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$1/f$ Noise in doped and undoped amorphous silicon

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Abstract

We measured the spectrum of conductance fluctuations in n-type, p-type, and undoped hydrogenated amorphous silicon (a-Si:H) as a function of temperature. In general, the spectra can be fit to a power law, $1/f^{\alpha}$, although in the p-type and undoped samples deviations from a strict power law occur. For n-type and p-type samples, the noise magnitude increases with temperature by approximately a factor of 5 from 295 to 450 K. The slope parameter, α, also increases with temperature in the p-type samples from near unity to 1.4 but not in the n-type sample where it remains near 1.05 independent of temperature. The undoped sample could be measured only over a limited range of elevated temperatures, but α does trend larger. The undoped and lightly doped material have similar noise levels but larger p-type doping reduces the noise by two orders of magnitude. Correlation measurements indicate the $1/f$ noise is Gaussian for all samples. However, intermittent random-telegraph noise is observed in n-type material.

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) has proven an interesting material for the study of conductance fluctuations. A number of unusual phenomena have been reported such as non-Gaussian noise statistics and random-telegraph-like noise (RTN) [1,2]. Recently, the spectrum of undoped a-Si:H was analyzed; the conclusion being that the noise is due to many thermally activated processes [3]. However, the connection between these processes and the dynamic percolation models [4] proposed to explain RTN is not known. Often overlooked in the emphasis on spectral shape or non-Gaussian effects is the magnitude of the noise power. We measured a number of samples with various dopings to determine if the magnitudes are consistent from sample to sample and whether there was any systematic change with doping.

2. Experimental

Five samples of a-Si:H were measured: two doped n-type, two doped p-type and one without doping. The a-Si:H samples were prepared by a number of methods. The n-type samples, doped 10^{-5} and 10^{-4}, and one p-type sample, doped 10^{-4}, were deposited by rf glow-discharge decomposition of silane using conditions known to produce device quality material. The 5×10^{-2} doped p-type sample was fabricated using a dc saddle-field glow-discharge apparatus [5] and the undoped sample was fabricated in a dc glow-discharge system using optimized conditions [6]. In all cases the doping number refers to the ratio of either diborane or

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phosphine to silane. All samples are about 1 μm-thick.

All samples have co-planar electrical contacts formed by evaporating metal onto the surface. The gap between the electrodes range from 1 to 2 mm. Because of the difficulty obtaining ohmic contacts to n-type a-Si:H, the 10^{-4} doped sample has a 500 nm layer of n^+ material underneath the metal. The 10^{-5} doped sample does not have an n^+ layer, and, as a consequence, the current as a function of voltage, $I(V)$, is not linear especially at room temperature. This sample was measured only at several elevated temperatures where $I(V)$ had a greater linear region. For all the other samples, the $I(V)$ is linear to the highest currents used in the experiments.

Details of the noise measurement apparatus and procedures are discussed in detail elsewhere [7]. For each temperature, $1/f$ noise spectra were obtained for several dc bias currents as well as zero bias current. The spectrum for zero bias current which consists of Johnson and amplifier noise is digitally subtracted from the other spectra. The maximum bias current is limited by the sample's conductance, and the minimum usable bias current is limited by the Johnson noise. Because of the resistance of the undoped sample, noise measurements were not possible at temperatures <450 K.

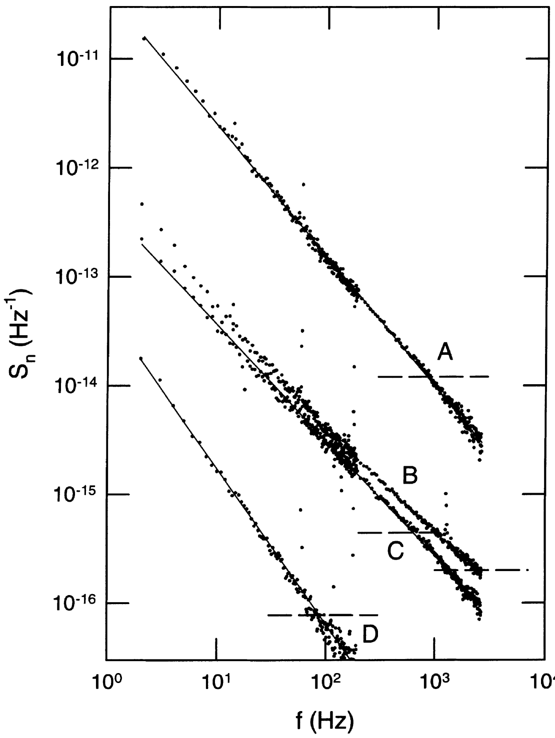

Fig. 1. Normalized noise power density spectra for four a-Si:H samples: (A) doped 10^{-5} n-type at 448 K; (B) doped 10^{-4} p-type at 390 K; (C) doped 10^{-4} n-type at 295 K; (D) doped 5×10^{-2} p-type at 388 K. The lines are fits to $1/f^{\alpha}$ with (A) $\alpha = 1.21$; (C) $\alpha = 1.07$; (D) $\alpha = 1.45$.

