Conductance fluctuations in doped hydrogenated amorphous silicon

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Conductance fluctuations in n-type doped hydrogenated amorphous silicon (a-Si:H) films are described. The spectral density of the coplanar current fluctuations has a $1/f$ frequency dependence for frequency f from $1 < f < 10^4$ Hz over the temperature range $300 < T < 450$ K. The noise power density displays a power-law dependence on the dc current passing through the film, with a temperature-dependent power-law exponent. Random telegraph switching noise is observed in coplanar current measurements in samples with effective volumes of 10^{-6} to 10^{-7} cm^3 with fluctuations as large as $\Delta R/R \sim 1\%$. Statistical analysis of these fluctuations indicates that the $1/f$ noise is strongly non-Gaussian, suggestive of cooperative interactions between fluctuators. A model is proposed in which the noise is dominated by inhomogeneous current paths whose local conductivity is modulated by bonding rearrangements enabled by hydrogen motion.

I. INTRODUCTION

A diverse class of materials display conductance fluctuations for which the spectral density varies as the inverse of the frequency f, often termed flicker or $1/f$ noise.[1-8] These systems include metal films, semiconductors, spin glasses, and electronic devices. A common feature of the material systems displaying flicker noise is the presence of disorder, which leads to a broad distribution of relaxation times. Trapping and release of charge carriers from localized defects (number fluctuations) or scattering from mobile lattice imperfections or impurities (mobility fluctuations) lead to variations in the sample's resistance in time which can have a $1/f$ spectral density.[1] A microscopic identification of the traps responsible for flicker noise is lacking for most experimental systems; nevertheless, there is a general consensus that thermally activated defect motion underlies $1/f$ noise in most metals and semiconductors.

Recently there has been a growing interest in studying the noise characteristics of randomly inhomogeneous materials for which the standard models for $1/f$ noise do not apply.[5,9,10] In these systems electronic conduction occurs through percolation networks or clusters. Noise measurements are well suited for examining such percolation clusters, since the noise spectral density diverges as the connectivity of the network approaches the percolation threshold.[11-14] Thus, even if only a small proportion of the current in a system is transported through such percolation clusters, their influence on the $1/f$ noise will be significant. The sensitivity of the noise in a percolation network to a small subset of the total number of available conduction paths is reflected in the non-Gaussian statistics which characterize the $1/f$ noise in such systems.[15,16]

In this paper we report experimental measurements of conductivity fluctuations in doped hydrogenated amorphous silicon (a-Si:H) films, the prototypical and best understood amorphous semiconductor. While electronic transport in a-Si:H is assumed to occur through extended states above the mobility edge, the connection between the electronic states and the structural disorder of the amorphous film remains poorly understood. Many attributes of the $1/f$ noise in a-Si:H indicate that the noise actually arises from inhomogeneous current filaments in the semiconductor. The $1/f$ noise has a nonlinear dependence on the dc current passing through the film,[17] the magnitude of the noise is larger than that observed in comparable semiconductors, random telegraph switching noise is observed in the time dependence of the resistance,[18] the $1/f$ noise is strongly non-Gaussian and shows dramatic changes in noise magnitude with time.[19] All of these results are unanticipated for coplanar current measurements in a system with Ohmic electrodes free of contact noise. The noise studies described here therefore reveal important aspects of the electronic states through which conduction occurs, and may also provide a model system to explore noise in percolation systems.

This paper is organized as follows. We begin by briefly reviewing the sample preparation, electrode geometries, and measurement procedures in Sec. II. The $1/f$ noise measurements as a function of dc current and temperature, and the resistance switching noise results are described in Sec. III, as are statistical analysis of the noise power as a function of time. Section IV contains a description of a general model whereby variations in the hydrogen microstructure lead to inhomogeneous current paths in the a-Si:H film, which may account for the results of Sec. III. Finally, the main conclusions are summarized in Sec. V.

II. EXPERIMENTAL METHODS

A. Sample preparation and electrode geometry

The films used in these studies are n-type doped a-Si:H deposited via the rf (13.56 MHz) glow-discharge decomposition of silane (SiH_4) and phosphine (PH_3) in a capacitively coupled reaction chamber. The gas phase doping level was 10^{-3} PH_3/SiH_4. The a-Si:H films were deposit-

ed onto Corning 7059 glass substrates; substrate temperature during deposition was 500 K for sample 1 and 450 K for sample 2. The rf power was 2 W for an electrode area of 50 cm^2, yielding a deposition rate of ~ 1 Å/s. Both films are approximately 1 μm thick. Details of the deposition process[20] and electronic properties[21,25] of the samples studied here have been published previously.

The coplanar electrode configurations for the two *a*-Si:H films are shown in Fig. 1. For sample 1 shown in Fig. 1(a), electrical contact to *a*-Si:H is made via a mesa structure consisting of a 100-Å-thick layer of n^+ *a*-Si:H (gas phase doping level 10^{-2} PH_3/SiH_4) followed by an evaporated 1000-Å-thick Cr layer. The n^+ *a*-Si:H between the metal pads is removed by plasma etching. The Cr electrodes are 0.3 cm wide and have a 0.1-cm separation. The effective volume between the coplanar electrodes is 3×10^{-6} cm^3. Four-probe measurements, described below, were made by scratching the metal contact and the *a*-Si:H film with a diamond scribe as indicated in Fig. 1(a) in order to split each Cr contact. The four contacts are then at the corners of a rectangle 0.1 cm long and 0.05 cm wide, leaving an effective volume of $\sim 10^{-6}$ cm^3. The width of each scratch is ~ 0.01 cm. One diagonal pair of electrodes is used as current leads and the resulting voltage drop is measured across the other diagonal pair of electrodes. For sample 2 the *a*-Si:H film is first patterned into the arrangement shown in Fig. 1(b) using conventional optical photolithography followed by ion beam milling. No n^+ *a*-Si:H layer was used for sample 2. The *a*-Si:H film extends into the regions marked *A-A'* and *B-B'* in Fig. 1(b). The area between leads *B-B'* is approximately 800 μm by 200 μm, with an effective volume of 1.6×10^{-7} cm^3. Electrical contact is made by applying silver paint directly on the *a*-Si:H pads *A-A'* for two-probe measurements and also onto *B-B'* for four-probe measurements.

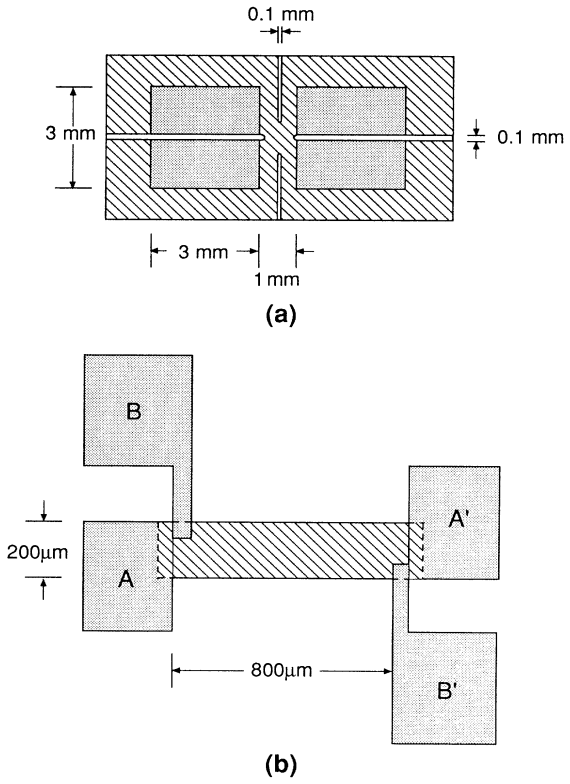

FIG. 1. Coplanar electrode configurations used for the noise measurements. The shaded regions represent the metal contacts and the crossed regions represent the *a*-Si:H film. (a) For sample 1, a 100-Å thin n^+ *a*-Si:H (1% gas phase doping level of PH_3 in SiH_4) layer lies between *a*-Si:H and Cr. The open regions indicate where the metal and semiconductor material was removed with a diamond scribe for four-probe measurements. (b) Sample 2 was patterned using photolithography; no n^+ layer was used and the *a*-Si:H film also extends into the regions labeled *A-A'* and *B-B'*. Two-probe measurements are performed using electrodes *A-A'* while in the four-probe configuration these electrodes are the current leads and *B-B'* are the voltage leads.

