Light-induced changes of the $1/f$ noise in hydrogenated amorphous silicon

J. Fan and J. Kakalios
The University of Minnesota, School of Physics and Astronomy, Minneapolis, Minnesota 55455
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The $1/f$-noise power spectra of coplanar current fluctuations in n-type doped hydrogenated amorphous silicon (a-Si:H) are measured before and after light-induced metastable defects (the Staebler-Wronski effect) are created. The noise spectral density for the annealed state is strongly non-Gaussian, with large correlations of the noise power between differing octaves. Upon illumination the noise becomes Gaussian and the correlation coefficients of the noise power *decrease*, which is consistent with an increase in the disorder at the mobility edge in a-Si:H in the light-soaked state.

A major unsolved problem in the physics of amorphous semiconductors is the determination of the microscopic origin for the light-induced metastable conductance changes in hydrogenated amorphous silicon (a-Si:H), termed the Staebler-Wronski effect.[1] Extended illumination with visible light of a-Si:H leads to a decrease of both the photoconductivity and dark conductivity σ which is reversible upon annealing above 420 K. The magnitude of the decrease of the dark conductivity depends on the material properties of the a-Si:H film, such as the deposition conditions and doping level, and the ratio of the annealed σ to that in the light-soaked state can be as large as four orders of magnitude. This light-induced conductance change leads to a degradation of the efficiency of a-Si:H-based photovoltaic devices,[2] and is a major obstacle to a-Si:H fulfilling its technological potential.

It is generally believed that the recombination of photocreated electron-hole pairs leads to the formation of excess dangling-bond defects, which act as additional recombination centers, decreasing the photocurrent and moving the Fermi energy toward midgap, and decreasing the dark conductivity. Most models for the Staebler-Wronski effect involve the breaking of strained Si-Si bonds to create new dangling-bond defects, and typically require the motion of covalently bonded hydrogen in order to stabilize the newly formed defects.[3] In these models the severing of a strained Si-Si bond is a localized event, affecting only the nearest neighbors of the broken bonds, though the accompanying motion of hydrogen can involve long-ranged diffusion.

Alternative models for the Staebler-Wronski effect have been proposed which are intrinsically nonlocal in nature, involving changes in long-ranged potential fluctuations or strain fields.[4–8] In these models the creation of light-induced defects can change the electronic properties of the current-carrying extended states and influence the electronic properties of the amorphous silicon over long length scales. For example, an increase in the difference between the dark conductivity and thermopower activation energies following illumination[7] has been interpreted as evidence of an increase in the Staebler-Wronski effect of the magnitude of long-ranged (i.e., several 10^3 Å) potential fluctuations. Recent nuclear-magnetic-resonance measurements[8] and supercell calculations[6] indicate that the creation of new defects in the highly strained amorphous silicon network leads to large-scale atomic reorientations, involving the motion of hundreds of atoms. These nonlocal models imply that the change in a defect's charge state can influence the film's conductance over distances many times longer than the spatial extent of the defect, and would challenge our understanding of the electronic transport states in disordered semiconductors; however, previously there was no experimental evidence of changes in many-body or cooperative interactions in the Staebler-Wronski effect.

Measurements in n-type doped a-Si:H of the nonlinear current dependence of the $1/f$ noise,[9] random telegraph switching noise,[10–12] and non-Gaussian statistical properties[13] of the noise spectral density have been interpreted as indicating the presence of inhomogeneous current filaments whose electronic properties vary in time due to the motion of bonded hydrogen. In this paper we report the influence of light soaking on the non-Gaussian statistics which characterize the $1/f$ noise in a-Si:H. There is a striking decrease in the non-Gaussian nature of the noise following illumination, which is consistent with the degree of disorder at the mobility edge increasing in the Staebler-Wronski effect. These results support models which involve long-range or many-body interactions to account for the light-induced conductance changes.