3. Results and discussion

Fig. 1 shows normalized noise power density spectra for the four doped samples. The noise has been normalized by removing the dependence on bias current $S \propto I^2$. For the n-type samples and the higher doped p-type sample, the spectra fit to a $1/f^{\alpha}$ power law. For the 10^{-4} doped p-type sample, the slope parameter, α, is greater at low frequency.

Space does not permit the display of all the data so we briefly describe the general trends. For the 10^{-4} doped n-type sample α is 1.05 ± 0.03 independent of temperature. The magnitude of the noise increases by a factor of 5 from 295 to 450 K. Measurement of α in the p-type samples is imprecise due to deviations from a strict power law especially at higher temperatures as shown in Fig. 1. With this proviso, the average αs do trend higher with temperature from near unity to 1.4. Above about 430 K the spectra deviate from a power law at lower frequencies, rounding off at frequencies <20 Hz. The rounding is larger in the lighter doped sample. The increase in α and changes in spectral shape make determining a noise magnitude in the p-type samples a problem. However, from 360 to 430 K, the noise power at 10 Hz increases by a factor of 5 for the 10^{-4} doped sample and by 2 for the 5×10^{-2} doped sample. The undoped sample could only be measured between 450 and 500 K. α at low frequencies tends to increase with temperature over this range from 1.15 ± 0.1 to 1.3 ± 0.1. However, the spectra cannot be fit with the same power law at high frequencies. Similar noise magnitudes and spectral shape are observed for other undoped samples made by a variety of deposition techniques. [2] The noise magnitude at 10 Hz does not change over the limited temperature range.

For noise generated homogeneously in the interior, the magnitude varies inversely with sample volume. To compare different samples, we adjust the noise magnitude to a standard volume of 25×10^{-3} mm^3. The adjusted noise magnitudes at 10 Hz for all the samples are summarized in Fig. 2. Also shown are noise magnitudes taken from three publications where the sample volume, bias current and noise magnitude are reported. Our results show similar noise levels for the undoped and lightly doped samples except for the 10^{-5} doped n-type sample. However, the somewhat larger noise in this sample may be due to the problems with contacts. The undoped sample is somewhat noisier than the rest but the difference is less than the normal variation among similar material. The heavily doped p-type sample has less noise by a factor of 100. This decrease should not necessarily be attributed to a doping effect since alloying may be taking place. Also this sample was made by a different deposition technique than the other doped samples. Although unlikely to produce different material since deposition conditions are optimized, we cannot exclude an effect of deposition technique on noise. The noise magnitudes obtained from the literature are approximately consistent with our measurements except for those from Ref. [9] which are ~ 2 orders of magnitude larger. These samples differ from the rest by being of much smaller volume 0.16×10^{-3} mm^3 compared to $\sim 15 \times 10^{-3}$ mm^3 for our samples. From this difference we suggest that processes near the surface may contribute to the noise. In addition, the noise signal for these samples has a non-Gaussian component, and it has been noted that samples with non-Gaussian noise tend to have a greater noise magnitude. The changes in noise spectra with moderate doping for our samples are subtle. The failure of moderate doping to change the noise magnitude implies that quantities that do change with doping, such as defect density, defect charge state, carrier type and concentration, do not directly affect the noise generation mechanism.

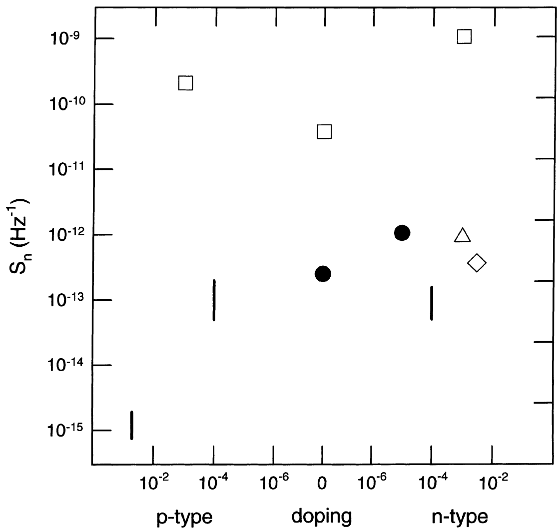

Fig. 2. Normalized noise power at 10 Hz for the five samples. The bars show the range of noise power over the measured temperature range. The open symbols are values taken from the literature: square from Ref. [9], triangle from Ref. [17], lozenge from Ref. [16]. The values have been adjusted to account for differences in sample volume.