B. Measurement procedure

In the experimental setup used for the noise measurements the *a*-Si:H film sits on a copper block inside a vacuum chamber. A turbo pumping station is used to achieve pressures of $\sim 10^{-6}$ Torr. Resistive heaters in the Cu block allow the sample temperature to be varied from room temperature to 500 K. The temperature is monitored via a platinum resistor sitting next to the *a*-Si:H film; a temperature controller regulates the temperature to within ± 0.1 K. In the two-probe setup a constant voltage is supplied by a voltage source across the electrodes and the resulting current is amplified using a current amplifier (Ithaco 564). For four-probe measurements a constant current is applied across one pair of electrodes, supplied using a Kiethley 224 current source, and the resulting voltage across a separate pair of electrodes is amplified using a SR 560 low noise amplifier. The signal from the current or voltage amplifier is then sent to an HP 3561A spectrum analyzer. The spectrum analyzer is used to record either a time trace of the resistance or the power spectrum of the resistance fluctuations using a fast-Fourier-transform subroutine. The dc current passing through the sample is measured separately using a Kiethley 485 picoammeter.

To check the instrumental noise background we replaced the *a*-Si:H sample with a commercial metal film resistor with similar impedance (about five MΩ). This background noise was at least 2 orders of magnitude smaller than the *a*-Si:H noise. Both the Johnson noise and shot noise of the *a*-Si:H film are many times smaller than the $1/f$ noise. Minority carrier density fluctuations at a rectifying contact are a common source of $1/f$ noise in semiconducting systems.[22] It is therefore important to verify that our noise results are not due to contact effects. We periodically compared the two-probe and four-probe results and found no significant difference (within the normal variations observed from data set to data set) between power spectra using the two methods. As a further test that our results are not influenced by changes in the contact resistance, which would affect the current supplied by the current source, we have simultaneously measured the current and voltage fluctuations in the four-

probe configuration for sample 2. The ratio of current to voltage fluctuations was less than 10%, indicating that our results are due to resistance fluctuations of *a*-Si:H. The two-probe measurement technique was used for most of the data reported here. Except where otherwise noted, the power spectra reported here are the result of 1000 rms averages, and were calculated for the frequency range 0–1 kHz with a bandwidth of 2.5 Hz. When necessary, a background subtraction was performed for each spectrum by subtracting a spectrum measured with a zero dc current.

All measurements were made in the dark and in an oil-free vacuum. The samples were annealed at 450 K prior to any measurements to remove any surface adsorbates which might influence the conductance of the thin-film amorphous silicon,[23] and to remove any effects of prior light exposure.[24] The *a*-Si:H film was then slowly cooled to the measurement temperature. Recent experiments have demonstrated that the density of electronically active dopants in *n*-type *a*-Si:H is governed by a metastable thermal equilibrium.[25] When the cooling rate exceeds the rate at which the localized state distribution comes into equilibration, the system is frozen into a metastable nonequilibrium state. This metastable state then decays with a stretched exponential time dependence.[26] In order to avoid complications due to the decay of the electrical conductivity following the high-temperature anneal, the data were taken following the stretched exponential decay, when the sample's conductivity is essentially time independent. The time τ for the defect structure to come into equilibrium in *n*-type doped *a*-Si:H is thermally activated (activation energy ~ 0.95 eV) and becomes shorter at higher temperatures ($\tau \sim 100$ s at 400 K).[25] Since $\tau > 10^6$ s for temperatures below 350 K, equilibration is achieved only for temperatures above 350 K. In order to avoid irreversible annealing effects, the highest temperatures studied were always 20 K below the sample deposition temperature.

III. RESULTS

The main experimental results involve fluctuations in the coplanar current in *n*-type *a*-Si:H. As described below, these samples display linear current-voltage characteristics, consequently the fluctuations in the current imply changes in the bulk resistance of the *a*-Si:H, provided that contact effects are eliminated as a source of the noise. The (*n*-type) conductivity σ of *a*-Si:H is given by $\sigma = ne\mu$, where n is the density of electrons excited to or above the conduction-band mobility edge, e is the electron charge, and μ is the free-carrier mobility. The free-carrier density is given, in turn, by $n = N_c kT \exp[-(E_c - E_F)/kT]$, where N_c is the density of states at the mobility edge E_c and E_F is the Fermi energy. Fluctuations in n of the order of 0.1–1 % therefore imply a room-temperature shift of the Fermi energy of 120–180 meV, assuming a constant density and location of the mobility edge. A shift of the Fermi energy of this magnitude could readily result from the variation of only approximately $10^{15}/\text{cm}^3$ midgap defects, that is, relatively small shifts of the Fermi level reflect large changes in the free-carrier concentration. On the other hand, measurements by many different experimental techniques[21,27] indicate that $\mu \sim 10$–20 cm^2/V s, which corresponds to an electronic mean free path on the order of 5–10 Å. If the current fluctuations result from changes in the electron's mobility then this would imply changes in the density of scattering centers (presumably midgap defects) of order $10^{19}/\text{cm}^3$ in order to achieve a 1% variation in the mean free path. Variations of such a high density of defects are unlikely to have been undetected by the large class of spectroscopies of the localized state distribution that have been brought to bear on *a*-Si:H. The experimental results discussed below are therefore described in terms of fluctuations of the number of electronic charge carriers in the semiconductor.

A. dc conductivity

As mentioned above, the defect structure of doped *a*-Si:H can be described by a metastable thermal equilibrium, having temperature-dependent densities of electronically active dopants and dangling bond defects.[25] One consequence of the thermal equilibration of the electronic conductivity is that there is a kink in Arhennius plots of the temperature dependence of σ at T_E, the equilibration temperature. Below T_E, σ undergoes a relaxation towards its equilibrium value with a stretched exponential time dependence, while above T_E the dark conductivity is in thermal equilibrium and is independent of thermal history. There is extensive evidence that the changes in the defect structure are enabled by hydrogen motion.[25,26] As mentioned in Sec. II B, the *a*-Si:H film was allowed to come into equilibration at any given temperature prior to making measurements of the noise spectral density. The fact that the conductivity has reached its equilibrium value is reflected in Fig. 2, which shows a plot of σ against inverse temperature for sample 1. There is no indication of a kink or change in the conductivity activation energy and preexponential factor, that is, the high-temperature equilibrium σ state extends all the way down to 325 K. The activation energy of 0.29 eV and prefactor $\sigma_0 = 200\ \Omega^{-1}\ \text{cm}^{-1}$ are in excellent agreement with earlier measurements based only upon high-temperature ($T > 400$ K) data.[21]

All of the noise data reported here were measured at dc current values within the Ohmic regime. For sample 1 with n^+ *a*-Si:H pads between the Cr contacts and the *a*-Si:H film, the *I-V* characteristics were linear from ± 100 V down to ± 0.05 V, passing linearly through the origin. For sample 2, electrical contact is achieved by using silver paint directly onto the *a*-Si:H film. This film also displayed linear *I-V* characteristics for voltages less than ± 20 V.

B. Power spectra

Noise in semiconductors is usually characterized by the spectral density of the current or voltage fluctuations. Figure 3 shows a log-log plot of the spectral density S_I against frequency for the frequency range 10–10 000 Hz for sample 1 (prior to scratching the contacts) at 310 K, using the two-probe measurement configuration. The

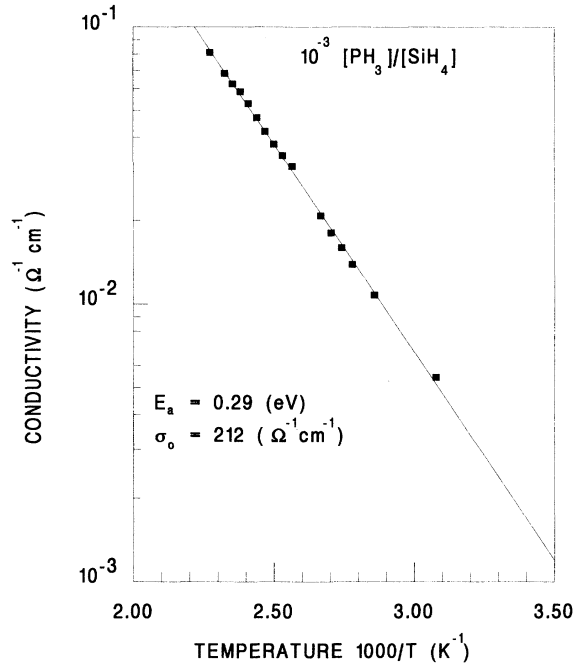

FIG. 2. Plot of the dc conductivity of sample 1 against inverse temperature. The sample was allowed to undergo a complete relaxation at each temperature prior to measurement, as explained in the text. The activation energy and preexponential factor obtained from a least-squares fit are indicated.

