

Study of the distribution of localized states in a -Si:H using the thermally-stimulated-currents technique

D. S. Misra, A. Kumar,* and S. C. Agarwal

Department of Physics, Indian Institute of Technology, Kanpur 208016, Uttar Pradesh, India

(Received 11 July 1984)

Thermally stimulated currents (TSC) in hydrogenated amorphous silicon (a -Si:H) are studied for different initial excitation conditions and various heating rates and are found to show two peaks: one at ≈ 120 K and another at ≈ 300 K. The peak near ≈ 300 K is resolved using two almost identical samples in a bridge configuration. From analysis of the heating rate it would appear that the TSC peaks near ≈ 120 and 300 K arise from states which lie within $2kT$ of 0.16 and 0.60 eV below the conduction-band edge, respectively. TSC is reduced considerably after light soaking (Staebler-Wronski effect). It is shown that a peak in the initial occupancy of states caused by the product of a fast-rising $g(E)$ and an exponentially decaying occupancy function near ≈ 0.16 eV may be responsible for the TSC peak observed at ≈ 120 K and may not necessarily imply a structure in $g(E)$.

I. INTRODUCTION

The thermally-stimulated-currents (TSC) technique has proved very useful in obtaining information about traps and their parameters in semiconductors.¹⁻¹³ In this method, the traps in semiconductors are filled by excitation (by light or a high electric field) at a low temperature and then the excitation is turned off. If the temperature is low enough the carriers remain trapped even in the absence of excitation. The temperature of the semiconductor is then raised at a constant rate and as a result the carriers are freed. The liberated carriers contribute to an excess conductivity, measured as an excess current in the presence of an electric field. This excess current, when measured as a function of temperature during heating, is called the TSC curve. A single trap level in the semiconductor shows a peak in the TSC curve at a temperature which depends upon the energy of the trap level, its capture cross section, trapping kinetics, and the heating rate. By making suitable assumptions about trapping kinetics, the position of the trap level and its capture cross section can be determined by varying the heating rate.⁶⁻⁸ If there is a discrete distribution of traps in the material, the TSC may show several peaks or a structure corresponding to the distribution of the trap depths. These peaks can be separated by using a technique called step heating^{6,9} which consists of measuring the TSC while the sample is heated to successively higher temperatures in steps. After each step the sample is cooled back to the lowest temperature. The carriers from deeper traps are liberated progressively and the logarithmic plot of the TSC as a function of $1/T$ is expected to yield a straight line for each step. Its slope is directly related to the trap depth.⁶ Other methods of analyzing the TSC data use the peak position⁶ and their detailed shape.⁵

TSC measurements, in the case of disordered solids, have been done mainly on chalcogenide glasses and have not yielded much information.^{14,15} This is mainly because the carriers in the chalcogenide glasses usually have a small drift range (Schubweg) and also their drift mobility

is small.^{16,17} a -Si:H, which is relatively free from these difficulties, has recently been studied with this technique.¹⁸⁻²² However, the results and interpretation of TSC from various groups differ.

In the present case a detailed study of TSC in a -Si:H in the temperature range $30 \leq T \leq 300$ K is reported. The experimental setup is described in Sec. II. Section III contains the analysis of the TSC measurements for a single trap level as well as for a continuous distribution of traps. In Sec. IV we give the results of the TSC measurements in heat-dried and light-soaked states in a -Si:H. In the interpretation of these results in Sec. V D, it is suggested that the observed structure in TSC does not necessarily imply a structure in the distribution of localized states (DOLS) in a -Si:H.

II. EXPERIMENTAL

Well-characterized samples of undoped a -Si:H prepared by the glow-discharge method having a pair of nichrome electrodes²³ were used for the TSC measurements. The sample temperature could be varied between 30 and 300 K using a closed-cycle helium refrigerator. Teflon feed-throughs were used to reduce the leakage current. The sample could be cooled in darkness to 30 K. At this temperature a red light ($\lambda \approx 670$ nm, $F \approx 30$ mW/cm²) was shone on the sample for ≈ 30 s. Shorter exposures yielded the same TSC, showing that the light-induced changes [Staebler-Wronski (SW) effect] have a negligible effect on the TSC for this exposure. After waiting for ≈ 10 min to allow the transients to subside, the sample was heated at a constant rate and the TSC recorded with an electric field ≈ 50 V/cm across the sample.

The TSC and dark currents become comparable near 300 K and thus to separate the TSC peak in this region two almost identical samples (prepared in the same run) in a bridge configuration, shown in Fig. 1, were used. Prior to each TSC set, the samples were balanced at 300 K us-

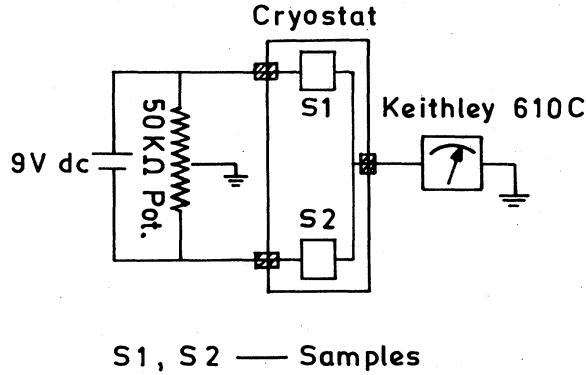


FIG. 1. Bridge configuration used for resolving the TSC peak at $T \approx 300$ K.

ing a 9-V battery and cooled in darkness. The difference between the currents of the unexcited samples (called the error signal) was measured from 120 to 300 K as the samples were heated at a constant rate β . For TSC, they were cooled in darkness and one of them was excited with a red light at 120 K. After waiting for transients to subside, the samples were heated in darkness at a constant rate β . The measured current, which is the difference in the currents of the excited sample and the sample in darkness, was the required TSC.

