# High-Temperature Dielectric Relaxations in LiF Single Crystals

Jing Wang,<sup>‡</sup> Chunchang Wang,<sup>‡,†</sup> Qiuju Li,<sup>‡</sup> Yi Yu,<sup>‡</sup> Jian Zhang,<sup>§</sup> Jun Zheng,<sup>¶</sup> Chao Cheng,<sup>¶</sup> Yide Li,<sup>‡</sup> and Hong Wang<sup>‡</sup>

<sup>‡</sup>Laboratory of dielectric functional materials, School of Physics and Material Science, Anhui University, Hefei 230601, China

<sup>§</sup>School of Electronics Science and Applied Physics, Hefei University of Technology, Hefei 230009, China

<sup>¶</sup>Center of Modern Experimental Technology, Anhui University, Hefei 230039, China

By means of dielectric permittivity, electric modulus and impedance, the dielectric properties of LiF single crystals were investigated in the temperature range of  $30^{\circ}\text{C}-800^{\circ}\text{C}$  and frequency range of 50 Hz–10 MHz. Two thermally activated relaxations, R1 and R2, were observed. The relaxation R1 showing activation energy around 0.8 eV was found to be related to the Li-ion diffusion in the crystal. The relaxation R2 contains three Arrhenius segments, the low-, mid-, and high-T segments, separated by boundary temperatures of 325°C and 425°C. These segments in the order of ascending temperature were found to be associated with F<sub>3</sub>, F<sub>3</sub><sup>+</sup> centers, F<sub>2</sub> centers, and F centers, respectively.

## I. Introduction

ITHIUM fluoride (LiF) has gained considerable interest in recent years owing to various applications: because of its extremely wide energy gap (~14.2 eV), LiF crystal was first used as an optical material for vacuum ultra violet range.<sup>1</sup> Later, the doped LiF was developed for dosimetry;<sup>2-4</sup> Because of its simple crystalline structure, LiF crystals also serve as model objects in solid-state physics; Besides, as one of the initially transparent materials, the stability of optical transparence even under strong shock compression makes LiF crystals a promising material used as optical windows in laser interferometric, spectroscopic, and pyrometric measurements;<sup>5–8</sup> Moreover, LiF doped with WO<sub>3</sub> and TiO<sub>2</sub> was used as a scintillator for neutrino registration as well.<sup>9</sup> Over the last three decades, alkali-halide crystals with color centers (CCs) have been used for tuning laser-active media,<sup>10</sup> etc. All these applications require a thorough understanding of the properties of LiF crystals. The wide energy gap of LiF allows the properties of LiF to be readily modulated by both native defects and alien impurities intentionally introduced by dop-ing or other methods,<sup>11</sup> as these defects can induce various energy levels in the band gap. Therefore, understanding and engineering the defects are critical in the applications of LiFbased devices.

In the past years, defects in LiF crystals induced by gamma rays, electrons, neutrons, and heavy ions were extensively studied.<sup>12–15</sup> However, among the primary defects, F centers, i.e., electrons at an empty anion site, were formed relatively easily. At higher irradiated dose, the F centers aggregate and induce F clusters ( $F_2$ ,  $F_3$ , and  $F_4$  centers, in concrete terms,  $F_2$  center is an anionic vacancy pair trapping

cn

Manuscript No. 36061. Received December 16, 2014; approved April 23, 2015. <sup>†</sup>Author to whom corrrespondence should be addressed. e-mail: ccwang@ahu.edu.

two electrons and so on). Doped with divalent impurities, under ionizing radiation, LiF crystals involve the  $F_2^{\pm}$  center and impurity-vacancy (IV) dipole.<sup>16</sup> The presence of the IV dipole directly leads to a stabilization effect, that is, lengthening the disintegration time. The model for CCs in other defects like the well-known oxygen and OH<sup>-</sup>-containing lithium and sodium-fluoride laser crystals, has not been precisely established.<sup>10,17</sup> Some prior dynamic studies and annealing experiments showed that the F centers are stable at room temperature, but will recombine with hole centers at temper-atures higher than 360 K ( $\sim$ 87°C),<sup>18,19</sup> and the annihilation and transformation of color centers during thermal annealing of LiF crystals irradiated with high-energy ion projectiles are complex processes depending on the initial defect spectrum and on the annealing temperature.<sup>20</sup> The optical spectra were widely investigated, and the density of the different kinds of crystal defects like F, F2, or F3 centers can be determined from the intensity of the respective absorption lines.<sup>21–24</sup> It is well known that the optical properties are directly correlated with the dielectric properties. So, the dielectric properties of LiF single crystals are of vital importance for understanding their optical properties. In this paper, we carried out detailed investigation on the dielectric properties of pure LiF single crystals in the temperature range from room temperature (~30°C) to 800°C and the frequency range of 50 Hz-10 MHz. The obtained results indicate that the dielectric properties of LiF single crystals are strongly related to the F-like centers.