data in Fig. 3 represent the result of 1000 rms averages. Similar data are obtained using the four-probe measurement technique. The spectral slope γ, defined as $\gamma = -d(\log_{10}S_I)/d(\log_{10}f)$ is extracted by fitting a power-law form to the power spectrum between 10 and 900 Hz. The noise power is well described by the frequency dependence $S_I \alpha f^{-\gamma}$, where $\gamma = 1.1$. The spectral slope is plotted as a function of the sample temperature in Fig. 4 over the temperature range $300 < T < 450$ K. While there may be a weak temperature dependence to γ, described

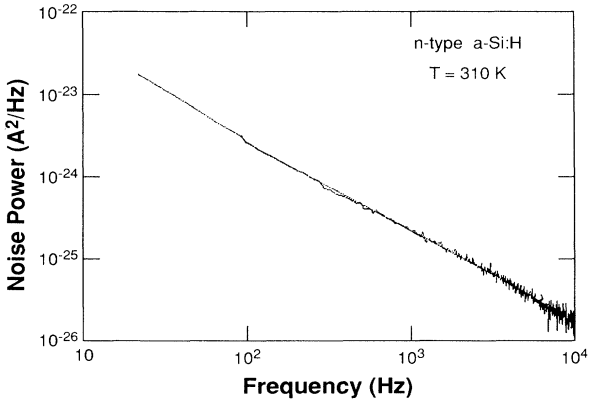

FIG. 3. A log-log plot of the coplanar current noise power density S_I against frequency for sample 1 measured at 310 K. The data are the result of 1000 rms averages and the solid line is a least-squares fit to the data from 100 to 900 Hz.

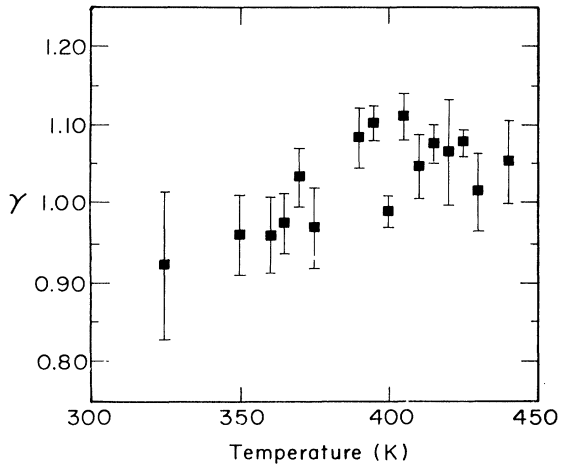

FIG. 4. Plot of the spectral slope γ [$= -d(\log_{10}S_I)/d(\log_{10}f)$] of the noise power density against temperature for sample 1.

by the relationship $\gamma \sim 1 + (T - T')/T_0$, where $T_0 \sim 700$ K and $T' \sim 350$ K, however, given the range of γ values obtained at each temperature the data are also consistent with the current fluctuations being pure $1/f$ noise over the entire temperature range investigated. The error bars in Fig. 4 are not due to the uncertainty in the power-law fits but rather reflect the random variations of γ values obtained at each temperature for different applied currents. These variations in the spectral slope are described in detail in Sec. III D.

The spectral density is the Fourier transform of the current-current correlation function; thus, for Ohmic systems, which describe the samples investigated here, the noise power should vary as the square of the applied dc current. The applied voltage was varied at each temperature in order to test whether the $1/f$ noise in a-Si:H is "linear," that is, $S_I \alpha I^2$. The currents were limited to less than 500 μA in order to avoid heating effects in the high impedance amorphous semiconductor. Figure 5 shows a log-log plot of the noise power, measured over a 100-Hz-wide frequency bin against the dc current for the sample in Fig. 3 at two different temperatures. The noise power data in Fig. 5 are obtained by summing the spectral density (1000 rms averages) over the frequency range 100–200 Hz; similar results are found using other frequency ranges. The data can be described by a power-law dependence $S_I \alpha I^b$, where $b = 1.9$ at 420 K, but is ~ 1.0 at 370 K. There is a clear temperature dependence of the power-law exponent b for the $1/f$ noise in a-Si:H. A preliminary report of the nonlinear $1/f$ noise in a-Si:H has been published.[17]

The variation of the power-law exponent b for two separate a-Si:H films is shown in Fig. 6. The circle data points are for sample 1 , deposited at a substrate temperature of 500 K, while the square data points are for a film grown with the same gas phase doping level but at a substrate temperature of 450 K. The two-probe electrode geometry used for the noise measurements for each sample are identical to that shown in Fig. 1(a). Each data point at each temperature represents the average b value

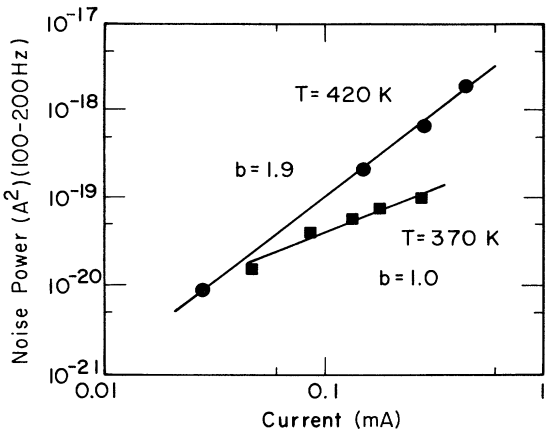

FIG. 5. A log-log plot of the noise power measured from 100 to 200 Hz for sample 1 against the applied dc current at 370 and 420 K.

obtained from four log-log plots of S_I against current I, as in Fig. 5, for the frequency ranges 100–200, 300–400, 500–600, and 700–800 Hz. This power-law behavior is also observed in four-probe noise measurements. The uncertainty in the $b(T)$ value obtained from a single power-law fit as in Fig. 5 is less than the size of the data points in Fig. 6. The error bars in Fig. 6 represent the spread in b values obtained from the power-law fits over the four measured frequency bins. While there is a considerable amount of scatter to the data, a clear temperature dependence is observed. Different samples can display different $b(T)$ values at a fixed temperature, and more important a given sample can show different b values after thermal cycling to 450 K. We therefore have not attempted to fit a temperature dependence to the data in Fig. 6, but simply note that the general trend is for b to increase with temperature. Measurements below 325 K indicate that the power-law exponent saturates to $b \sim 1$ at lower temperatures, though further studies on this point are warranted.

The noise power magnitude is normally expressed using the phenomenological expression[28] $S_I = \alpha_H I^2/(Nf)$, where N is the number (not the density) of charge carriers which can fluctuate in the sample and α_H is a dimensionless number, termed the Hooge parameter which has a typical value of $\alpha_H \sim 2\times 10^{-3}$ (but ranges from 10^{-5} to 10).[2] The nonlinear current dependence of the $1/f$ noise in a-Si:H complicates any attempt to analyze the temperature dependence of S_I using Eq. (1) or to extract a density of energy barriers using the analysis of Dutta and Horn.[1] Nevertheless, if the temperature dependence of b is ignored and one assumes that $b=2$ independent of temperature (which is not such a bad approximation above 400 K, as indicated in Fig. 6), then one can represent the noise magnitude using the Hooge formula. In a-Si:H above $T=400$ K where $b \sim 2$, α_H is approximately unity, which is nearly 3 orders of magnitude larger than typical values observed in semiconductors,[28] while below 400 K, α_H is roughly thermally activated with an activation energy of ~ 0.5 eV. The value of N used to evaluate α_H was obtained from the sample volume between the coplanar electrodes, the measured conductivity activation energy (Fig. 2) and the known density of states of a-Si:H. One possible explanation for the larger magnitude of α_H is that the effective volume which contributes to the $1/f$ noise is much smaller than the total available volume between the electrodes.