III. THEORY OF TSC

A. Single trap analysis

The simplest case is for the material in which only one trap level is contributing to the TSC at a time. Although a -Si:H has traps distributed throughout the mobility gap, it appears justifiable to use the single trap analysis to calculate the trapping parameters of a -Si:H, in view of the analysis of Simmons *et al.*²⁴ (cf. Sec. III B). We summarize the results for a single trap level, in the slow and fast retrapping limits, and show how the trap parameters can be obtained in this simple case.

Slow retrapping means that the probability of recapture of thermally liberated carriers by traps is much smaller than recombination, whereas in fast retrapping the recombination probability is small as compared to the recapture.⁸ Both cases have been treated in the literature, and one finds that the TSC for a material with a single trap level in the fast as well as the slow retrapping case is given by a general equation,

$$I(T) = A \exp \left[-\frac{E_t}{kT} - \frac{B}{\beta} \int_{T_0}^T \exp \left[-\frac{E_t}{kT} \right] dT \right], \quad (1)$$

where A and B are dependent on the trapping parameters and given in Table I. E_t is the trap depth, β is the heating rate, T_0 is the initial temperature, and k is the Boltzmann constant. At a time t after the heating has started, the temperature $T = T_0 + \beta t$.

From Eq. (1) the condition of maxima in TSC (i.e., a peak in TSC) can be obtained by using the condition

TABLE I. Values of A and B for slow and fast retrapping cases. q is the electronic charge, n_{t0} is the number of electrons in traps at $t=0$, N_t is the total number of traps, μ is the mobility of electrons in the conduction band, ν is the escape frequency, τ is the lifetime of the electrons, E is the electric field, C is the cross-sectional area of the sample, and N_c is the effective density of states in the conduction band.

Parameter	Fast	Slow
A	$\frac{qn_{t0}N_c\mu EC}{N_t}$	$qn_{t0}\nu\tau\mu EC$
B	$N_c/\tau N_t$	ν

$$\frac{dI(T)}{dT} \Big|_{T=T_m} = 0, \quad (2)$$

and is

$$\exp \left[\frac{E_t}{kT_m} \right] = \frac{B}{\beta} \frac{kT_m^2}{E_t}. \quad (3)$$

Equation (3) predicts that the TSC maxima temperature (T_m) will shift towards higher temperature for an increase in β . Also, for temperatures close to T_m , the contribution from the integral in Eq. (1) is quite small and the TSC at maxima can be approximated as⁸

$$I(T_m) = A \exp \left[-\frac{E_t}{kT_m} - 1 \right]. \quad (4)$$

In the literature one normally uses Eqs. (3) and (4) to obtain the trap depth. Two experimental techniques are used.

1. Initial rise method (Ref. 9)

If T is not far from T_0 , the integral in Eq. (1) may be neglected to obtain

$$I(T) = A \exp \left[-\frac{E_t}{kT} \right]. \quad (5)$$

Thus by heating the sample to a temperature T which is not much greater than T_0 , the slope of $\ln I$ versus $1/T$ should yield E_t . Since A does not affect the slope, the value obtained will be independent of the trapping kinetics.

2. Variation of heating rate

By performing the experiment with different heat rates, Eqs. (3) and (4) can be used to obtain the trap depth E_t as follows:

(a) If two heat rates β_1 and β_2 are used,⁷ Eq. (3) gives

$$E_t = k \frac{T_{1m} T_{2m}}{T_{1m} - T_{2m}} \ln \left[\frac{\beta_1 T_{2m}^2}{\beta_2 T_{1m}^2} \right]. \quad (6)$$

(b) A plot of $\ln(T_m^2/\beta)$ versus $1/T_m$ should be a straight line whose slope is related to E_t .

(c) From Eq. (4), if $E_t/kT_m \gg 1$, a plot of $\ln I(T_m)$

versus $1/T_m$ is a straight line for different heat rates with slope E_t .

It is interesting to note that in these cases the trap depth obtained does not depend on the trapping kinetics, since the constants A and B do not play any role in this analysis. Whereas it may appear to be advantageous to use these methods when the trapping kinetics are not known, in order to obtain the trap parameters (other than E_t) one must know which of the two cases (whether fast or slow retrapping) is applicable. In principle it should be possible to decide between the two alternatives for trapping kinetics by looking at the detailed shape of TSC and comparing it with Eq. (1). Lushick¹¹ has shown that for fast retrapping,

$$E_t = \frac{kT_m^2}{T' - T_m},$$

where T' is the temperature at which TSC is half of its maximum value in the decay region of TSC. In practice, such detailed comparison is usually not possible, since for $T > T_m$ other peaks usually start appearing. Garlick and Gibson⁹ described two ways of distinguishing between slow and fast retrapping.

a. Decay of TSC. Heating is stopped during the TSC measurements at a temperature T and the decay of TSC is observed with time. It is argued⁹ that the decay will be exponential for slow retrapping and hyperbolic for the fast case. However, this holds only for the case of a single trap level. For an exponential distribution of traps, a hyperbolic decay will be observed even in the case of slow retrapping.

b. Shape of the TSC peak. It can be argued that in the case of slow retrapping, the shape of TSC is independent of n_{t0} (i.e., initial excitation conditions, such as temperature of excitation, intensity and wavelength of excitation, etc.). However, it should depend on n_{t0} if strong retrapping takes place. Thus it does not seem to be easy to find out which of the two extreme cases discussed here is important by only measuring the TSC, and one needs information from the other experiments before one can determine the trap parameters, other than the trap depth, with any confidence.

