CHAPTER V

TEMPERATURE DEPENDENCE OF EL AND THERMOLUMINESCENCE
A. Temperature Dependence of Electroluminescence

5.1 Introduction

The study of temperature dependence of electroluminescence (EL) provides an insight into the mechanism of luminescence and nature of trap levels. It has been observed that traps can play a double role in the EL mechanism. On the one hand, by participating in the formation of regions with 'a high field' and of acting as a source of accelerated electrons they play a positive role, on the other hand by inhibiting the accelerated electrons under particular conditions they play a negative role. The latter can occur at those temperatures where the most intense exchange of electrons can occur between the traps and the conduction band. The release of electrons from electron traps and holes from luminescent centres depends on temperature and time. Therefore it becomes necessary to consider the effect of frequency and temperature simultaneously as emphasized by many workers. (1-7)

It has been shown that any combination of frequency (f) and temperature (T) which satisfies the relation

\[ f = c \exp \left( - \frac{E}{kT} \right) \]  \hspace{1cm} (5.1)

[where, E the trap depth, k the Boltzmann's constant and c a constant;]
produces essentially the same conditions in the phosphors; high frequency is equivalent to low temperature and may therefore be counteracted by increasing the temperature.

Temperature influences EL emission in various ways:

(i) It changes the occupancy of the important traps and mean trapping time.

(ii) It influences indirectly by thermal ionization of space charge responsible for the high field region. In this way the local field and consequently the probability that the charged carriers are accelerated to optical energies become temperature dependent.

(iii) It affects directly by thermal ionization of deep donors before the local field becomes sufficient to field ionize these sources and to accelerate the carriers. In other words the thermal energy of the crystal influences EL excitation by modifying the configuration of the local field and by changing the concentration of bound charge which may be made available for acceleration in the high field region by field ionization.

(iv) The conductivity of the dielectric and the phosphor changes as does the capacitance which results in a redistribution of the voltage between the dielectric of the cell - the phosphor grains - and in different conductivities in
regions of the microscopic crystals participating in the EL emission.

(v) The level of excitation i.e. the number of luminescence centres excited by the external source per unit time is also temperature dependent.

(vi) The recombination or de-excitation processes are temperature dependent, however, since the rates of excitation and recombination are equal in the state at all temperatures, an analysis of the dependence of EL brightness on temperature may focus attention on either processes.

The temperature dependence of EL emission have been studied by many. The results obtained are widely divergent, may be due to the nature of host and activator and the method of preparation of phosphors. The present investigation aims to study how electron trapping is effective in electroluminescence process. The effect of voltage and frequency on temperature dependence of EL have been studied. An attempt to calculate trap depth has also been made.

Thermoluminescence studies were also undertaken for comparing the results of trap depths calculated by both the methods.
5.2 General Review

Destriau\(^{(8)}\) was probably the first who studied the temperature dependence of EL of ZnS – ZnO phosphors. Roberts\(^{(9)}\) observed only a small effect of temperature in the frequency range 60 Hz to 1 kHz and inferred that "whatever the mechanism for electroluminescence may be, it does not depend on thermal activation". Alfrey and Taylor\(^{(1)}\) have had considerable success in explaining temperature dependence of light output in terms of thermal release of trapped electrons. In their later works\(^{(2)}\) they abandoned the thermal ionization mechanism as it could not explain several experimental facts and favoured field ionization mechanism. The dependence of EL brightness on temperature and frequency was in accordance with field controlled mechanism for creating charge carriers which are accelerated in the high field region. The analysis of Alfrey and Taylor\(^{(2)}\) and Haake\(^{(7)}\) have drawn attention to the temperature dependence of recombination as influenced by electron trapping in the low field region.

Thornton\(^{(5)}\) has shown that many of the effects of frequency and temperature on the output of EL of ZnS : Cu phosphors can be explained by taking into account the fact that the return of electrons to the excitation region is controlled by their thermal release from the traps. The number of electrons which can return
to the excitation region is a function of the releasing rate (voltage and temperature) and also the time available (frequency). An increase in voltage is theoretically equivalent to a decrease in frequency since depletion of ionized activators during the cycle is more severe. Temperature dependence is therefore minimum at high voltage and low frequency. Frequency dependence is maximum at high fields and high temperature and voltage dependence should be maximum at low temperature and high frequency.

