hexapole around it. This mode is specialized for the production of large-sized, low-ionized plasmas and provided the fullerene beams for a number of experiments.

The ATOMKI-ECRIS-B source was selected as a prototype for another new ECRIS just built in Toyo University, Kawagoe, Japan [6].

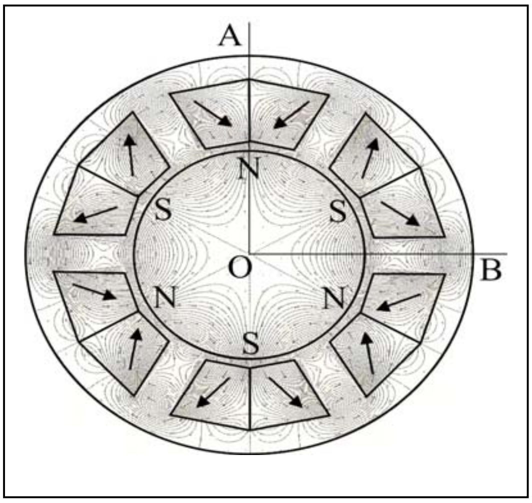

Fig.1.

The new ion source was designed to produce iron encapsulating fullerene ions in beam and in deposited layer form. The details of the technical solutions and the latest beam results are presented in a separated paper at this workshop [7]. Here we list only the basic features of the source.

- Geometry: plasma chamber diameter is 14 cm, length is 35 cm.
- Microwave: 8-10 GHz and optionally 2.45 GHz, as second frequency.
- Mirror field: two identical room-temperature coils, peak fields max. 0.64 Tesla.
- Hexapole: NdFeB, modified AECR-U design, field at poles is 0.72 Tesla. The magnet borders at radial positions were calculated to form parallel slits for a future easier radial approach to the plasma (see Figure 1.).
- Fullerene gas: using simple filament oven or evaporation boat.
- Iron gas: by induction oven (under development).
- Extraction: grounded, movable puller, einzel triplet.
- Beamline: bending magnet to transport upto 5 KV beams with M=800.
- Other: an optional processing chamber is under construction to be connected at the extraction side. It will be equipped with biased meshes and cooled electrodes to help the iron-fullerene synthesis.
- Name: because the ion source is being built at the Bio-Nano Electronics Research Center of the Toyo University and it is aimed to produce new materials useful for physical, biological and medical research and application, it is called Bio-Nano-ECRIS.

The Bio-Nano-ECRIS delivered the first gaseous and fullerene plasmas and beams in 2008. Further details and results are in [7].

III. APPLICATIONS

Moving towards the applications in bio-nano-sciences, , in collaboration with the Faculty of Dentistry of the Debrecen University, we have started a research program in order to coat titanium surfaces by fullerenes with various velocity and thickness. Then biological tests will be carried out on the covered samples by growing bone cells on them.

The next important research topic is ion bombardment and surface modification of solid materials, which can be used in optics, photonics and nanoelectronics. Ion bombardment and ion implantation are versatile tools for modification of properties of thin near-surface layers of solid materials, as well as for some etching processes. In case of singly charged ions and a large variety of materials this effect is rather well understood and widely used in different branches of the modern industry. The effect of the bombardment of multiply and highly charged ions has been studied only in a few materials, such as HOPG (highly oriented pirolytic graphite), mica, Al_2O_3, SiO_2 and Se [10-13]. These studies concentrated on the nanohillock and crater formation caused by impact of single ions depending on the ion charge state and on the materials properties. There have not been studies on the effects caused by ions while travelling through and stopping inside the solid, since the charge state dependence was thought to be too small to detect experimentally [14,15]. The complementary changes in the optical absorption, refractive index and volume are native just for amorphous chalcogenide films, therefore we can use the results of basic research for the development of new technology of optical and geometrical surface relief at micro-and nanometer scales.