The a-Si:H films measured here are n-type doped a-Si:H, grown in a rf glow discharge deposition reactor. The gas phase doping level was 10 ppm phosphine in silane, the substrate temperature was 500 K, and the incident rf power was 2 W. The films are 1 μm thick and are deposited onto Corning 7059 glass substrates. A 100-Å-thick n^+ a-Si:H layer was deposited on top of the a-Si:H film prior to evaporation of the Cr top contacts (width, 0.3 cm; separation, 0.1 cm). The n^+ layer between the electrodes was then removed by plasma etching. The effective sample volume is 3×10^{-6} cm^3. The sample is annealed at 450 K for 30 min (state A) under a turbo-pumped vacuum to remove any surface adsorbates and any effects of prior light exposure. Metastable conductance changes were created by exposure to heat-filtered white light from a tungsten-halogen lamp. All of the noise data reported here are measured in the dark and were obtained for applied voltages for which the current-voltage characteristics were linear. In the two-probe noise measurements a constant voltage is applied across the coplanar electrodes and the fluctuations in the current passing through the *a*-Si:H are measured using a spectrum analyzer (HP 3561A). Four-probe noise measurements were also performed by splitting each metal electrode with a diamond scribe and applying a constant current across one diagonal pair of electrodes and measuring the voltage fluctuations across the other diagonal electrode pair. Details of the sample preparation and measurement technique are published separately.[14,15]

The noise power S_I for *n*-type *a*-Si:H is accurately described by a $1/f$ frequency dependence over the range of $1-10^3$ Hz for both the annealed state *A* and following light exposure (state *B*). For the *a*-Si:H film studied here the dark conductivity decreased by a factor of 10^4 after a 30 min exposure. The light exposure was therefore intentionally brief ($\sim 1-2$ min) so that the state *B* current yielded a S_I above the instrumental background of the spectrum analyzer. The magnitude of the $1/f$ noise for states *A* and *B*, measured by averaging (rms) 10^3 power spectra, are roughly comparable when the applied voltage is varied so that the same current is passing through the film.[16] There is thus no striking change in the average magnitude of S_I following light-induced defect creation.

Previous studies of the $1/f$ noise in *a*-Si:H have found that the noise is strongly non-Gaussian, indicating highly cooperative interactions between the fluctuators[13] which are not reflected in the average properties of the power spectra. The non-Gaussian statistics of the noise power can be quantified in the following manner. A single power spectrum is calculated from a 1024 point time series; 10^3 of these power spectra are then measured. The power spectra are summed into seven octaves, with the lowest octave 2 (5–10 Hz) consisting of two power spectra points and the highest octave 8 (320–640 Hz) containing 128 power spectra points. For $1/f$ noise each octave contains the same total noise power. For Gaussian noise systems [such as thermal (Johnson) noise] arising from a large number of statistically independent processes, the normalized noise power per octave is expected to have a χ^2 distribution for the variable $P/\langle P \rangle$ where P is the noise power per octave and $\langle P \rangle$ is the averaged noise power.[17]

Figure 1 shows a histogram for 10^3 measurements of the noise power in octave 8 for an *n*-type *a*-Si:H film in state *A* and after a 160-sec light exposure (state *B*) for which the conductance decreased by a factor of 8, following the procedure developed by Restle and co-workers.[17] The solid line in Fig. 1 represents the expected histogram for Gaussian noise, that is, a χ^2 distribution with $2N$ degrees of freedom where N is the number of fast Fourier transform points in octave 8. The noise power of *a*-Si:H in state *A* has a much broader distribution, suggesting that a small effective number of fluctuators dominate the noise. There is a striking change in the noise statistics in state *B*, with the noise power histogram resembling the χ^2 distribution for a Gaussian noise process. This change in the noise statistics is reversible upon annealing and is also observed in four-probe noise measurements.

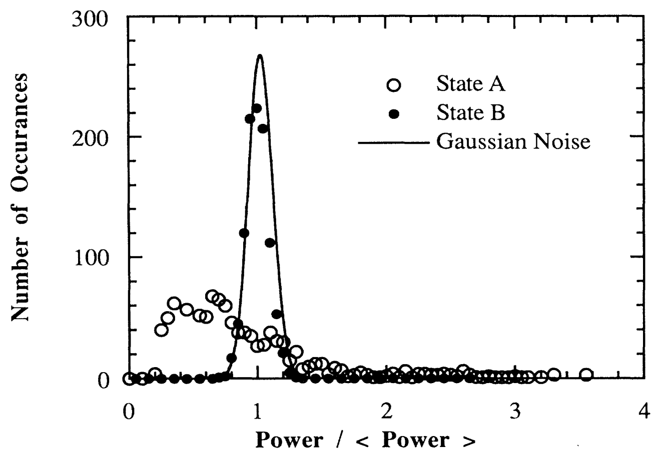

FIG. 1. Histogram of 10^3 measurements of the noise power in octave 8 (320–640 Hz) for the annealed state *A* (open circles) and following light exposure of 160 sec (state *B*, closed circles) for an *n*-type *a*-Si:H film at 300 K. The solid line is the expected χ^2 distribution for Gaussian noise.