Haake(7) and Mattler(10) studied the complications arising due to embedding media. According to Curie(11), Alfrey(12) and Haake(7) effect of temperature on EL excitation should be separated from that of the recombination by measuring the temperature dependence of photoluminescence.

At sufficiently low temperature the photoluminescence efficiency is almost constant but it decreases at higher temperatures due to thermal quenching. In the same way the EL brightness should also decrease at high temperatures. In the case of EL the quenching factor can be written as

\[ Q = \left[ 1 + A/\tau \exp \left( -q/kT \right) \right]^{-1} \quad (5.2) \]

Equation (5.1) has been taken into account where \( q \) is the quenching energy. Recently Rabotkin et al. (13) inferred that mechanism of thermal extinction is identical in EL and PL for zinc sulphide phosphors.
Destriau\(^{(8)}\) observed that the threshold voltage of excitation falls as the temperature is lowered. But Johnson et al. suggested that at low temperatures traps may be field ionized whereas at high temperatures they are thermally emptied enhancing the intensity of the field in the barrier region. From the temperature dependence studies of EL, attempts to calculate trap depth and correlating them with thermoluminescence measurements have been reported.\(^{(3,7,14,15)}\)

Ryzhkov et al.\(^{(15)}\) have observed that the mean intensity for temperature dependence of ZnS : Cu, Al crystals was determined by certain mechanism which is related with the injection of electrons from the valence band of the second phase Cu\(_2\)S into the conduction band of ZnS. Nuvareva et al.\(^{(17)}\) found some additional peaks at high temperatures for which he proposed a hypothesis in terms of polar cations connected with localization levels close to the boundaries of tiny crystals.

Vlasenko\(^{(18)}\) studied the a-c EL of thin films of ZnSiMn and found that the emission increased as the temperature was increased above the room temperature inspite of the fact that photoluminescence decreased. At high temperatures the dependence of output on frequency becomes much smaller than at low temperatures. The temperature dependence of EL of ZnO : Mn phosphors around 590 nm was studied by Gupta and Mohan\(^{(19)}\) and they reported that with rise in voltage only overall intensity is
increased whereas with increase in excitation frequency the L - T curves exhibit peak shift.

Maxia et al.\(^{(20)}\) have investigated the spectral composition of ZnS : Cu EL on exciting frequency and temperature. The ratio of green and blue band was found to decrease with frequency in a way which becomes less marked when the temperature is lowered. At higher frequency this ratio increases with temperature while at still higher frequency it remains almost constant. The temperature dependence of EL is sensitive to the structure and composition of phosphors. This dependence can differ in phosphors which seem to be same in composition. Thus in ZnS : Cu phosphors the dependence of brightness were observed to have a low temperature minima\(^{(3,7,21,22)}\) while over the same temperature range the dependence is found to be monotonic.\(^{(23,24)}\)

The effects of heating rates on EL have also been reported. Faster heating rates cause a peak shift towards lower temperature side.

5.3 Calculation of Trap depth

Daunay\(^{(26)}\) considered the non-monotonous growth of luminescence as a function of temperature. Suppose that the probability of ionization \(P_{1}\) varies with time as

\[
P_{1} = \exp \left[ - \frac{b}{\sqrt{V_{0} \sin \omega t}} \right]
\]
where \( b \) and \( V_0 \) are constants.

The emission of primary electrons in a semiperiod is of the form

\[
\frac{dn}{dt} = \frac{n_0}{\tau} \exp \left( - \frac{t}{\tau} \right)
\]

where similar traps of initial population \( n_0 \) and mean life time \( \tau \) are supposed to be effective.

These primary electrons accelerated by the field in the vicinity of occlusion provoke the ionization of centres. If it is assumed that the time of transit of electrons in the conduction band is negligible, then the number of centres ionized per second may be given by the relation

\[
\frac{dN_t}{dt} = \rho_1 \frac{dx}{dt} = \frac{n_0}{\tau} \exp \left( - \frac{t}{\tau} \right) \exp \left( - \frac{b}{\sqrt{b_0 \sin \omega t}} \right) \quad (5.3)
\]

If Equation (5.3) is integrated over a semiperiod, it is found that the whole of the centres ionized in one half of the crystal (depending on the phase of excitation) correspond exactly to the whole of radiative recombination in the other half of the crystal.

