Noise in hydrogenated amorphous silicon

R.E. Johanson, M. Günes and S.O. Kasap

Abstract: Published work on conductance fluctuations in hydrogenated amorphous silicon is surveyed. There are many reports of $1/f$ noise, some describing unusual features such as non-Gaussian statistics. The relative insensitivity to doping and temperature is highlighted. In addition to the $1/f$ noise, random-telegraph-like noise is often reported. The successes and failures of generation–recombination models for $1/f$ noise and current filament models for the telegraph noise are summarised.

1 Introduction

This paper reviews the published work on conductance fluctuations in hydrogenated amorphous silicon (a-Si:H). In the past 20 years, over 40 papers have described noise data, some of which are similar to the typical $1/f$ noise found in many other conductors and some of which are very unusual. These results are causing us to re-evaluate how charge conduction has been viewed in a-Si:H.

At first glance, a-Si:H would appear to be less than an ideal material for studying the physics of noise because of its complexity. Since the hydrogen typically amounts to about 10 at. %, the material is actually a binary alloy, and the hydrogen plays an important role in the electronic properties of the material. Silicon is overcoordinated for forming an ideal amorphous network causing elemental a-Si to have a high concentration of dangling-bond defects located within the mobility gap, the energies between the extended states of the conduction and valence bands. The defects pin the Fermi level near midgap preventing doping or a field effect from varying the free-carrier concentration and also provide a channel for rapid recombination of photoexcited carriers. Conduction typically is via hopping in the defect band. The material is useless for devices. Adding hydrogen passivates the dangling bonds, lowering the defect density from as much as $10^{20}\,cm^{-3}$ in evaporated a-Si to under $10^{16}\,cm^{-3}$ in the best quality a-Si:H. Doping with trivalent and pentavalent atoms then becomes effective in producing p- and n-type semiconductors; there also is a large field effect and photoconductivity. Devices made from a-Si:H such as thin-film transistors, photoconductor arrays, and solar cells are now commonplace. However, hydrogen plays a more active role than simply reducing defects. At moderately elevated temperatures hydrogen can diffuse readily and even at room temperature some motion occurs. As hydrogen moves, weak Si–Si bonds can be broken and the configuration stabilised by the insertion of a hydrogen atom creating a Si–H bond and a dangling bond. Thus the defect density is constantly fluctuating.

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Offsetting the inherent complexity is an immense amount of research into the electronic properties of a-Si:H. Of immediate relevance to noise models is the density of localised states in the mobility gap which has been the subject of much research. The number of mobile charge carriers fluctuates as they are alternately trapped and released by the localised states. It is impossible here to give a full account of the physics of a-Si:H and the reader is referred to the excellent treatise on the subject by Street [1].

a-Si:H is made by a variety of techniques, the most popular involve the plasma decomposition of silane. Adding phosphine or diborane causes dopants to be incorporated into the silicon; doping ratios are given in this paper in parenthesis and refer to the volume ratio of dopant gas to silane, not the concentration of active dopants. The resulting film is at most a few microns thick. Samples can be prepared with either a transverse current path between electrodes on either side of the film or a longitudinal current path between coplanar electrodes. Metallic contacts, especially to doped a-Si:H, often display non-ohmic behaviour which can distort noise measurements. In the experiments carried out in our laboratory, we have checked for ohmic electrodes and collected data (using a two-probe geometry) at currents where the I–V curve is linear.

2 $1/f$ noise

In common with most conducting materials, a direct bias current passing through a sample of a-Si:H will fluctuate in time. The power spectrum of the fluctuations generally fits a power law $S_I \propto f^{-\alpha}$. Fig. 1 shows several examples of normalized noise spectra for four samples of doped a-Si:H with coplanar electrodes. The noise power has been normalised by removing the dependence on the bias current $S_n = S_I/I^2$. Three of the curves fit very well to the power law which is typically the case for the data reported in the literature. Reported values of the slope parameter α vary from 0.6 to 1.4. For the p-type (doped 10^{-4}) sample in Fig. 1, there is some curvature with the local slope greater at low frequency. Such deviations from a power law are occasionally seen. Fig. 2 shows a more extreme example for undoped a-Si:H between 450 and 500 K.