The non-Gaussian nature of the $1/f$ noise in *a*-Si:H is also reflected in strong correlations in the noise power between differing frequencies.[13] The correlation coefficients ρ_{ij} between octaves i and j are quantified using the 10^3 power spectra summed into octaves as described above, and using the expression[13,17]

$$\rho_{ij} = \sum (P_i - \langle P_i \rangle)(P_j - \langle P_j \rangle)/\sigma_i \sigma_j, \quad i \neq j ,$$

where σ_i is the ith octave's standard deviation and the sum is over the total number of noise power spectra measured. The correlation coefficients between all pairs of octaves are calculated. All ρ_{ij}'s for an octave separation of one are averaged together, as are the coefficients for octave separations of two, three, and so on. The ρ_{ij} values range from $+1$ (-1) for exactly positively (inversely) correlated noise spectra.

The ρ_{ij} for the *a*-Si:H film in state *A* and following illumination of increasing exposure times are shown in Fig. 2. The data in Fig. 2 represent the average of ten sequential measurements of the correlation coefficients described above. The correlation coefficients in state *A* are quite high, decreasing with increasing octave separation but even octave 2 and 8 have a ρ_{ij} of ~ 0.6. The results for state *A* are similar to that previously reported for *n*-type *a*-Si:H.[13] After a 40-sec light exposure (triangle data points) for which the dark current decreases by a factor of 2 compared to state *A*, there is a marked decrease in the magnitude of the ρ_{ij}'s for all octave separations. The correlation coefficients decrease further after an additional 40-sec exposure (open squares), for which the conductance is 4 times smaller than in state *A*. Further illumination (filled squares) of an additional 80 sec, for which $\sigma_B/\sigma_A \sim 1/8$, decreases the ρ_{ij} values toward zero. All of the state *B* power spectra are at least an order of magnitude above the instrumental background. The *a*-Si:H film was reannealed into state *A* between each

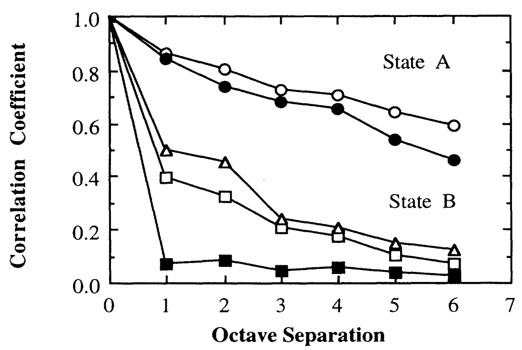

FIG. 2. Plot of the average correlation coefficients against octave separation for an *n*-type *a*-Si:H sample at 300 K, following annealing at 420 K (state *A*, open circles) and after light exposures of 40 sec (triangles), 80 sec (open squares), and 160 sec (filled squares). The filled circle data points represent the correlation coefficients after the metastable conductance changes have been removed by reannealing the film into state *A*.

light exposure, the changes in ρ_{ij} are reversible as indicated by the filled circle data points in Fig. 2. This reversible decrease in ρ_{ij} upon light soaking is also observed in four-probe noise measurements, indicating that these observations are due to the bulk *a*-Si:H film. This decrease in the non-Gaussian nature of the $1/f$ noise in *a*-Si:H is also seen in films deposited at higher doping levels[18] and is reflected in the second spectra of the noise power fluctuations, as described in detail elsewhere.[18,19]

We now address possible microscopic mechanisms which would lead to a reversible change in the non-Gaussian statistics of the $1/f$ noise with illumination. Previous studies of the noise power of doped *a*-Si:H by our laboratory[15] are consistent with the $1/f$ noise arising from current filaments in the *a*-Si:H, that is, the noise arises from current paths which are a small subset of the total available conduction paths. These microchannels could result from the bonded hydrogen microstructure, from long-ranged potential fluctuations induced by charged defects and dopants or from the intrinsic disorder of the silicon network.[15] The strongly non-Gaussian statistics which characterize the $1/f$ noise in state *A* indicate that there are highly cooperative interactions between these current paths.[13] If, associated with the Staebler-Wronski effect, there is an increase in the disorder at the mobility edge, then these interactions would weaken, and the correlation coefficients will be lowered in state *B*, though the exact mechanism by which the interactions decrease is not presently understood.

