$$Q_3=\tfrac{1}{2}[a_4N_{-1F}+(a_1+a_2)N_{0F}+a_3N_{-1F}],$$

$$\alpha_\pm=(a_4-\tau_\pm^{-1})/a_2,$$

$$e_1=a_4-a_3,$$

$$e_2=a_1+a_2-a_3,$$

$$N_{0F}=\frac{N_{TT}}{1+a_2/a_4+a_1/a_3},\quad N_{1F}=\frac{a_2}{a_4}N_{0F},$$

$$N_{-1F}=\frac{a_1}{a_3}N_{0F},$$

$$a_1=e_{n0}{}^t+e_{n0}{}^0,\quad a_2=e_{p0}{}^t+e_{p0}{}^0,$$

$$a_3=e_{p-1}{}^t+e_{p-1}{}^0,\quad a_4=e_{n1}{}^t+e_{n1}{}^0,$$

$$N_{00}=\frac{N_{TT}}{1+e_{p0}{}^t/e_{n1}{}^t+e_{n0}{}^t/e_{p-1}{}^t},\quad N_{10}=\frac{e_{p0}{}^t}{e_{n1}{}^t}N_{00},$$

$$N_{-10}=\frac{e_{n0}{}^t}{e_{p-1}{}^t}N_{00}.$$

Again, the values of the four optical emission rates depend on the energy and intensity of the incident photons. If the incident photon energy is assumed to be less than 0.8 eV so that $e_{n0}{}^0\simeq 0$, and if use is made of the fact that $e_{p-1}{}^t \gg e_{n1}{}^t$, $e_{n0}{}^t$, $e_{p0}{}^t$, Eq. (A4) reduces to Eq. (2) in the text.

PHYSICAL REVIEW B VOLUME 1, NUMBER 2 15 JANUARY 1970

Effects of Heat Treatment and Background Divalent Cation Impurity on the Growth of *F* Centers in Highly Pure KCl Crystals

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The effects of heat treatment and background divalent cation impurity on the growth of *F* centers in highly pure KCl crystals (divalent impurity concentration $\lesssim 1$ ppm) have been studied from the growth of the thermoluminescence peaks. For a heating rate of 40°C/min, these peaks occur at 135 and 190°C (for highly pure crystals) and at 95, 135, and 190°C (for crystals containing ~30 ppm of background divalent cation impurity). The peaks at 95, 135, and 190°C are associated with the *F* centers due to the background divalent cation impurities, and with the first- and the second-stage *F* centers, respectively. The growth of the thermoluminescence areas with the time of x irradiation can be fitted with the equations of Mitchell, Wiegand, and Smoluchowski and of Frohlich. Various parameters in these equations are evaluated and discussed.

I. INTRODUCTION

In highly pure KCl crystals, x irradiated at room temperature (RT), only two thermoluminescence peaks are observed.[1] The two peaks occur at 135 and 190°C, when the heating rate is 40°C/min. The rates of increase of areas Δ_i and Δ_g under the 135 and the 190°C thermoluminescence peaks, respectively, are given by

$$\Delta_i=Kn(1-e^{-bt})\tag{1}$$

and

$$\Delta_g=K[at-(a/c-n')(1-e^{-ct})],\tag{2}$$

where n and n' are the concentrations of the anion vacancies released into the crystal by some radiochemical processes perhaps involving some impurity or impurity-defect complex and which give rise to the first and the second stage of *F* centers' coloration, respectively; b and c are the rates of capture of electrons by n and n' vacancies, respectively; a is the rate of generation of the anion vacancies by the x rays, and K is the ratio of the total thermoluminescence area $\Delta(=\Delta_i+\Delta_g)$ to the OD_F (the optical density at the peak of *F* band) or to the total number f of *F* centers formed by the x irradiation.

It was shown earlier[1] that the concentrations[2–4] f_i and f_g corresponding to the first- and the second-stage *F* centers, respectively, are related to the thermoluminescence areas Δ_i and Δ_g by the relation

$$\frac{\Delta_i}{f_i}=\frac{\Delta_g}{f_g}=\frac{\Delta}{f}=K.\tag{3}$$

This result is rather important, since it shows that the areas under the 135 and 190°C thermoluminescence peaks in highly pure KCl crystals are separately related

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[1] S. C. Jain and P. C. Mehendru, Phys. Rev. **140**, A957 (1965).

