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Ion Irradiation Studies of Soft Magnetic Metallic Glasses

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Finemet and Vitrovac® 6025 metallic glasses were irradiated by light (N) and heavy (Au and Ta) ions at different energies from 110 keV to 250 MeV/u (MeV per mass unit) and fluences from 1×10^{11} ions/cm^2 to 1×10^{17} ions/cm^2. They were analysed by the Mössbauer spectrometry and magnetic susceptibility measurements. Qualitative differences were observed between the radiation effects caused by light and heavy ions.

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1. Introduction

Some metallic glasses are considered as candidates for magnetic cores of accelerator radio-frequency (RF)-cavities. In this particular application, they are exposed to ion radiation that may alter their magnetic properties [1]. The spectrum of particle species, energies and fluences is rather broad because the irradiating ions origin from complex interaction of lost primary heavy ions with the beam-pipe wall. That is why a systematic study of the influence of ion bombardment on magnetic properties of the materials used for the magnetic cores of the RF-cavities is necessary.

2. Materials and methods

This paper deals with Finemet and Vitrovac® 6025. These materials are considered for the facility for antiproton and ion research (FAIR) RF-cavities [2]. Finemet ($Fe_{74}Cu_1Nb_3Si_{16}B_6$) was irradiated by 110 keV N and 593 MeV Au ions. In case of N ions, the fluences up to 1×10^{17} ions/cm^2 were applied. The mean projected range was 133 nm ±47 nm (straggling). In case of Au ions, the fluences up to 1×10^{13} ions/cm^2 were applied. The mean projected range was 18.9 μm ±575 nm. The influence of ion bombardment on surface and bulk regions of the samples was analysed by conversion electron Mössbauer spectrometry (CEMS) and transmission Mössbauer spectrometry (TMS), respectively.

Vitrovac® 6025 ($Co_{67}Fe_4Mo_2Si_{16}B_{11}$, [3]) was irradiated by Au ions at 11.1 MeV/u and Ta ions at 11.1 MeV/u and 250 MeV/u. At these energies, the range is longer than the sample thickness (about 23 μm). Irradiations with fluences up to 1.2×10^{13} ions/cm^2 were performed. The samples were analysed by magnetic susceptibility measurements [4].

Irradiation experiments were accompanied by SRIM2010 simulations (stopping and ranges of ions in matter, SRIM). The depth-profiles of ionization and vacancy-concentration were simulated. The vacancy-concentration was converted to dpa (displacement per atom) that depends on the fluence. The fluences were chosen according to actual results of the sample analysis.

3. Results and discussion

Samples of Finemet irradiated by 110 keV N ions showed changes in spectral parameters, especially in isomer shift, at 2×10^{16} ions/cm^2 [5]. This is the fluence that causes radiation damage of dpa > 10 due to elastic nuclear stopping. The electronic stopping is on the level of 0.6 MeV/μm. Its depth-profile is nearly uniform within the depth accessible by CEMS (≈ 200 nm) [6].

TMS of the samples irradiated with 593 MeV Au ions exhibited changes in orientation of the net magnetic moment at 1×10^{12} ions/cm^2 [5], which is a fluence causing the radiation damage due to nuclear stopping of less than 0.01 dpa (Fig. 1). Moreover, the damaged region is restricted mainly to the range-region of irradiating ions and can hardly influence significantly the MS-spectra in transmission geometry that provides information from the sample bulk. It is the electronic stopping that reaches considerably higher values of about 47 MeV/μm in comparison with nitrogen and that influences a larger sample volume (its depth-profile is broader compared with the nuclear stopping one). All these arguments indicate that whereas the damage by light ions is dominated by nuclear stopping and can be correlated to dpa, the damage by heavy ions is governed by electronic stopping and cannot be correlated to dpa. As a consequence, heavy ions are more effective in damaging the materials because of higher proton number, Z, which increases the electronic stopping by Z^2 at the same projectile velocity. Therefore changes of magnetic properties must be expected at lower fluences compared with light ions.

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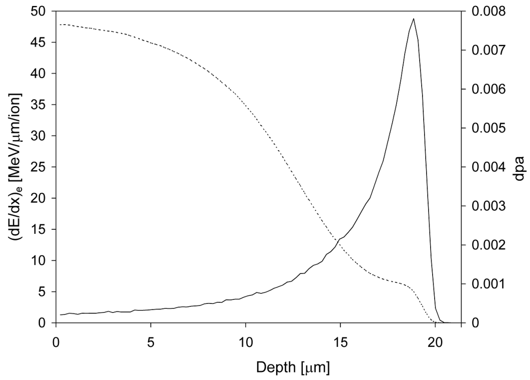

Fig. 1. Electronic stopping (dotted line) and dpa (solid line) in Finemet irradiated by 593 MeV Au ions, 1×10^{12} ions/cm^2.