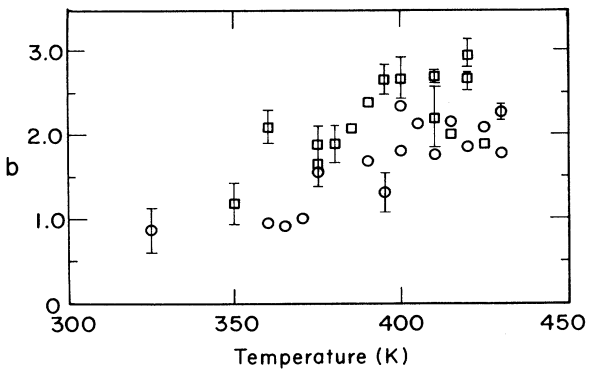

FIG. 6. Plot of the temperature dependence of the power-law exponent b $[=d(\log_{10}S_I)/d\log_{10}(I)]$ for two different samples. The circle data points are for sample 1 (grown at 500 K) and the square data points are for a similar film (with identical electrode configurations) grown at 450 K.

To summarize the noise power results, the current fluctuations in doped a-Si:H obey a $1/f$ frequency dependence over the frequency range of $1 < f < 10^4$ Hz for temperatures ranging from room temperature to 425 K. The noise power displays a power-law dependence on the dc current passing through the a-Si:H film, that is, $S_I \alpha I^b$, where $b \sim 1$ at 350 K and increases to ~ 2.5 at 425 K. The exact b value observed is both sample and thermal history dependent. The a-Si:H films are Ohmic, and four-probe measurements confirm that these results are not due to contact effects. The measured noise magnitude is roughly a factor of 10^3 larger than expected when analyzed using the conventional Hooge expression.

C. Random telegraph switching noise

In a system with many fluctuation processes operating simultaneously, direct measurement of the time dependence of the resistance is not particularly useful. Time traces of the resistance contain important information in systems for which the number of fluctuators are small enough so that individual fluctuations can be observed. In such systems studies of the resistance fluctuations can reveal details about the electronic properties and defect kinetics which are not reflected in the bulk transport measurements.

Figure 7 shows two single time traces of the resistance for sample 1, measured at 350 K, for a fixed applied voltage. Figure 7(a) was taken a few minutes before Fig. 7(b) with no changes to the power supplied or meters between the two traces. A resistance time trace taken a few minutes after the trace in Fig. 7(b) resembled Fig. 7(a) again. There is very obvious large-scale switching between two resistance levels. Fourier transforms of the data in Fig. 7(a) display a $1/f$ spectral density when

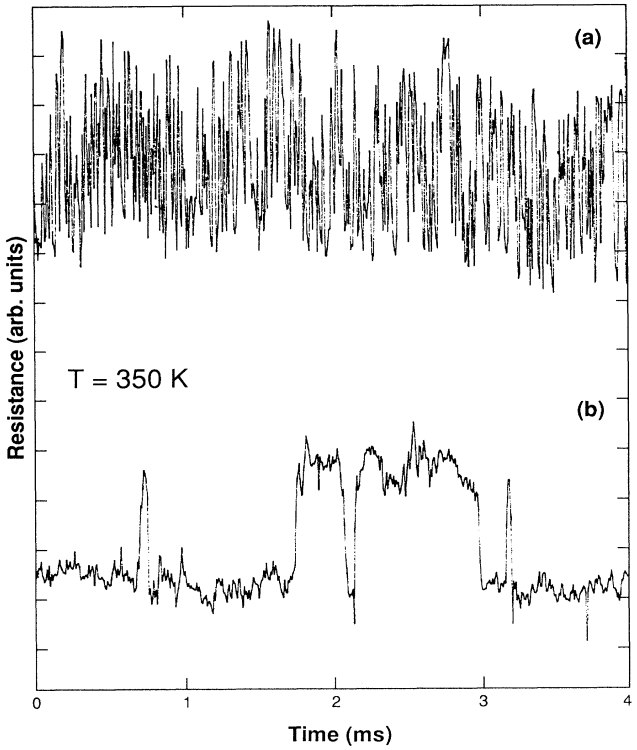

FIG. 7. Plot of resistance against time for sample 1 at 350 K. (b) was recorded a few minutes after the time trace in (a) was measured.

sufficient averages over long times are taken. The size of the largest switches in the two figures is $\Delta R/R = 10^{-3}$, the two curves in Fig. 7 have been offset for clarity. The two traces clearly show a change in the frequency and duty cycle of the switching events. In Fig. 7(a), the system spends nearly the same amount of time in the high and low resistance states, switching quite rapidly between these states, while in Fig. 7(b) the frequency of switches between states is much lower. A brief first report of switching noise in *a*-Si:H has been published elsewhere.[18]

The time scales for the switching events for both samples 1 and 2 can vary from a few milliseconds to several tens of seconds. In Fig. 8, several time records of the resistance, measured using the two-probe configuration for sample 2 at 300 K, are plotted. Each trace was taken several seconds apart and are offset for clarity. This figure clearly shows that the noise power of this material evolves as a function of time. The largest switches are $\Delta R/R = 6 \times 10^{-3}$. The switching pattern is more discrete than in Fig. 7 (sample 1), which is consistent with the smaller effective volume of sample 2. The resistance of the *a*-Si:H film will be fairly constant for some traces (curves 2, 5, and 6 in Fig. 8) and free of switching events, and will then suddenly demonstrate persistent switching as in curves 3 and 8. Trace 7 indicates that a switching event can "turn on" or initiate noise produced by more than one fluctuator. Typically a given switching pattern will not persist without change for more than a few time traces. These changes in the resistance with

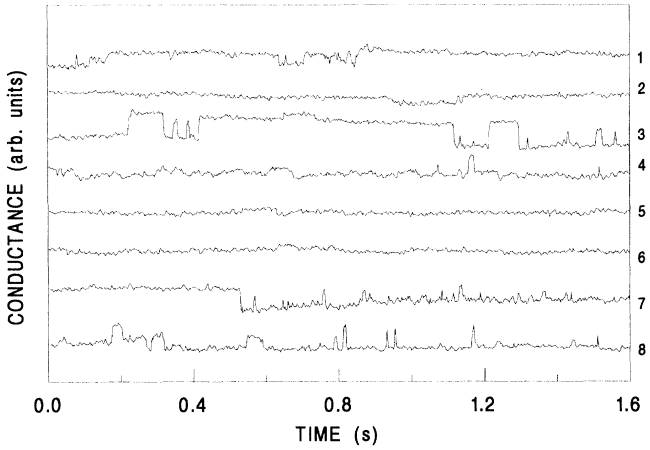

FIG. 8. Resistance time traces for sample 2, measured with the two-probe electrode configuration, at 300 K. The curves are offset for clarity and the time traces were recorded sequentially starting from curve (1), with a 5-s pause between each trace.

time are reflected in the time dependence of the noise power, as described in detail in Sec. III D.

D. Noise statistics

The average spectral densities reported above are the Fourier transforms of the two-point current-current correlation function. For the $1/f$ noise of most systems, there is no additional information contained in higher-order correlation functions, and higher moments can be uniquely decomposed into the sum of pairwise correlation functions. These noise signals are termed Gaussian, and the $1/f$ noise can be expressed as the superposition of a large number of statistically independent Lorenztian spectra. Deviations from Gaussian behavior can arise from a small number of statistically independent fluctuators or when the noise processes are highly cooperative.[15,16]

To analyze the noise statistics a series of power spectra are calculated, each from a single fast-Fourier transform (FFT) of a time record. The power spectra are then summed into seven octaves, where the first octave (5–10 Hz) consists of two FFT frequency points, and the last (320–640 Hz) consists of 128 points. The time record for each octave is then recorded and stored for later analysis. Figure 9 shows a typical time record of the noise power per octave for the seven octaves for sample 2 at 400 K. These time records clearly show strong correlations in the noise power between octaves, with the arrows marking several "events" indicating sudden changes in the noise power across several octaves. The events are not always positively correlated, that is, the noise power does not always change in the same direction for differing octaves. It is clear from Fig. 9 that variations in the noise power at one frequency are correlated with the noise power at other frequencies.[19]

The changes in noise power from one frequency octave to another as a function of time observed for *a*-Si:H are not seen in Gaussian noise systems, such as Johnson

