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Color center creation in LiF crystals irradiated with Xe, Kr and N ions: Dependence on fluence and beam current density

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ABSTRACT

Single LiF crystals were irradiated with Xe (195 MeV), Kr (117 MeV), and N (18 MeV) ions. Using absorption spectroscopy, color center creation was analyzed as a function of the ion energy loss, fluence, and flux. The concentration of single F centers and F_2 centers versus fluence and flux exhibits a nonlinear evolution with saturation at higher fluences. For LiF irradiated with N ions at high fluence, the concentration of F centers is proportional to the cube root of the flux indicating the strong interaction of primary hole centers. Macroscopic hillocks were observed in all irradiated LiF crystals by atomic force microscopy.

1. Introduction

Heavy ion induced damage in LiF and other alkali halides can be described by a nanosize core region with defect aggregates and a larger halo of several tens of nanometers with color centers [1–3]. The defect creation in alkali halides is determined by electronic excitations (excitons, electrons and holes) [3–5]. Therefore, the defect creation strongly depends on the energy loss of the ions.

The aim of this study is investigate peculiarities of damage creation in LiF crystals irradiated with heavy ions at high beam current (flux). Color centers were studied by absorption spectroscopy in the spectral range of 6–1.5 eV (200–850 nm), and atomic force microscopy (AFM) was used for macro-defect studies on the irradiated surface.

2. Ion irradiation

LiF crystals (GOI, St. Petersburg, Russia) cleaved along one of the (1 0 0) plane with the thickness of 1 mm were irradiated at the ion cyclotron accelerator DC-60 (Astana, Kazakhstan). All experiments were carried out at room temperature with normal beam incidence. The irradiation for 195 MeV Xe ions ranged from 6×10^{10} to 10^{13} ions/cm^2 with a flux (φ) from 6.24×10^9 to 10^{10} ions/cm^2 s, for 117 MeV Kr ions from 6×10^{10} to 4×10^{11} ions/cm^2 with a flux 10^{10} ions/cm^2 s, and for 18 MeV N ions from 2.4×10^{11} to 10^{13} ions/cm^2 with a flux from 3×10^9 to 3×10^{11} ions/cm^2 s. The irradiation parameters are presented in Table 1 [6]. The flux φ depends on the effective charge of the ion (k) and the beam current density i_{beam} (nA/cm^2) and is equal to $\varphi = 6.24 \times 10^9$ $i_{beam} \times k^{-1}$. The ion range was in all cases smaller than the sample thickness. For all ions and at this range of energy the electronic energy loss was much larger than the nuclear energy loss which can be neglected [1].

3. Results and discussion

3.1. Optical absorption and the concentration of color centers

Absorption spectra were measured in the range 1.5–6 eV which corresponds to the absorption of the main electron color centers in LiF crystals. Stable at room temperature hole centers (V_3) have the absorption maximum in VUV spectral region (10.8 eV) and are not discussed in this study [7]. In the absorption spectra, F and F_2 centers are dominating (Fig. 1). The absorption at $h\nu \leqslant 4$ eV depends on the energy loss and the fluence, as well on the beam current density [1–3]. We studied color center creation via fluence and flux (beam current). At low fluences ($\Phi < 10^{10}$ ions/cm^2) and for lower energy loss ($(dE/dx)_e < 10$ keV/nm) only F and F_2 centers are created with the absorption maximum at 4.95 eV (250 nm) and 2.79 eV (445 nm), respectively. At higher fluences ($\Phi > 10^{11}$ ions/cm^2) and for higher energy losses ($(dE/dx)_e > 10$ keV/nm) and higher beam current density ($i_{beam} > 50$ nA/cm^2) besides F_2 centers also F_3, F_4 and other aggregate centers are created [2]. The increase of the beam current leads to a higher excitation level during irradiation and an enhancement of the efficiency of color center creation takes place, especially for F_n and F center aggregates [2]. The ratio of the concentration of F to F_n centers depends on several factors:

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Table 1
Irradiation parameters [6].

E_{ion} (MeV)	R (μm)	Effective charge (k)	$(dE/dx)_e$ (keV/nm)	$(dE/dx)_n$ (keV/nm)
Xe, 195	17.6	+20	18.85	0.052
Kr, 117	15.3	+13	12.11	0.026
N, 18	11	+2	1.65	0.0013

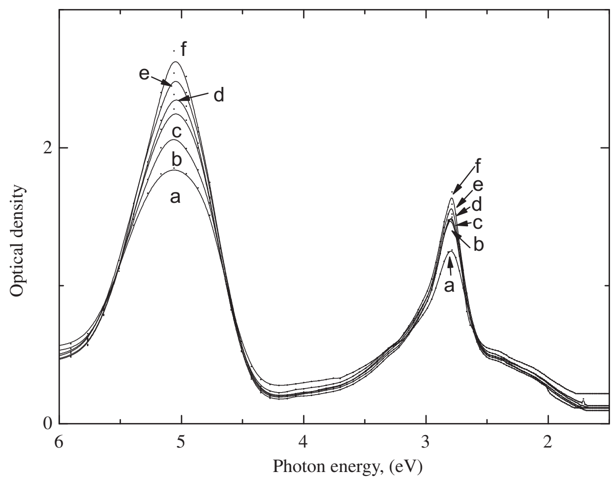

Fig. 1. Absorption spectra for LiF crystals irradiated with 195 MeV Xe ions at a fluence $\Phi = 9.5 \times 10^{12}$ ions/cm^2 with various beam current density [nA/cm^2]: a, 20; b, 35; c, 50; d, 65; e, 80; f, 100.