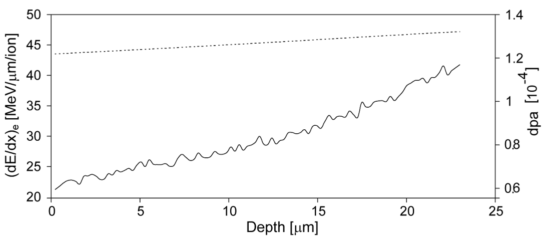

Fig. 2. Electronic stopping (dotted line) and dpa (solid line) in Vitrovac® irradiated by 11.1 MeV/u Ta ions, 1×10^{12} ions/cm^2.

Based on the results obtained for Finemet, irradiations of Vitrovac® 6025 concentrated on heavy ions. The energy of 11.1 MeV/u was used to ensure high electronic stopping with a uniform depth-profile (Fig. 2). An extra experiment was done at 250 MeV/u representing low electronic stopping of about 9.75 MeV/μm. Magnetic susceptibility was measured before and after irradiation and its relative change is plotted as a function of the fluence in Fig. 3 for 11.1 MeV/u. Samples irradiated by 250 MeV/u showed no remarkable changes of magnetic susceptibility because of lower electronic stopping compared with the 11.1 MeV/u. A deeper discussion on physical aspects of radiation damage caused by light and heavy ions can be found in Ref. [7].

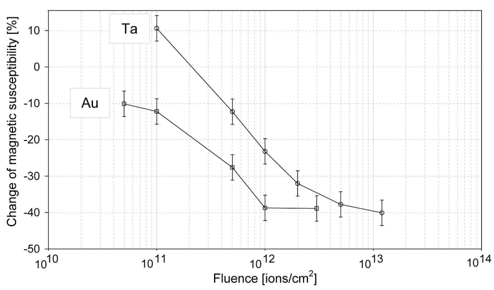

Fig. 3. Relative change of magnetic susceptibility of Vitrovac® after irradiation by Ta (circles) and Au (squares) ions as a function of fluence, 11.1 MeV/u.

Although the materials were studied by two different techniques, the results are reasonably consistent, as both materials started showing degradation changes at fluences crossing 1×10^{11} ions/cm^2. Application of other complementary techniques is currently in progress as well as MS and susceptibility measurements of the same material (Vitroperm).

4. Conclusions

Radiation damage of materials caused by ion irradiation is intensively studied and it is observed that there are qualitative differences in damage mechanisms between light and heavy ions [7]. This finding was confirmed also by our experiments for ions irradiating the soft magnetic metallic glasses at very high energies up to 250 MeV/u. An attempt to find quantitative criteria was done as well. Whereas the radiation damage by light ions can be correlated to dpa and occurs at dpa > 10 for materials under investigation, radiation damage by heavy ions is related to high ionisation density (about 47 MeV/μm) and occurs even at very small dpa values (less than 1.2×10^{-4}). In terms of fluence, the Mössbauer isomer shift changed at 2×10^{16} ions/cm^2 for 110 keV N, whereas the fluence of 1×10^{12} ions/cm^2 led to reorientation of the net magnetization in case of 593 MeV Au (both in Finemet).

Irradiation of Vitrovac® 6025 showed that magnetic susceptibility changed at fluence as low as 1×10^{11} ions/cm^2 at energies about 11 MeV/u, but no change was observed at 250 MeV/u. An enhancement of susceptibility was observed at low fluences (for Ta but not for Au) and a saturation tendency appeared at fluencies over 1×10^{12} ions/cm^2 (for both ion species). The saturation level was about -40% of the non-irradiated samples. The saturation tendency may be caused by overlapping of individual ion tracks.

Acknowledgments

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References

[1] R. Dubey, A. Gupta, P. Sharma, N. Darowski, G. Schumacher, *J. Magn. Magn. Mater.* **310**, 2491 (2007).

[2] P. Spiller, K. Blasche, B. Franczak, M. Kirk, P. Huelsmann, C. Omet, S. Ratschow, J. Stadlmann, *Nucl. Instrum. Methods Phys. Res. A* **544**, 117 (2005).

[3] S. Flohrer, G. Herzer, *J. Magn. Magn. Mater.* **322**, 1511 (2010).

[4] V. Jančárik, E. Ušák, *J. Electr. Eng.* **50**, 63 (1999).

[5] M. Miglierini, A. Lančok, M. Pavlovič, *Hyperfine Interact.* **189**, 45 (2009).

[6] M. Miglierini, A. Lančok, M. Pavlovič, *Phys. Met. Metallogr.* **109**, 469 (2010).

[7] A. Rivera, J. Olivares, G. García, J.M. Cabrera, F. Agulló-Rueda, F. Agulló-López, *Phys. Status Solidi A* **206**, 1109 (2009).