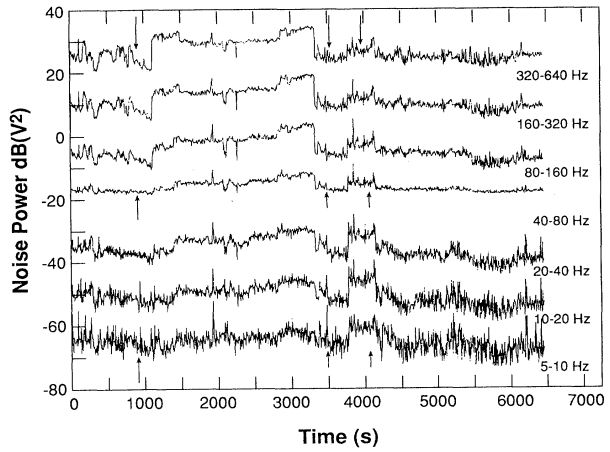

FIG. 9. Plot of the noise power for seven octaves as a function of time for sample 2 at 400 K. Each data point is the result of 10 rms averages.

noise. Figure 10 shows a plot of the noise power per octave as a function of time for Johnson noise of a resistor at 300 K. The data in Fig. 10 were obtained by measuring the noise of the internal resistance of the current amplifier used in the two-probe measurements. All measurement conditions were identical to those for which the data in Fig. 9 were taken. There is clearly no correlation between octaves, as expected for thermal noise. This reflects one of the basic properties of Gaussian noise systems, that the noise at one frequency is statistically independent from that at other frequencies.

Noise arising from a large number of independent processes is expected to have well-defined statistical properties.[2,15] The normalized noise power for a given frequency octave is expected to have a chi-square distribution. This chi-square distribution for the variable $P/\langle P\rangle$, where P is the noise power in that octave and $\langle P\rangle$ denotes the time-averaged noise power, has $2N$ degrees of freedom, where N is the number of FFT points in the given octave. Following the procedure developed by Restle and co-workers[15,16] we have made histograms of the normalized noise power for a given octave. Figure 11 shows histograms for the noise power of octave 5 (80–160 Hz) for both a-Si:H at 400 K and the Johnson noise of a resistor. The solid line in Fig. 11 is a plot of the expected chi-square distribution for this octave, which agrees well with the Johnson noise data but not with the a-Si:H results. The noise of the a-Si:H film has a much broader distribution, suggesting that there are a small number of processes dominating the noise in this material. This broader than expected distribution is termed "excess variance."[2]

The spectral slope of the noise data for a-Si:H is time dependent, also reflecting the non-Gaussian nature of the noise. We have taken 1000 individual spectra summed into octaves for sample 1 measured at 375 K, and made averages consisting of 200 spectra each. It is not possible to use bands exactly one octave wide because of the discrete frequency points of the FFT. A small correction factor[15] will be used to make comparisons of the octave noise power (for a power spectrum with an exact $1/f$ frequency dependence each octave should have the same noise power). The data are plotted as noise power per octave against frequency in a log-log plot in Fig. 12. Pure $1/f$ noise, that is $\gamma=1.0$, would be a horizontal line on such a plot. From Fig. 12 it is clear that the spectral slope "wanders" as a function of time, that is, the value of the noise power and the γ value which characterizes the deviation from pure $1/f$ noise are not constant, but evolves with time. The noise power found by averaging the first 200 spectra, labeled curve (1), is quite different from that found by averaging the second 200 spectra, and so on. It is important to note that when sufficient averages are taken the slope approaches $\gamma=1.0$, that is, the noise is described by a $1/f$ frequency dependence. This spectral wandering is consistent with both the non-Gaussian noise statistics and the random telegraph switching noise.

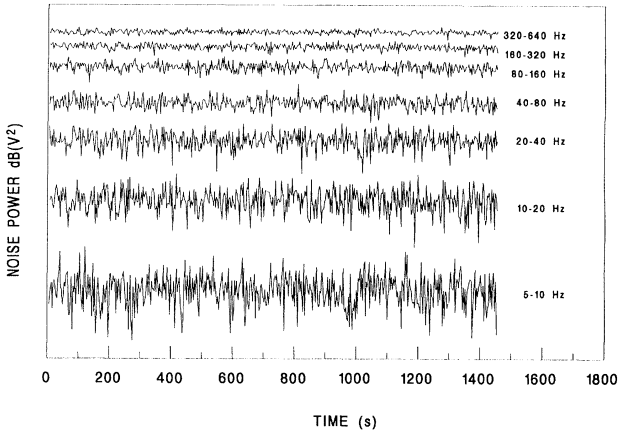

FIG. 10. Plot of the noise power for seven octaves as a function of time for Johnson noise at 300 K. Each data point is the result of 4 rms averages.

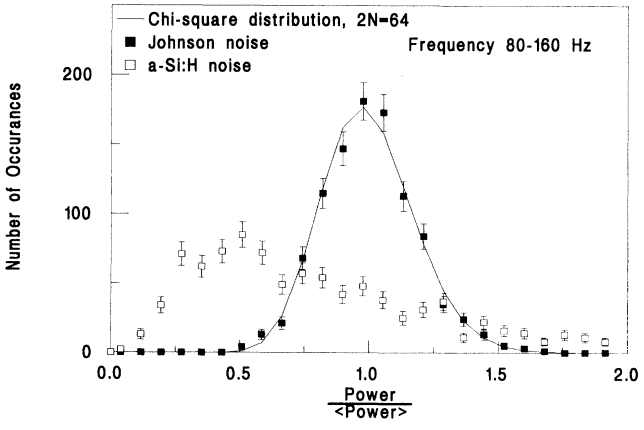

FIG. 11. Histogram of the noise power for octave 5 of an n-type a-Si:H film (open squares) and Johnson noise (solid squares). The expected chi-square distribution is also shown.

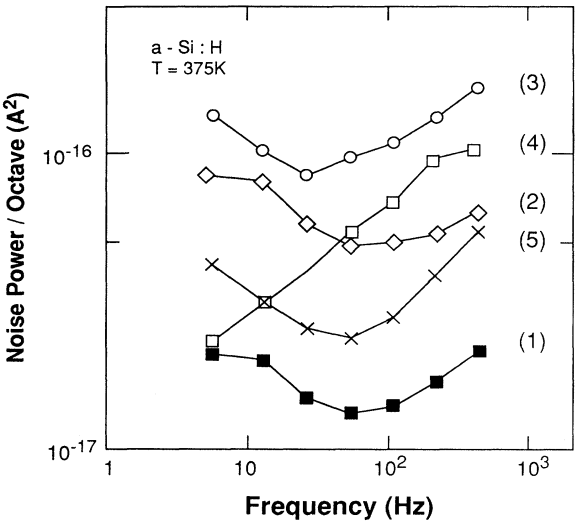

FIG. 12. Plot of the noise power per octave against frequency for sample 2 at 375 K. Each curve is the result of 200 rms averages. The average of the first 200 spectra are labeled curve (1), the average of the second 200 spectra are labeled curve (2), and so on.

IV. DISCUSSION

The results described in this paper are consistent with previous studies of $1/f$ noise in amorphous semiconductors which have been on device structures, for which the current fluctuations were measured transverse to the film's thickness. Studies by Bathaei and Anderson[29] of undoped and n-type doped a-Si:H samples found that the $1/f$ noise spectral density increased quadratically when the applied voltage was increased from 1 to 2 V, however, some of the data presented indicate that the spectral density actually obeys a subquadratic voltage dependence. The samples studied by Bathaei and Anderson displayed strongly non-Ohmic current-voltage characteristics for voltages greater than 2 V applied across the 2-μm-thick a-Si:H film. A subquadratic dependence of the $1/f$ noise on the dc current has been observed in the amorphous semiconductor $As_2Te_3Tl_2Se$ by Main and Owen.[30] Similarly switching noise has been reported in a-Si:H-based device structures, where the sample resistance is measured transverse to the film thickness.[31–33] These studies concluded that current filaments were responsible for the switching noise. The coplanar and four-probe measurements of switching noise reported here strongly indicate that this phenomena is due to conductance changes of the bulk a-Si:H film and do not arise from the contact-semiconductor interface.

The experimental results of Sec. III are at odds with common models for $1/f$ noise in semiconductors. The nonlinear dependence of the spectral density on the dc current passing through the sample, the excess magnitude of the noise power density, the non-Gaussian statistics, and the random telegraph switching noise are unexpected results for a film with the high carrier density and large sample volume used here. However, all of the above results can be reconciled in a model whereby electronic conduction occurs, at least in part, through inhomogeneous current filaments. If the exact connectivity of this filament network is sensitive to the detailed atomic configurations in the a-Si:H film, then changes in the local bonding arrangements could lead to changes in the filament's resistance, accounting for the switching noise, spectral wandering, and the nonlinear nature of the $1/f$ noise. We first describe how current filaments could explain the results presented above, and then speculate on possible microscopic origins for such filaments.

