ORIGIN FOR IRRADIATION EFFECT OF 0.56 GeV C^{6+} ON CaVSn:YIG*

Xiong Hongqi (熊宏齐)
(*Analytical and Testing Center, Southeast University, Nanjing 210096*)
Hsia Yuanfu (夏元复)
(*Physics Department, Nanjing University, Nanjing 210018*)
and Hou Mingdong (侯明东)
(*Institute of Modern Physics, the Chinese Academy of Sciences, Lanzhou 730000, China*)

ABSTRACT

This paper presents numerous physical characteristics of Ca, V, Sn doped yttrium iron garnet (CaVSn:YIG) irradiated with 0.56 GeV carbon ions delivered by the Heavy Ion Research Facility of Lanzhou (HIRFL). The reason for change of the magnetic properties of the samples induced by energetic carbon ions bombardment is discussed. By comparison of this results with the irradiation effects of YIG induced by energetic argon, krypton and xenon obtained on the GANIL, Caen, France, it is concluded that the irradiation effect of 0.56 GeV C^{6+} on CaVSn:YIG arises from the electronic energy losses.

Keywords Energetic carbon ion, Yttrium iron garnet, Irradiation effect, Electronic energy losses

1 INTRODUCTION

The study of highly energetic heavy ion effects in magnetic oxides has been carried out for about 10 a. In materials like $Y_3Fe_5O_{12}$, $BaFe_{12}O_{19}$ and $NiFe_2O_4$, the magnetic properties are very sensitive to the irradiation-induced defect which results in a decrease in the saturation magnetization[1−4]. General behavior of the damage observed in magnetic insulators was summarized recently by Studer *et al* [5]. Most experiments around GeV energy range for the irradiation were carried out at the GANIL accelerator at Caen, France and GSI accelerator at Darmstadt, Germany. The energetic heavy ions delivered by the GANIL accelerator have a wide range of the electronic energy losses values (between 1 MeV/μm and 25 MeV/μm). As the electronic energy losses increase, the isolated spherical extended defects, cylindrical defects and the long continuous trails are appeared respectively. When the electronic energy losses becomes larger than a certain value (T_m), the damage yield ceases to increase as rapidly as in the previous range ($dE/dX < T_m$).

However, till now, there is a lack of data in the case that the electronic energy losses dE/dX are lower than 1 MeV/μm. In this electronic energy losses, an interesting problem is: does the defect induced by energetic heavy ions bombardment comes from the electron stopping or from the nuclear collisions? So an irradiation experiment is performed using carbon ions in order to cover lower dE/dX values in yttrium iron garnet following the

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successful extracting of the 50 MeV/u C^{6+} beam from the Heavy Ion Research Facility of Lanzhou (HIRFL). In this paper, numerous physical characteristics of yttrium iron garnet irradiated by 0.56 GeV carbon ions will be reported.

2 EXPERIMENT

The irradiation experiments were performed at HIRFL with 0.56 GeV carbon ions at the temperature lower than 30K. The details of the experiment are presented Refs.[6-8]. Induced microstructure and magnetic properties changes have been characterized by Mössbauer spectrometry, high resolution electron microscopy (HREM), X-ray diffraction (XRD), positron annihilation techniques (PAT), vibrating sample magnetmetry (VSM) and ferrimagnetic resonance (FMR).

3 RESULTS

The crystallographic structure of YIG can be described as the iron atoms occupying the 24d and 16a positions and they are surrounded by oxygen atoms (96h) with a tetrahedral (d-site) and octahedral (a-site) structure respectively. The Mössbauer spectrum gives quantitative information on the hyperfine magnetic field at the iron nuclei. From the intensity ratio of the peaks, the directions of the hyperfine magnetic field and the magnetization can be deducced. By investigation, it is concluded that:

3.1 The irradiation mainly introduced the point defects (monovacancies). Only a few extended defects which exist in the sample were observered by HREM. The $[Fe^{3+}, O_4^{2-}]_d$ tetrahedron is found to be more strongly affected by irradiation than the $[Fe^{3+}, O_6^{2-}]_a$ octahedron. The induced defects give rise to an increase in the lattice constant of the samples[6].

3.2 The hyperfine magnetic fields and the saturation magnetization decrease after the irradiation[7].

3.3 The irradiation results in an isotropic distribution of the hyperfine magnetic field, lowers the magnetic anisotropy constant and also the average magnetic anisotropic field, whereas the FMR line width of the samples rises after the irradiation[8].