The quadratic dependence on bias current used in the normalisation is expected providing the bias current only acts as a probe of the fluctuations but does not influence them. We have checked this relation for all our samples and find it obeyed except for one p-type sample at elevated temperatures. However, Parman *et al.* find significant

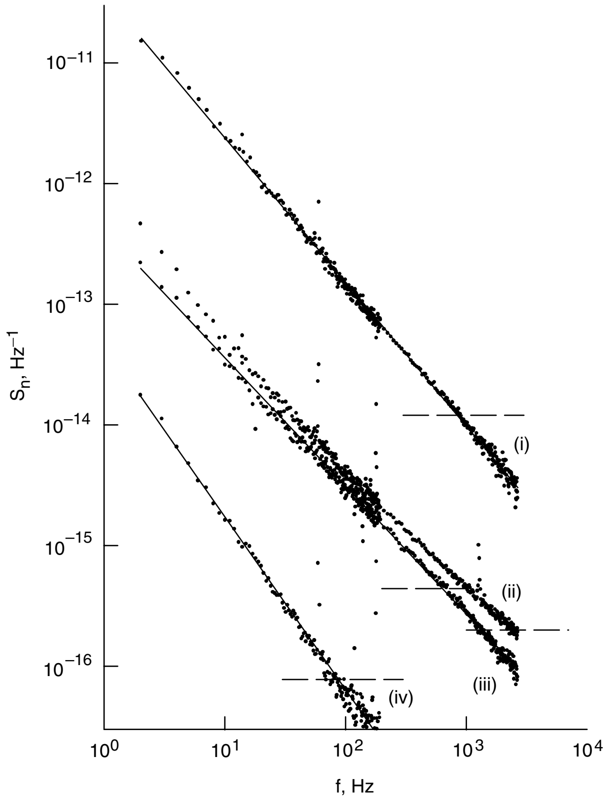

Fig. 1 *Normalised noise power density spectra for four a-Si:H samples*
(i) n-type (10^{-5}) at 448 K; (ii) p-type (10^{-4}) at 390 K; (iii) n-type (10^{-4}) at 295 K; (iv) p-type (5×10^{-2}) at 388 K
Lines are fits to $f^{-\alpha}$ with (i) $\alpha = 1.21$, (iii) $\alpha = 1.07$, (iv) $\alpha = 1.45$

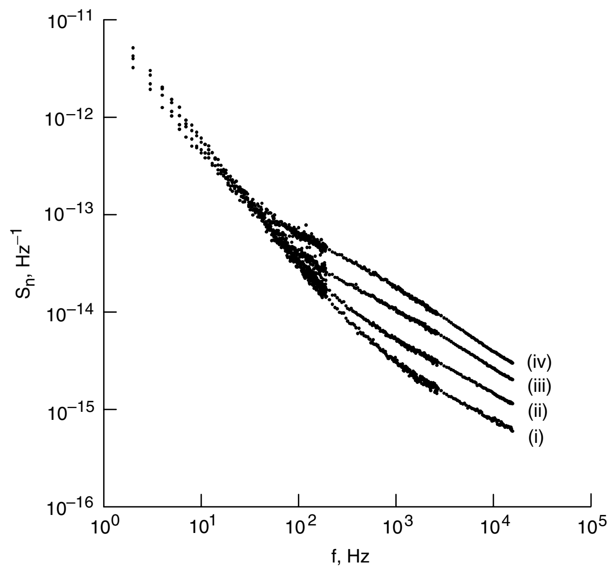

Fig. 2 *Normalised noise power spectra of undoped a-Si:H at four temperatures*
(i) 495 K; (ii) 483 K; (iii) 467 K; (iv) 454 K

deviations; the parameter b in $S_I \propto I^b$ varied from unity at room temperature to near 3 at 430 K for several samples of n-type a-Si:H [2]. There has been no satisfactory explanation of such 'nonlinear' behaviour.