The notion that long-ranged electronic or structural disorder would determine the electronic conductance of amorphous semiconductors was first stressed over 20 years ago.[20] Zallen and Scher[21] have likened the localized-delocalized transition associated with the mobility edge to a classical percolation threshold. They argued that for a continuous system an energy-dependent critical density ϕ describes the fraction of space accessible to charge carriers at an energy E; the mobility edge E_c occurs when $\phi(E_c)=\phi_c$, which is the critical density value at the percolation threshold. By increasing the disorder of the current-carrying states in the Staebler-Wronski effect, the percolation threshold is pushed toward a higher density and the mobility edge moves upward. Hence the increase of the dark conductivity activation energy upon light soaking could be due to both the Fermi energy moving toward the midgap due to the increase of dangling-bond defects and to an upward shift of the mobility edge.

The changes in the non-Gaussian statistics of the current noise indicate that in addition to light-induced dangling-bond formation in the Staebler-Wronski effect there is also a strong modification of the interactions between current paths at the mobility edge. This conclusion was also reached by Hauschildt, Fuhs, and Mell[7] from observations of an increase in the difference between the dark conductivity and thermopower activation energies in *n*-dark *a*-Si:H following light soaking, which was interpreted as evidence of an increase in long-ranged potential fluctuations. Since this early work there has been a growing appreciation of the influence of long-ranged potential fluctuations on the transport properties of *a*-Si:H.[22] von Roedern[5] has suggested that in the Staebler-Wronski effect strained Si-Si bonds are broken which result in the formation of both charged and neutral dangling-bond defects. In von Roedern's model the additional potential fluctuations arising from the light-induced charged dangling-bond defects decreases the band mobility of charge carriers in extended states. Branz and Silver,[4] extending a model originally put forth by Adler,[23] have argued that even in undoped *a*-Si:H there is a considerable density of charged dangling-bond defects, created by variations in the material homogeneity. In this case light soaking leads to the neutralization of some of these charged defects, increasing the density of neutral dangling bonds, which are then stabilized by some form of lattice relaxation. Consequently, this model would predict that the magnitude of the potential fluctuations would decrease in state *B*. However, supercell calculations by Fedders, Fu, and Drabold[6] have found that, due to the large amount of strain energy stored in the amorphous silicon lattice, the change of the charged state of a single defect leads to rearrangements of hundreds of atoms. Therefore in the model of Branz and Silver[4] it is possible that even if charged defects are neutralized there could still be an increase in the disorder at the mobility edge upon light soaking.

On the other hand the changes in the non-Gaussian statistics of the noise power upon illumination could be due to changes in structural rather than electronic heterogeneities in the *a*-Si:H, such as variations in the hydrogen microstructure in state *B*. It has been noted that the magnitude of the Staebler-Wronski effect is correlated with the density of hydrogen bonded in clusters.[24] Whether this correlation is due to the relevance of the cluster phase itself, the associated changes in strained Si-Si bonds or some other material parameter is not known. Further studies are presently underway in order to further elucidate the origin of the current filaments and to test various models of the Staebler-Wronski effect that involve long-range interactions.

The key result of this paper is that associated with the Staebler-Wronski effect in a *a*-Si:H is a change in the non-Gaussian statistics of the $1/f$ noise which is reversible upon annealing. This result would indicate that associated with the creation of light-induced defects is an increase in the disorder at the mobility edge, changing the current paths through the amorphous film.

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[1]D. L. Staebler and C. R. Wronski, Appl. Phys. Lett. **31**, 292 (1976); J. Appl. Phys. **51**, 3262 (1980).

[2]See, for example, C. R. Wronski, in *Stability of Amorphous Silicon Alloy Materials and Devices,* Proceedings of an International Conference on Stability of Amorphous Silicon Alloy Materials and Devices, edited by B. L. Stafford and E. Sabisky, AIP Conf. Proc. **157** (AIP, New York, 1987), p. 1.

