Nonlinear 1/f Noise in Amorphous Silicon

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Measurements of coplanar current fluctuations in n-type hydrogenated amorphous silicon (a-Si:H) find that the spectral density of the noise accurately obeys a $1/f$ frequency dependence for frequency f in the range $1 < f < 10^3$ Hz over a temperature range $300 \leq T \leq 450$ K. The noise power density displays a power-law dependence on the dc current, where the power-law exponent b increases with temperature from $b \sim 1$ at 350 K to ~ 2.5 at 450 K. These results are discussed in terms of models for noise in composite and inhomogeneous materials.

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A strikingly wide variety of experimental systems display conductance fluctuations which have spectral densities varying approximately as $1/f$ over a large range of frequency f [1-3]. A common feature of these material systems is the presence of some form of disorder. Although the microscopic mechanisms associated with conductance fluctuations in general have yet to be identified, it is believed that for many materials the underlying mechanism involves the trapping or scattering of charge carriers in localized states. The disorder in the trapping sites then leads to a broad distribution of relaxation times, necessary to account for flicker or $1/f$ noise. A basic assumption of the theoretical models for $1/f$ noise, realized in most, though not all, experimental systems, is that the current passing through the material is simply a probe of, and does not cause, the electronic noise. This "linear" criterion yields, for Ohmic samples, a noise power density which varies as the square of the measurement parameter (voltage, current, etc.).

In this Letter we report measurements of current fluctuations in hydrogenated amorphous silicon (a-Si:H) which display a nonlinear dependence on the dc excitation current. Amorphous silicon, a "hydrogen glass" material, has unique advantages as a probe of relaxation phenomena in disordered systems. In addition to $1/f$ noise, a-Si:H also displays a stretched exponential relaxation of its electronic properties [4], a glass transition temperature which has a logarithmic dependence on cooling rate [5], and an ac conductivity with a linear frequency dependence [6], all of which are also associated with a distribution of barriers which inhibit transitions to a lower-energy configuration.

Nonlinear $1/f$ noise has been observed in other amorphous semiconductor systems. Main and Owen found that the $1/f$ noise in the chalcogenide glass $As_2Te_3Tl_2Se$ displayed a subquadratic dependence on the dc current, though no special precautions were described to eliminate the possible influence of contact noise [7]. Previous studies of $1/f$ noise in a-Si:H have been on device structures (i.e., measuring current fluctuations transverse to the film thickness) which displayed strongly non-Ohmic current-voltage characteristics for voltages greater than 2 V across a 2-μm-thick undoped a-Si:H film [8]. Bathaei and Anderson report $1/f$ noise measurements for these device structures which scale quadratically when the noise spectral density is measured at applied dc voltages of 1 and 2 V, from room temperature to 150 °C. While some of the spectral density data of Bathaei and Anderson indicate a nonquadratic voltage dependence of the $1/f$ noise, it is difficult to draw firm conclusions based upon two data points. In this Letter we find a marked nonquadratic current dependence for the $1/f$ noise in Ohmic samples over this same temperature range.

The measurements reported here were performed on n-type doped a-Si:H deposited via the rf glow-discharge decomposition of silane (SiH_4) and phosphine (PH_3). The gas-phase doping level of PH_3/SiH_3 was 10^{-3}, the substrate temperature during deposition was 500 K, and the incident rf power was 2 W. Details of the deposition technique, growth conditions, and electronic properties for these samples have been published previously [9]. Ohmic electrical contact is made to the 1-μm-thick a-Si:H films via a 100-Å-thick layer of n^+ a-Si:H (1%-PH_3-doped a-Si:H) deposited onto the a-Si:H sample, followed by evaporated chrome coplanar contacts of area 0.3×0.3 cm^2 with a separation of 0.1 cm. The n^+ a-Si:H between the coplanar electrodes is then removed by plasma etching. This electrode configuration yields linear current-voltage characteristics from ± 100 V down to ± 0.05 V, passing linearly through the origin.

The a-Si:H sample is first annealed at 450 K under a turbopumped vacuum to remove any surface adsorbates which might influence the conductivity of the thin film [10] and any effects of prior light exposure [11]. Previous studies have found that the electrical conductivity of doped a-Si:H is time dependent below 400 K, decaying with a stretched exponential time dependence, $\exp[-(t/\tau)^\beta]$, where both β and τ increase with temperature [4]. In order to avoid any complications in our noise measurements due to this slow decay, the a-Si:H sample was allowed to come into complete equilibration before any data were taken. Since $\tau > 10^6$ sec for $T \leq 350$ K, complete relaxation was only achieved for temperatures greater than 350 K. Similarly, in order to avoid irreversible annealing effects [12], the highest temperature was restricted to 10-20 K below the sample deposition temperature.