B. TSC for a continuous distribution of traps

The problem of thermally stimulated currents in materials having a continuous distribution of traps has been taken up by Simmons *et al.*²⁴ They consider a distribution of traps $g(E)$ from an intrinsic level E_i to the conduction-band edge E_c and assume that the retrapping is negligible. The recombination is also neglected since it is assumed that the field is high enough to sweep out all the carriers before they recombine. With these assumptions the corresponding TSC is given as

$$I(T) = \frac{1}{2} qdC \int_{E_i}^{E_c} f_0(E)g(E)P(E,T)dE, \quad (7)$$

where d is the spacing between the electrodes, q is electronic charge, $f_0(E)$ is initial occupancy probability, C is the cross-sectional area of the sample, and the function $P(E,T)$ is given by

$$P(E,T) = \nu \exp \left[-\frac{E_t}{kT} - \frac{1}{\beta} \int_{T_0}^T \nu \exp \left[-\frac{E_t}{kT} \right] dT \right]. \quad (8)$$

The function $P(E,T)$ exhibits a pronounced narrow peak whose position E_{mn} depends on T and it has a half width of $2kT$. This important result clearly means that during the thermal scan of the sample in TSC, it is those traps positioned within $2kT$ of E_{mn} which contribute significantly to the current at a certain temperature. Thus single trap analysis to α -Si:H may be applied since the continuous distribution of traps in the band gap can be thought of as being made up of discrete levels, each with a half width of $\approx 2kT$. Further, Simmons *et al.*²⁴ have shown that TSC in samples which contain a continuous distribution of traps is proportional to the initial occupancy, i.e.,

$$I(T) = \frac{1}{2} qdC D f_0(E)g(E_{mn}), \quad (9)$$

where D is a constant and is only very slightly temperature dependent.

Equation (9) implies that TSC provides a direct image of the occupied trap distribution after initial excitation, i.e., $f_0(E)g(E)$. Further, the escape frequency (ν) according to the model for a system with continuous traps is given as²⁴

$$\nu = 10^Y$$

with

$$Y = \frac{(T_{2m} \log_{10} \beta_2 - T_{1m} \log_{10} \beta_1)}{T_{2m} - T_{1m}} - 1.66, \quad (10)$$

where β_1 and β_2 are two heating rates and T_{1m} and T_{2m} are the corresponding temperatures at the maxima.

IV. RESULTS

State A is reached after annealing the α -Si:H sample at 150°C for 2 h and B is after an exposure to AM1 (Air Mass 1) light for 2 h in vacuum. Figure 2 shows the TSC for a typical α -Si:H sample (solid curves A and B) along with respective dark currents (dashed curves A and B) in states A and B . In state A , the TSC shows a peak at low temperature and then increases monotonically up to 300 K. A peak exists near 300 K also, but cannot be seen in this experiment because of the large dark current. The TSC is considerably reduced in state B , and in the sample which shows a large SW effect, the low-temperature peak is reduced below the limit of detection. These results are in agreement with others.¹⁸⁻²¹ If the vacuum is poor ($\approx 10^{-1}$ Torr), an additional peak at ≈ 200 K appears. This peak is observed even without exciting the sample with light at low temperature. It is probably caused by adsorbates in the poor vacuum, since when the vacuum of the system is better ($\approx 10^{-5}$ Torr) the peak does not appear.²⁰

A. Intensity dependence of the TSC peak (≈ 120 K)

The effect of varying the relative intensity of excitation on the TSC peak at $T \approx 120$ K is shown in Fig. 3. The

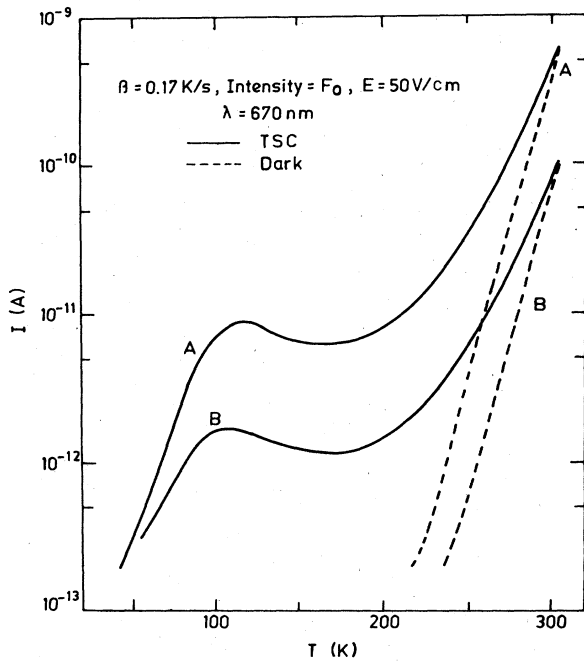


FIG. 2. TSC and dark currents in *a*-Si:H in heat-dried (A) and after-SW-effect (B) states.

TSC does not change appreciably upon changing the intensity from F_0 to $10^{-2} F_0$ ($F_0 \approx 30 \text{ mW/cm}^2$). Below $10^{-2} F_0$, however, the height of the peak reduces with intensity but the position of the peak remains unchanged.