Reports have described noise in a-Si:H that have non-Gaussian statistics [2,9,10]. One measure used to detect non-Gaussian components is correlations in the spectrum to spectrum fluctuations of noise power at different frequencies. In a typical experiment, the noise power is summed over several frequency bands and the correlation coefficients, r, between each band are calculated [11]. rs are then averaged over many spectra. Instead of summing over frequency bands, we calculate r for each pair of a selected set of N frequencies in the discrete Fourier transform [12]. Each method has some minor advantages. Summing increases positive correlations and suppresses uncorrelated fluctuations. Also, all the information content of the spectrum is used. Selecting discrete frequencies allows extraneous signals, such as interference from the mains, to be avoided. Although some information content is wasted, our method can achieve an equivalent sensitivity simply by averaging over a greater number of spectra. The results of the measurement are a set of $N(N-1)/2$ rs that

[2] For a more complete discussion of noise in undoped a-Si:H see [8].

for a Gaussian signal are distributed about zero. Fig. 3 shows typical histograms of the measured correlation coefficients for undoped, n-type, and p-type samples obtained by averaging over 1000 spectra. The lines are the expected distribution for uncorrelated noise power fluctuations. For the n-type and undoped samples, the histograms are consistent with no correlations to a limit of ±0.005. The histogram for the p-type sample is displaced towards positive correlations by about 0.01. The positive result might indicate a very small component of non-Gaussian noise in the signal. Positive correlations of similar size are occasionally seen in undoped and n-type samples as well. We have never measured the large correlations >0.5 reported by others [9].

The results described above have been obtained during times when the fluctuating signal viewed on an oscilloscope has, to the eye, the appearance of typical flicker noise. We have also from time to time observed manifestly non-Gaussian noise signals that take the form of random-telegraph noise – that is, the conductance abruptly jumps between a number of discrete states – superimposed on the flicker noise. Several reports have described similar RTN in samples of n-type a-Si:H [1,13–16]. Studying RTN in a-Si:H is difficult since the signals are unstable. Often the signal will abruptly acquire new levels or have bursts of transitions

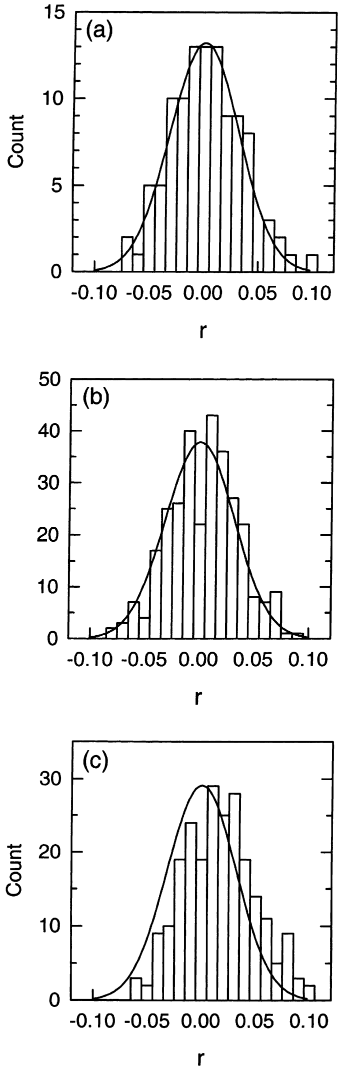

Fig. 3. Histograms of correlation coefficients for three samples. The lines are the expected distribution for uncorrelated, Gaussian noise. The samples are: (a) undoped at 500 K; (b) 10^{-4} doped n-type at 298 K; (c) 10^{-4} doped p-type at 426 K.

