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Data consistencies of swift heavy ion induced damage creation in yttrium iron garnet analyzed by different techniques

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ABSTRACT

Pronounced swelling is observed when single crystals of yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG) are irradiated in the electronic energy loss regime with various swift heavy ions. The out-of-plane swelling was measured by scanning across the border line between an irradiated and a virgin area of the sample surface with the tip of a profilometer. The step height varied between 20 and 600 nm depending on fluence, electronic energy loss and total range of the ions. The step height divided by the ion range as a function of the ion fluence exhibits a linear increase in the initial phase and saturates at high fluences leading to a density decrease of around 1.7%. With complementary channeling-Rutherford-backscattering experiments (c-RBS), the damage fraction and the corresponding damage cross section were extracted and compared to the cross section deduced from swelling measurements. Irradiation effects were also characterized by scanning force microscopy (SFM). A threshold for damage creation as deduced from all the present physical characterizations is 5.5 ± 1.0 keV/nm. The value is in full agreement with previous measurements confirming that swelling and SFM characterizations can provide information concerning the electronic energy loss threshold for track formation. In contrast, track radii deduced from swelling measurements are smaller and radii from SFM are larger than deduced from c-RBS analysis. The results of $Y_3Fe_5O_{12}$ of this work are compared with data obtained for other crystalline oxides and for ionic crystals.

1. Introduction

The effects of swift heavy ions irradiations on yttrium iron garnet ($Y_3Fe_5O_{12}$ or YIG) have been extensively studied for the past twenty years motivated by technological interest of this material e.g. in electronics industry, nuclear engineering and space application. On their way through a solid, swift heavy ions primarily deposit mainly their energy by inelastic collisions with the electrons of the target. In $Y_3Fe_5O_{12}$ garnets, the irradiation in the electronic energy loss regime generates tracks [1–3] and induces modifications of the magnetic [1] and electric properties [4]. The tracks are characterized by an amorphous structure as observed by high-resolution electron microscopy [5,6]. The size of the track radii observed directly by high resolution electron microscopy is in agreement with the track radii deduced indirectly from disorder near the surface quantified by channeling-Rutherford-backscattering as well as with the one deduced from Mössbauer spectroscopy analyzing the evolution of the beam-induced paramagnetic phase of bulk samples as a function of the ion fluence [2].

In this paper, the existing $Y_3Fe_5O_{12}$ data set is complemented by applying additional characterizations in order to investigate the consistency of track radii deduced from swelling measurement of bulk material [7–9] and from direct observation of surface track by scanning force microscopy [9,10] as compared to previous observations [1–6]. Moreover, channeling-Rutherford-backscattering experiments (c-RBS) were performed on the same samples used for swelling measurements in order to compare to previous results [3,11].

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2. Experimental conditions of irradiations

The samples were 100 μm thick films of $Y_3Fe_5O_{12}$ epitaxially grown on (1 1 1)-$Gd_3Ga_5O_{12}$. The irradiations were performed at different large accelerator facilities such as GANIL (Caen) and GSI (Darmstadt) using beam energies between 1 and 8 MeV/u leading to the corresponding respective ranges between 10 and 50 μm. Details of the irradiation parameters are listed in Tables 1–3. All irradiations were carried out at room temperature and normal to the sample surface. During irradiation, the crystals were partially masked in order to analyze the irradiated surface in direct comparison with a virgin area. For each ion species, several fluences were applied in order to follow the damage yield evolution. The maximum fluence was between 5×10^9 and 10^{14} ions/cm^2, depending of the physical characterization used afterward. In some cases, thin aluminum foils were placed in front of the samples to change the initial beam energy and thus the electronic energy loss (S_e) of the ions when impinging on the sample surface. The (S_e) values were calculated using the SRIM 2013-code [12].

3. Surface profilometry: swelling measurement

The quantitative analysis of out-of-plane swelling performed with a profilometer (Dektak III) where a high-precision stage moves the sample beneath a diamond-tipped stylus across the borderline between the irradiated and the virgin sample areas [8]. Fig. 1(a) shows the step height profiles of samples irradiated with 4.1 MeV/u Pb ions at different fluences. The evolution of the footstep height (F_{sh}) as function of the fluence is presented in Fig. 1 (b). A mean step height was extracted from several scans at each fluence. After an initial linear increase, swelling becomes sublinear and finally approaches saturation (S_{ath}) at high fluences where track overlapping becomes significant. For the irradiation with Pb and Xe, the saturation level was not reached because the sample broke at large fluence. We note that swelling scales with the range of the ions. This is obvious for the two Ni irradiations with (1.5 and 2.3 MeV/u) for which the electronic energy loss as the surface is identical, but swelling is higher for the larger beam energy and range (Table 1). In order to compare different irradiations the measured step height is thus normalized by the ion range [7–9]. In the following, we consider the mean electronic energy loss within the bombarded layer of the sample (total energy divided by ion range) and not the energy loss at the surface because the entire irradiated layer contributes to swelling.