[3]M. Stutzmann, W. B. Jackson, and C. C. Tsai, Phys. Rev. B **32**, 23 (1985).

[4]H. Branz and M. Silver, Phys. Rev. B **42**, 7420 (1990).

[5]Bolko von Roedern, in *Amorphous Silicon Materials and Solar Cells,* Proceedings of the International Meeting on Stability of Amorphous Silicon Materials and Solar Cells (Denver, CO, 1991), edited by Byron L. Stafford, AIP Conf. Proc. No. 234 (AIP, New York, 1991), p. 122.

[6]P. A. Fedders, Y. Fu, and D. A. Drabold, Phys. Rev. Lett. **68**, 1888 (1992).

[7]D. Hauschildt, W. Fuhs, and H. Mell, Phys. Status Solidi. B **111**, 171 (1982).

[8]R. E. Norberg, P. A. Fedders, J. Bodard, R. Corey, Y. W. Kim, W. Paul, and W. Turner, in *Amorphous Silicon Technology—1991,* edited by Arun Madan, Y. Hamakawa, M. J. Thompson, P. C. Taylor, and P. G. LeComber, MRS Symposia Proceedings No. 219 (Materials Research Society, Pittsburgh, 1991), p. 223.

[9]C. Parman and J. Kakalios, Phys. Rev. Lett. **67**, 2529 (1991).

[10]R. Arce and L. Ley, in *Amorphous Silicon Technology—1989,* edited by Arun Madan, Malcolm, J. Thompson, P. C. Taylor, Y. Hamakawa, and P. G. LeComber, MRS Symposia Proceedings No. 149 (Materials Research Society, Pittsburgh, 1989), p. 675.

[11]W. K. Choi, A. E. Owen, P. G. LeComber, and M. J. Rose, J. Appl. Phys. **68**, 120 (1990).

[12]C. Parman, N. Israeloff, and J. Kakalios, Phys. Rev. B **44**, 8391 (1991).

[13]C. E. Parman, N. E. Israeloff, and J. Kakalios, Phys. Rev. Lett. **69**, 1097 (1992).

[14]R. A. Street, J. C. Knights, and D. K. Biegelsen, Phys. Rev. B **18**, 1880 (1978).

[15]C. E. Parman, N. E. Israeloff, and J. Kakalios, Phys. Rev. B (to be published).

[16]For Ohmic and linear-noise systems, for which $S_R/R^2=S_I/I^2$, the comparable S_I measured under identical currents would imply that the resistance noise magnitude S_R increases in state *B*. However, the nonlinear dependence of the noise power on current (Ref. 9) complicates a comparison of the resistance noise with the Staebler-Wronski effect, as discussed further in Ref. 18.

[17]P. J. Restle, M. B. Weissman, and R. D. Black, J. Appl. Phys. **54**, 5844 (1983); P. J. Restle, R. J. Hamilton, M. B. Weissman, and M. S. Love, Phys. Rev. B **31**, 2254 (1985).

[18]J. Fan and J. Kakalios (unpublished).

[19]The random telegraph switching noise (Ref. 12) is obscured by 60 cycle pick up for the high impedance film studied here. Studies of more conductive films are presently underway in order to investigate the influence of light soaking on the switching noise.

[20]J. Tauc, Mater. Res. Bull. **5**, 721 (1970); H. Fritzsche, J. Non-Cryst. Solids **6**, 49 (1971).

[21]Richard Zallen and Harvey Scher, Phys. Rev. B **4**, 4471 (1971).

[22]H. Overhof, in *Amorphous Silicon Technology—1992,* edited by Malcolm J. Thompson, Yoshiro Hamakawa, Peter G. LeComber, Arun Madan, and Eric A. Schiff, MRS Symposia Proceedings No. 258 (Materials Research Society, Pittsburgh, 1992), p. 681; J. A. Howard and R. A. Street, Phys. Rev. B **44**, 7935 (1991).

[23]D. Adler, Solar Cells **9**, 133 (1983).

[24]M. Ohsawa, T. Hama, T. Ichimura, T. Akasaka, H. Sakai, S. Ishida, and Y. Uchida, J. Non-Cryst. Solids **77&78**, 401 (1985); E. Bhattacharya and A. H. Mahan, Appl. Phys. Lett. **52**, 1587 (1988).