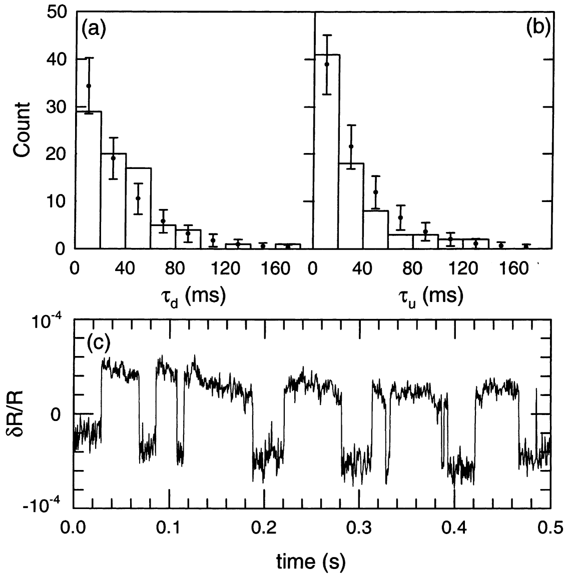

Fig. 4. Random-telegraph noise in n-type a-Si:H: (a) histogram of time delays for downward transitions. The points are the expected values for $\tau_d = 34$ ms with one sigma error bars; (b) same as (a) but for upward transitions and $\tau_u = 28$ ms; (c) portion of the two-level random-telegraph noise signal; the *y*-axis is the fractional change in resistance. The bias current is 10 μA.

followed by periods of quiescence, or the RTN may disappear entirely. Fig. 4(c) shows a trace of RTN from the 10^{-4} doped n-type sample at room temperature immediately after annealing. During this period the RTN was unusually stable and showed switching between only two levels. Fig. 4(a) and (b) show a histogram of times for downward and upward transitions. The distribution is in agreement with the Poisson statistics for a single two-level system with transition times of 34 ms in one direction and 28 ms in the other. If we assume the times are due to crossing an energy barrier then the barrier height is about 0.6 eV using a typical phonon frequency for the attempt to hop rate. We note that after opening the apparatus for several minutes the RTN vanished, although, whether because of the brief exposure to light, atmosphere, or something else is unknown. No RTN signals have been detected in the p-type samples or the undoped sample.

4. Conclusions

Moderate doping changes the the noise level in a-Si:H by less than an order of magnitude which is comparable to the changes seen over a temperature range from 295 to 450 K and to the variations in values taken from the literature. Heavy p-type doping (5%) decreases the noise by two orders of magnitude although the decrease may be due to fundamental changes to the a-Si:H structure at this doping level. We fail to detect evidence of non-Gaussian statistics except for occasional random-telegraph noise in the n-type samples.

Acknowledgements

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References

[1] C.E. Parman, N.E. Israeloff, J. Kakalios, Phys. Rev. B 44 (1991) 8391.
[2] C.E. Parman, N.E. Israeloff, J. Kakalios, Phys. Rev. Lett. 69 (1992) 1097.
[3] P.A.W.E. Verleg, J.I. Dijkhuis, Phys. Rev. B 58 (1998) 3904.
[4] L.M. Lust, J. Kakalios, Phys. Rev. Lett. 75 (1995) 2192.
[5] R.V. Kruzelecki et al., J. Vac. Sci. Technol. A 7 (1989) 2632.
[6] C.M. Fortmann, J. O'Dowd, N. Newton, J. Fisher, in: B.L. Stafford, E. Sabisky (Eds.), Stability of Amorphous Silicon Alloy Materials and Devices, vol. 157 of AIP Conf. Proc., AIP, New York, 1987, p. 103.
[7] R.E. Johanson, D. Scansen, S.O. Kasap, Philos. Mag. B 73 (1996) 707.
[8] M. Güneş, R.E. Johanson, S.O. Kasap, these Proceedings, p. 304.
[9] G.M. Khera, J. Kakalios, Phys. Rev. B 56 (1997) 1918.
[10] J. Fan, J. Kakalios, Philos. Mag. B 69 (1994) 595.
[11] P.J. Restle, M.B. Weissman, R.D. Black, J. Appl. Phys. 54 (1983) 5844.
[12] R.E. Johanson, D. Scansen, S.O. Kasap, J. Vac. Sci. Technol. B 17 (1999) 73.
[13] T. Teuschler, M. Hundhausen, L. Ley, R. Arce, Phys. Rev. B 47 (1993) 12687.
[14] C.E. Parman, N.E. Israeloff, J. Kakalios, Phys. Rev. B 47 (1993) 12578.
[15] J. Fan, L.M. Lust, J. Kakalios, J. Non-Cryst. Solids 164–166 (1993) 469.
[16] K.M. Abkemeier, D.G. Grier, Phys. Rev. B 54 (1996) 2723.
[17] C. Parman, J. Kakalios, Phys. Rev. Lett. 67 (1991) 2529.