[2] The total concentration f of *F* centers was separated into the concentrations f_i and f_g by the method of Mitchell *et al.* (see Ref. 3), and of Fröhlich (see Ref. 4). Although the significance of the parameters in the equations of Mitchell *et al.* is far from well established, it is a convenient method for separating the total concentration f into the concentrations f_i and f_g.

[3] P. V. Mitchell, D. A. Wiegand, and R. Smoluchowski, Phys. Rev. **121**, 484 (1961).

[4] F. Fröhlich, Z. Naturforsch. **16a**, 211 (1961); **17a**, 327 (1962).

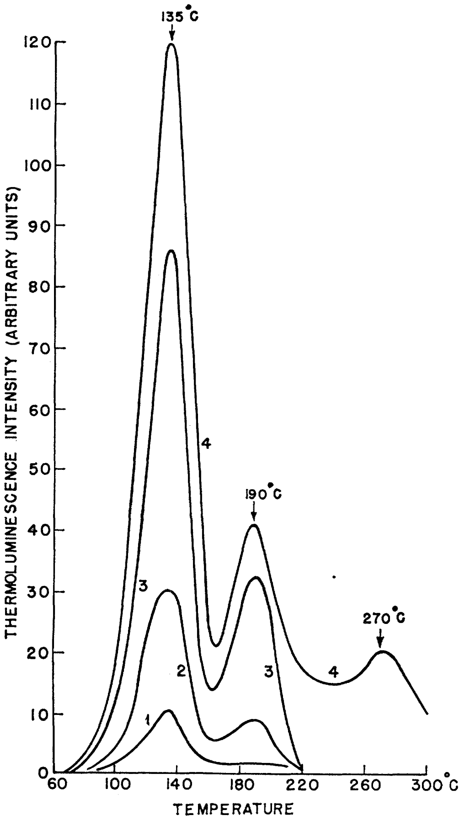

FIG. 1. The effect of heat treatment on the thermoluminescence of four identical slices cleaved from crystal *H*1. Curve 1 is for the as-cleaved slice 1 which had not received any further heat treatment. Curves 2 and 3 are for slices 2 and 3 quenched from 500 and 650°C, respectively, to room temperature. Curve 4 is for slice 4, quenched from 650°C to liquid-nitrogen temperature.

to the thermal bleaching of the first- and the second-stage *F* centers.

Since each thermoluminescence peak is now a quantitative measure of the concentration of each state of *F* centers' coloration, it is more convenient to study the properties of each stage of coloration and the parameters in Eqs. (1) and (2) by measuring the thermoluminescence areas Δ_i and Δ_g than by measuring the mixed growth of *F* centers with the time of x irradiation. The effects of heat treatment and of background divalent cation impurity on the various parameters have been investigated in detail and the results of these investigations are reported in this paper.

II. EXPERIMENTAL

Single crystals of highly pure and of British Drug Houses Analar KCl (background divalent cation impurity $\lesssim 1$ and ~ 30 ppm, respectively) were grown in the laboratory by the Kyropoulos method.[1] The letters H and B are used to denote the crystals grown from highly pure and British Drug Houses Analar-purity KCl, respectively. Different numerals placed after the letter H indicate the number of the batches of these crystals grown at different times. Blocks of approximate size 1 cm^3 were cleaved from the central portion of the large grown crystals and were given the heat treatment by keeping them at a certain high temperature for 2 h prior to rapid cooling to RT ($\sim$20°C). The blocks were cleaved into slices of approximate dimensions $10\times10\times0.5$ mm. The slices were x irradiated at RT through their broad faces with a Philips PW 1009 x-ray diffraction unit, using a Mo target and operating at 35 kV and 10 mA. A thin KCl filter ($\sim$0.3 mm thick) was used to cut off the effect of soft x rays. For uniform coloration the slices were x irradiated from both the sides for half of the time from each side.[5] The dose rate at the crystal position was measured by an R-meter (Atomic Energy Establishment, Trombay, Bombay, Type MR-125) and was in the range of $\sim$300 R/h. Care was taken to protect the crystals from exposure to stray light during the x irradiation and the subsequent optical absorption measurements. The methods used for optical absorption and thermoluminescence measurements have been described earlier.[1]