2.1 Effect of temperature and doping on spectrum

In general, both temperature and doping have only modest effects on the shape of the $f^{-\alpha}$ spectrum, and perhaps for this reason such measurements are not often reported. For n-type samples we find that α is between 0.95 and 1.15 with no obvious trend with temperature in agreement with Parman *et al.* [3]. Some of our p-type samples showed variation from a pure power law as shown in Fig. 1 and thus assigning an α is imprecise. With this proviso, the average α values do trend higher with temperature from near unity at room temperature to 1.4 at 400 K. Above about 430 K the spectra deviate from a power law at low frequencies, rounding off significantly below 20 Hz [4].

Our measurements of undoped samples with co-planar electrodes could only be carried out at elevated temperatures between 450 and 500 K (Fig. 2). The spectra divided into two power laws with a larger α at low frequencies. α at low frequencies tended to increase with temperature from 1.15 to 1.3 whereas α of the high frequency branch remained at 0.6 independent of temperature. Reynolds *et al.* reported a similar spectrum for undoped a-Si:H with excess weight at higher frequencies [5]; most studies report simple power laws at lower temperatures.

2.2 Effect of temperature and doping on noise magnitude

The normalised noise power varies only weakly with temperature when compared to the conductivity [4, 6, 7]. Fig. 3 shows a typical example for n-type (10^{-4}) a-Si:H. The

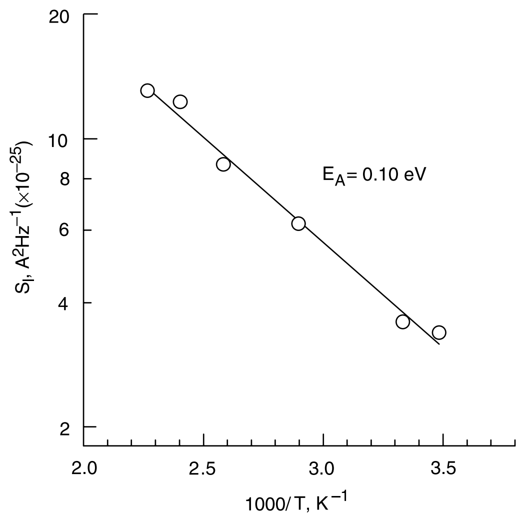

Fig. 3 *Temperature dependence of noise power density at 1000 Hz for n-type (10^{-4}) a-Si:H*
All measurements used the same bias current 50 μA

noise power at constant bias current increased by a factor of four from 290 to 440 K. The graph shows an Arrhenius behaviour over the limited temperature range, and although the apparent activation energy of 0.1 eV is likely to be meaningless, it can be compared with much larger conductivity activation energy of 0.3 eV. For our p-type samples the increase in α and changes in spectral shape render comparisons of the overall noise level difficult. However, from 360 to 430 K, the noise power at 10 Hz increased by a factor of five for one sample (10^{-4}) comparable to what is observed for n-type material. In contrast, for a p-type sample in [6], the noise increased by nearly three orders of magnitude between from 330 to 410 K.

The empirical formula of Hooge relates the normalised noise power to the number of free carriers N_f [8]

$$S_I/I^2 = \alpha_H/fN_f$$

where α_H is often quoted as a phenomenological parameter measuring the relative noisiness of the material. However, this use of α_H is problematic for a-Si:H. Consider the data from Fig. 3. The free-carrier density n can be estimated from the conductivity $\sigma = en\mu$ where the free carrier mobility μ is taken to be $10\,\mathrm{cm^2 V^{-1} s^{-1}}$. Using these values, we calculate $\alpha_H \approx 1.2 \times 10^{-2}$ at room temperature. But, because both the noise and N_f increase with temperature, α_H increases rapidly with temperature reaching 0.3 at 440 K. The increase in α_H clearly does not properly reflect the change in the noise so its use in comparing different samples is questionable. Further difficulty in using α_H is demonstrated by Fig. 4. Noise at room temperature after annealing (state A) is compared with noise measured in the dark but after prolonged illumination with bandgap light (state B). The dark conductivity and therefore N_f in state B is a factor of 80 below that of state A, yet the noise level has not changed significantly except for a reduction of the slope. Quoted values of α_H in the literature range from 3×10^{-4} [9] to 1 [2].

