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Color centers induced in $Y_3Al_5O_{12}$ single crystals by swift heavy ions and reactor neutrons

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Abstract

The induced damage in single crystals of yttrium alumina garnet ($Y_3Al_5O_{12}$) bombarded at GANIL with 561 MeV ^{51}Cr, 466 MeV ^{128}Te, and 957 MeV ^{208} Pb ions, and at Algiers with reactor neutrons has been studied by optical measurements. Optical absorption bands centered at 250, 300 and 380 nm are observed after irradiation with ions and neutrons. The variation of the absorption as a function of fluence and electronic stopping power are presented and discussed. Photoluminescence, excited from 380 nm optical absorption band of this garnet is measured at room temperature. The results show the increase of the emission band width with increasing electronic stopping power. The confrontation of the results obtained with ions and neutrons irradiation confirm the contribution of the energetic heavy ions to point defects production. Furthermore, the existence of an electronic stopping power threshold between 10 and 15 keV/nm for oxygen ions displacements is derived.

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Keywords: Radiation damage; Luminescence; Swift heavy ions; Neutrons

1. Introduction

Colors centers induced in $Y_3Al_5O_{12}$ crystals by low ionizing radiation (γ rays, electrons, protons and neutrons) has intensively been studied in the past [1–6]. Most of the defects produced by fast neutrons via elastic collision are oxygen vacancies [7,8] and each vacancy can trap one or two electrons to form F and F^+ center, respectively. The latter can be identified by their absorption bands centered at about 243 and 380 nm [9,10], respectively. Meftah et al. [11], have studied the effects of heavy ions in yttrium alumina garnet in the electronic stopping power regime. The extent of the induced damage has been extracted from channeling Rutherford backscattering and the corresponding track radii are deduced. Indeed, it is now well established that swift heavy ions penetrating into matter lose their energy by elastic collisions with the target atom nuclei (the nuclear stopping power S_n), and by interaction with the target electron (the electronic stopping power S_e). For swift heavy ions with energy higher than around 1 MeV/amu, the energy deposition, a few keV/nm, is mainly done through ionization and electronic excitation process and can produce amorphous ionization tracks along the ion path. Despite the work performed in some oxides, Al_2O_3 [12,13], TeO_2 [14], $LiNbO_3$ [15], MgO [16,17], the efficiency of swift heavy ions for point defect production is not clear.

In this paper, the optical measurements are carried out in order to study the color center creation by swift heavy ions at different fluences and different electronic stopping powers S_e and compare these measurements with those obtained from irradiations with reactor neutrons.

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2. Experimental procedure

High-quality single crystals of $Y_3Al_5O_{12}$ have been irradiated [11] with 561 MeV ^{51}Cr, 466 MeV ^{128}Te, and 957 MeV ^{208}Pb ion beams. The irradiations were performed at the GANIL accelerator in Caen, France. A degrador was used whenever possible for covering different values of electronic stopping power S_e (6–29) keV/nm in the same irradiation. Table 1 lists the beam parameters of different irradiation experiments. The S_e and the projected range R_p values were calculated using SRIM2003 code. The mean dose D was deduced from the fluence using the following formula [18]:

$$D = 1.6 \times 10^{-10} \frac{E\phi}{\rho R_p}, \tag{1}$$

where D is given in Gy, E is the total energy in MeV, ϕ denotes the fluence in ion/cm^2, $\rho = 4.56$ g/cm^3 is the mass density of $Y_3Al_5O_{12}$, and R_p is the range in cm.

The irradiation with neutrons was performed at NUR research reactor, Algiers, at a position where the maximum temperature and the fast neutron flux were approximately 40 °C and 1.48×10^{13} cm^{-2} s^{-1}, respectively. This flux was measured with a Cd-covered Indium foil based on ^{115}In (n, n') In^{115m} reaction with neutron energy threshold of 1.2 MeV.