The current fluctuations were measured using a standard two-probe method, applying a constant voltage across the coplanar electrodes and measuring the fluctuations in the current passing through the *a*-Si:H sample. The voltage was supplied by mercury batteries in series with the semiconductor film. A virtual-ground current amplifier was used to measure the current fluctuations. The first stage of the amplifier uses a low-noise operational amplifier (OP-97). This first stage is ac coupled to a high-gain operational amplifier which yields a net gain of approximately 10^6 V/A. This amplifier was found to have a frequency-independent gain for the frequency range 1–2000 Hz. The output of the amplifier is sent to a spectrum analyzer (HP 3561A) where the current noise spectral density S_I is calculated for a frequency range of 0–1 kHz, with a bandwidth of 2.5 Hz. The instrumental background noise of this system was measured by replacing the *a*-Si:H film with a metal film resistor of equal impedance. This background was found to be at least 2 orders of magnitude lower than the film noise, except at the low end of the temperature range. Both the Johnson noise and the shot noise of the *a*-Si:H are orders of magnitude lower than the background noise of the spectrum analyzer. A background subtraction was performed at all temperatures for each spectrum by subtracting a spectrum taken with a zero dc current. All data reported here are the result of 1000 rms averages. Identical results are obtained using a four-probe electrode configuration at the corners of a rectangle (1 mm long and 0.5 mm wide), indicating that our observations are not due to contact effects. Details of the measurement technique will be published separately [13].

Figure 1 shows a log-log plot of the spectral density against frequency for an *n*-type *a*-Si:H sample at 420 K for increasing applied dc current. The spectral slope γ, defined as $-d(\log S_I)/d(\log f)$, is obtained by fitting a power-law form to the power spectrum between 10 and 900 Hz. As shown in Fig. 1, there is no systematic variation in γ as the dc current passing through the sample is increased. The spectral slope γ is 1.0 ± 0.10 over the entire temperature range ($325 \leq T \leq 450$ K) studied here. The γ value range is not due to the uncertainty in the power-law fits, but rather reflects the variations of γ values obtained at different currents at each temperature. This spectral wandering is described in detail elsewhere [13].

To test whether the noise power is linear with the dc current (that is, $S_I \propto I^2$), the applied voltage was varied at each temperature. To avoid heating effects in these relatively high-impedance samples the currents were limited to less than 500 μA (applied voltages 1.5–40 V). Figure 2 shows a log-log plot of the spectral density S_I against dc current I for two temperatures. The data can be described by the power-law relationship $S_I \propto I^b$ where $b=1.9$ at 420 K but decreases to ~ 1.0 at 370 K. The value of b is obtained from a power-law fit to the total noise power, measured over a 100-Hz-wide frequency bin against the dc current. The data in Fig. 2 are for a frequency bin from 100 to 200 Hz; similar results are found for other frequency bins.

The dependence of this power-law exponent b on temperature is shown in Fig. 3. Each data point represents an average of four b values, obtained from log-log plots of S_I against I in the frequency ranges of 100–200, 300–400, 500–600, and 700–800 Hz. The error bars in Fig. 3 represent the spread in b values obtained over the four frequency bins; the uncertainty in the b value obtained from a single power-law fit is less than the size of the data points. Figure 3 presents data for two separate samples; the second sample is identical to that used in Figs. 1 and 2 except for a lower deposition temperature of