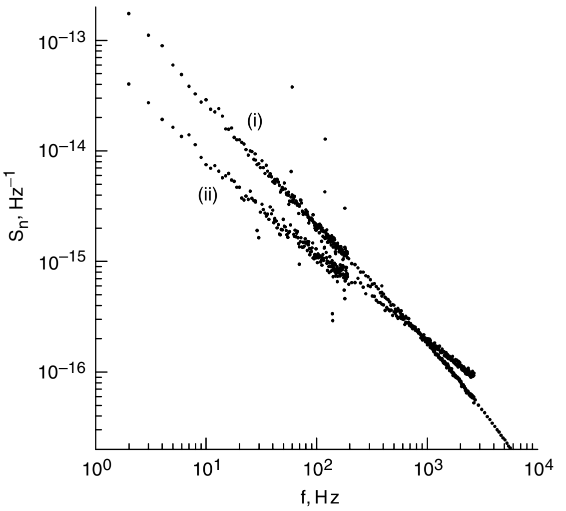

Fig. 4 *Normalised noise power density spectrum after annealing and after 3610 min exposure to bandgap light for n-type (10^{-4}) a-Si:H*
(i) After annealing (state A); (ii) after exposure (state B)

Lacking a measure like α_H, it is best simply to compare directly the normalised noise power at a particular frequency in various samples. Of course, the noise power needs to be adjusted to account for differing sample volumes; for noise generated uniformly throughout the material, the magnitude varies inversely with sample volume. Fig. 5 shows the adjusted noise power at 10 Hz normalised to a volume of $25 \times 10^{-3}\,\mathrm{mm^3}$ for a number of samples of various dopings. For samples measured at various temperatures the range in noise power is shown as a vertical bar. The noise levels for undoped and lightly doped samples lie within about one and a half orders of magnitude of one another with no obvious trend with doping. The larger noise level of the 10^{-5} doped n-type sample might be due to slightly non-ohmic contacts. Heavy doping (actually alloying) either n or p significantly lowers the noise by several orders of magnitude. Values obtained from the literature are consistent with our measurements with the exception of the three data points taken from [6] which are over two orders of magnitude higher. However, the statistics of the noise produced by these samples differed significantly from the others which may account for the large noise levels.

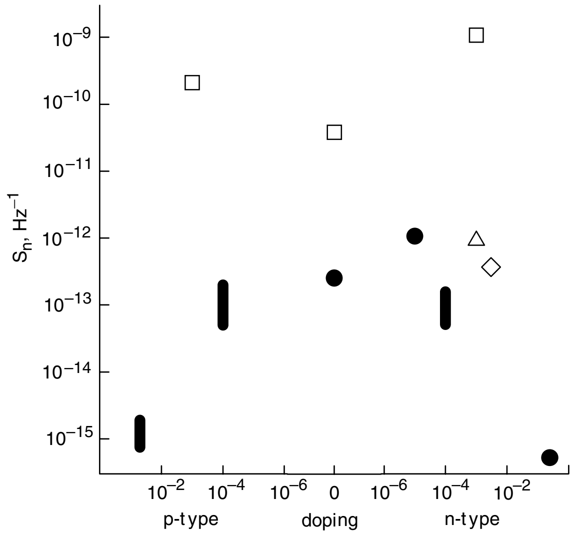

Fig. 5 *Noise power density at 10 Hz for a-Si:H samples with various dopings normalised with respect to current and sample volume.*
The bars indicate the range of noise power over measured temperature range
● present author's data
□ from [6]
△ from [2]
◇ from [27]

Conclusions from this data are limited since although the noise does change with doping and temperature, the effect is subtle and, lacking clear direction, is difficult to interpret. The failure of moderate doping to significantly change the noise level implies that the noise generation mechanism does not depend on quantities that change with doping, such as defect density, defect charge state, carrier type and concentration.