4 DISCUSSION

4.1 The relations between the microstructure and the magnetic properties changes induced by energetic carbon ions bombardment

The origin of the magnetic behavior for $Y_{1.6}Ca_{1.4}V_{0.45}Sn_{0.5}Fe_{4.05}O_{12}$ comes from the supertransferred interaction between Fe^{3+} at a- and d-sites. After the irradiation, the chain Fe(a)-oxygen-Fe(d) becomes longer and some chains were broken by the induced point defects $[Fe^{3+}, O_3^{2-}]_d$ and $[Fe^{3+}, O_5^{2-}]_a$ can lower the supertranferred interaction and also the hyperfine magnetic fields at iron nuclei as well as the saturation magnetization.

For the defects induced by energetic carbon ions bombardment, the atomic density of the interstitial area is larger than that of the undamaged area. Consequently the atoms press each other in the interstitial area and thereby result in a "pressure stress" directing

along the surface of the defects. In order to get a minimum stress energy, the direction for the magnetization must be along the surface of the defects and in the interstitial area as well. Assuming that the defects induced by energetic carbon ions bombardment are spherical in shape, then a sphericcal stress would take place around them, inducing an isotropic hyperfine magnetic field. This also lowers the magnetic anisotropy constant and the average magnetic anisotropic field (see Figs. 1–2).

The broadening of the ferrimagnetic resonance line width in the virginal sample is due to the presence of inhomogenous and effective local magnetic fields. These effective local fiels arise, for instance, from the magneto-crystalline anisotropy, which causes a variation in the direction of the anisotropic field in different grains, or from the inhomogeneity of the local saturation magnetization induced by air pores. Besides these two main contributions, other ccontributions due to surface roughness and the presence of strong relaxing impurities, have also to be taken into consideration. These are normally one order of magnitude smaller.

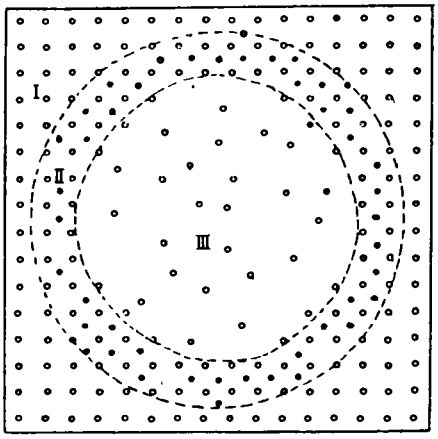

Fig.1 Model of defect in samples induced by energetic carbon ions bombardment

I. Perfect zone, II. Interstitial atom zone, III. Vacancy zone

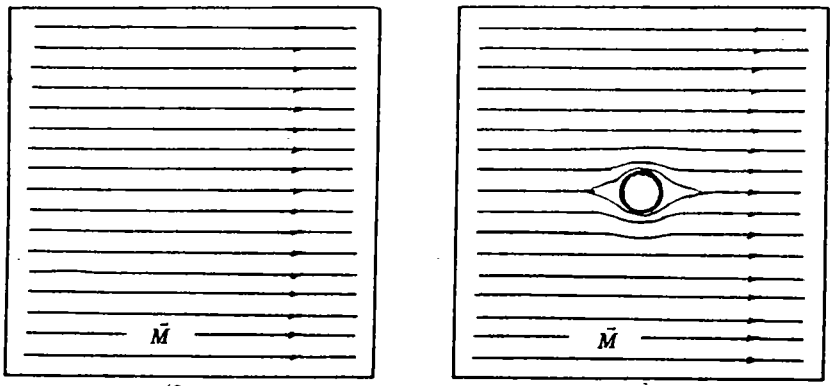

Fig.2 Magnetic structure model of the perfect lattice (a) and the zone near the induced defect (b)

For an irradiated sample, a new broadening $\Gamma_{\rm def}$, arising from the defects induced by energetic carbon ions bombardment, is introduced. In this investigations the vacancies and the extended defects can be regarded as being "pores" induced by energetic carbon ion bombardment. An addition effective local field which arise from the inhomogeneity of the local saturation magnetization (see Fig.2b) induced by the defects leads to increase the ferrimagnetic resonance linewidth.