The author carried out the integration and for chosen values of voltages projected the evolutions of integral as a function of different values of \( \tau \) and proved that the integral light conforming to the semiperiod passes through the maximum
when $\gamma$ takes up the optimum value $\gamma^*$ in relation to $T$.

Integrating

$$\int_0^{T/2} (dN)_t = \int_0^{T/2} k \frac{h_0}{\gamma} \exp \left( - \frac{t}{\gamma} \right) \exp \left( - \frac{b}{\sqrt{V_0 \sin \omega t}} \right) \, dt$$

$$\approx a \exp \left( - \frac{b}{\sqrt{V}} \right)$$

for different values of $\gamma$ (within a limited range of frequency and temperature). This confirms the validity of Eqn. (5.3) governing the dynamics of ionization.

Daunay also represented the evolution of $\gamma^*$ as a function of voltage and obtained a curve that may be linearized for the range of voltages usually applied to a cell.

$$\log V = 6 - \frac{32}{T} \gamma^*$$

Substituting the value of $V = \frac{V_0}{b^2}$ and $T = \frac{1}{f}$ the following relation is obtained

$$\gamma^* = \frac{1}{16 f} \left[ 3 \log \frac{b (\Theta, f)}{\sqrt{V_0}} + \log \frac{b (\Theta, f)}{\sqrt{V_0}} \right]$$  (5.4)

The value of $\gamma^*$ obtained from Eqn. (5.4) depends for a given voltage on the frequency and the temperature because $b$ is a function of both $\Theta$ and $f$. 
For a temperature $\theta$, the duration of life time is related to the trap depth $\epsilon$ by a classical expression

$$\tau = \frac{1}{s} \exp \left( \frac{\epsilon}{k \theta} \right)$$ (5.5)

For a cell operating at a voltage $V$, the trap depth (responsible for the maximum luminescence at a temperature $\theta^*$) may be deduced from the intersection of the two networks of curves i.e. (i) the network of exponentials $\tau = \text{s}^{-1} \exp \left( \frac{\epsilon}{k \theta} \right)$ for different values of $\theta$ and (ii) the network of curves

$$\tau^* = \frac{1}{16 \pi} \left[ 3 + \log \frac{b(\theta, f)}{\sqrt{V_0}} \right]$$

for different values of $V$ at a particular frequency (utilizing the experimental evolution of $b(\theta)$ for that frequency. This method of determination of trap depth is long and cumbersome due to comparison of network of curves. Rapid calculation can be done if we consider that $b$ varies relatively less with temperature (less than 10%) and hence it can be taken as constant without gross error when $\theta$ varies.

The two Equations (5.4) and (5.5) can possibly be equated and we get

$$\epsilon = 2.3 k \theta^* \left[ \log \frac{s}{16 \pi} + \log \left\{ 3 + \log \frac{b(\theta, f)}{\sqrt{V_0}} \right\} \right]$$ (5.6)

which directly relates the trap depth $\epsilon$ with the temperature $\theta^*$ of the maximum.
In order to use the formula (5.6), a preliminary study of $EL$ is necessary to know the factor $b(\Theta, f)$. The Equation (5.6) was reduced to a simple form by Daunay(25) who found empirically that $\gamma^*$ varies around a mean value of $\frac{23}{100} T$, the optimum deviation being about $\pm \frac{80}{100}$ for usual voltages. Substituting this mean value of $\gamma^*$ in place of $\gamma$ and $\Theta^*$ in place of $\Theta$ in the relation (5.5)

$$\epsilon = 2.3 k \Theta^* \log \left( \frac{23.5}{100 \, f} \right)$$

(5.7)

for the mean trap depth. Here $T$ is replaced by $\frac{1}{f}$. We found out for CaO : RE phosphors that $\gamma^*$ varies around a mean value of $\frac{24}{100} T$, and the equation (5.7) can be slightly modified to

$$\epsilon = 2.3 k \Theta^* \log \left( \frac{24 \, s}{100 \, f} \right)$$

(5.8)

5.4 Experimental Arrangement

The special cell designed for the measurements of temperature dependence of $EL$ is described in Chapter III, Fig. 3.3. The block diagram of the arrangement is shown in Fig. 5.1.