2.3 Statistics

The noise power spectrum is, by the Wiener–Khintchine theorem, equivalent to the two point autocorrelation function. If the higher-order correlation functions can be decomposed into products of the two-point functions then the signal is said to be Gaussian. A noise signal that is the sum of many independent fluctuators should by the central limit theorem be Gaussian. Most materials produce Gaussian noise. There are several experimental signatures of non-Gaussian noise. One can compute the covariance of the noise power between separated frequencies. Since the noise power at one frequency should not be correlated with that at another frequency for Gaussian noise, the covariance should be zero; a non-zero correlation indicates non-Gaussian noise. The noise power in a frequency band itself will fluctuate over time and it is possible to compute the spectrum of these fluctuations. Termed the second-spectrum, it should be essentially flat for Gaussian noise. Both of these tests have been applied to noise from a-Si:H with mixed results.

Several papers from the University of Minnesota researchers reported non-Gaussian noise in a-Si:H [3, 6, 10–12]. The covariance between octaves was found to differ significantly from zero; the correlation coefficient was over 0.6 even for widely spaced octaves. The second spectrum was found to be frequency dependent varying with a $1/f$ power law. Interestingly, after a brief 160 second exposure to broadband light the non-Gaussian signatures vanished; the covariances neared zero and the second spectrum became flat [13, 14]. An earlier report also hinted at a non-Gaussian component [15]. Our work on both doped and undoped a-Si:H has shown little evidence for non-Gaussian noise [16, 17]. Measurements of the covariance between the noise power at a set of discrete frequencies on n-type and undoped samples showed no correlations; the coefficient was within 0.01 of zero; p-type samples occasionally showed a very small positive correlation coefficient of roughly 0.01 (Fig. 6). Likewise, the second spectrum had no frequency dependence for any of the samples. Verlag and Dijkhuis also found no evidence of non-Gaussian statistics in measurements of the covariance for transverse samples of undoped a-Si:H except at high temperatures which they attributed to contact noise [18].

randomly jumps between two or more discrete values. RTN in other materials is typically seen only when the current is restricted to a very small area [19]. The changes in conductance are likely to be due to changes in a localised electronic state such as a trap or a two-level tunnelling system contained within the current path. Since the influence of the localised state extends over a limited volume, only when the area is small will the conductance change be measurable. RTN in a-Si and a-Si:H was first measured in small area ($<120\,\mu m^2$) tunnel junctions at low temperatures with the silicon acting as the insulator; the jumps in conductance were attributed to the filling and emptying of individual traps [20]. An unusual report of well-

