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Space-charge limited conduction in n^+nn^+ amorphous hydrogenated silicon films

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High field conduction in n^+nn^+ amorphous hydrogenated silicon (*a*-Si:H) films has been investigated at different temperatures. The results can be explained by assuming space-charge limited conduction (SCLC) with a uniform density of traps. The value of density of states at the Fermi level, $g(E_F)$, obtained from the SCLC measurements ranges between $7\text{–}9\times10^{16}$ $cm^{-3}\,eV^{-1}$. Similar values are obtained by measurements of field effect and frequency and temperature dependence of Schottky barrier capacitance on material grown under identical conditions.

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I. INTRODUCTION

There has been considerable interest in the study of amorphous hydrogenated silicon ($a-$Si:H) in recent years. These films are characterized by a low density of states (DOS) in the gap and it has been established that hydrogen present in the material saturates the dangling bonds and reduces the states in the gap. The states in the gap play a very important role in determining the electronic and optical properties of the material and determination of DOS in the gap has therefore received a great deal of attention.

The most widely used method is based on the measurement of field effect. This method was first used by the Dundee group[1,2] to show that glow-discharge decomposed films are characterized by a much lower DOS in the gap; later the method has been used by several laboratories[3–5] and typical values between 5×10^{16} to 10^{17} $cm^{-3}\,eV^{-1}$ have been obtained for DOS at the Fermi level (typically 0.6 eV from the band edge) for good quality undoped material. The analysis of field effect measurements neglects the presence of surface states. The density one calculates is therefore an upper limit; if the surface state density is large, the true value for the density of states at the Fermi level $g(E_F)$ would be much lower. There is another argument that has been put forward against use of field effect measurements to obtain bulk properties. It has been shown[6a] that in a typical field effect configuration, the current flows only in a narrow channel at the film-substrate interface. Since the property of the material during the first 100 Å of growth may be different from that in the bulk, questions have been raised[6b] if the field effect experiment measures the bulk properties.

Information about $g(E_F)$ can also be obtained by studying the frequency[7] and/or temperature dependence[8] of capacitance of Schottky diodes. In this method also, surface states will play a role but by choosing a suitable temperature/frequency range, the effect can be minimized.[9] Estimates of $g(E_F)$ as obtained by this method agree with results obtained from field effect measurements.

Deep level transient spectroscopy (DLTS) has been widely used for measurement of deep traps in crystalline semiconductors.[10] This method has the advantage that it can separate spatial and energy measurements of gap states and therefore in principle is free from surface state effects. DLTS has been used for measurement of DOS in *a*-Si:H. Initial measurements[11] gave a value of DOS less than 10^{15} $cm^{-3}\,eV^{-1}$ at about 0.4–0.5 eV from the conduction band edge; DOS was found to be larger near midgap. Later results[12] also showed a similar trend with a minimum at that energy; the midgap density is larger ranging from 2×10^{15} $cm^{-3}\,eV^{-1}$ for undoped material and higher for *P*-doped samples. These results are in sharp contrast with those from field effect[3–5] or *C-T-ω* measurements[7,8] where the midgap density for undoped films is found to be at least one order higher. Moreover, field effect measurements indicate a minimum in DOS around the midgap with increasing number of states as one approaches the band edges. The discrepancy between the results obtained from DLTS and the other set of measurements is not easily understood. The analysis of the DLTS data for amorphous semiconductors is rather involved. Clearly, an independent method of determining $g(E_F)$ which is free from effects of surface states will be necessary before one can ascribe the larger value of $g(E_F)$ obtained from field effect or *C-T-ω* studies to surface state effects.

Study of space-charge limited current (SCLC) has been used extensively to obtain information about deep traps in crystalline semiconductors.[13] Recently, this technique has been used to obtain information on DOS in *a*-Si:H. The study by Ashok *et al.*[14] is on Schottky barrier diodes which intriguingly had a nonlinear log *I-V* behavior for low forward bias. A power law relationship between current and voltage was observed for larger bias with a temperature dependent exponent which was explained in terms of SCLC with an exponential distribution of traps. Boer[15] studied SCLC in the n^+nn^+ structures. He did not observe a similar power law dependence of current on voltage and interpreted his results on the basis of a nearly constant distribution of traps around the Fermi level (0.5 to 0.6 eV below E_c). Typical trap concentration was found to be around 2×10^{16} $cm^{-3}\,eV^{-1}$. In none of these two experiments, DOS for the material was determined by any other method.