The pellet was prepared by spreading a thin layer of phosphor on a very thin mica sheet using araldite as an adhesive
CIRCUIT ARRANGEMENT FOR STUDYING THE TEMPERATURE DEPENDENCE OF EL
substance and dried at room temperature. It was then pressed between the electrodes with the layer in direct contact with the conducting face of the conducting glass.

The source of excitation used was a wide band amplifier (0 - 1000 V) in conjunction with an audio frequency oscillator (30 Hz to 30 KHz). The integrated light emission was measured by an Il' 21 photomultiplier coupled with a Rubicon galvanometer as described earlier. The photomultiplier was not screwed to the cell, but an attachment was connected to it which was kept very close to the cell. The attachment was covered with moistened cloth to keep it cool. The temperature was recorded by a precalibrated copper constantan thermocouple connected to a millivoltmeter.

The heater coil is connected through a variac. By adjusting the current through the variac suitable heating rates can be obtained.

The cell was subjected to a potential difference at room temperature and EL brightness was measured for three different frequencies. Then the heater was switched on. Observations were taken at a fixed temperature at different frequencies and at different voltages. This was repeated for different temperatures from room temperature to 443°K. Similar sets of readings were taken with other samples.
5.3 Results

The temperature dependence study was carried out in two parts:

(a) by varying the voltage keeping frequency constant (voltage dependence).

(b) by varying the frequency keeping voltage constant (frequency dependence).

(a) Voltage dependence - Average brightness versus temperature curves are plotted for different values of the applied field keeping frequency constant (Figs. 5.2 - 5.4).

For all the phosphors increase in voltage enhances the brightness as a whole at different temperatures in the range 303 to 443°K but no peak shift is observed.

In the case of CaO : Eu (1.0%) phosphors a new peak is observed on the higher temperature side with increase in voltage which is not present at 400 volts (Fig. 5.2). Main peak occurs at 395°K while there are less prominent peaks on both lower as well as higher temperature side, 368°K and 425°K for the voltage of excitation 560 volts. The peak at 425°K shows a slight shift of a degree or two which may be within the experimental error.

CaO : Tb (1.5%) phosphor shows a main peak at 382°K. In
FIG. 5.2

TEMPERATURE DEPENDENCE OF EL FOR CaO: Eu 1.0%

FREQUENCY 500Hz
A - L vs t at 400 V
B - L vs t at 480 V
C - L vs t at 520 V
D - L vs t at 560 V.

INTENSITY IN ARB. UNITS

TEMPERATURE °K

Eu-7
addition a shoulder appears which shows a shift towards higher temperature side with increase in voltage. The curve for 550 volts shows a minimum at 423°C and the intensity increases slightly suggesting the probable appearance of a peak on the higher temperature side (Fig. 5.3).

In the case of CaO : Sm (1.5%) there is only one peak at 420°C and the curve is slightly asymmetric on the higher temperature side (Fig. 5.4).

(b) Frequency dependence — The time averaged brightness is measured as a function of temperature for different frequencies at constant voltages (Figs. 5.5 – 5.8).

In the case of CaO : Eu (1.0%) phosphor two peaks are observed at 400 volts (Fig. 5.5). At 150 Hz a main peak is observed at 395°C and a subsidiary peak on the lower temperature side at 353°C. At 500 Hz the main peak shows a negligible shift but it is asymmetric towards higher temperature side as compared to the symmetric peak observed at 150 Hz. The subsidiary peak shows considerable shift from 353°C to 368°C. The main peak is more intense than at 150 Hz while the intensity of the subsidiary peak is much reduced. At 1kHz the main peak is at the same temperature as at other frequencies but the curve is slightly asymmetric, however, the subsidiary peak vanishes.

The onset of EL emission appears to move towards higher
**FIG. 5.5**

TEMPERATURE DEPENDENCE OF EL FOR CaO: Eu 7.5%

VOLTAGE 400 VOLS
A - L vs t at 150 Hz
B - L vs t at 500 Hz
C - L vs t at 1000 Hz

**FIG. 5.6**

TEMPERATURE DEPENDENCE OF EL FOR CaO: Tb 1.5%

VOLTAGE 500 VOLS
A - L vs t at 150 Hz
B - L vs t at 500 Hz
C - L vs t at 1000 Hz
temperature side as the frequency is increased.