## **II. Experimental Procedure**

LiF single crystals with (100) orientation and the size of  $3 \text{ mm} \times 3 \text{ mm} \times 1 \text{ mm}$  were purchased from MTI Corporation (Hefei, China). Element analysis performed with an inductively coupled plasma (ICP-OES, IRIS Intrepid II, Thermo Electron, Waltham, MA) revealed some trace impurities of Na, Fe, Ca, and Cl with the concentration less than 0.005 mg/L. The frequency-dependent dielectric properties were measured by using a Wayne Kerr 6500B precise impedance analyzer (Wayne Kerr Electronic Instrument Co., Shenzhen, China) with the sample mounted in a holder placed inside the PST-2000HL dielectric measuring system (Wuhan Pusite Instrument Co., Wuhan, China). The temperature variations rate is 3°C/min which was automatically controlled by a PCT10 Stanford temperature controller (Stanford Research System Instrument, Sunnyvale, CA). The amplitude of the ac measuring signal was 100 mV. Electrodes were made by coating both sides of the samples with silver paste (or platinum paste which will be explicitly noted for comparison) then fired at about 300°C for 30 min to remove the polymeric component and achieve good sample/electrode contacts. The remaining Ag (Pt) cap can effectively prevent the most likely defects such as oxygen and/or OH<sup>-</sup> from entering the crystal during

J. Nino-contributing editor

the thermal treatments. It is quite sure that other defects are not been generated in our investigation.

## III. Results and Discussion

The temperature (T) dependence of the real  $(\varepsilon')$  and imaginary  $(\varepsilon'')$  parts of the complex permittivity  $(\varepsilon^*)$  at various frequencies for an LiF single crystal is displayed in Figs. 1(a) and (b), respectively. It is seen that there are two step-like increases in  $\varepsilon'(T)$  accompanied by two sets of relaxation peaks in the curves of  $\varepsilon''(T)$ . The positions of the peaks shift to high temperature with increasing frequency, indicating that there are two thermally activated Debye-like relaxations in the investigated sample. For brevity, the relaxations were termed as R1 and R2, as indicated in Fig. 1(b), in the order of ascending temperature. Due to the pronounced increasing background caused by conductivity in the high temperature range, both of the peaks actually behave as humps, which lead to the exact peak positions not being read out from the curves of  $\varepsilon''(T)$ . In this case, the electric modulus spectroscopy,  $M^*$ , defined as  $M^* = 1/\varepsilon^*$ , known as a "good" dielectric function in revealing the hidden dielectric relaxation is needed. The temperature dependence of the imaginary part of electric modulus (M'') at various frequencies is shown in the inset of Fig. 1(a). It is clearly seen that the plots contain two dielectric peaks convincing the two relaxation processes. Activation energy analysis is favorable for better understanding the relaxation mechanism. Thus, we tried to calculate the activation energy of the two relaxations. In doing so, the accurate positions of these relaxations are required. We, therefore, applied multipeak fitting method by using two Deby peaks to fit the experimental data of M''(T). As we all know, a Debye peak is symmetric, we therefore used formula

$$y = (A_1/(w_1 \times \sqrt{\pi/2})) \times \exp(-2 \times ((x - x_{c1})/w_1)^2) + (A_2/(w_2 \times \sqrt{\pi/2})) \times \exp(-2 \times ((x - x_{c2})/w_2)^2)$$
(1)

where  $A_i$ ,  $w_i$ , and  $x_{ci}$  (i = 1, 2) represent the peak area, width, and position, respectively, to fit the experimental data of M''(T) and M''(f). The fitting can give the accurate peak position, particularly at high frequencies (~10<sup>6</sup>) where two



Fig. 1. Temperature dependence of  $\varepsilon'$  (a) and  $\varepsilon''$  (b) for LiF single crystal measured at various frequencies. The inset shows temperature dependence of electric modulus (M'') at various frequencies.