We have been making[16,17] in our laboratory *a*-Si:H

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films by glow-discharge decomposition of silane-hydrogen mixture and have shown that the films have comparable properties to that obtained from 100% silane. In this paper we present conduction properties of n^+nn^+ structure at high electric fields and show that the data can be explained by SCLC with a uniform DOS near the Fermi level. We also measure $g(E_F)$ by field effect and C-T-ω measurements on films grown under identical conditions and find that the results are in agreement with values obtained from SCLC.

II. EXPERIMENTAL DETAILS

a-Si:H films are prepared by dc glow-discharge of silane (10%)-hydrogen (90%) mixture. Typical deposition conditions are[16]: pressure = 0.6 Torr, flow rate = 0.3 cc/sec, and substrate temperature = 300 °C. For the field effect measurements, films are deposited on 150–170-μm-thick Corning 7059 glass substrates with predeposited NiCr contacts 2 mm apart. The gate electrode is an evaporated Al contact at the back of the substrate; details are given elsewhere.[5] For the C-T-ω measurements, Schottky diode structures are used. First, a thin (~ 500 Å) n^+ layer is deposited on Corning 7059 glass substrate with predeposited NiCr contacts. A mixture of 2% PH_3 in SiH_4 is used for the n^+ growth.[18] The undoped layer is next grown without breaking vacuum. The sample is next taken out, briefly etched in a dilute HF solution, and Pd dots are evaporated. For the n^+nn^+ structures,[18] after the growth of n on n^+ structure as in a Schottky run, another n^+ layer is grown on top of the n on n^+ film. The sample is taken out, given a brief etch in dilute HF solution, and NiCr is evaporated on to the top with the substrate kept at 150 °C. Individual diodes are isolated using photolithographic technique. For all the studies, the thickness of the undoped layer was about 8000 Å to 1 μm and growth conditions were kept identical.

All measurements were carried out in vacuum after heat drying the sample. For measurement of capacitance, a PAR 126 lock-in amplifier was used.

III. RESULTS AND DISCUSSIONS

The n^+nn^+ samples were found to be ohmic for field strengths below 5 kV cm^{-1}. The conductivity activation energy in the ohmic region was between 0.50 to 0.55 eV. For higher fields the I-V characteristic is nonlinear. However, we do not find a linear log I-log V characteristic, which implies that SCLC with an exponential distribution of traps does not explain the experimental data. For a uniform density of traps, the field dependence of the current under SCLC condition can be written as[13]

$$\ln J/F = SF + C, \tag{1}$$

with $S = 2/g(E_F)kTeL$ and C = constant. Here, L is the thickness of the sample and the other symbols have the usual meaning. We do find a linear dependence of $\ln J/F$ on field strength F as seen in Fig. 1. From Eq. (1) we note that S, which is the slope of the $\ln J/F - F$ characteristic, is inversely proportional to temperature and from a plot of S as measured against different temperature against $1/T$, one may find out $g(E_F)$. Figure 2 shows the plot of S against $1/T$ and from the slope we calculate $g(E_F) = 8 \times 10^{16}$ cm^{-3} eV^{-1}.