III. RESULTS AND DISCUSSION

A. Effect of Heat Treatment on *F*-Center Density and Thermoluminescence in Highly Pure Crystals

The effect of heat treatment on the thermoluminescence of four neighboring slices, 0.45 mm thick, cleaved from crystal *H*1, grown from highly pure KCl material, was studied. Slice 1 was as cleaved (and was not given any further heat treatment), whereas slices 2 and 3 were kept at 500 and 650°C, respectively, for 2 h prior to quenching to RT in the draught of an electric fan. Slice 4 was kept at 650°C for 2 h and then quenched to liquid-nitrogen temperature (LNT). The four slices were x irradiated for 15 min each. The x-irradiated slices were then heated at the rate of 40°C/min for thermoluminescence measurements under similar sensitivity conditions of the recorder.[1] The thermoluminescence results of the slices 1–4 are shown by curves 1–4 in Fig. 1, respectively.

A comparison of curves 1–4 in Fig. 1 shows that the areas Δ_i and Δ_g under the thermoluminescence peaks at 135 and 190°C increase when the slices are quenched rapidly (curves 2–4 in Fig. 1) as compared with the areas under these peaks for the slowly cooled as-cleaved slice 1 (curve 1). It is further seen from curves 2 and 3 that the higher the temperature from which the slices are quenched, the larger are the areas under both the thermoluminescence peaks. However, the increase in the area under the thermoluminescence peak at 135°C is greater than that under the 190°C peak. In addition to the large increase in areas under the 135 and 190°C thermoluminescence peaks, a new thermoluminescence peak at 270°C appears for the slice 4 which was quenched rapidly from 650°C to LNT (curve 4, Fig. 1).

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[5] C. T. Walker, Phys. Rev. **132**, 1963 (1963).

TABLE I. The values of the parameters in Eqs. (1), (2), and (4) describing the growth of the thermoluminescence with the time of x irradiation. The parameters n_c and b_c are for the combined areas under the 95 and 135°C thermoluminescence peaks and correspond to the parameters n and b of Eq. (1).

Crystal	Treatment	a (cm/h)	b (h^{-1})	c (h^{-1})	n (cm^{-1})	n' (cm^{-1})	n_{95} (cm^{-1})	d (h^{-1})	n_c (cm^{-1})	b_c (h^{-1})
*H*2	Slowly cooled	0.72	2.0	0.12	3.0	1.5	···	···	···	···
*H*2	Quenched	1.32	2.2	0.30	4.2	3.6	···	···	···	···
B	Slowly cooled	0.29	2.0	0.11	6.0	1.2	3.5	6	9.5	3
B	Quenched	1.20	2.8	0.22	7.0	3.0	3.8	18	10.8	5.4

Although the slices 3 and 4 have been quenched from the same high temperature, i.e., 650°C, the thermoluminescence areas Δ_i and Δ_g under the 135 and 190°C peaks for these two slices (shown by curves 3 and 4 in Fig. 1) are not the same. The areas Δ_i and Δ_g obtained for slice 4 (quenched rapidly from 650°C to LNT) are larger than those obtained for slice 3 (quenched from 650°C to RT in the draught of an electric fan). These observations clearly show that the magnitudes of Δ_i and Δ_g depend not only on the temperature from which the slices are quenched but also on the rate of quenching.

The increase in the areas Δ_i and Δ_g on quenching from higher temperatures or on the rate of quenching occurs either because (1) the number of the released traps (negative-ion vacancies) increases, or (2) the rate of capture of electrons per vacancy increases, and (3) in the case of 190°C peak the rate of generation of vacancies during the x irradiation becomes larger when the slice is quenched from higher temperatures. The relative significance of these factors will be discussed quantitatively later in this section.

The observation that a new peak appears at 270°C when slice 4 is quenched from 650°C to LNT indicates that yet another process operates for the thermal bleaching of *F* centers in slice 4 which emits thermoluminescence at still higher temperatures. As reported earlier,[1] the thermoluminescence peak at 270°C is also observed in plastically deformed slices. The appearance of 270°C peak in the thermoluminescence of slice 4 indicates that perhaps plastic flow occurs when the hot crystals are cooled extremely rapidly to LNT.