B. Dependence of the TSC peak ($\approx 120 \text{ K}$) on the wavelength of excitation

To check whether the peak near 120 K arises from the surface or the bulk, lights of different wavelengths (λ)

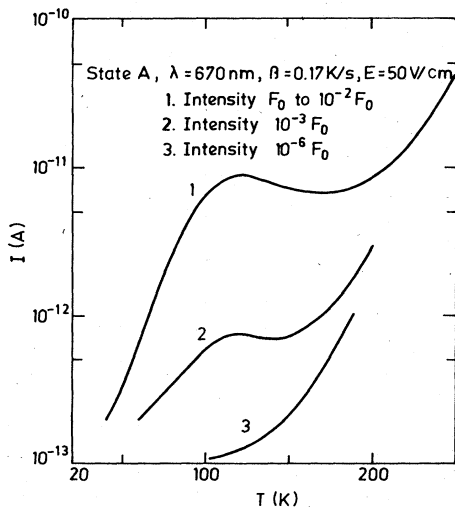


FIG. 3. Dependence of the TSC peak near $\approx 120 \text{ K}$ in *a*-Si:H in heat-dried state (A) on the intensity of excitation. For intensities $10^{-2} F_0$ to F_0 ($F_0 = 30 \text{ mW/cm}^2$), the sample is in the saturation region of TSC.

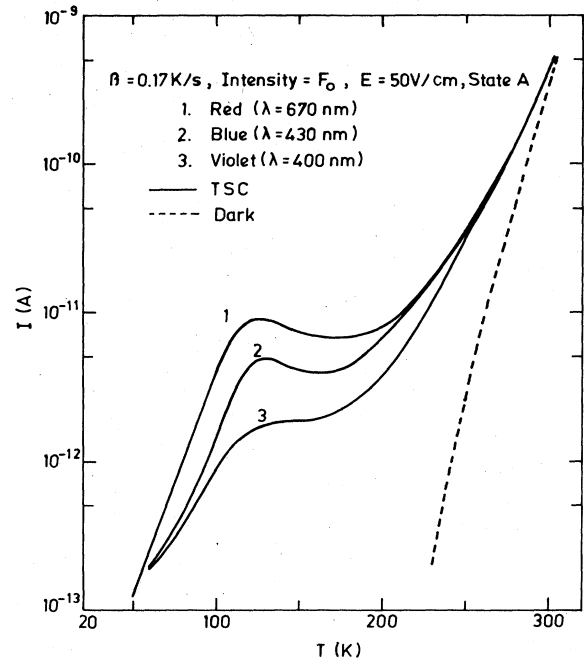


FIG. 4. Dependence of the TSC peak near 120 K in *a*-Si:H in the heat-dried state (A) on the wavelength (λ) of excitation. The intensity of the TSC peak is highest for band-gap light ($\lambda = 670 \text{ nm}$) and for the highest-energy light ($\lambda = 400 \text{ nm}$) the TSC peak reduces to a shoulder.

were used for excitation of the sample, in state A. The results are shown in Fig. 4. The intensities of various wavelengths were high enough that the TSC lay in the saturation region (i.e., between F_0 and $10^{-2} F_0$). It can be seen that the height of the peak is largest for red light ($\lambda \approx 670 \text{ nm}$), and that the peak reduces to a shoulder for violet

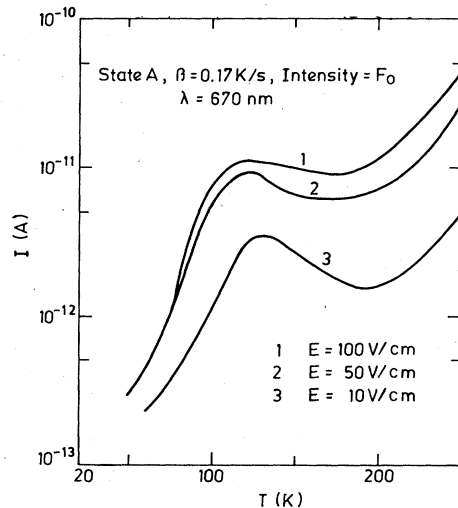


FIG. 5. Electric field (applied across the sample for collecting the carriers) dependence of TSC peak near 120 K in *a*-Si:H [in heat-dried state (A)]. The electric field at which the TSC saturates is $\approx 100 \text{ V/cm}$.

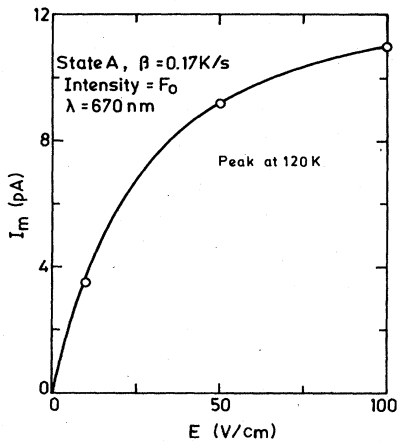


FIG. 6. Plot of $I(T_m)$ vs applied electric field for collection for peak ≈ 120 K.

light ($\lambda \approx 400$ nm). From this it appears that the dominant contribution to the TSC is from the bulk.

C. Electric field (E) dependence of TSC peak (≈ 120 K)

A saturation of TSC is observed when the collection field is about 100 V/cm, as shown in Fig. 5, and in the plot of TSC at T_m versus E in Fig. 6.