A. Noise due to current filaments

The nonlinear current dependence of the noise power is a fundamental and basic issue that must be addressed before other aspects of the $1/f$ noise are taken up. The fact that the spectral density does not scale as I^2 despite the fact that the current-voltage characteristics of a-Si:H are linear would imply that the noise does not represent fluctuations of the bulk resistance of the amorphous silicon, and that rather than merely being a probe of the fluctuations, the current is somehow causing the $1/f$ noise. Though not common, nonlinear $1/f$ noise has been observed previously in two different classes of experimental systems. Device structures for which the current is space charge limited typically display $1/f$ noise spectral densities which do not scale quadratically with the measurement parameter (i.e., current, voltage, etc.).[34,35] Such devices are by definition non-Ohmic, with the current density increasing as the square or higher power of the applied voltage. It is highly unlikely that the results of Sec. III B are due to space charge limited currents in the a-Si:H films studied here. The current-voltage characteristics of the doped a-Si:H films are linear at all temperatures studied. We have verified that the samples are Ohmic particularly at those temperatures for which the noise is nonlinear. Moreover, the electric fields applied across the coplanar electrodes (separation $\sim$1 mm) used to measure the noise data are typically less than 500 V/cm, while space charge limited effects have been observed in a-Si:H only for electric fields exceeding 30 kV/cm.[36]

The second class of materials which exhibit nonlinear $1/f$ noise are strongly inhomogeneous materials, such as discontinuous metal films and granular composite resistors.[37–40] The granular composite materials can be described as conducting metallic islands separated by insulating barriers. In this case the key conduction step is tunneling across the insulating barriers where the tunneling rate is not a linear function of the applied potential. In these material systems it is known that the structural disorder leads to inhomogeneous current densities. The current-voltage characteristics for conduction through such inhomogeneous filaments will not necessarily be linear, which can then lead to a nonlinear spectral density of the fluctuations of the current passing through such microchannels.

The essential physics for the nonlinear $1/f$ noise in these inhomogeneous composite systems is therefore identical to that of space charge limited devices. A fraction of the current passing through the composite material is carried through these filamentary channels. The majority of the current does not pass through these filaments, and is instead carried through conduction states

for which the current varies linearly with voltage. The bulk current-voltage characteristics of these materials therefore appear to be Ohmic. However, the small amount of current passing through the inhomogeneous filaments will display a nonlinear variation of the current on the applied voltage, that is $I \alpha V^{\alpha}$, with the actual I-V dependence being either sublinear or superlinear depending on the structural and electronic properties of the conducting filament, which will influence the local current density. The noise spectral density is highly sensitive to the presence of these filaments. As an illustrative example, consider a filament that arises through classical site percolation on a disordered lattice. The connectivity of such a filament will strongly depend on the location of every conduction state along the infinite percolation cluster. The energy level of these conduction states will plausibly depend on the detailed atomic bonding along the percolation cluster. Consequently, the motion of a single defect, or a change of a defect's charge state, could shift one of the conduction states out of registry with the rest of the infinite cluster, thereby breaking the percolation chain. The current carried by this filament will therefore vary discontinuously from some finite value to zero. Fluctuations in the connectivity of the percolation filament produce much larger changes in the fractional resistance $\Delta R/R$, and their contribution to the noise spectral density will be much greater than from other conduction paths, which, despite the fact that they carry much more current have a much smaller sensitivity to the variation of a single defect configuration or charge state.

There are thus two properties of the conjectured inhomogeneous current paths necessary to account for the observed nonlinear $1/f$ noise: (i) the fractional resistance change due to a fluctuation in the structure of the filament must be much larger than for other conduction pathways, and (ii) the current-voltage characteristics for the inhomogeneous channel must be nonlinear. The first property ensures that such filaments dominate the measured noise spectral density while the second property accounts for the nonlinear dependence of the power spectrum on the dc current passing through the sample. Furthermore, if we make the additional plausible assumption that the details of the non-Ohmic current-voltage characteristics of the filament depend on the exact structural configuration of the infinite percolation cluster, then the data of $b(T)$ in Fig. 6 can be understood. If the particular inhomogeneous current filament or filaments which dominate the $1/f$ noise spectral density are indeed sensitive to the detailed atomic configurations or charge state of localized defects which lie spatially along the infinite percolation channel, then it is natural that different samples will have different clusters which influence the noise spectra. These different filaments will not have the same I-V characteristics and therefore the b values which reflect the influence of the percolation filaments on the noise will show a sample-to-sample variation. Moreover, these defect configurations or charge states can plausibly vary following a high-temperature anneal, and so changes in the particular filaments which influence the noise data will be reflected in the different b values observed in a given sample following thermal cycling or at a fixed temperature over time. The subquadratic b values observed below ~ 400 K would imply that the I-V characteristics of the filaments present at these temperatures are superlinear, that is, the inhomogeneous current pathways produce regions of high electric field which create space charge limited conduction conditions for the current passing through the filament. At higher temperatures where $b \sim 2$ the connectivity of the filaments might have a higher level of redundancy and consequently the deviations from linearity are not as great.

Random telegraph switching noise (RTSN) is typically only observed in small devices with effective volumes of less than 10^{-10}–10^{-11} cm^3 at very low ($T < 10$ K) temperatures.[31,41,42] In these small semiconductor samples the current density is confined to a spatially narrow region for which the resistance is sensitive to charge trapping or emission from a single defect. Given the charge carrier densities of $\sim 10^{14}$ cm^{-3} and effective volumes as large as 10^{-6} cm^3 in the doped a-Si:H films studied here, approximately 10^5 charge carriers would have to be simultaneously trapped in order to cause an observed fractional resistance change as large as 1%. It therefore seems implausible that simple charge trapping could account for the RTSN in a-Si:H. However, if electronic transport in the a-Si:H films occurred through inhomogeneous current filaments near a percolation threshold, then minor deviations in atomic bonding configurations could give rise to large changes in the connectivity and resistance of these filaments.

Previously observations of RTSN in relatively large area a-Si:H-based devices were also attributed to the presence of current carrying microchannels of a small cross-sectional area.[32,33] In these experiments the current was measured transverse to the a-Si:H film's thickness, which makes it difficult to separate possible tunneling and contact effects from bulk resistance fluctuations of a-Si:H. The observations of RTSN in the coplanar current reported here suggest that current filaments do indeed exist throughout the bulk of the a-Si:H and the RTSN is not the result of contact or interface effects.

The fact that the fluctuations in a-Si:H are strongly non-Gaussian is not surprising given the observation of RTSN and the nonlinear current dependence of the $1/f$ noise. Both RTSN and non-Gaussian statistics typically arise from current fluctuations being regulated by a small number of processes.[2,15,16] This can be achieved in submicron scale devices for which the number of defects which can modulate the conductance is low, or in systems for which many fluctuators are highly coupled or cooperative, thus leading to a small number of effective fluctuators. The observation of spectral wandering in Fig. 12 and the time dependence of the resistance traces and noise power in Figs. 8 and 9 indicate that in a-Si:H the properties of the fluctuators responsible for the $1/f$ noise are time dependent. These changes in the characteristics of the noise suggest that the regions of the film responsible for the noise varies with time, or that there are large changes in the local material properties, or possibly both. The non-Gaussian nature of the $1/f$ noise thus also indicates that inhomogeneous current paths are present in the a-Si:H film.

B. Inhomogeneities in amorphous silicon

Given that variations in the properties of current filaments can account for the noise results reported here, one is then left with the question of the possible origin of the inhomogeneous current paths in doped *a*-Si:H films. In a relatively heavily doped amorphous semiconductor, as studied here, there is no shortage of potential sources of structural or electronic heterogeneities. The challenge rather lies in finding justifications to eliminate various heterogeneities as not being responsible for the noise data. The three most likely candidates as sources of inhomogeneous current densities are the localized band tail states, potential fluctuations induced by the charged impurities introduced by the doping process, and the known bonded hydrogen microstructure. We now consider each in turn.