In order to understand the relative significance of the factors which are responsible for the increase in the areas Δ_i and Δ_g due to the increase in the rate of quenching, detailed experiments were performed. Two adjacent blocks were cleaved from the middle of another highly pure KCl crystal *H*2. Both the blocks were heated simultaneously at 650°C for 2 h. Block 1 was cooled slowly at the rate of 25°C/h to RT, whereas block 2 was quenched rapidly at a rate of 250°C/min to RT. Slices 0.50 mm thick, were cleaved from blocks 1 and 2 and x irradiated at 35 kV and 10 mA, for different lengths of time. After measuring the optical density OD_F at the peak of the *F* band the slices were heated at the rate of 40°C/min for thermoluminescence measurements.

The areas Δ_i and Δ_g were separated from the total thermoluminescence areas Δ for the differently heat treated crystals *H*2, in the manner described earlier[1] and the value of the parameters a, b, c, n, and n' were evaluated[1] and are given in Table I.

The concentration of the first stage *F* centers, f_i, is not sensitive to small changes in the parameter b. The values of b are, therefore, reliable within ±10%. Hence the two values of b, i.e., $b=2$ for the quenched and $b=2.2$ for the slowly cooled slices from crystal *H*2 (given in Table I) are within experimental error the same. The parameter n increases from 3.0 for slowly cooled slices to 4.2 for the quenched slices. This shows that in quenched slices, the increase in f_i is due to the increase in the parameter n. These results are in agreement with those of Mitchell *et al.*[3]

The rate of generation of anion vacancies by x rays represented by the parameter a, increases from 0.72 for slowly cooled slices to 1.32 for the quenched slices. Thus the anion vacancies are generated at a faster rate in quenched slices than in slowly cooled slices. The parameters c and n' also increase from 0.12 and 1.5 for the slowly cooled slices to 0.30 and 3.6, respectively, for the quenched slices, showing thereby that the increase in the concentration of the second-stage *F* centers, f_g, in quenched slices is due to the increase in the parameters a, c, and n'.

A comparison of these parameters for the slowly cooled and the quenched slices (given for crystal *H*2 in Table I) shows that on quenching the change in the parameter n is only ~40%, although the change in parameter n' is ~250%. Again, there is almost no change in the parameter b, whereas the parameter c increases by about 250% with the quenching heat treatment. The parameter a is also found to increase by almost 100% on quenching. The results reported in this section show that the parameters a, c, n, and n' are very sensitive to the quenching heat treatment and the enhancement of all these parameters (and perhaps also slight increase observed in the parameter b on quenching, i.e., from $b=2$ for the slowly cooled slice, to $b=2.2$ for the quenched slices) is responsible for the increase in the *F*-center coloration in the quenched crystals.

B. Crystals with Background Impurity

It was shown earlier[1] that the crystals grown from British Drug Houses Analar KCl material (designated

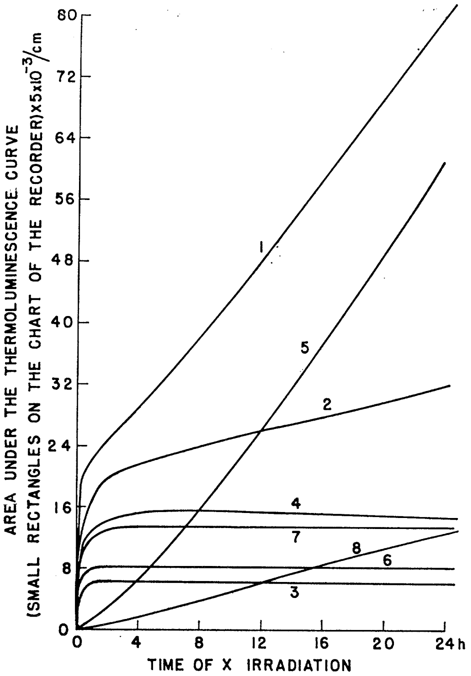

FIG. 2. Growth of thermoluminescence areas with the time of x irradiation in *B* crystal. Curves 1 and 2 show the growths of the total thermoluminescence area with the time of x irradiation for quenched and slowly cooled slices, respectively. Curves 3–5 and 6–8 show the growths of the separated thermoluminescence areas Δ_{95}, Δ_i, and Δ_g, respectively, for the quenched and the slowly cooled slices cleaved from *B* crystal.

as *B* crystals) contained ~30 ppm of background divalent cation impurity which on x irradiation also generated *F* centers or centers having absorption under the *F* band. Thermal bleaching of these centers gave rise to an additional thermoluminescence peak at 95°C. The positions of the thermoluminescence peaks for the first and the second-stage *F* centers for *B* crystals were the same as those for the *H* crystals.[1] The area under the thermoluminescence peak at 95°C was fastest to grow and saturated in ~10 min. In general, the behavior of the growths of the areas Δ_i and Δ_g with time of x irradiation for the *B* crystals was similar to that observed in *H* crystals.