**Fig. 2.** (a) The comparison between the experimental data (open circles) measured at 10 kHz and fitting result (solid curve through the data points). The dashed curves are the resultant fitting peaks for R1 and R2. (b) The Arrhenius plots for R1 and R2 deduced from the fitting peaks, with an inflection temperature at ~400°C.

peaks are almost overlapped. As a typical example, the resultant Debye peaks and the comparison between the fitting result and the experimental data obtained at 10 kHz are shown in the Fig. 2(a). The solid fitting curve passes through all the data points indicating that the fitting is perfect. The measuring frequency, f, as a function of the peak position,  $T_{\rm P}$ , was plotted according to the Arrhenius law

$$f = f_0 \exp\left(-E_a/k_{\rm B}T_{\rm P}\right) \tag{2}$$

where  $f_0$  is the pre-exponential factor,  $E_a$  is the activation energy for relaxation, and  $k_B$  is the Boltzmann constant. Figure 2(b) shows the Arrhenius plots for R1 and R2. It is found that R1 features perfect Arrhenius relation. The data points of R2, however, distinctly deviate from the Arrhenius relation leading to two Arrhenius segments, separated by an inflect temperature of ~400°C. The activation energy and pre-exponential frequency factor for R1, the low-, and high-T segments of R2 were found to be 0.78, 1.37, 0.76 eV and  $1.13 \times 10^{11}$ ,  $1.05 \times 10^{15}$ ,  $1.59 \times 10^{10}$  Hz, respectively.

To obtain more information about the dielectric properties of an LiF single crystal, we carried out detailed impedance and modulus analysis in the frequency domain. Figure 3(a) shows the spectroscopic plots of electric modulus at various temperatures. The values of the electric modulus were calculated from the data of the impedance in terms of the relationship  $M^* = M' + jM'' = j2\pi f C_0 Z^*$ , where  $j = \sqrt{-1}$ ,  $Z^* = \overline{Z'} + j\overline{Z''}$  is the complex impedance, and  $C_0$  is the vacuum capacitance. It is seen that the first M'' peak appears when the measuring temperature rises to higher than 150°C. This peak moves to high frequency with increasing temperature. When the measuring temperature was elevated higher than 250°C, the second M'' peak comes into the measuring frequency window. The two M" peaks indicating two relaxation processes can be clearly seen as there is no detectable background. The frequency gap between the two peaks becomes smaller and smaller as the peaks move to high frequency with increasing temperature. When temperature rises to higher than 400°C, both peaks superimpose each other and only one peak can be observed hereafter. For a





**Fig. 3.** (a) Frequency dependence of electric modulus (M'') for LiF crystal measured at 35°C, 100°C, 150°C, 175°C, 200°C, 225°C, 250°C, 275°C, 300°C, 325°C, 350°C, 375°C, 400°C, 425°C, 450°C, 500°C, 550°C, 600°C, 650°C, and 700°C (from left to right). (b) The comparison between the experimental data (open circles) measured at 375°C and fitting result (solid curve through the data points). The dashed curves are the resultant fitting peaks for R1 and R2. (c) The Arrhenius plots for R1 and R2 deduced from the fitting peaks.