CaO : Tb (1.5%) phosphors show only an increase in brightness with frequency in the range 150 Hz to 1 KHz with no change in peak position (Fig. 5.6). At 150 Hz the main peak occurs at 382 K and there is a shoulder on the higher temperature side. At 500 Hz the main peak slightly increases in intensity without any shift while the shoulder appears a little well developed. At 1 KHz the main peak increases in magnitude without shift but there is a well defined peak at 410 K instead of the shoulder and the two peaks are well resolved (Fig. 5.6).

The onset of EL emission moves towards lower temperature as the frequency is increased.

For CaO : Sm (1.5%) phosphors the frequency is changed at a fixed voltage of 460 and 500 volts (Figs. 5.7 and 5.8). At 150 Hz there is a peak at 382 K and the curve shows an upward tendency towards higher temperature side suggesting the possibility of a maxima at a temperature beyond the available range. At 500 Hz the peak increases in magnitude and occurs at 395 K. The curve shows a tendency towards a maxima and possibility of a second peak beyond the observed range of temperature. At 1 KHz the peak shows a considerable shift occurring at 421 K. At lower voltage 460 volts the maximum intensity is for the frequency 150 Hz while at higher voltage 500 volts the maximum intensity is for the frequency 500 Hz.
FIG. 5.7

TEMPERATURE DEPENDENCE OF EL CaO: Sm 1.5%

VOLTAGE = 460 VOLTS
A - L vs t at 150 Hz
B - L vs t at 500 Hz
C - L vs t at 1000 Hz

FIG. 5.8

TEMPERATURE DEPENDENCE OF EL CaO: Sm 1.5%

VOLTAGE = 500 VOLTS
A - L vs t at 150 Hz
B - L vs t at 500 Hz
C - L vs t at 1000 Hz
Trap depths have been calculated using the formula 5.8 and the values of $\varepsilon$ are shown in Table 5.1 for two values of $a \times 10^9 \text{sec}^{-1}$ and $10^{14} \text{sec}^{-1}$.

B. Thermoluminescence

5.6 Introduction

Thermoluminescence (TL) provides a method for determining the number of filled traps and their energy distribution. TL studies were undertaken so that trap depths obtained from TL studies could be compared with similar data from EL.

The TL method consists of exciting the phosphor at a low initial temperature to fill all the empty traps and then allowing it to decay for a short time so that shallow traps are emptied. Then the temperature is raised at a constant rate; the traps filled during the excitation process are emptied releasing the frozen-in luminescence. The plot of luminescence intensity versus temperature shows peaks characteristics of the trapping levels. The curve known as a glow curve is a direct image of the traps, which give rise to thermoluminescence peaks and furnish qualitative information about the trap distribution.
5.7 Theories of thermoluminescence

The theory due to Randall and Wilkins (27) assumes a monomolecular mechanism and forms the basis for the analysis of glow curve data and calculation of trap depth. The differential equation in this case is

$$\frac{dn}{dt} = -n_0 s \exp \left( -\frac{E}{kT} \right) \quad (5.9)$$

$$\frac{dn}{n} = -s \exp \left( -\frac{E}{kT} \right) dt$$

where $n$ is the number of traps filled at time $t$, $s$ is the attempt to escape frequency, $k$ the Boltzmann constant, $T$ the absolute temperature and $E$ is the ionization energy of the traps. If the phosphor is heated at a uniform rate $\beta$ deg/sec then $dT = \beta dt$. Substituting and integrating we get

$$n = n_0 \exp \left[ -\int_{T_0}^{T} \exp \left( -\frac{E}{kT} \right) \frac{dT}{\beta} \right] \quad (5.10)$$

where $n_0$ is the number of traps filled at $t = 0$

The TL intensity at a temperature $T$ is given by

$$I = n_0 s \exp \left( -\frac{E}{kT} \right) \exp \left[ -\int_{T_0}^{T} s \exp \left( -\frac{E}{kT} \right) \frac{dT}{\beta} \right] \quad (5.11)$$
This formula gives by numerical integration the complete form of thermoluminescence curve. This expression represents the glow curve for only a single trap depth. The glow curves of most phosphors would have to be calculated by integration over the distribution of trap depths. However, Randall and Wilkins have shown that the mean life time of the trapped electrons is little different from one second at the temperature of maximum glow $T_g$. Hence

$$s \exp \left[ - \frac{E}{k T_g \left\{ 1 + f(s, \beta) \right\}} \right] = 1$$

where $f(s, \beta)$ is nearly constant and has a very small value compared with unity. $T_g$ is a fairly simple function of $E$ and we can write

$$E = k T_g \left[ 1 + f(s, \beta) \right] \log s \quad (5.12)$$

Neglecting $f(s, \beta)$ in comparison to unity the equation yields

$$E = k T_g \log s \quad (5.13)$$

from which the trap depth can be calculated.