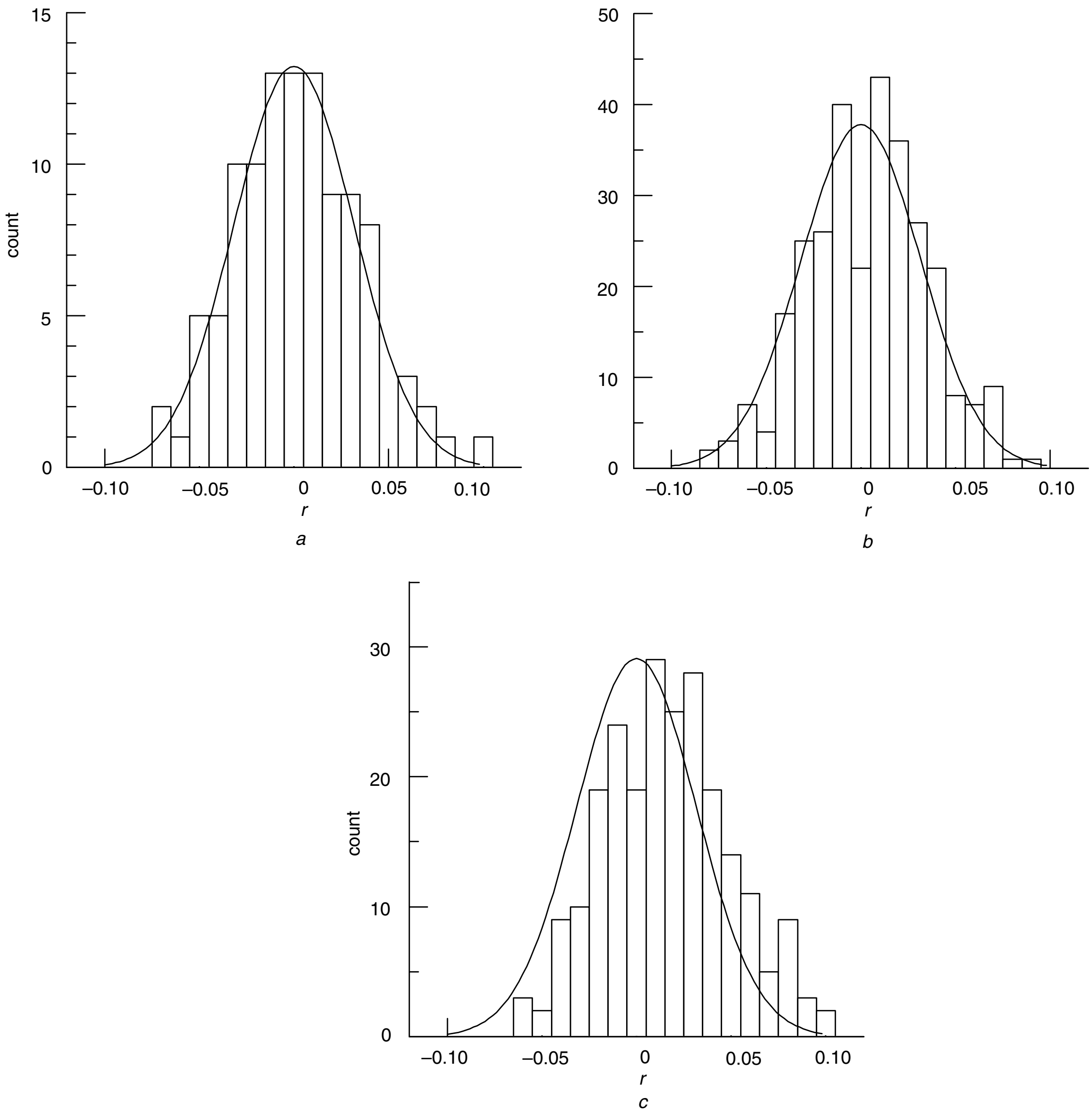

Fig. 6 *Histograms of correlation coefficients for three samples*
The lines are the expected distribution for uncorrelated, Gaussian noise
a Undoped at 500 K
b n-type (10^{-4}) at 298 K
c p-type (10^{-4}) at 426 K

3 Random telegraph noise

Most of the our results described have been obtained during times when the fluctuating signal viewed on an oscilloscope has the appearance of typical flicker noise. Certain a-Si:H samples can at times produce manifestly non-Gaussian noise signals that take the form of random telegraph-like noise (RTN), that is, the conductance abruptly and

defined RTN also involved a tunnel junction, an n^+ a-Si:H layer between two $Si_{1-x}N_x$ layers, but with a surprisingly large area of $0.25\,mm^2$ [21, 22]. The authors determined that the current formed a filament of less than $10\,\mu m$ in diameter presumably at a thin spot in the nitride layer so that a change in the charge state of a single trap in the nitride could strongly influence the conduction [23].