thermally activated relaxation, the high (low)-frequency relaxation in the frequency domain corresponds to the low (high)-temperature relaxation in the temperature domain. Therefore, the high- and low-frequency relaxations can be identified to be R1 and R2, as observed in the temperature domain [see Fig. 1(b)], respectively. To extract the peak position accurately in the whole measuring temperature range, two Debye peaks were used to fit the experimental data. As a representative example, Fig. 3(b) displays the comparison between the fitting results and the experimental data recorded at the temperature of  $375^{\circ}$ C. It is seen that the fitting curve perfectly mimics the experimental data (open circles). The two resulting Debye peaks (dashed curves) are also shown in the Fig. 3(b). The peak position  $f_P$  was plotted as a function of the reciprocal of the measuring temperature T according to the Arrhenius law [Fig. 3(c)]. Again, we can see that R1 shows perfect Arrhenius behavior, whereas R2 shows three Arrhenius segments with two crossover temperatures locating at ~325°C and 425°C. For brevity, the low-, mid-, and high-T segments of R2 were termed as LTSR2, MTSR2, and HTSR2, respectively. It is seen that much more detailed information can be obtained in the frequency domain as compared with the temperature domain; thanks to the fact that much more data points can be tested in the frequency domain. The values of  $f_0$  and  $E_a$  for R1 and R2, deduced from the Arrhenius plots are listed in Table I.

Figure 4(a) presents the Nyquist plots for LiF single crystals in the temperature range from room temperature (35°C) to 700°C as tested in Fig. 3(a). The plots were obtained by plotting Z" versus Z', where Z' and Z" are the real and imaginary parts of the complex impedance Z\*. A semicircle is clearly seen with its diameter decreasing with increasing measuring temperature. Theoretically, the semicircle can be modeled by a RC (R = resistance and C = capacitor) unit with both elements collected in parallel. Since the semicircle reaches its apex with the value of Z'' = R/2 at the frequency where  $2\pi/RC = 1$  is fulfilled, we can easily read out the resistances at the tested temperatures. From Fig. 4(b), it can be seen that the resistance data follow the Arrhenius law which can be described as:

$$R = R_0 \exp\left(E_{\rm cond}/k_{\rm B}T\right) \tag{3}$$

where  $R_0$  is the pre-exponential term,  $E_{\rm cond}$  is the activation energy of conduction. The Arrhenius plot reveals two linear segments of the resistance with the values of  $E_{\rm cond} = 1.59$ , and 1.06 eV for the low- and high-temperature segments and a crossover temperature of ~425°C. This temperature is the same as that deduced from M''(f), indicating that the relaxation R2 is intimately linked with the conduction. Therefore, R2 might be ascribed to be conduction-related relaxation. It should be a bulk response rather than an interfacial response. This inference is confirmed by further dielectric measurements on the same crystal used in Fig. 3 with the silver electrodes replaced by platinum ones.

Figure 5(a) shows the electric modulus M''(f) of the crystal covered with platinum electrodes measured at the same temperatures as those tested in Fig. 3(a). The comparison between the perfect fitting and the experimental data at the temperature of 350°C is shown in the inset of Fig. 5(a). Figure 5(b) displays the Arrhenius plots of R1 and R2. The values of  $f_0$  and  $E_a$  for R1 and R2 calculated from the Arrhenius plots were also listed in Table I. After careful comparison, two main features can be summarized: (1) Changing electrode has negligible influence on R1, indicating that R1 is also a bulk response; (2) LTSR2 disappears completely, and the activation energy for MTSR2 (1.90 eV) is somewhat higher than before (1.75 eV). These results strongly indicate that the relaxing species for R2 might be F-like (F<sub>2</sub>, F<sub>3</sub>, and F<sub>3</sub><sup>+</sup>) centers, because they are sensitive to

Table I.Relaxation Parameters ( $E_a$  and  $f_0$ ) for Relaxations 1 (R1) and the Low-, Mid-, and High-T Segments (LTS, MTS, and<br/>HTS) of Relaxation 2 (R2) of LiF Crystal Measured at Different Cases (Ag, Pt = sAg electrode, Pt electrode)

Measuring case				R2					
	R1		LTSR2		MTSR2		HTSR2		
	$E_{\rm a}~({\rm eV})$	$f_0$ (Hz)	$\overline{E_{\rm a}~({\rm eV})}$	$f_0$ (Hz)	$E_{\rm a}~({\rm eV})$	$f_0$ (Hz)	$E_{\rm a}~({\rm eV})$	$f_0$ (Hz)	
As-prepared (Ag) As-prepared (Pt) After-quenched (Ag)	0.81 0.82 1.06	$\begin{array}{c} 2.54 \times 10^{11} \\ 2.97 \times 10^{11} \\ 3.05 \times 10^{12} \end{array}$	1.12	2.68 × 10 <sup>12</sup>	1.75 1.90	$5.32 \times 10^{17}$ $1.06 \times 10^{19}$	1.07 1.04 0.83	$5.13 \times 10^{12} \\ 3.96 \times 10^{12} \\ 3.16 \times 10^{9}$	



Fig. 4. (a) Complex impedance plots for LiF crystal at the temperatures as tested in Fig. 3(a). (b) The Arrhenius plot for resistance.

the thermal annealing process as the measurement is virtually a heating run after the firing electrode treatment.