An alternate mode of analysis has been proposed by Grossweiner\(^{(22)}\) who expressed $E$ in terms of the peak temperature and the temperature at half maximum. Another method of determining $E$ was proposed by Booth\(^{(29)}\). The temperature $T^*$ at which the TL emission is maximum may be obtained by
differenetrating Equation (3.1) with respect to $T$ and 
equating the result to zero. This gives

$$\frac{E}{k T^2} = s \exp \left(-\frac{E}{k T} \right)$$  (5.14)

In this expression $E$ is an implicit function of $T^*$, the 
relation being defined by a parameter $\theta = \beta/s$. For 
numerical calculations this relation has been reduced to

$$E \ (eV) = \frac{T^* \ (K) - T_0 (\beta/s)}{K \ (\beta/s)}$$  (5.15)

with sufficient accuracy by Curie.\(^{(30)}\)

The values of $T_0 \ (K)$ and $K \ (K/eV)$ for different 
values of $\theta$ have been drawn from the data given by Curie.\(^{(30)}\)
The $\beta/s$ values were evaluated taking two probable extreme values 
of $s$ equal to $10^9$ and $10^{14}$ sec\(^{-1}\).

5.8 Experimental arrangement

The TL apparatus used is described in Chapter III, 
Sec. 3.6. The source of excitation was X-rays from a Philips 
X-ray Unit No. 11704. The tube voltage was fixed at 35 kV and 
current was kept constant at 12 mA. The glow curves were recorded 
with a photomultiplier-galvanometer system.

The first part of the experiment consists of determination
of the phosphor temperature during heating as a function of time. A copper-constantan thermocouple was calibrated. One junction was kept in ice and the other junction was immersed in mercury taken in a small beaker. The beaker was heated and the temperature was recorded as a function of millivoltmeter deflection. Then one junction of the thermocouple was connected to the brass holder containing the phosphor while the other junction was kept in ice. The current, which was to be used, was passed through the coil. The millivoltmeter deflection was recorded after every fifteen seconds. A graph was plotted between time and millivoltmeter deflection. First from the calibration of thermocouple a graph was plotted between temperature and millivoltmeter deflection. From these two curves a third curve between temperature and time was obtained for knowing the phosphor temperature as a function of time.

Second part of the experiment consists of measuring the glow curves. For that 200 mg of the phosphor was filled in the cavity of the sample holder and pressed uniformly. It was excited by X-rays for three minutes and was allowed to decay for sufficient time so as to empty all the shallow traps. Then the sample was heated at a uniform rate of 1°C/sec. The galvanometer deflection was noted as a function of time and a glow curve was plotted with the help of calibration curve. The apparatus was cooled and other samples were studied.
5.9 Results

The glow curves of CaO activated by Eu, Tb and Sm are plotted between thermoluminescence intensity and temperature for the heating rate $1^\circ K/\text{sec}$. Some representative curves are shown in Figs. 5.9 - 5.14.

For CaO : Eu (0.5\%) three peaks occur at 408, 458 and 548$^\circ$K. The peak at 458$^\circ$K is more intense than the peaks on either side. For CaO : Eu (1.0\%) the peaks occur at 408, 448 and 529$^\circ$K. There is no shift for the peak on the lower temperature side. But there is a shift of 19$^\circ$ in the case of the peak on the higher temperature side. For europium 1.0\% the peaks are not sharp and well resolved as for 0.5\% which happens to be the optimum concentration for EL (Fig. 5.9 and 5.10).