In this section are discussed the effect of heat treatment on the growth of the areas under the 95, 135, and 190°C thermoluminescence peaks in *B* crystals. Two neighboring blocks were cleaved out of the middle portion of a large *B* crystal. Both blocks were kept at 650°C for 2 h. One of the blocks was quenched at a rate of ~250°C/min to RT, whereas the other was allowed to cool slowly (~25°C/h) to RT. Several neighboring slices, 0.50-mm thick, were cleaved from both the blocks and were x irradiated at RT with x-ray anode voltage and current at 35 kV and 10 mA, respectively. The time of x irradiation was varied from 2 min to 24 h. The x-irradiated slices were heated at a rate of 40°C/min to emit thermoluminescence. The area under the 95°C thermoluminescence peak (henceforth denoted as Δ_{95}) and the areas Δ_i and Δ_g were determined[6] for the different thermoluminescence curves obtained for the quenched and the slowly cooled slices cleaved from *B* crystal and x irradiated for different lengths of time. The growth of the total areas $[\Delta=\Delta_{95}+\Delta_i+\Delta_g]$ for the quenched and the slowly cooled slices are shown by curves 1 and 2, respectively, in Fig. 2. Curves 3–5 and curves 6–8, respectively, in Fig. 2 show the growths of the separated areas Δ_{95}, Δ_i and Δ_g with the time of x irradiation for the quenched and the slowly cooled slices from *B* crystal.

It is seen from curves 3 and 6 (for the 95°C peak) and curves 4 and 7 (for the 135°C peak) in Fig. 2 that the growths of the areas under the 95 and 135°C thermoluminescence peaks are similar. The observation that the areas under the peaks at 95 and 135°C saturate with the time of x irradiation indicates that the traps (vacancies) released into the crystal and which eventually give rise to the thermoluminescence peaks at 95 and 135°C are limited in number. From the similarity in the saturation behavior of Δ_{95} and Δ_i with the time of x irradiation, the growth of Δ_{95} with the time of x irradiation can be represented by an equation

$$\Delta_{95}=Kn_{95}(1-e^{-dt}) \tag{4}$$

similar to Eq. (1), where n_{95} is the concentration of the traps which on x irradiation form *F* centers or centers having absorption under the *F* band (and which on thermal bleaching give rise to the 95°C thermoluminescence peak) and *d* is the rate of capture of electrons by the n_{95}-type of traps.

From the growth of the areas Δ_{95}, Δ_i, and Δ_g for the quenched and the slowly cooled *B* crystals with the time of x irradiation (given by curves 3–5 and 6–8, respectively, in Fig. 2) and from the value of $K=420$, obtained under standard sensitivity conditions,[1] the magnitudes of the various parameters in Eqs. (1), (2), and (4) were evaluated and are included in Table I.

1. *Effect of Heat Treatment on B Crystals*

It is seen from Table I that the parameter *d* increases from 6 for the slowly cooled slices, to 18 for the quenched slices. The values of the parameters *b* and *c* also increase from 2.0 and 0.11 for the slowly cooled slices to 2.8 and 0.22, respectively, for the quenched slices. Thus with the quenching treatment the increase in parameter *d* is comparatively more than the increase in the parameters *b* and *c*. It is also seen from Table I that the magnitude of n_{95} is 3.8 for the quenched *B* slices, whereas for the slowly cooled slices the value of this parameter is 3.5. Thus, within experimental error, the magnitude of the parameter n_{95} for the quenched and the slowly cooled slices is almost the same. This observation indicates that the concentration of n_{95}

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[6] The area under the 95°C thermoluminescence peak was determined in a manner described earlier[1] for the 135 and 190°C peaks.

type of traps is perhaps only a function of the concentration of the background divalent cation impurity present in *B* crystal and is not very much affected by the heat treatment. Similar results, namely, that the concentration of the n_{95} traps remains almost unaffected by the heat treatment (not shown here) were also observed in Ca-doped KCl crystals.[7] The parameters n and n' are observed to increase from 6 and 1.2 for the slowly cooled slices to 7 and 3.6, respectively, for the quenched slices. The parameter a for *B* crystals (as for the *H* crystals) also increases from $a=0.29$ for the slowly cooled slices to $a=1.20$ for the quenched slices. Thus the rate of generation of anion vacancies by x rays in the case of *B* crystals increases almost four times with the quenching treatment.