Based on the above results, we can discuss the mechanism of the observed dielectric relaxations. Firstly, we focus on R1. The activation energy of R1 (0.81 eV obtained from the frequency domain and 0.78 eV obtained from the temperature domain), is comparable with the value 0.89 eV reported



**Fig. 5.** (a) Frequency dependence of electric modulus (M'') for LiF crystal with platinum electrode measured at various temperatures as tested in Fig. 3(a). Inset shows the comparison between the experimental data (open circles) measured at 350°C and fitting result (solid curve through the data points). (b) The Arrhenius plots for R1 and R2 deduced from the fitting peaks.

by Zaafouri et al.,<sup>25</sup> which is correlated with the diffusion of Li-ion in the crystal. Therefore, R1 can be argued to be related to the diffusion of Li-ion in the crystal.

We now turn our attention to the origin of R2. As aforementioned that F centers in LiF are stable at room temperature, but at temperatures higher than ~87°C (360 K) their mobility is high enough to recombine with hole centers. It was reported that F center clusters ( $F_2$ ,  $F_3$ ,  $F_3^+$ , and  $F_4$ ) in LiF crystals present a similar annealing process. The  $F_3$ ,  $F_3^+$ are the first centers to disappear (above ~300°C) according to the recent findings.<sup>26</sup> The temperature matches well with the boundary temperature of  $\sim 325^{\circ}$ C between LTSR2 and MTSR2. So, LTSR2 is caused by F<sub>3</sub>, F<sub>3</sub><sup>+</sup> centers. Then, the  $F_2$  centers disappear at ~420°C, which is in good agreement with the crossover temperature (~425°C) of R2. Besides, the activation energy of the thermal annealing stage of F2 centers is ~1.6 eV reported by Izerrouken et al.<sup>27</sup> Klempt et al.<sup>14</sup> also explained the process with the activation of 1.7 eV could be an annealing of F center clusters. All these reported results match well with the activation energy 1.75 and 1.59 eV for MTSR2 found in Figs. 3(a) and 4(b), respectively. Thus, MTSR2 can be attributed to the annealing process of F<sub>2</sub> centers. As to the HTSR2, whose activation energy of 1.07 eV agrees quite well with 1.0 eV claimed by Klempt et al.,<sup>14</sup> which was interpreted as an F center diffusion process. Hence, F center is considered to be the cause of HTSR2.

In order to convince the above points, further measurements were performed on a new LiF pellet after being



**Fig. 6.** (a) Frequency dependence of electric modulus (M'') for the air-quenched LiF crystal measured at various temperatures as tested in Fig. 3(a). (b) The comparison between the experimental data (open circles) measured at 350°C and fitting result (solid curve through the data points). (c) The Arrhenius plots for R1 and R2 deduced from the fitting peaks.

subjected to annealing treatment at 800°C for two hours followed by quenching rapidly to room temperature (cooling rate >100°C/s) in air. The spectroscopic plots of electric modulus at the temperatures tested in Fig. 3(a) were measured and shown in Fig. 6(a). At a first glance, the M''(f) plots have the same characteristic as that observed in Fig. 3(a)except for the fact that the two peaks almost overlap at the lowest measuring temperatures. Likewise, the two peak fitting was conducted in order to obtain the accurate peak position. The representative fitting results of the data recorded at 350°C were given in Fig. 6(b), from which we can see a larger peak locating around 10<sup>4</sup> Hz and a smaller peak appearing around 10<sup>3</sup> Hz. Compared with the results presented in Fig. 3(b) and the inset of Fig. 5(a), the larger peak can be identified to be the R2 relaxation. Hence, the smaller one represents the R1 relaxation. With the peak positions deduced from the fittings, the Arrhenius plots for the two relaxations were presented in Fig. 6(c). The calculated values of  $f_0$  and  $E_a$  of the two relaxations were also listed in Table I. It is seen that the activation energy of R1 for the quenched crystal is almost the same as that of the blank crystal. One also notes that the pre-exponential factor  $(3.05 \times 10^{12} \text{ Hz})$  and the activation energy (1.06 eV) of R2 are in good agreement with those of HTSR2  $(f_0 = 5.13 \times 10^{12}, E_a = 1.07 \text{ eV})$ . These findings are just as expected, because the F center clusters disappear at high enough temperatures. The annealing treatment completely destroys the clusters, whereas the Li-ions and F centers are remained. This case was held to room temperature by airquenching treatment. Therefore, only the Li-ion diffusioninduced relaxation (R1) and the F-center-induced relaxation (HTSR2) can be observed in the following measurement run.