For CaO : Tb (1.0\%) there is a main glow peak at 453$^\circ$K and an ill developed shoulder on the low temperature side 403$^\circ$K and a better developed shoulder on the higher temperature side at 463$^\circ$K. For CaO : Tb (1.5\%) the main peak occurs at the same temperature but is sharper. Instead of a slight shoulder there is a well developed peak on the low temperature side at 391$^\circ$K and there is a shoulder on the higher temperature side. At 2.0\% concentration again besides the main peak at 453$^\circ$K there is a well developed peak on the lower temperature side and a
FIG. 5.9

TL CURVES FOR CaO:Eu (0.5%)

FIG. 5.10

TL CURVES FOR CaO:Eu (1%)
shoulder on the higher temperature side. The peaks are sharper and better resolved (Figs. 5.11 - 5.13).

In the case of CaO : Sm (1.3%) there is a single peak at 398°K and the glow curve is asymmetric probably due to unresolved peaks occurring on the higher temperature side (Fig. 5.14).

Trap depths have been calculated by using Curie Eq. (5.14) as well as Randall and Wilkins Eq. (5.12) for two values of 10^9 and 10^{14} sec^{-1}. Results are shown in Tables 5.2 and 5.3.
FIG. 5.14

TL CURVES FOR CaO:Sm (1.5%)

INTENSITY IN ARB. UNITS

TEMPERATURE °K

Sm-6
### Table 5.1

<table>
<thead>
<tr>
<th>Activator</th>
<th>Frequency of excitation</th>
<th>Temperature of brightness max. in °K</th>
<th>Trap depths in eV</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( s = 10^9 \text{sec}^{-1} )</td>
</tr>
<tr>
<td>Eu 1.0%</td>
<td>150 Hz</td>
<td>354</td>
<td>0.43</td>
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<tr>
<td></td>
<td></td>
<td>393</td>
<td>0.48</td>
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<td></td>
<td>500 Hz</td>
<td>368</td>
<td>0.41</td>
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<tr>
<td></td>
<td></td>
<td>395</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>1000 Hz</td>
<td>395</td>
<td>0.47</td>
</tr>
<tr>
<td>Tb 1.5%</td>
<td>150 Hz</td>
<td>381</td>
<td>0.47</td>
</tr>
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<td></td>
<td></td>
<td>381</td>
<td>0.43</td>
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<tr>
<td></td>
<td>1000 Hz</td>
<td>381</td>
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<td></td>
<td></td>
<td>410</td>
<td>0.44</td>
</tr>
<tr>
<td>Sm 1.5%</td>
<td>150 Hz</td>
<td>382</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>396</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>1000 Hz</td>
<td>422</td>
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### Table 5.2

**Trapped depth as obtained from thermoluminescence studies**

<table>
<thead>
<tr>
<th>Activator</th>
<th>Peak Temperature $T^*$ °K</th>
<th>Trap depth (eV)</th>
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<tr>
<td></td>
<td></td>
<td>$s=10^9$ sec$^{-1}$</td>
</tr>
<tr>
<td>Eu 1.04</td>
<td>408</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>448</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>529</td>
<td>1.08</td>
</tr>
<tr>
<td>Tb 1.34</td>
<td>385</td>
<td>0.78</td>
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<tr>
<td></td>
<td>453</td>
<td>0.92</td>
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<td>513</td>
<td>1.04</td>
</tr>
<tr>
<td>Sm 1.56</td>
<td>398</td>
<td>0.80</td>
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Table 5.3

Trap depth as obtained from thermoluminescence studies

Randall and Wilkins formula

<table>
<thead>
<tr>
<th>Activator</th>
<th>Peak Temperature $T^\circ \text{K}$</th>
<th>Trap depth (eV) $s = 10^9 \text{sec}^{-1}$</th>
<th>Trap depth (eV) $s = 10^{14} \text{sec}^{-1}$</th>
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<tbody>
<tr>
<td>Eu 1.0%</td>
<td>408</td>
<td>0.72</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>448</td>
<td>0.80</td>
<td>1.24</td>
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<tr>
<td></td>
<td>529</td>
<td>0.94</td>
<td>1.46</td>
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<tr>
<td>Tb 1.5%</td>
<td>385</td>
<td>0.68</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>453</td>
<td>0.81</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>513</td>
<td>0.91</td>
<td>1.42</td>
</tr>
<tr>
<td>Sm 1.5%</td>
<td>398</td>
<td>0.70</td>
<td>1.10</td>
</tr>
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<td>Reference</td>
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<td>Journal/Book</td>
<td>Page/Volume</td>
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