For each irradiation the normalized swelling, i.e. the step height divided by the range, is plotted as a function of the ion fluence (ϕt) (Fig. 2a). The solid lines represent a fit of the experimental data by an exponential law, $F_{sh}\ (\phi t) = S_{ath} \times (1 - \exp\ (-\sigma_s \times \phi t))$ which allows us to deduce the saturation value S_{ath} and the swelling cross section σ_s and the extracted values for all irradiations are reported in Table 1. In order to test the correlation between swelling and the energy loss [7–9], the normalized swelling rate per ion in the low fluence regime (no track overlap) was determined. This relative dimensional change per ion plotted versus the mean energy loss is shown in Fig. 2(b). A linear extrapolation to the energy loss axis yields a swelling threshold of 5 ± 1 keV/nm, quite in agreement with previous observations [3,10]. The error of the energy loss threshold takes into account the uncertainty of the values given by the SRIM 2013-code [12] (between 10% and 20%) and the end of the ion range which is not damaged for S_e values below the S_e threshold.

Table 2
Ion beam parameters and results of channeling-Rutherford-backscattering analysis; S_e is the electronic energy loss at the surface, σ_d the cross section of the track cylinder in which disorder is created and R_d is the track radius deduced from the cross section σ_d.

Ions*	Energy (MeV/u)	S_e (keV/nm)	σ_d (cm^2)	R_d (nm)
^{58}Ni	1.5	13	$(2.8 \pm 0.5) \times 10^{-13}$	2.9
^{136}Xe	1.2	24	$(8.6 \pm 1.7) \times 10^{-13}$	5.2
^{136}Xe	4.2	29	$(1.2 \pm 0.3) \times 10^{-12}$	6.2
^{208}Pb	4.1	41	$(1.3 \pm 0.3) \times 10^{-12}$	6.4
^{238}U	5.9	46	$(2.0 \pm 0.4) \times 10^{-12}$	8.0

* Apart from the irradiation with U ions, all samples were used for c-RBS and swelling measurements.

The volume expansion of the irradiated sample is limited by the constraints of the non-irradiated substrate. Beam-induced swelling thus occurs mainly normal to the sample surface and leads to a reduction in mass density according to [8]:

$$\frac{S_{ath}}{R_p} \approx \frac{\Delta V}{V} = \frac{\rho_{virgin} - \rho_{irradiated}}{\rho_{virgin}}$$

S_{ath} denotes the step height value at saturation extrapolated from the fit at large fluence and reported in Table 1, V is the volume and ρ the density. From our step height measurements, a mean density decrease for irradiated $Y_3Fe_5O_{12}$ of 1.7 ± 0.3% was obtained.

4. Damage analysis by channeling-Rutherford-backscattering (c-RBS)

Radiation damage of the irradiated crystal was analyzed by means of Rutherford backscattering under channeling condition (c-RBS). The analysis was performed at the 4 MV Van de Graff accelerator of INeSS laboratory in Strasbourg [12] using a 2-MeV $^4He^+$ beam. The backscattered ^4He particles were detected in a silicon detector placed at an angle of 160° with respect to the incident beam and providing a solid angle of 0.65×10^{-3} steradians. Using the surface approximation, the backscattering yield χ was measured by extrapolating the energy evolution of the yield over the first 500 nm up to the mean energy of the random edge. The damage fraction (F_d) of the material was calculated with the formula $F_d = (\chi_i - \chi_v)/(\chi_r - \chi_v)$, where χ_i and χ_v are the backscattering under channeling condition of the irradiation and of the virgin part of the sample, respectively, and χ_r corresponds to the yield of the randomly-oriented crystal. Assuming that at high ion fluence the maximum disorder is reached [3], the overlapping of tracks

Table 1
Ion beam parameters and swelling results obtained by profilometry. $\langle S_e \rangle$ is the mean energy loss equal to the beam energy divided by the range R_p [12], σ_s is the swelling cross section, S_{ath} is the step height value at saturation extrapolated to large fluence and R_s is the damage radius deduced from the cross section σ_s.

Ions	Energy (MeV/u)	S_e at surface (keV/nm)	σ_s (cm^2)	S_{ath} (nm)	R_p (μm)	Mean S_e (keV/nm)	Initial slope/R_p (cm^2)	S_{ath}/R_p	R_s (nm)
^{58}Ni	2.3	13	$1.4 \cdot 10^{-13}$	230	15	10	$2.1 \cdot 10^{-15}$	0.0152	2.2
^{58}Ni	1.5	13	$1.5 \cdot 10^{-13}$	140	10	8	$2.1 \cdot 10^{-15}$	0.0140	2.3
^{107}Ag	7.8	23	$2.8 \cdot 10^{-13}$	670	40	21	$4.7 \cdot 10^{-15}$	0.0168	3.0
^{136}Xe	1.2	25	$2.2 \cdot 10^{-13}$	220	11	14	$4.0 \cdot 10^{-15}$	0.0204	2.5
^{136}Xe	4.2	29	$2.2 \cdot 10^{-13}$	(550)*	26	22	$4.7 \cdot 10^{-15}$	0.0210	2.7
^{208}Pb	4.1	41	$7.5 \cdot 10^{-13}$	(450)*	28	30	$1.1 \cdot 10^{-14}$	0.0160	4.9

* By extrapolation.