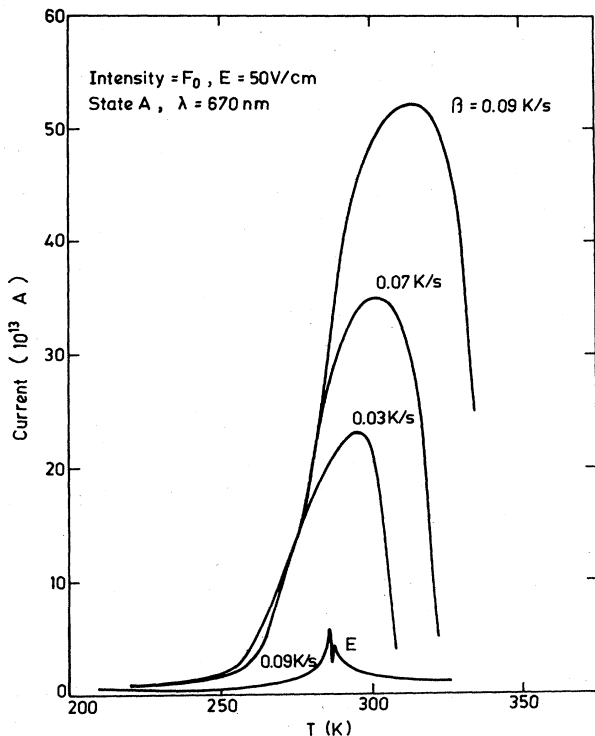


FIG. 7. TSC peak at ≈ 300 K observed using two almost identical samples in a bridge configuration in the heat-dried state (A). The heating-rate dependence of the peak is also shown.

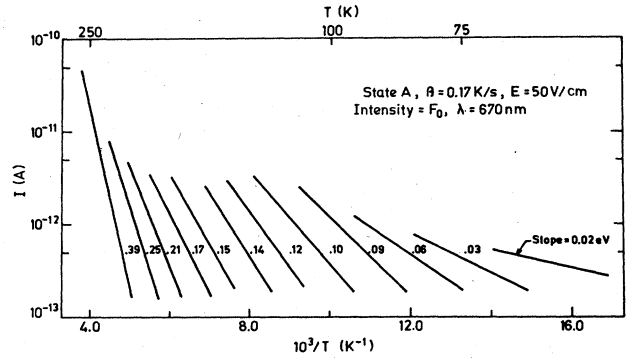


FIG. 8. Plots of $\ln I$ vs $10^3/T$ for various steps of step-heating analysis in a -Si:H in the heat-dried state (A) for $50 \leq T \leq 200$ K. After each step the sample is cooled back in darkness to 30 K (T_0).

D. Results in bridge configuration

As shown in Fig. 2, the TSC and the dark currents become comparable near 300 K, and therefore the TSC peak in this region is resolved by using the bridge configuration¹⁴ described in Sec. II (Fig. 1). Figure 7 shows the results. The technique allows us to see clearly, for the first time, this peak near 300 K whose position and height depend on the heating rate β . Curve E shows the error signal of the samples in darkness and is negligible in comparison to TSC.

V. DISCUSSION AND CONCLUSIONS

A. Step heating

To test whether a -Si:H contains a discrete or a continuous DOLS, the step-heating analysis, described in Sec. I, was employed. The results are shown in Fig. 8 (for the low- T region) and 9 (for the high- T region using the

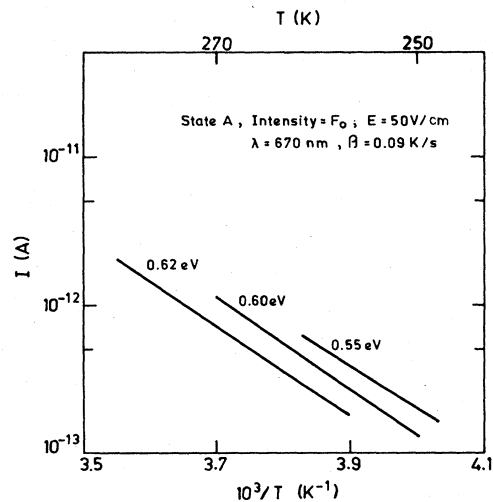


FIG. 9. Plots of $\ln I$ vs $10^3/T$ for various steps of step-heating analysis in a -Si:H in heat-dried state (A) in bridge configuration (in the temperature range $250 \leq T \leq 300$ K). After each step the sample is cooled back in darkness to 120 K (T_0).

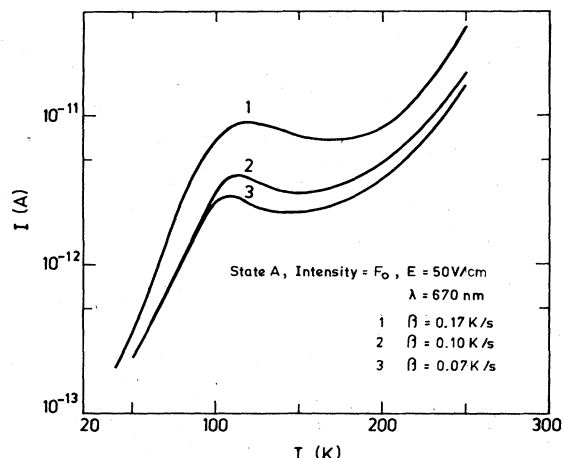


FIG. 10. Heating rate (β) dependence of TSC peak near ≈ 120 K in a -Si:H in heat-dried state (A).

bridge). The plots of $\ln I$ versus $10^3/T$ were found to be straight lines with slopes ranging from 0.02 to 0.62 eV (i.e., the dark values of E_F). It is evident from these results that a -Si:H contains a continuous distribution of traps in the upper half of mobility gap.