## **IV.** Conclusions

In conclusion, the dielectric relaxations and electrical conduction of LiF single crystals have been studied in the temperature range of 30°C-800°C and the frequency range of 50 Hz-10 MHz. Two thermally activated relaxations, R1 and R2, were observed. R1 was ascribed to the diffusion of Li-ion in the crystal. R2 is composed of three Arrhenius segments, LTSR2, MTSR2, and HTSR2. They were argued to be associated with the  $F_3$ ,  $F_3^+$  centers,  $F_2$  centers, and F centers, respectively.

## Acknowledgments

The authors are grateful for the financial support from the National Natural Science Foundation of China (grant nos 11404002, 11404003, and 51402001). This work was supported in part by Zhejiang Provincial Natural Science Foundations of China (grant nos LY12F02014 and LY13F010006) and Doctoral Startup Foundation of Anhui University (grant no. 33190077).

#### References

<sup>1</sup>W. R. Hunter and S. A. Malo, "The Temperature Dependence of the Short Wavelength Transmittance Limit of Vacuum Ultraviolet Window Materials-I. Experiment," J. Phys. Chem. Solids, 30 [12] 2739-45 (1969).

<sup>2</sup>A. I. Nepomnyashchikh, E. A. Radzhabov, and A. V. Egranov, Color Centers and Luminescence in LiF Crystals. Nauka, Novosibirsk, 1984.

<sup>3</sup>G. Baldacchini, "Colored LiF: An Optical Material for All Seasons," J. Lumin., 100 [1-4] 333-43 (2002).

<sup>4</sup>G. Baldacchini, et al., "Optical Properties of Colored LiF Crystals with Given Content of Oxygen, Hydroxyl and Metal Impurities," Phys. Status Solidi (C), 4 [3] 744-8 (2007).

<sup>5</sup>J. Li, X. M. Zhou, W. J. Zhu, J. B. Li, and F. Q. Jing, "A Shock-Induced Phase Transformation in a LiTaO3 Crystal," J. Appl. Phys., 102 [8] 083503,

5pp (2007). <sup>6</sup>C. S. Yoo and Y. M. Gupta, "Time-Resolved Absorption Changes of Thin Carbon Disulfide Samples Under Shock Compression: Electronic and Chemical Implications," J. Phys. Chem., 94 [7] 2857-65 (1990).

<sup>7</sup>P. A. Urtiew, "Effect of Shock Loading on Transparency of Sapphire Crystals," J. Appl. Phys., 45 [8] 3490-3 (1974).

<sup>8</sup>R. C. McQueen and D. G. Isaak, "Characterizing Windows for Shock Wave Radiation Studies," *J. Geophys. Res.*, **95** [B13] 21753–65 (1990).

<sup>9</sup>A. M. Pshukov, "Scintillation Properties of Doped LiF Crystals, Preprint. INR RAS. Moscow, 2004.

<sup>10</sup>V. M. Khulugurov, et al., "Laser Active F-Aggregate Colour Centres in LiF Monocrystals Doped by Divalent Impurity Cations," J. Phys-Condens. Mater., 11 [36] 7005–19 (1999).