2. *Comparison of H and B Crystals*

The magnitudes of the various parameters, evaluated for the *H* and the *B* crystals under identical conditions of x irradiation and heat treatment are given in Table I. It is seen from Table I that the magnitudes of n and b for the quenched crystals increase from 4.2 and 2.2 for the *H* crystals to 7 and 2.8, respectively, for the identically quenched *B* crystals. Similarly, for the slowly cooled crystals the parameters n and b are larger for the *B* crystals than for the *H* crystals. Comparing the magnitude of $n=7$ for the quenched *B* crystals with $n=4.2$ for the quenched *H* crystals (or $n=6$ for the slowly cooled *B* crystals with $n=3$ for the slowly cooled *H* crystals), it appears that the increase in the concentration of the background impurity, besides introducing the n_{95}-type of traps, enhances the release of n-type traps. From the values of the parameter $b=2.0$ for the slowly cooled *H* or *B* crystals (or $b=2.2$ for the quenched *H* crystals and 2.8 for the quenched *B* crystals), it appears that the rate of capture of electrons by the n type of traps to form the first stage *F* centers is not very much affected. (As mentioned earlier, the growth of early stage *F* centers, f_i, is not very sensitive to small changes in parameter b.) Thus the nature or the mechanism for the capture of electrons by the n-type of traps released during the x irradiation remains unchanged with the presence of divalent cation impurities. Similar results showing almost no change in the value of b and a large change in the value of n were also observed[7] in crystals deliberately doped with Ca (results not reported here). The increase in the concentration of n-type of traps on the introduction of background divalent cation impurity is perhaps due to the release of additional traps (by some mechanism such as that of Crawford and Nelson[8]) which on capture of electrons form the first stage *F* centers.

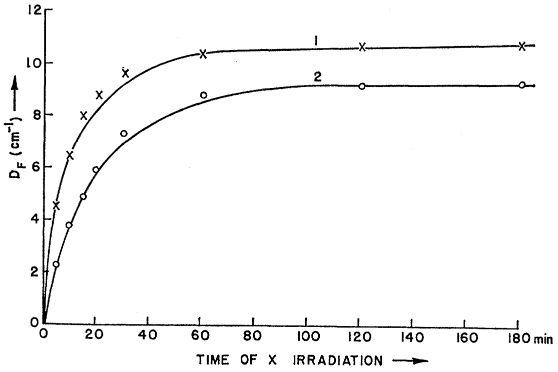

FIG. 3. Growth of the combined optical density (OD_F) corresponding to the 95 and 135°C thermoluminescence peaks with the time of x irradiation in *B* crystals. Curves 1 and 2 show the growths of OD_F for the quenched and slowly cooled slices, respectively. The crosses and circles denote the observed values of the combined OD_F for these two thermoluminescence peaks.

The magnitudes of the parameters a, c, and n' (responsible for the growth of the second stage *F* centers) for the *H* and the *B* crystals, which have undergone identical heat treatment are given in Table I. It is seen that the respective values of the parameters a, c, and n' for the quenched *H* crystals, are 1.32, 0.30, and 3.6, whereas the values of these parameters for the quenched *B* crystals are 1.20, 0.22, and 3.0, respectively. Thus all the parameters, namely, a, c, and n', responsible for the growth of second-stage *F* centers, f_g, under identical conditions of x irradiation and heat treatment, are suppressed more in *B* crystals than in *H* crystals.