B. Analysis of TSC peaks

Simmons *et al.*²⁴ have pointed out that for a sample containing a continuous distribution of traps, the maximum contribution to TSC at a certain temperature comes mainly from the traps which lie within $2kT$ of the energy

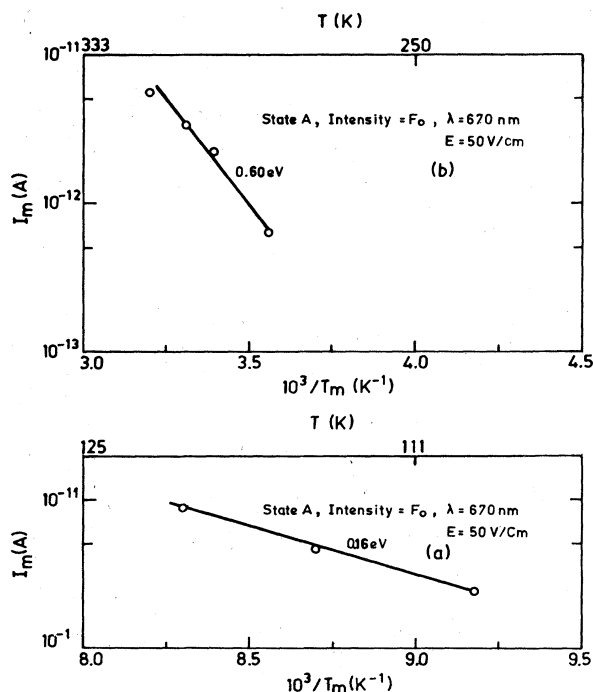


FIG. 11. (a) Plot of $\ln I(T_m)$ vs $10^3/T_m$ for three different heating rates used for analysis of the TSC peak at 120 K. (b) Plot of $\ln I(T_m)$ vs $10^3/T_m$ for four different heating rates used for analysis of the TSC peak at ≈ 300 K.

$[E_{mn}(T)]$ being probed. In view of this it appears worthwhile to first analyze the TSC results in a -Si:H with one trap-level model. Let us calculate the trap depth for the two peaks.

The results of a heat-rate analysis for the low-temperature peak are shown in Fig. 10 and for the high-temperature peak in Fig. 7. The plots of $\ln I(T_m)$ versus $10^3/T_m$ for various heating rates are straight lines (Fig. 11). The slopes are 0.16 and 0.60 eV for the low- and high-temperature peaks, respectively. This implies that the states contributing the most to these TSC peaks are expected to be those which are within $2kT$ of 0.16 and 0.60 eV below E_c . Plots of T_m^2/β versus $1/T_m$ also yield straight lines which give similar values for the trap depth. It may be mentioned that these methods used for determination of trap depths are independent of the trapping kinetics.

Using Eqs. (3) and (4) the values of A and B are calculated to be $\approx 10^{-5}$ and 10^5 , respectively, for the low-temperature peak and 10^{-1} and 10^9 for the high-temperature peak.²⁵ Since the retrapping kinetics are not known, the values of the parameters n_{t0} , N_t , and ν cannot be determined unambiguously. However, it appears from these calculations that retrapping plays an important role in a -Si:H at low temperature.²⁵

C. Decay of TSC peak (≈ 120 K)

The decay of the TSC (Ref. 9) peak near $T \approx 120$ K is shown in Fig. 12. In this experiment the sample (after excitation) is heated at a constant rate ($\beta \approx 0.17$ K s $^{-1}$) and the temperature of the sample is held constant near the peak temperature (≈ 120 K). The decay of the TSC with time is then measured. Curve 1 in Fig. 12 is the TSC without decay and curve 2 is the decay of the TSC with

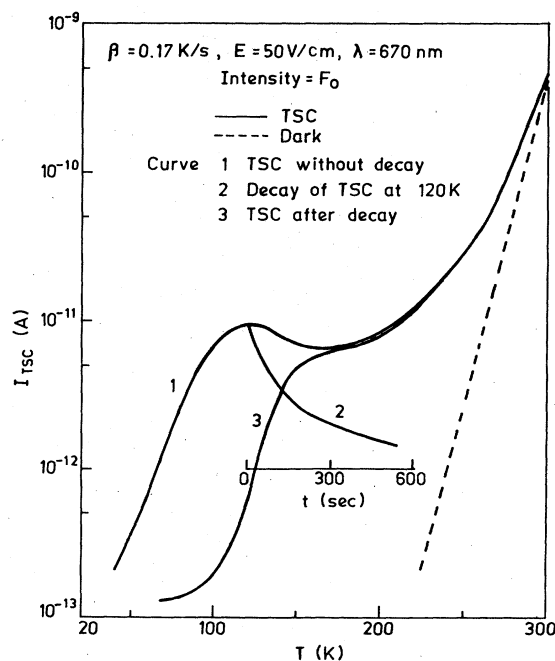


FIG. 12. Decay of the TSC peak at ≈ 120 K in a -Si:H in heat-dried state (A).

time at ≈ 120 K. After letting TSC decay for about 10 min, the sample is cooled back to 30 K in darkness and the TSC subsequently measured (curve 3). The TSC after decay is found to be considerably reduced near 120 K and below. From the slope of the initial part of the decay curve (2) the time constant (τ_t) and the escape frequency (ν) of the traps can be estimated,^{9,14} if retrapping is neglected and the single-peak analysis is assumed to be valid. τ_t is given by

$$\tau_t = \frac{1}{\nu} \exp \left[\frac{E_t}{kT} \right]. \quad (11)$$

Using $E_t \approx 0.16$ eV the value of ν is found to be $\approx 10^5$ s⁻¹ which is quite small as compared to the values observed normally in crystalline semiconductors¹⁴ ($\approx 10^8$ – 10^{15} s⁻¹). This small value of ν suggests that the retrapping is quite significant in *a*-Si:H at low temperatures.