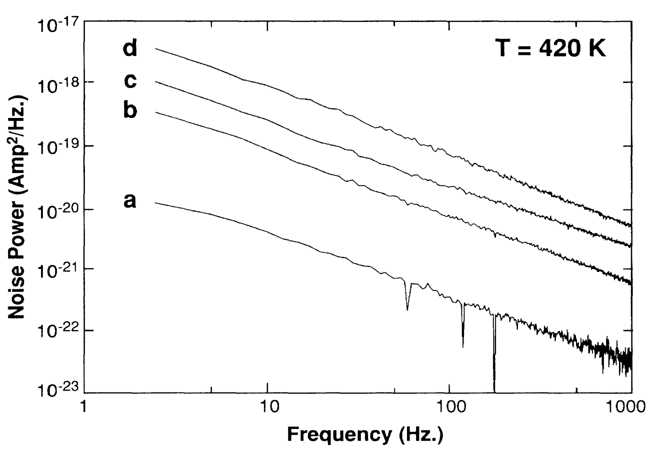

FIG. 1. Log-log plot of the noise power density against frequency for increasing applied dc current for an *n*-type *a*-Si:H sample. The applied current and spectral slope γ [$\equiv -d(\log S_I)/d(\log f)$] for the four curves are the following: (curve *a*) $I=0.028$ mA, $\gamma=1.00$; (*b*) $I=0.15$ mA, $\gamma=1.07$; (*c*) $I=0.29$ mA, $\gamma=0.99$; (*d*) $I=0.45$ mA, $\gamma=1.14$. The removal of 60-Hz noise by the background subtraction is evident in curve *a*.

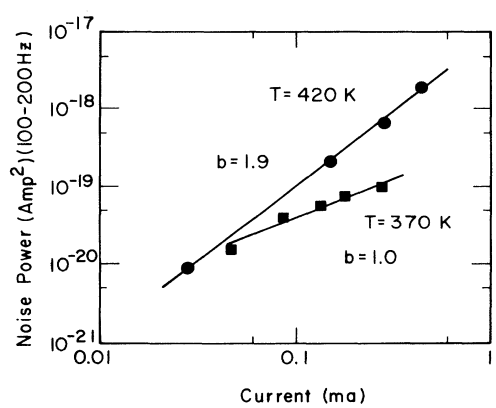

FIG. 2. Log-log plot of the noise power, measured from 100 to 200 Hz, against the applied dc current for two temperatures, for the same sample as in Fig. 1.

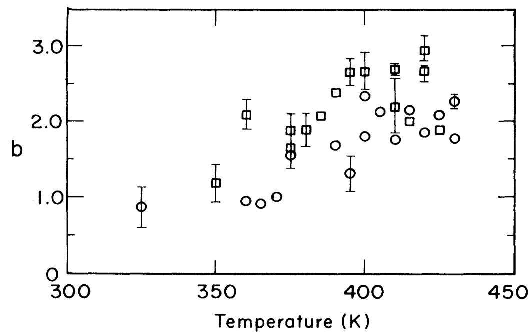

FIG. 3. Power-law exponent b [$\equiv d(\log S_I)/d(\log I)$] against temperature for two n-type a-Si:H films. The circle data points are for a sample deposited at 500 K while the square data points are for a film grown at 450 K.

450 K. Although there is a considerable amount of scatter to the data, there is a clear increase of b with temperature seen for both samples. Different b values are obtained following thermal cycling for a particular sample, and there is a variation in b at a fixed temperature for differing samples. The noise spectral density has an identical current dependence for both two-probe and four-probe electrode configurations, indicating that the temperature dependence of b is not a contact effect. Four-probe measurements below 325 K (when the a-Si:H has not come into complete equilibration) indicate that b saturates at a value near unity at lower temperatures.

Given the unusual current dependence of the noise, one cannot express the temperature dependence of the noise using the standard phenomenological expression [14] $S_I = \alpha_H I^2/N_c f$, where N_c is the number of free carriers in the sample and α_H is a dimensionless constant (the Hooge parameter) frequently found to be $\alpha_H = 2\times 10^{-3}$. Nevertheless, if we use this expression for S_I, or rather, plot $\alpha = S_I N_c f/I^2$ against temperature (which is not a bad approximation for $T > 400$ K, from Fig. 3), we find α is roughly thermally activated with an activation energy of ~ 0.5 eV. The value of α is quite high, with $\alpha \sim 1$ at $T = 400$ K rather than the lower value of $\sim 10^{-3}$ commonly found. The value of N_c used to evaluate α was obtained from the measured conductivity activation energy and the known density of states for a-Si:H.

We now address possible origins for the temperature dependence of the power-law exponent b. For Ohmic systems, which apply for the samples studied here, one would expect $b = 2.0$, independent of temperature or any other external parameter. Nonlinear $1/f$ noise has been observed in two different classes of experimental systems: (i) in device structures where the current is space-charge limited [14–16], and (ii) in discontinuous thin films and granular composite resistors [3,17–20]. It is unlikely that our results are due to space-charge-limited currents. We have verified that the I-V curves are linear in those cases where $b \neq 2$. Moreover, space-charge-limited currents are observed in the transverse conductance in a-Si:H only for fields greater than 30 kV/cm [21], while the largest field applied across our coplanar electrodes is 500 V/cm. We therefore consider alternative explanations for the nonlinear $1/f$ noise.