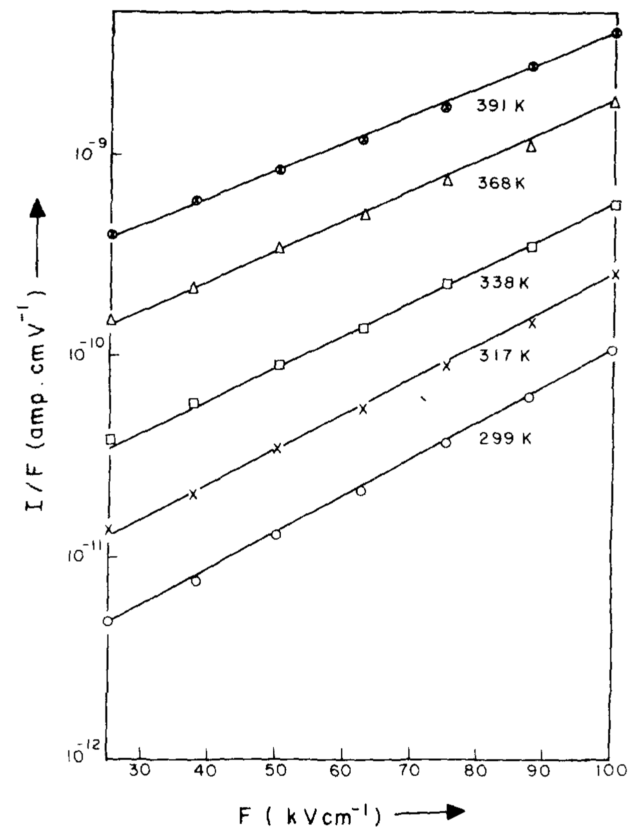

FIG. 1. Plot of I/F as a function of field strength at different temperatures for a-Si:H n^+nn^+ structures.

We may point out that since for the highest field applied the quasi-Fermi level does not shift by more than 3 kT, the mea-

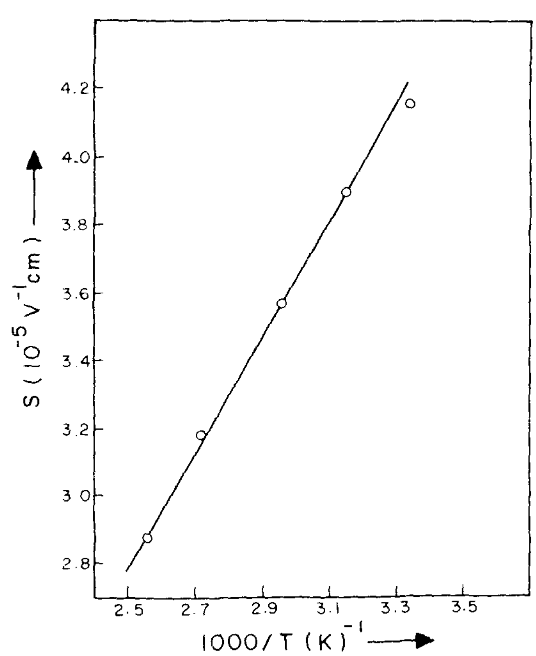

FIG. 2. Plot of S (obtained from the slope of plots in Fig. 1) as a function of $1000/T$.

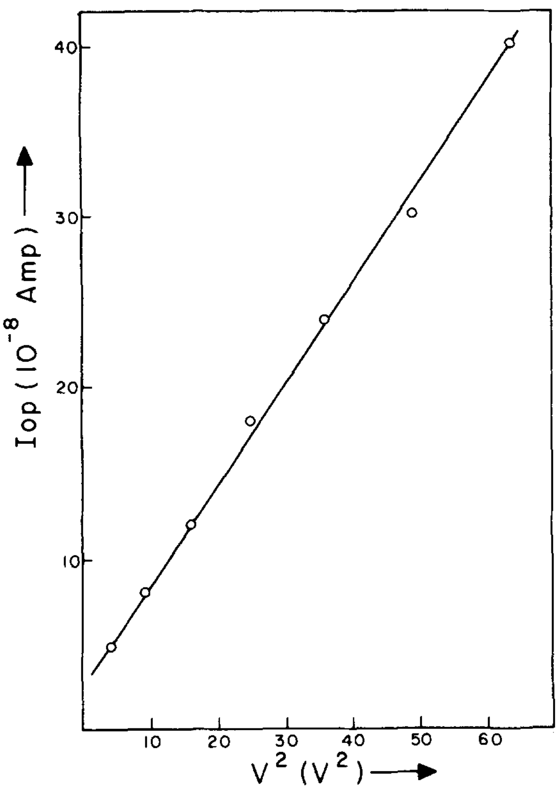

FIG. 3. Photocurrent for sub-band-gap light illumination in n^+nn^+ structures as a function of square of applied voltage.