After irradiation, the optical absorption measurements and the photoluminescence were carried out using Cintra 40 UV–visible spectrometer in the wavelength range 190–900 nm and Perkin–Elmer LS50B Luminescence Spectrometer, respectively. The measurements were made at room temperature.

The absorption coefficients were determined from:

$$\mu = \frac{\mathrm{OD}}{e}, \tag{2}$$

where OD is the optical density and e is the sample thickness in the case of neutron irradiations and the ion range in the case of ions irradiations.

All the measurements are made in the same conditions at 300 K and the color center concentration N is calculated using Smakula's formula by assuming a Gaussian shape of the absorption band:

$$N = 0.87 \times 10^{17} \frac{n}{f(n^2+2)^2} w\mu, \tag{3}$$

where f is the oscillator strength, n is the refractive index, and w is the FWHM of the band.

3. Results and discussion

3.1. Optical absorption measurements

The optical absorption of the irradiated $Y_3Al_5O_{12}$ single crystals was investigated as a function of both fluences and electronic stopping power S_e. The optical absorption spectra obtained for samples irradiated with Cr (11.6 MeV/u), Te (2 MeV/u) and Pb (0.93 MeV/u) ions, and for comparison with reactor neutrons are illustrated in Fig. 1. The same absorption bands centered at 250, 300 and 380 nm are observed in all irradiations suggesting the identical nature of the defects induced by ion and neutron irradiation.

Fig. 2 shows the optical absorption for $Y_3Al_5O_{12}$ irradiated with Cr (11.6 MeV/u), Te (1.15 MeV/u) and Pb (0.93 MeV/u) ions with different fluences. The absorption intensity clearly depends on the ion fluence. However, it is

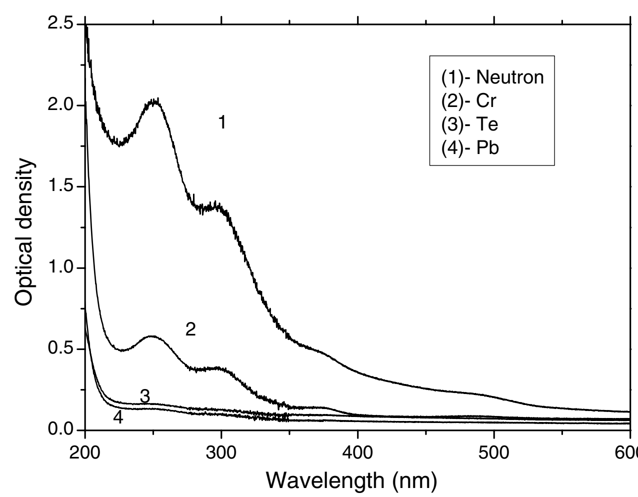

Fig. 1. Optical absorption spectra of $Y_3Al_5O_{12}$ single crystal irradiated with fast neutrons (En > 1.2 MeV, 20.6 MGy, 5.86×10^{17} cm^{-2}), 511 MeV Cr ions (20 MGy, 70×10^{11} cm^{-2}), 256 MeV Te ions (3 MGy, 7×10^{11} cm^{-2}) and 193 MeV Pb ions (4 MGy, 8×10^{11} cm^{-2}).

Table 1
Irradiation conditions of the samples

Ion species	Energy (MeV/u)	S_e (keV/nm)	S_n (keV/μm)	R_p (μm)	Fluence range (cm^{-2})
^{52}Cr	1.7	10	17	10.9	4×10^{11}–7×10^{12}
	4.6	9	7	25.7	4×10^{11}–7×10^{12}
	6.6	8	5	37.5	4×10^{11}–7×10^{12}
	11	6	3	69.9	4×10^{11}–7×10^{12}
^{128}Te	1.15	19	104	12.56	3×10^{11}–7×10^{11}
	2	23	68	17.33	3×10^{11}–7×10^{11}
^{208}Pb	0.93	29	284	11.6	2×10^{11}–8×10^{11}