D. Origin of the structure in TSC in *a*-Si:H

Although structure in the TSC in the form of peaks has been reported by various authors for *a*-Si:H,^{18–22} its origin is not yet fully understood. Fuhs and Milleville¹⁸ have attributed it to the structure in the DOLS reported by Spear and LeComber.²⁶ The TSC peak at $T \approx 150$ K is ascribed by them to a peak observed near 0.4 eV below E_c in the DOLS (Ref. 26) and the peak at 250 K to the structure in the DOLS about 0.6 eV below E_c .²⁷ Chenevas-Paule and Dijon¹⁹ also found two TSC peaks, one near 130 K and the other at ≈ 260 K. They have attributed them to the presence of quasiscrete levels in the gap. Yamaguchi²⁰ has observed only one peak near ≈ 100 K and argued that the peak at ≈ 240 K is caused by adsorbates. Yamaguchi has attributed the peak at ≈ 100 K to the presence of a hole trap level about 0.2 eV above the valence band. Ibaraki and Fritzsche²¹ observed a pronounced structure near 160 K and explained their results in terms of the multiple-trapping theory.²⁸ They have concluded that the structure in the TSC does not signify a structure in the DOLS. All authors have observed a strong decrease in the TSC after light-induced changes (SW effect), however, no satisfactory explanation has been offered for this.

The TSC in the present case shows two peaks; one at ≈ 120 K and the other at ≈ 300 K. The low-temperature peak in our opinion is the same as the one reported by others.^{18–21} The peak near ≈ 300 K (which has been observed by us) is probably present in all other studies also, but might not have been observed due to a large dark current near this temperature. The appearance of a peak near ≈ 300 K which corresponds to states near the Fermi level is understandable. However, the origin of the low- T peak is not clear. It does not correspond directly¹⁸ to the DOLS structure reported by Spear and LeComber²⁶ since the energy of the localized states responsible for this peak is ≈ 0.16 eV below E_c , whereas the DOLS structure is ≈ 0.4 eV below E_c . The low- T peak can also not be related to the presence of quasiscrete levels¹⁹ because the step-heating analysis (Sec. V A) shows that there is a continuous distribution of traps. The possibility that the peak at low T arises from the contribution of surface

states to TSC is ruled out by the wavelength dependence, as discussed in Sec. IV B. In Sec. III B, it was pointed out that in a material which has a continuous distribution of states (e.g., *a*-Si:H), the observed TSC is expected to be a direct reflection of the initially occupied DOLS in the excited state. This result, although obtained by Simmons *et al.*²⁴ in the limit of no retrapping, seems to hold qualitatively in the fast retrapping case also.²⁹ Thus if there is a peak in the initially occupied DOLS, the corresponding TSC peak can be expected even though there is no peak in the DOLS. We show below that the product of a fast rising DOLS and an exponentially decaying occupation function $f_0(E)$ might be responsible for the low- T peak. Neglecting the hole contribution, the electron occupancy function $f_0(E)$ above E_F is given by³⁰

$$f_0(E) = \frac{Rn}{Rn+p} [1 + \exp(E - E_{fn})/kT]^{-1}, \quad (12)$$

where R is the ratio of the electron to the hole capture rates and E_{fn} is the quasi Fermi level for electrons after excitation at low temperature. Figure 13(a) shows $f_0(E)$ for $E_{fn} = 0.17$ eV, $T = 30$ K (curve I), $E_{fn} = 0.21$ eV, $T = 80$ K (curve II), and $E_{fn} = 0.48$ eV, $T = 200$ K (curve III). Taking the DOLS $g(E)$ [Fig. 13(b), solid curve] which is identical to the Spear and LeComber plot²⁶ between E_F and 0.2 eV and is slightly modified in the region close to E_c , the corresponding density of occupied states $f_0(E)g(E)$ is obtained [Fig. 13(b), dashed lines I, II, and III]. It shows, in addition to the peak at 0.4 eV corresponding to the peak in $g(E)$, another peak near 0.16 eV. Since $g(E)$ increases rapidly and $f_0(E)$ decays exponen-

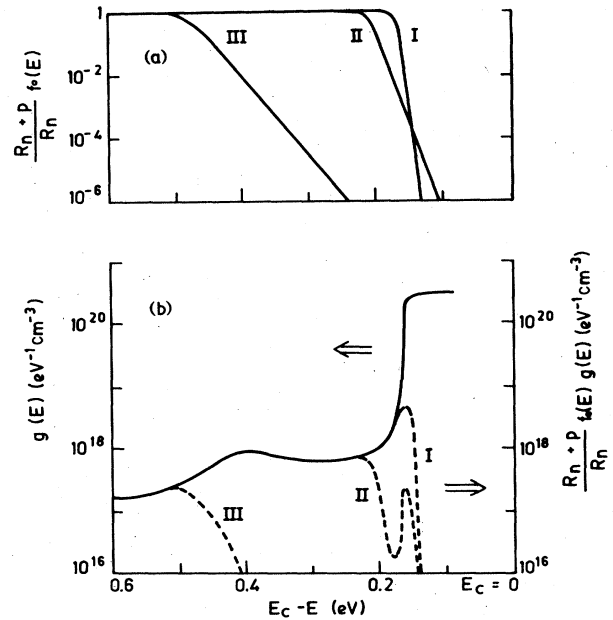


FIG. 13. (a) The occupation function [$f_0(E)$] in *a*-Si:H: (I) $E_{fn} = 0.17$ eV, $T = 30$ K; (II) $E_{fn} = 0.21$ eV, $T = 80$ K; (III) $E_{fn} = 0.48$ eV, $T = 200$ K. (b) Solid curve shows $g(E)$ (scale on the left) and the dashed curves (I, II, and III, scale on the right) show the density of occupied states $f_0(E)g(E)$ for different $f_0(E)$ as in (a).

tially as a function of E in this region, the product $f_0(E)g(E)$ has a peak at ≈ 0.16 eV although $g(E)$ does not have a peak at this energy. Thus, according to Eq. (9), a corresponding peak is expected in TSC.