The main results of this section, that the concentration of the second stage *F* centers (given by the area under the 190°C thermoluminescence peak) is suppressed and that the concentration of the first-stage *F* centers (given by the area under the 135°C thermoluminescence peak) is enhanced with the presence of or on deliberate introduction of divalent cation impurities, are in agreement with the results reported earlier.[9]

3. *Combined Growth of 95 and 135°C Peaks*

Since the thermoluminescence peaks at 95 and 135°C show a saturation behavior with the time of x irradiation, these two peaks are qualitatively similar. It can be shown that within experimental error Eq. (1) can be fitted with different values of n and b (say, n_c and b_c, respectively) to the curves for the growth of combined areas under the 95 and 135°C thermoluminescence peaks. The values of the combined OD_F corresponding to area Δ_{95} and Δ_i and given by $(\Delta_{95}+\Delta_i)/K$ for the quenched and the slowly cooled slices from crystal *B* are plotted as a function of the time of x irradiation and are shown as crosses and circles on

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[7] P. C. Mehendru (to be published).

[8] J. H. Crawford and C. M. Nelson, Phys. Rev. Letters **5**, 314 (1960).

[9] W. A. Sibley, E. Sonder, and C. T. Butler, Phys. Rev. **136**, A537 (1964).

curves 1 and 2 in Fig. 3. The values of $n_c = 10.8$ and 9.5, and $b_c = 5.4$ and 3.0 are obtained for the quenched slices (to fit with crosses) and the slowly cooled slices (to fit with circles). Curves 1 and 2 in Fig. 3 have been drawn theoretically with these values of n_c and b_c for the quenched and the slowly cooled slices.

A comparison of the values of the parameters $n_{95} = 3.8$ and $d = 18$ for the 95°C peak, and $n = 7.0$ and $b = 2.8$ for the 135°C peak with $n_c = 10.8$ and $b_c = 5.4$ obtained from curve 1, in Fig. 3 for the two combined peaks, for the quenched B crystal shows that $n_c = n + n_{95}$, as expected. It is further seen that $d > b_c > b$. As is seen from Table I, similar relationships between the parameters n_c and b_c with the parameters n_{95}, n, b, and d are obtained for the slowly cooled B crystals.

The observation that the saturation behavior of the growths of the OD_F (or area) for the 95 and 135°C peaks is similar and that Eq. (1) with modified values of the parameters n and b can be fitted with the combined growth of these two peaks, indicates that the earlier workers[3,4] might have attributed the combined growth of the centers formed by the capture of electrons by the traps corresponding to 95 and 135°C peaks to the first-stage F centers only. A part of the variation in the values of the parameters n and b for various crystals which have undergone almost similar treatments, observed by Mitchell *et al.*[3] might be due to the variations of the concentration of the background impurity in the crystals used by them.

C. Process of Thermal Bleaching of *F* Centers

It was reported earlier[1] that for various times of x irradiation the ratio Δ / OD_F in B crystals (where Δ and OD_F now include the thermoluminescence area and F-center concentration, respectively, for the 95°C peak) was the same as that obtained with H crystals. These observations indicate that the n_{95} type of traps on x irradiation, capture electrons and form F centers or centers having absorption under the F band. The result that the centers responsible for the 95°C peak also have absorption under the F band is further supported by the observation[7] that the areas under all the three thermoluminescence peaks (namely, at 95, 135, and 190°C) are reduced when the x-irradiated slices were partially bleached with F light ($\lambda = 565$ nm), prior to heating to emit thermoluminescence (results not shown). The mechanism of generation of F centers by the n_{95} type of traps may perhaps be the one suggested by Crawford and Nelson.[8]

From the thermoluminescence results obtained with B crystals it is observed that there are more than two types of processes involved for the thermal bleaching of F centers. The process of thermal destruction of the F centers to give different thermoluminescence peaks may involve the release of a hole from some trap such as an impurity ion (likely for the 95°C peak) or the migration of an interstitial halogen to the former from some trap or aggregates of traps. This suggestion indicates that the spectral composition of the different thermoluminescence peaks may be different and indeed Halperin *et al.*[10] have already made such observations. This suggestion is further supported by the fact that the F center is virtually immobile in this temperature range and since it does not ionize thermally until much higher temperatures, several annihilation processes may be responsible for the various thermoluminescence peaks.

ACKNOWLEDGMENTS

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[10] A. Halperin and N. Kristianpoller, J. Opt. Soc. Am. **48**, 996 (1958); A. Halperin, N. Kristianpoller, and A. Ben-Zvi, Phys. Rev. **116**, 1081 (1959).