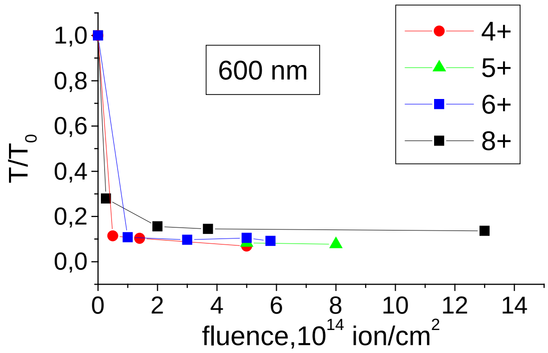

Fig. 2. Ion-induced darkening of AsSe films.

We have observed significant charge state dependence in darkening of amorphous AsSe thin films bombarded with Ne^{q+} (q=4..8) ions. The thickness of the AsSe films was 800 nm which is about three times as large as the expected thickness of the modified layer (SRIM [18] calculations gave 196 nm range and 116 nm longitudinal straggling). In Fig 2 one can see the optical transmission decreasing with the ion fluence while reaching saturation value at about $\sim 3 \cdot 10^{14}$ ion/cm^2 in this particular case. The saturation value of the relative transmission depends on the thickness of the modified layer .

Previous ion irradiation experiments with 80-180 keV protons and deuterons have shown [16,17] that the ion bombardment causes structural rearrangements in AsSe and in similar amorphous chalcogenide thin films, which in turn result in optical band gap decrease (i.e. decrease of optical transmission at certain wavelengths). The relative transmission change during bombardment with Ne^{q+} (q=4..8) ions (measured at 600 and 640 nm) versus ion fluence plots is shown in Fig. 2. The total kinetic energy of all ions was set to 120 keV, therefore the ion source extraction voltage was from 15 to 30 KV.

The saturation value of the relative transmission depends on the thickness of the modified layer (see the equation) and on the depth distribution of the induced absorbance $\Delta\alpha(z)$:

$$\left(\frac{T}{T_0}\right)_{sat} \propto \exp\left(-\int_0^l \Delta\alpha dz\right).$$

Our experiment shows that the $(T/T_0)_{sat}$ is larger for the sample irradiated with Ne^{8+} ions than for the one irradiated with Ne^{4+} ions. Since the change of absorption $\Delta\alpha(z)$ is proportional to the total energy/volume deposited in the material by the ions (i.e. the higher the deposited energy the larger the $\Delta\alpha$) [16, 17] and the ions with higher charge are expected to have higher specific energy loss [15], the observed difference in the $(T/T_0)_{sat}$ values by necessity means that thickness of the modified layer is smaller for the Ne^{8+} ions than for Ne^{4+} ions by 25%. As the modified layer thickness is in strong correlation with the stopping range of the ions, the above stated relation is true also for the range of the ions.

This result has impact on our knowledge of charge equilibration processes of ions travelling in solids and also on a number of basic scientific and technical problems, which along with the details of the experiment will be discussed in detail in a forthcoming paper [19].

IV. CONCLUSIONS

Finally in the Table 1 we give a simple overview of the theree different applications of heavy ions detailed in the paper. The tasks and beam requirements are very different, but the ECR source proved to be versatile enough to fulfill all these requirements and serves as a real multi-purpose facility.

Table 1. Summary and comparison of the projects which require heavy ion beams from the ion source point of view.

Project short name	Endohedral fullerenes	Ti implants coating	Thin layer modification
Ion source	ATOMKI-ECRIS-B and Bio-Nano-ECRIS	ATOMKI-ECRIS-B	ATOMKI-ECRIS-A
Plasma/beam	Fe^+, C_{60}^+	C_{60}^+	$Ne^{4+\ldots8+}$
Beam diameter (mm)	10-20	50	4
Extraction voltage (V)	500-5000	250-500	15000-30000
Microwave frequency (GHz)	8-12	12-14	14.3
Microwave power (W)	1-50	4-20	200-400
Specification	Synthesis in plasma or on surface	Irradiation in the zero-degree beamline	Beams with same total energy

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