As mentioned above, the other class of experimental systems which exhibits nonlinear $1/f$ noise is composite or granular resistors. Measurements of carbon composite resistors [18] have found b values ranging from 1.5 to 1.9. Bell accounted for these data as arising from inhomogeneous current paths which produce regions of high electric potential, decreasing b from 2.0. The $1/f$ noise in chromium and silicon monoxide cermet resistors display a sample-dependent current-dependence power-law exponent b which varies from 1.5 to 3.5 [17]. Similarly, in discontinuous Pt films [19] one finds $S_v \propto V^b$, where $1 < b < 4$; b was found to increase with temperature, but with a slower variation than reported here for a-Si:H. The granular composite systems can be described as conducting metallic islands separated by an insulating tissue; the rate-limiting conduction step is then tunneling across the insulating barriers. In this case the nonlinear aspect of the noise can be ascribed to variations in the distribution of tunneling barriers induced by the dc current [19], though the physical origin of this current dependence is not described.

There are several known structural and electronic heterogeneities in n-type a-Si:H which could produce inhomogeneous current paths. Nuclear magnetic resonance studies have found that the approximately 10-at.% bonded hydrogen in a-Si:H exists in two distinct phases: a dilute phase of isolated Si-H bonds and a phase of hydrogen clusters, containing roughly six hydrogens in close proximity [22]. The influence of this hydrogen microstructure on the electronic transport properties of a-Si:H has not been determined, though it has been suggested that conduction occurs predominantly through the dilute phase, while the clusters act as barriers or traps (not unlike conduction through a percolation network) [23]. In any model for $1/f$ noise whereby the current fluctuations are dominated by a small subset of the total number of available conduction paths, the noise is expected to be non-Gaussian [2,24]. By comparing the variance of the $1/f$ noise power spectra in differing frequency octaves to that expected for Gaussian fluctuations, we have found that the current fluctuations in a-Si:H are indeed strongly non-Gaussian over the entire temperature range studied here. A full account of the non-Gaussian nature of the $1/f$ noise in a-Si:H will be published separately [13]. Non-Gaussian noise in Nb resistors has been attributed to the collective motion of interstitial hydrogen in the material [25]. The motion of bonded hydrogen may be responsible for the non-Gaussian $1/f$ noise in a-Si:H, suggesting that the hydrogen microstructure has an influence on the nonlinear noise measurements. As the temperature is raised, the detailed configurations of the bonded hydrogen will vary, which will in turn change the current paths which contribute to the $1/f$ noise. This sensitivity to the variations in the hydrogen bonding configurations would be reflected in the temperature dependence of the power-law exponent b, and also account for the sensitivity of b on sample and thermal history. In addition, the excess magnitude of the $1/f$ noise could result from the effective volume which contributes to the noise being much smaller than the total available volume between the electrodes.

The hydrogen diffusion coefficient in a-Si:H has a dispersive time dependence which has been attributed to a distribution in energy of hydrogen trapping sites [4]. Thus if hydrogen rearrangements are indeed responsible for the nonlinear $1/f$ noise, then it is plausible that both the flicker noise and stretched exponential relaxation in a-Si:H result from the same microscopic barriers which inhibit hydrogen motion. Alternatively, there are other possible sources of inhomogeneous current paths in doped amorphous silicon. Experiments are in progress comparing the $1/f$ noise in a-Si:H samples for which the doping level, deposition conditions, and hydrogen microstructure are systematically varied, in order to determine the relative influence of these heterogeneities in the noise spectrum.

In conclusion, measurements of coplanar current fluctuations in n-type doped a-Si:H have shown that the power spectrum accurately follows a $1/f$ frequency dependence in the temperature range $300 \leq T \leq 450$ K. The noise power displays a power-law dependence on the dc current, $S_I \propto I^b$ where b increases with temperature over this same temperature regime. These samples are Ohmic over the current range examined, and four-probe measurements confirm that these results are not due to contact noise. Our results are tentatively discussed in terms of a model for noise in composite systems where the nonlinear $1/f$ noise arises from inhomogeneous current paths.

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