Although the work on tunnel junctions is interesting in itself, it does not have an obvious connection to noise in bulk a-Si:H. However, RTN has been observed in bulk samples without tunnel junctions and with exceptionally large volumes. First reported in a sample of p-type a-Si:H with transverse electrodes with an area of 10^{-4} mm^2 [24], the surprising reports of RTN are those in samples with coplanar electrodes [25–27]. Despite volumes as large as 10^7 µm^3 and several mm between electrodes, the conductance can abruptly change by 1%. Fig. 7 shows an example of RTN at room temperature from a sample of n-type (10^{-4}) a-Si:H 1 µm thick with longitudinal electrodes 8 mm wide separated by 2 mm. During this period the RTN was unusually stable and showed switching between only two levels. Histograms of times for downward and upward transitions agree 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 (Fig. 7). If the switching is controlled by a two-state system with an energy barrier, the barrier height is 0.6 eV using a typical phonon frequency 10^{12} s^{-1} for the attempt to hop rate. Studying RTN in large volume samples of a-Si:H is difficult since the signal is usually unstable. Often the signal will abruptly acquire new levels or have bursts of transitions followed by periods of quiescence, or the RTN may disappear entirely. Minor changes in temperature or vacuum are enough to alter or eliminate the RTN signal. We note that after opening the apparatus for several minutes the RTN signal of the sample vanished, although whether this is because of the brief exposure to light, atmosphere, or something else is unknown. Our experience is that RTN signals like that of Fig. 7 are rare. We have not seen such signals in p-type or undoped samples although others have.

4 Models

Two types of noise model have been applied to a-Si:H: generation–recombination (g–r) models involving trapping

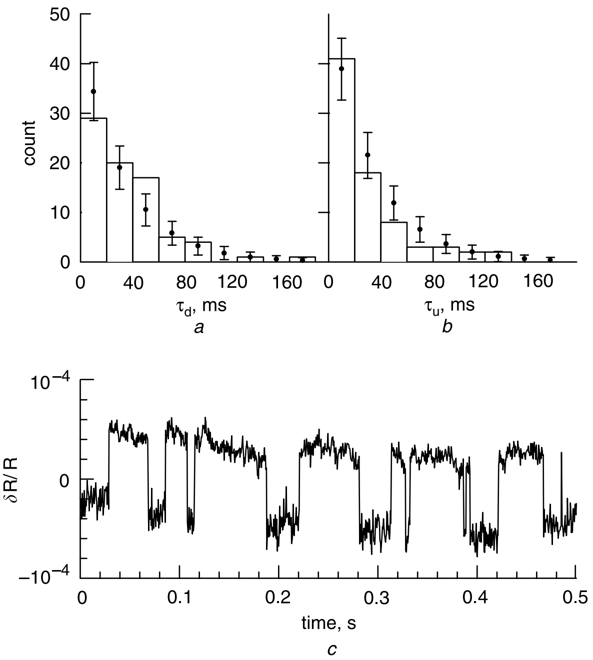

Fig. 7 *Random-telegraph-like noise in n-type a-Si:H*
a Histogram of time delays for downward transitions. Points are expected values for $\tau_d = 34$ ms with one-sigma error bars
b Same as *a* but for upward transitions and $\tau_u = 28$ ms
c Portion of two-level random-telegraph noise signal; *y*-axis is fractional change in resistance; bias current 10 µA

by and emission from localised states in the mobility gap and models based on current filaments. The g–r approach is appealing because the density of localised states and the trapping cross-section are well known. Also many researchers are familiar with g–r concepts since a similar formalism has been extensively and successfully applied to various transient experiments on amorphous semiconductors such as dispersive time-of-flight [28, 29]. Indeed, it would be a great surprise if g–r noise were not present in a-Si:H; the open question is whether g–r is the only noise source of any significance or whether another noise source of greater magnitude overwhelms the g–r signal. Models based on current filaments are inspired by the random telegraph-like noise and are discussed later in this Section.