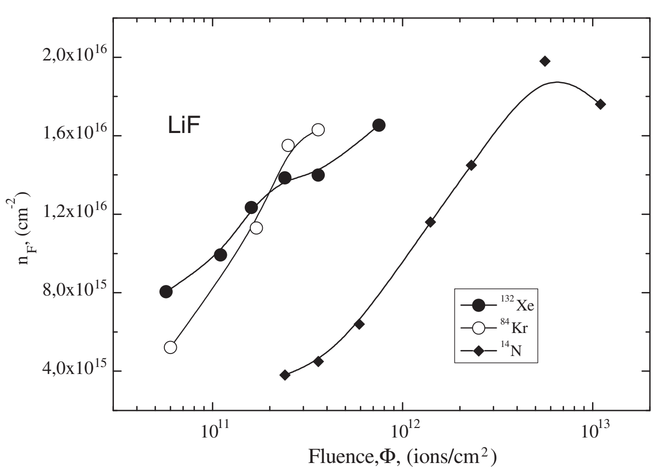

Fig. 2. Concentration of F centers (n_F, cm^{-2}) via fluence (Φ) in LiF crystals irradiated with ^{14}N, ^{84}Kr, and ^{132}Xe-ions at a constant beam current density of 10 nA/cm^2.

(1) the energy loss of the ion, (2) the fluence, and (3) the beam current (flux).

It is difficult to estimate the exact concentration of F_n centers due to the overlapping of various F_n centers and F center aggregates [1,2]. Therefore, we used an approximation and estimated the whole concentration of various F_n centers using the optical density of F_2 centers (the absorption of F_2 centers is dominating in the spectral region $h\nu \leqslant 4$ eV) [1].

The efficiency of color center creation was estimated from the concentration of F and F_2 centers, the number of F centers in a single track, and the energy to create an F center ΔE_F.

The concentration of created F and F_2 centers was estimated from the optical density at the absorption maxima [1,2] according to $n_F[\text{cm}^{-2}] = 9.48 \times 10^{15} \times D_{opt}(F)$ and $n_2[\text{cm}^{-2}] = 4.421 \times 10^{15} \times D_{opt}(F_2)$. The average volume concentration of F and F_2 centers can be estimated as $N_F = n_F/R$ and $N_2 = n_2/R$, where R is the ion range.

The number of F centers in a single ion track n^s is equal to $n^s = n_F/\Phi$. From n^s, we can estimate the average energy for F center creation $\Delta E_F = E_{ion}/n^s = E_{ion} \times \Phi/n_F$. The value of ΔE_F characterizes the efficiency of color center creation under various irradiation conditions [1–3].

3.2. Efficiency of color center creation via fluence

We analyzed the efficiency of color center creation versus fluence and beam current density. In Fig. 1 the absorption spectra are presented for LiF irradiated with Xe ions at a constant fluence ($\Phi = 9.5 \times 10^{12}$ ions/cm^2) with various beam current. We observed only a small increase of the absorption for the F and F_n centers by increasing i_{beam} from 20 to 100 nA/cm^2. The influence of the beam current density was much smaller than in the study of Lushchik et al. for LiF irradiated with 5 and 10 MeV Au ions [2]. This, probably, can be explained by the higher energy and higher $(dE/dx)_e$ for Xe ions which leads to a saturation of color centers at $\Phi = 9.5 \times 10^{12}$ ions/cm^2.

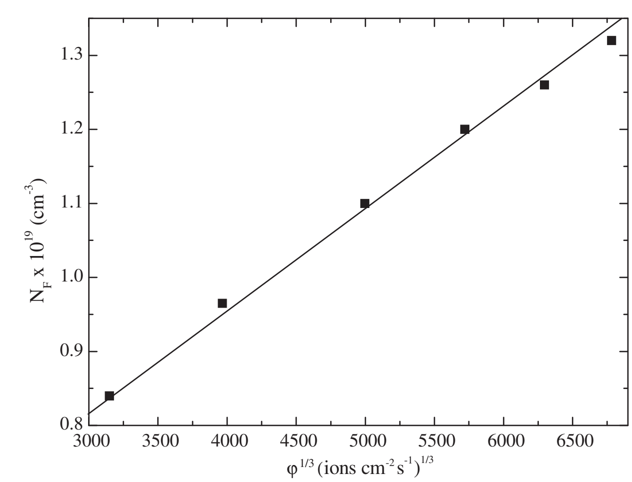

Fig. 3. In LiF irradiated with 18 MeV N ions at a constant fluence of 9.5×10^{12} ions/cm^2 the volume concentration of F centers N_F is proportional to $\varphi^{1/3}$.

Table 2
Color centers in ion irradiated LiF crystals at a constant beam current density of 10 nA/cm^2.

Ion	Φ (ions/cm^2)	E_{abs} (eV/cm^2)	$n_F \times 10^{15}$ (cm^{-2})	n_2/n_F	$n^s \times 10^4$	ΔE_F (keV)
^{132}Xe	5.71×10^{10}	1.10×10^{19}	8.1	0.17	14	1.4
	7.51×10^{11}	1.51×10^{19}	16.5	0.46	2.2	8.8
^{84}Kr	6.1×10^{10}	7.10×10^{18}	5.2	0.11	8.7	1.3
	3.61×10^{11}	4.21×10^{19}	16.3	0.15	4.5	2.6
^{14}N	2.41×10^{12}	4.30×10^{19}	3.8	0.14	1.5	1.1
	10^{13}	1.81×10^{20}	17.6	0.47	0.1	11.3