Charge transport via phonon-assisted hopping through the localized band tail states which lie within the mobility gap is one possible origin of inhomogeneous current paths in amorphous silicon. These band tail states are known to be electronically occupied in doped *a*-Si:H from voltage pulse charge sweep out experiments.[43] While the extended states have a much higher mobility than the band tails, nevertheless, it is still possible that even above room temperature a small fraction of the current in the *a*-Si:H is carried by charge carriers hopping through the localized band tail states. While the contribution of such currents to the total bulk dc current would be negligible, they could strongly influence the $1/f$ noise spectra as argued above. However, the presence of inhomogeneous current channels alone is insufficient to account for the dynamical and nonstationary aspects of the noise in *a*-Si:H. The additional feature needed is a mechanism by which the properties of the microchannel which determines the noise measurements can vary with time, either by having the particular filament which dominates the noise alternate or by changing the current carrying capabilities of a given filament.

There are several mechanisms by which this can occur. The hopping rate of a charge carrier along the microchannel can be modulated by changes in the charge state of other localized states which are spatially near but not part of the infinite percolation cluster. While it is unlikely that the density of the band tail states themselves is altered by structural rearrangements (since attempts to alter the band tail slope by thermal quenching have been unsuccessful),[44] changes at the 0.1–1 % level in the density of localized states, necessary to account for the noise data, cannot be excluded by the quenching studies. Alternatively it has been suggested that charge carriers may hop through an impurity band comprised of the phosphorus donor levels which are believed to lie within the mobility gap, within the conduction-band tail.[45] Further studies in materials for which the band tail slope is broadened by varying the deposition conditions under which *a*-Si:H is grown, and by varying the doping level and doping type, are needed to determine whether this heterogeneity is responsible for our noise results.

Another source of inhomogeneous current paths in amorphous silicon are internal potential fluctuations induced by charged impurities.[46,47] In *a*-Si:H phosphorus atoms can be incorporated in either threefold or fourfold coordinated configurations with only the latter serving as an electronic dopant. Positively charged phosphorus (P_4^+) will have four valence electrons and will consequently be fourfold coordinated. The defect compensation model of doping[48] in amorphous semiconductors suggests that the combination of overcoordinating a dopant and undercoordinating a silicon atom (i.e., creating a negatively charged dangling bond) lowers the total free-energy cost of adding a P_4^+. Studies of electronic transport in singly doped and compensated *a*-Si:H films indicate that the potential fluctuations due to the charged impurities induce upward shifts of the conduction-band mobility edge.[46,47] For the doping level used in the *a*-Si:H films studied here, the densities of P_4^+ and Si_3^- are approximately[48] 10^{18} cm^{-3}, while the density of occupied band tail states has been determined from sweep out measurements[43] to be $\sim 10\%$ of the charged defect concentration. This leads to potential fluctuations with a mean-square amplitude of ~ 0.2 eV and a fluctuation period of roughly 4000 Å.[46] Electronic transport would be dominated by those field-free regions where the conduction-band edge forms a local minimum. The dynamical transitions in the noise magnitude would then result from changes in phosphorus or silicon bonding configurations (enabled by hydrogen motion), which would alter the local potential profile and consequently change the regions of highest relative conductance.

The known microstructure of the bonded hydrogen could also lead to the formation of current filaments. Nuclear magnetic resonance (NMR) studies have shown that the ~ 10 at. % hydrogen in *a*-Si:H exists as two phases: ~ 3–4 at. % is in a dilute phase consisting of isolated Si-H bonds and the rest resides in a clustered phase where several hydrogen atoms are bonded in close proximity.[49] Multiple quantum NMR measurements have demonstrated a complex morphology of the hydrogen in *a*-Si:H.[50] While the exact effect of the hydrogen microstructure on the electronic properties of amorphous silicon is not understood, it has been suggested that conduction in *a*-Si:H proceeds as a classical percolation process.[51] Since alloying with hydrogen increases the bandgap of amorphous silicon, it was suggested that the regions of high hydrogen concentration would act as insulating barriers. This would indeed make conduction in these materials sensitive to a significant fraction of conduction paths which carry a large portion of the current. Changes in the hydrogen bonding configurations, known to occur from the studies of stretched exponential relaxation in doped *a*-Si:H,[26] would then change the connectivity and relative conductance of these current filaments in a natural manner.

The simplest manner to test the influence of the hydrogen microstructure on the noise results would be to vary the hydrogen concentration in the amorphous silicon films. However, the amount of hydrogen incorporated into *a*-Si:H is determined by complex and poorly understood reactions during the growth process and does not differ significantly from ~ 10 at. % without seriously degrading the electronic properties of the *a*-Si:H film. Nev-

ertheless, comparisons of films grown under a variety of deposition techniques and by studying amorphous semiconductor chalcogenide glasses (which do not contain bonded hydrogen) should help elucidate the role that the hydrogen morphology plays in the noise results.

Two key questions relevant to all of the noise mechanisms proposed above are whether there is a sufficient density of mobile hydrogen at room temperature to account for the observed fluctuations and how large is the characteristic volume dominated by a single current filament. To answer the first question we calculate the probability P_H of a hydrogen atom hopping from a bonded site by using the hydrogen diffusion coefficient $D_H=(P_H a^2)/6$, where a is a characteristic hop distance of ~ 5 Å. Extrapolating measurements[52] of the hydrogen diffusion coefficient activation energy and preexponential factor to room temperature yields $D_H \sim 10^{-26}-10^{-27}$ cm^2/s and consequently $P_H \sim 8\times 10^{-11}-8\times 10^{-12}$/s. The films studied here typically contained 10 at. % hydrogen, hence the density of mobile hydrogens per unit time at room temperature is $4\times 10^{11}-4\times 10^{10}$/cm^3 s. This should be compared to the variation of the density of free charge carriers n. A dark conductivity activation energy of ~ 0.3 eV (see Fig. 2) implies $n \sim 5\times 10^{14}$/cm^3, which for a fractional change of $\Delta n/n \sim 10^{-3}$ yields $\Delta n \sim 5\times 10^{11}$/cm^3. Hence, the density of hydrogen atoms hopping per unit time does seem to be sufficient to account for the variations in current reported here.

To address the issue of the characteristic volume of a microchannel we assume that the various current paths which influence the $1/f$ and switching noise act in parallel; a change in a fractional volume element is then associated with a fractional resistance change observed in the RTSN data. The fractional resistance changes of order 1% in Fig. 8 corresponds to a lower limit of a characteristic volume affected by a single current filament of 10^{-9} cm^3. Given that this filament must transverse the coplanar electrodes 0.8 mm apart in sample 2, this indicates a lower limit on the cross-sectional area of the volume influenced during a switching event of order ~ 1 μm. This order-of-magnitude estimate of the length scale of a filament is consistent with values deduced from switching noise measurements in a-Si:H/a-SiN$_x$:H device structures.[32] Consequently, a current filament has this cross-sectional area, or a much smaller filament is able to influence the conductivity of a region this large. All of the proposed scenarios outlined above to account for the existence of current filaments imply a sensitivity to local, that is of the scale of 3–5 Å, bonding rearrangements. It is difficult to understand how charge trapping or motion of hydrogen atoms could influence the conductivity of a volume element this large. One possible explanation would be if the various current filaments carried current in series rather than in parallel. In the case of some form of structural bottleneck that several filaments must pass through in order to carry current across the sample, it is plausible that the motion of hydrogen atoms (either singly or collectively) at a "weak link" could influence the conductivity on much larger length scales. Serially constrained kinetics would be consistent with the observed power-law frequency dependence of the second spectra of the noise power fluctuations in a-Si:H.[19] Alternatively if the conductance of the filaments were modulated not by hydrogen motion but rather by changes in the charge states of localized defects lying along the infinite percolation cluster, then the long-range nature of the Coulomb interaction could account for the long length scales involved. However, in order to be consistent with the data in Figs. 8 and 9, this explanation requires particular localized charge configurations to remain stable for tens of seconds at temperatures above 400 K, which is unlikely. Clearly further studies are warranted in order to elucidate the microscopic origin of the conductance fluctuations in amorphous silicon.

V. CONCLUSIONS

The main conclusions of the paper are as follows.

(1) The power spectrum of coplanar current fluctuations in n-type doped a-Si:H follows a $1/f$ frequency dependence for frequencies ranging from $1 < f < 10^4$ Hz over the temperature range $300 < T < 450$ K.