<sup>11</sup>N. R. J. Poolton, A. J. J. Bos, G. O. Jones, and P. Dorenbos, "Probing Electron Transfer Processes in YPO4:Ce,Sm by Combined Synchrotron-Laser Excitation Spectroscopy," J. Phys.: Condens. Matter, 22 [18] 185403, 12pp

(2010). <sup>12</sup>A. T. Davidson, A. G. Kozakiewicz, and J. D. Comins, "Photoluminescence and the Thermal Stability of Color Centers in y-Irradiated LiF and LiF (Mg)," J. Appl. Phys., **82** [8] 3722–9 (1997). <sup>13</sup>T. Klempt, et al., "Magnetic Resonance Investigation of the Dynamics of

F Centers in LiF," Solid State Commun., 119 [7] 453-8 (2001).

T. Klempt, et al., "Magnetic Resonance Investigations of F Centres in LiF Caused by Ionizing Radiation," Radiat. Eff. Defect. S, 155 [1-4] 159-63 (2001).

<sup>15</sup>T. Klempt, O. Kanert, and D. Suter, "F Centers in LiF: A Nuclear Magnetic Resonance Study," Phys. Status Solidi (b), 236 [1] 151-65 (2003).

<sup>16</sup>V. M. Khulugurov, V. N. Salomatov, I. M. Kalogeras, A. Vassilikou-Dova, and I. Christakis, "The Role of  $OH^-$  Ions in the Stabilization of  $F_2^+$ Colour Centres in LiF," *Eur. Phys. J.* **8**, **28** [1] 91–101 (2002). <sup>17</sup>M. G. Abramishvili, Z. G. Akhvlediani, T. L. Kalabegishvili, V. G. Kva-

chadze, and Z. K. Saralidze, "Relaxation Processes in Colored Crystals of LiF After the Coaction of UV Radiation and a Shock Wave," Phys. Solid State,

**42** [10] 1840–5 (2000). <sup>18</sup>C. J. Delbecq and P. Pringsheim, "Absorption Bands and Lines in Irradiated LiF," J. Chem. Phys., 21 [5] 794-800 (1953).

N. Bouchaala, E. A. Kotomin, V. N. Kuzovkov, and M. Reichling, "F Center Aggregation Kinetics in Low-Energy Electron Irradiated LiF," Solid State Commun., 108 [9] 629-33 (1998).

20K. Schwartz, A. E. Volkov, M. V. Sorokin, R. Neumann, and C. Trautmann, "Effect of Irradiation Parameters on Defect Aggregation During Thermal Annealing of LiF Irradiated with Swift Ions and Electrons," Phys. Rev. B,  $^{21}$ R. T. Bate and C. V. Heer, "Some Optical and Magnetic Properties of

Irradiated LiF," J. Phys. Chem. Solids, 7 [1] 14-21 (1958).

K. Schwartz, C. Trautmann, T. Steckenreiter, O. Geiss, and M. Krmer, "Damage and Track Morphology in LiF Crystals Irradiated with GeV Ions,"

Phys. Rev. B, 58 [17] 11232–40 (1998).
<sup>23</sup>C. J. Rauch and C. V. Heer, "Some E-Band Optical Oscillator Strengths in Additively Colored Alkali Halides," Phys. Rev., 105 [3] 914–20

(1957). <sup>24</sup>P. Durand, Y. Farge, and M. Lamber, "The Creation of F Centers in <sup>770</sup> and Their Interpretation by a Lithium Fluoride Between 77° and 600°K and Their Interpretation by a Recombination Model of Interstitial-Vacancies," J. Phys. Chem. Solids, 30 [6]

<sup>25</sup>A. Zaafouri, M. Megdiche, and M. Gargouri, "AC Conductivity and Dielectric Behavior in Lithium and Sodium Diphosphate LiNa<sub>3</sub>P<sub>2</sub>O<sub>7</sub>," J. Alloys Compd, 584 [15] 2-158 (2014).

<sup>26</sup>G. Baldacchini, et al., "Thermoluminescence of Pure LiF Crystals and Color Centers," J. Lumin., 122-123, 371-3 (2006).

<sup>7</sup>M. Izerrouken, L. Guerbous, and A. Meftah, "Thermal Annealing Study <sup>24</sup>M. Izerrouken, L. Gueroous, and A. Motani, *Theorem 1999*, of F Center Clusters in LiF Single Crystals," *Nucl. Instrum. Methods Phys.* Res., Sect. A, 613, 9-14 (2010).