It should be noted that the position of this peak should not depend upon E_{fn} [see Fig. 13(b)] so long as $|E_c - E_{fn}| > 0.16$ eV. E_{fn} is changed by changing the intensity of excitation and it is found that this results in a lower TSC peak but its position is unchanged as expected (see Fig. 3). However, no TSC peak corresponding to the 0.4-eV peak in $g(E)$ is observed. Retrapping can possibly obliterate it. Retrapping seems to be quite significant in α -Si:H especially at low temperatures. Further, it is possi-

ble that the SW effect may decrease the sharpness in $g(E)$ by creating more states in the gap. Since the low- T peak might arise because of sharply rising DOLS near band tails, the decrease in sharpness may give a smaller peak or no peak at all.

ACKNOWLEDGMENTS

Helpful discussions with Dr. V. A. Singh and Mr. Shailendra Kumar are gratefully acknowledged. We also thank the Department of Science and Technology, Science and Engineering Research Council (SERC), India, for financial assistance.

*Present address: Department of Physics, Harcourt Butler Technological Institute, Kanpur 208016, Uttar Pradesh, India.

- ¹P. Braunlich, P. Kelly, and J. P. Fillard, *Thermally Stimulated Relaxation in Solids*, Vol. 37 of *Topics of Applied Physics Series*, edited by P. Braunlich (Springer, Heidelberg, 1979), Chap. 2.
- ²R. H. Bube, *Phys. Rev.* **83**, 393 (1951).
- ³R. H. Bube, *J. Chem. Phys.* **23**, 181 (1955).
- ⁴G. A. Dussel and R. H. Bube, *Phys. Rev.* **155**, 764 (1967).
- ⁵L. I. Grossweiner, *J. Appl. Phys.* **24**, 1306 (1953).
- ⁶A review of different methods of analysis of data is given by K. H. Nicholas and J. Woods, *Brit. J. Appl. Phys.* **15**, 783 (1964).
- ⁷A. H. Booth, *Can. J. Chem.* **32**, 214 (1954).
- ⁸R. R. Haering and E. N. Adams, *Phys. Rev.* **117**, 451 (1960).
- ⁹C. F. J. Garlick and A. F. Gibson, *Proc. Phys. Soc. London* **60**, 574 (1948).
- ¹⁰P. J. Kelly and M. J. Laubitz, *Can. J. Phys.* **45**, 311 (1967).
- ¹¹Lushick, *Dokl. Akad. Nauk SSSR* **101**, 641 (1955).
- ¹²R. A. Street and A. D. Yoffe, *Thin Solid Films* **11**, 161 (1972).
- ¹³E. A. Fagen and H. Fritzsche, *J. Non-Cryst. Solids* **2**, 180 (1970).
- ¹⁴S. C. Agarwal and H. Fritzsche, *Phys. Rev. B* **10**, 4351 (1974).
- ¹⁵P. Muller, *Phys. Status Solidi A* **23**, 165 (1974); **23**, 395 (1974).
- ¹⁶S. C. Agarwal, *Phys. Rev. B* **10**, 4340 (1974).
- ¹⁷H. Fritzsche and S. Chandra, in *Proceedings of the Symposium on Thermal and Photostimulated Currents in Insulators*, edited by D. M. Smyth (Electrochemical Society, Princeton, N.J., 1976), p. 105.
- ¹⁸W. Fuhs and H. Milleville, *Phys. Status Solidi B* **98**, K29 (1980).
- ¹⁹A. Chenevas-Paule and J. Dijon, *J. Phys. (Paris) Colloq.* **42**, C4-605 (1981).
- ²⁰M. Yamaguchi, *J. Non-Cryst. Solids* **59-60**, 425 (1983).
- ²¹N. Ibaraki and H. Fritzsche, in *International Conference on Transport and Defects in Amorphous Semiconductors*, Bloomfield Hills, Michigan (unpublished).
- ²²D. S. Misra, A. Kumar, and S. C. Agarwal, *Philos. Mag. B* **49**, L69-74 (1984).
- ²³D. S. Misra, P. N. Dixit, and S. C. Agarwal, *Bull. Mater. Sci.* **3**, 247 (1981).
- ²⁴J. G. Simmons, G. W. Taylor, and M. C. Tam, *Phys. Rev. B* **7**, 3715 (1973).
- ²⁵D. S. Misra, Ph.D. thesis, I.I.T. Kampur University, 1984.
- ²⁶W. E. Spear and P. G. LeComber, *Philos. Mag.* **33**, 935 (1976).
- ²⁷W. E. Spear, in *Proceedings of the Fifth International Conference on Amorphous and Liquid Semiconductors, 1973, Garmisch-Partenkirchen FDR*, edited by J. Stuke and W. Brenig (Taylor and Francis, London, 1974), p. 1.
- ²⁸M. A. Kastner and D. Monroe, *Sol. Energy Mater.* **8**, 41 (1982).
- ²⁹A calculation including retrapping in the Simmons formulation is being done by us (unpublished).
- ³⁰J. G. Simmons and G. W. Taylor, *Phys. Rev. B* **4**, 502 (1971).