(2) The noise power displays a nonlinear dependence on the dc current passing through the sample, that is, $S_I \alpha I^b$ where the power-law exponent b is temperature dependent, increasing from $b \sim 1$ at 300 K to approximately 2.5 at 450 K. The power-law exponent $b(T)$ is sample and thermal cycling dependent.

(3) Random telegraph switching noise is observed with fluctuations as large as $\Delta R/R \sim 0.1-1$ % in the temperature range $350 < T < 450$ K in a-Si:H films with coplanar electrode spacings as large as 1 mm and effective sample volumes of $10^{-6}-10^{-7}$ cm^3.

(4) The $1/f$ noise in a-Si:H is strongly non-Gaussian, showing slow spectral wandering behavior suggestive of cooperative effects.

(5) The noise results are observed in samples which display Ohmic current-voltage characteristics and comparisons of two-probe and four-probe measurements confirms that these observations result from fluctuations of the bulk conductivity of a-Si:H.

(6) These observations indicate that the noise results arise from fluctuations in the conductivity of inhomogeneous current filaments threading through the amorphous silicon films, arising possibly from either the intrinsic disorder of the silicon network, potential fluctuations induced by charged defects introduced by doping, or the bonded hydrogen microstructure. Hydrogen motion could change the connectivity and resistance of these current filaments, leading to the anomalous aspects of the noise data.

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[1]P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).
[2]M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988).
[3]Sh. M. Kogan, Usp. Fiz. Nauk **145**, 285 (1985) [Sov. Phys. Usp. **28**, 170 (1985)].
[4]W. H. Press, Commun. Mod. Phys. C **7**, 103 (1978).
[5]G. A. Garfunkel, G. B. Alers, M. B. Weissman, J. M. Mochel, and J. J. Van Harlingen, Phys. Rev. Lett. **60**, 2773 (1988).
[6]Neil Zimmerman and Watt W. Webb, Phys. Rev. Lett. **65**, 1040 (1990).
[7]N. O. Birge, B. Golding, and W. H. Haermmerle, Phys. Rev. Lett. **62**, 195 (1989).
[8]R. F. Voss and J. Clarke, Phys. Rev. B **13**, 556 (1976).
[9]M. F. Shlesinger and E. W. Montroll, Proc. Ntl. Acad. Sci. USA **81**, 1280 (1984); J. Klafter and M. F. Shlesinger, *ibid.* **83**, 848 (1986).
[10]J. Machta, M. Nelkin, Th. M. Nieuwenhuiszen, and M. H. Ernst, Phys. Rev. B **31**, 7636 (1985).
[11]R. Rammal, C. Tannous, P. Breton, and A.-M. S. Tremblay, Phys. Rev. Lett. **54**, 1718 (1985); R. Rammal and A.-M. S. Tremblay, *ibid.* **58**, 415 (1987).
[12]G. A. Garfunkel and M. B. Weissman, Phys. Rev. Lett. **55**, 296 (1985).
[13]R. H. Koch, R. B. Laibowitz, E. I. Alessandrini, and J. M. Viggiano, Phys. Rev. B **32**, 6932 (1985).
[14]D. A. Rudman, J. J. Calabrese, and J. C. Garland, Phys. Rev. B **33**, 1456 (1986).
[15]P. J. Restle, M. B. Weissman, and R. D. Black, J. Appl. Phys. **54**, 5844 (1983).
[16]P. J. Restle, R. J. Hamilton, M. B. Weissman, and M. S. Love, Phys. Rev. B **31**, 2254 (1985).
[17]C. Parman and J. Kakalios, Phys. Rev. Lett. **67**, 2529 (1991).
[18]C. E. Parman, N. E. Israeloff, and J. Kakalios, Phys. Rev. B **44**, 8391 (1991).
[19]C. E. Parman, N. E. Israeloff, and J. Kakalios, Phys. Rev. Lett. **69**, 1097 (1992).
[20]R. A. Street, J. C. Knights, and D. K. Biegelesen, Phys. Rev. B **18**, 1880 (1978).
[21]J. Kakalios and R. A. Street, Phys. Rev. B **34**, 6014 (1986).
[22]A. Van der Ziel, Adv. Electron. Electron Phys. **49**, 225 (1979).
[23]M. Tanielian, Philos. Mag. B **45**, 435 (1982).
[24]D. L. Staebler and C. R. Wronski, Appl. Phys. Lett. **31**, 292 (1976).
[25]R. A. Street, J. Kakalios, C. C. Tsai, and T. M. Hayes, Phys. Rev. B **35**, 1316 (1987).
[26]J. Kakalios, R. A. Street, and W. B. Jackson, Phys. Rev. Lett. **59**, 1037 (1987).
[27]T. Tiedje, in *Semiconductors and Semimetals,* edited by J. I. Pankove (Academic, New York, 1984), Vol. 21C, p. 207; T. E. Orlowski and H. Scher, Phys. Rev. Lett. **54**, 220 (1985).
[28]F. N. Hooge, Physica **83**, 14 (1976).
[29]F. Z. Bathei and J. C. Anderson, Philos. Mag. B **55**, 87 (1987).
[30]C. Main and A. E. Owen, Phys. Status Solidi **1**, 297 (1970).
[31]C. T. Rogers, R. A. Buhrman, H. Kroger, and L. N. Smith, Appl. Phys. Lett. **49**, 1107 (1986).
[32]R. Acre and L. Ley, in *Amorphous Silicon Technology-1989,* edited by A. Madan, M. J. Thompson, P. C. Taylor, Y. Hamakawa, and P. G. LeComber, MRS Symposia Proc. No. 149 (Materials Research Society, Pittsburg, 1989), p. 675; T. Teuschler, M. Hundhausen, and L. Ley, J. Non-Cryst. Solids **137&138**, 1107 (1991).
[33]W. K. Choi, A. E. Owen, P. G. LeComber, and M. J. Rose, J. Appl. Phys. **68**, 120 (1990).
[34]F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, Rep. Prog. Phys. **44**, 479 (1981).
[35]T. G. Kleinpenning, Physica B **94**, 141 (1978); Solid State Electron. **22**, 121 (1979).
[36]S. Furukawa, T. Kagawa, and N. Matsuomoto, Solid State Commun. **44**, 927 (1982).
[37]J. L. Williams and R. K. Burdett, Brit. J. Appl. Phys. **17**, 977 (1966).
[38]D. A. Bell, *Electrical Noise* (Van Nostrand, London, 1960) p. 240.
[39]J. L. Williams and I. L. Stone, J. Phys. C **5**, 2105 (1972).
[40]J. V. Mantese, W. I. Goldburg, D. H. Darling, H. G. Craighead, V. J. Gibson, R. A. Buhrman, and W. W. Webb, Solid State Commun. **37**, 353 (1981).
[41]K. S. Ralls, W. J. Skocpol, L. D. Jackel, R. E. Howard, L. A. Fetter, R. W. Epworth, and D. M. Tennent, Phys. Rev. Lett. **52**, 228 (1984).
[42]C. T. Rogers and R. A. Buhrman, Phys. Rev. Lett. **53**, 1272 (1984).
[43]R. A. Street, Philos. Mag. B **60**, 213 (1989).
[44]R. A. Street and J. Kakalios, Phys. Rev. Lett. **58**, 2504 (1987).
[45]W. Fuhs (private communication).
[46]H. Overhof and W. Beyer, Philos. Mag. B **43**, 433(1981); H. Overhof, in *Amorphous Silicon Technology—1992,* edited by Malcolm J. Thompson, Yoshihiro Hamakawa, Peter G. LeComber, Aruu Madan, and Eric Schiff, MRS Symposia Proc. No. 258 (Materials Research Society, Pittsburg, 1992), p. 681.
[47]R. A. Street, J. Kakalios, and M. Hack, Phys. Rev. B **38**, 5603 (1988).
[48]R. A. Street, Phys. Rev. Lett. **49**, 1187 (1982).
[49]J. A. Reimer, R. W. Vaughan, and J. C. Knights, Phys. Rev. Lett. **44**, 193 (1980).
[50]K. K. Gleason, M. A. Petrich, and J. A. Reimer, Phys. Rev. B **36**, 3259 (1987).
[51]M. H. Brodsky, Solid State Commun. **36**, 55 (1980).
[52]R. A. Street, C. C. Tsai, J. Kakalios, and W. B. Jackson, Philos. Mag. B **56**, 305 (1987).