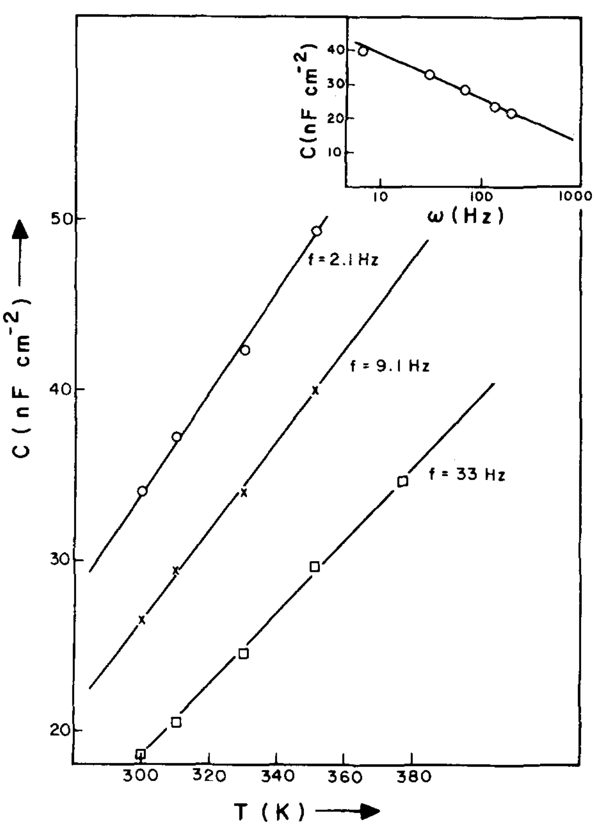

FIG. 4. Temperature dependence of low frequency capacitance of a-Si:H Schottky diodes at different frequencies. Inset: Frequency dependence of capacitance of a-Si:H Schottky diodes in the low frequency regime.

TABLE I. Values of $g(E_F)$ obtained from different experiments.

Method	$g(E_F)$ in $cm^{-3}\,eV^{-1}$
Space-charge limited conduction	$7–9\times10^{16}$
C-T	$1–3\times10^{16}$
C-ω	$3–6\times10^{16}$
Field effect	$5\times10^{16}–10^{17}$

sured value is for the density of state at the Fermi level only. We have made similar measurements on several samples and obtain values ranging from 7 to $9\times10^{16}\,cm^{-3}\,eV^{-1}$ for $g(E_F)$.

Further evidence that the conduction is space-charge limited comes from study of photocurrent at high fields when the sample is illuminated by sub-band gap light. Theoretically one expects[13] a transition from the exponential dependence of voltage for the dark current to a V^2 dependence of the photocurrent. This is indeed found to be the case as seen in Fig. 3.

The Schottky diodes used in the study had ideality factors less than 1.2. From the temperature dependence of the saturation current, the barrier height was found to be ~0.95 eV. The temperature dependence of low frequency capacitance of Schottky diodes at frequencies of 2.1, 9.1, and 33 Hz are shown in Fig. 4. A linear dependence of capacitance is observed and following Beichler *et al.*, $g(E_F)$ may be calculated either from the slope or the intercept at the C axis for $T=0$. The calculated values for the different frequencies range between 1 to $2\times10^{16}\,cm^{-3}\,eV^{-1}$. The inset in Fig. 4 shows the frequency dependence of the capacitance in the low frequency regime. Following Viktorovitch and Moddel we find $g(E_F)=5\times10^{16}\,cm^{-3}\,eV^{-1}$. We have investigated several samples and from the C-T-ω plots we find $g(E_F)$ ranging between $1–6\times10^{16}\,cm^{-3}\,eV^{-1}$. We have also measured $g(E_F)$ by field effect measurements. Details are given elsewhere.[5] For a large number of samples investigated we find $g(E_F)$ in the range $5\times10^{16}–10^{17}\,cm^{-3}\,eV^{-1}$. The results for $g(E_F)$ as obtained by different methods are tabulated in Table I. We find a good agreement among the values determined by the different methods. Since surface states do not affect space-charge limited conduction, the observed agreement implies that under the given conditions neither the C-T-ω nor the field effect measurement data are influenced by surface states and the value of $g(E_F)$ obtained from these measurements reflect bulk values.

In conclusion, we have measured the high field conduction properties of n^+nn^+ a-Si:H at different temperatures. The results can be explained by the model of space-charge limited conduction with a uniform density of traps. The measured value of density of states at the Fermi level ranges between $7–9\times10^{16}\,cm^{-3}\,eV^{-1}$ which agrees with the values obtained by field effect and C-T-ω measurements on material grown under similar conditions.

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