4.2 Comparison among irradiation effects on YIG induced by energetic argon, krypton and xenon ions

Table 1 summarizes the irradiation effect on yttrium iron garnet induced by energetic argon, krypton, xenon ions[5,9] and carbon ions[6–8]. From Table 1 it can be deduced

Table 1
The numerous physical characteristics of highly energetic carbon, argon, krypton and xenon ions effect in yttrium iron garnet

Ions	Energy MeV/u	$[-dE/dX]_e$ MeV/μm	$[-dE/dX]_e/[-dE/dX]_n$	Defect	Magnetic structure near the defects
$^{12}C^{6+}$	47	<1	1.5×10^4	Vacancy and spherical extended defect	Isotropic hyperfine magnetic field
$^{40}Ar^{16+}$	44	1–8	2×10^3	Vacancy and spherical extended defect	Isotropic hyperfine magnetic field
$^{84}Kr^{27+}$	35	8–20	2×10^3	Vacancy and extended defect when $[-dE/dX]_e$ <17 MeV/μm, vacancy and latent track when $[-dE/dX]_e$>17 MeV/μm	Isotropic hyperfine magnetic field when $[-dE/dX]_e$<17 MeV/μm, anisotropic hyperfine magnetic field when $[-dE/dX]_e$>17 MeV/μm
$^{132}Xe^{54+}$	23	20-31	2×10^3	Vacancy and latent track	Anisotropic hyperfine magnetic field

that the irradiation effect on YIG induced by energetic carbon ions is similar to that induced by energetic argon ions. Including the highly energetic argon ions, it has been shown that the effect of the electronic energy losses in yttrium iron garnet is the main effect of highly energetic heavy ions irradiations[5,9,10]. In the case of the yttrium iron garnet which has been irradiated with argon ions at an energy of 44 MeV/u and the dose of 6×10^{14} ions/cm^2, the irradiation results in an isotropic hyperfine magnetic field distribution. The irradiation-induced decrease of the saturation magnetization reached about 80% in the low energy zone (E<0.6 GeV). Whereas, it reached only about 8% in the high energy zone (1.2 GeV<E<1.8 GeV). When the yttrium iron garnet irradiated with carbon ions at an energy of 47 MeV/u and the dose of 11.4×10^{15} ions/cm^2, the decrease of the saturation magnetization reached about 7% in the low energy zone (E<0.2 GeV) and 1% in the high energy zone (0.4 GeV<E<0.56 GeV), respectively. It is worth noting that both the argon ions in high energy zone and the carbon ions in low energy zone are of almost the same electronic energy losses of about 1000 eV/nm. Moreover, it should be pointed out that the ratio between the electronic energy losses and the nuclear energy losses of the energetic carbon ions is about ten times larger than that of energetic argon ions. This comparison clearly confirms that the modification of the microstructure and magnetic properties for yttrium iron garnet induced by 0.56 GeV carbon ions is also arised mainly from the electronic energy losses. Thus, the relation between the disordered fraction $F_d(= M_s/M_{s0})$ and the defect number N_e can be written as:

$$F_d = 1 - \exp[-N_e V \phi t]$$

which fits the case where the energetic argon ions irradiated yttrium iron garnet[9]. In this relation V is the average volume of a defect and ϕt the dose of the energetic carbon ions. By using the data listed in Table 2 obtained by VSM measurement, N_{ei} / N_{e1}, the ratio between the defect number of the sample i and that of sample 1 can be calculated (see Fig.3).

Table 2
Data of the VSM measurement

Sample No.	i=0	i=1	i=2	i=3
$\Delta M_s/M_{s0}$ (%)	0	1	2	7
$[dE/dX]_e$ /MeV·μm^{-1}	0	0.17	0.26	0.54

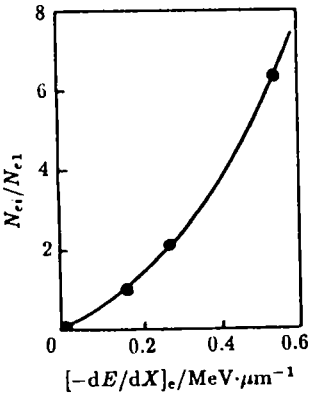

Fig.3 Change of N_{ei}/N_{e1} versus electronic energy losses

5 CONCLUSION

For 0.56 GeV carbon ion irradiated yttrium iron garnet, the decrease in the hyperfine magnetic fields and the saturation magnetization are caused by the longer Fe(a)-oxygen-Fe(d) chain and some broken chain induced by the irradiations. An additional effective local field arises from the inhomogeneity of the local saturation magnetization induced by the defects can lower the magnetic anisotropy constant and the average magnetic anisotropic field. Whereas, it leads to increase the ferrimagnetic resonance linewidth. The modification of the microstructure and magentic properties for yttrium iron garnet induced by 0.56GeV carbon ions arise mainly from the electronic energy losses.

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