G–r models have been applied to a-Si:H since the earliest papers [30, 31] and continue to be popular. The most thorough application to experimental data to date is by Verlag, *et al.* [18, 32]. Working with undoped a-Si:H with a transverse geometry, they analysed changes in the noise spectrum with temperature using the approach of Dutta, Dimon, and Horn (DDH) [33]. DDH models apply where the noise is generated by a large number of independent systems, each involving thermal activation across an energy barrier. The analysis determines the distribution of energy barriers required to reproduce the observed noise spectra. Because their measured spectra had a slightly Lorentzian-like shape, that is the local slope was flatter at lower frequencies and steeper at higher frequencies, the DDH analysis produced a distinctly peaked distribution of energy barriers centered at 0.85 eV that was reminiscent of the defect band in a-Si:H. Verlag, *et al.* then applied a g–r model involving transitions to both conduction and valence bands from recombination centres near mid-gap and found the predictions consistent with both the temperature and frequency dependence of the noise. They also found a g–r model best explains the noise produced while the samples are illuminated [34]. Further support for g–r models come from recent experiments that combine noise with electron spin resonance (ESR) [35, 36]. By using the noise signal to detect the ESR a direct identification can be made of any paramagnetic states involved in the generation of the noise. The signal observed corresponded to holes in the valence band tail. Unfortunately, the experiments could only be carried out with illuminated samples. If such experiments could be carried out in the dark, much uncertainty about the origin of the noise could be eliminated.

Our measurements of several samples of undoped a-Si:H produced spectra that exhibited a kink opposite to that seen by Verlag *et al.*, that is a lower slope at higher frequencies (Fig. 2). Applying the DDH analysis yielded a U-shaped distribution for the energy barriers. However, the test of the DDH approach is whether the temperature dependence and frequency dependence of the noise are consistent with a single distribution of energy barriers. We could not find a single distribution consistent with both the temperature and frequency dependence of the noise spectrum [37]. This result is not necessarily in conflict with those of Verlag *et al.* since our samples had coplanar electrodes rather than transverse. The geometry necessitated working at higher temperatures where the a-Si:H was sufficiently conducting to allow noise measurements. The difference in temperature dependence of the lower sloped branch of the noise spectrum at high frequencies compared with the higher sloped branch at low frequencies (Fig. 2) is difficult to reconcile with a single noise source and led us to speculate that we were observing two distinct noise sources at these temperatures [38].

We briefly comment about applying the simplest g–r model to doped material. For doped material in the dark, minority carriers can be ignored and the model simplifies to capture and release of majority carriers to the band edge. Each localised state causes fluctuations that contribute a Lorentzian to the total spectrum with a knee frequency ω_0 determined by the trap and release times $\omega_0 = \tau_t^{-1} + \tau_r^{-1}$. Since the traps are distributed in energy the release times vary over a wide range. The main contribution of each Lorentzian to the spectrum occurs near ω_0. So to produce a $1/f$ spectrum over a frequency range, traps with ω_0 over the same range must be present. However, it is important not to neglect the trapping time. By detailed balance, τ_t is smaller than τ_r for states below the Fermi level and thus determines ω_0 for these states. Since all deeper states have the same τ_r, the Fermi level effectively sets a lower limit on ω_0. For doped material, the lower limit on ω_0 is well above the low end of the measured frequency range and thus the g–r model predicts a flattened spectrum at low frequencies which is not observed.

The RTN requires a completely different model. For the conductance to suddenly change by 1% simultaneously throughout the sample due to the random action of independent fluctuators is highly unlikely. Further, the Poisson statistics of Fig. 7 is evidence of a single centre causing the jumps. Yet it is equally difficult to imagine a localised structure whose influence extends over a great enough volume if the current is essentially uniform throughout the material. The solution proposed is that a substantial fraction of the current is carried by narrow filaments, and that at one or a few locations along the filaments charge trapping or hydrogen motion can significantly affect the current [25]. The idea that long-range potential fluctuations created by charged defects can modulate the position of the mobility edge and create regions of varying conductivity was put forward by Overhof and Beyer [39]. The conjecture that under certain conditions current filaments may form in a network of random resistive elements was tested by computer modelling [26, 40]. Filamentary structures did form spontaneously in these simulations when the network neared the percolation threshold. Other simulations of random resistor networks have demonstrated non-Gaussian noise near the percolation threshold which may bear on the non-Gaussian noise reported for a-Si:H [41]. A potential experimental test involves compensated a-Si:H since the potential fluctuations are larger than in singly doped material however we are not aware of any noise measurements of compensated a-Si:H.

5 Summary and conclusions

To say that more work is needed to better understand the origin of noise in doped and undoped a-Si:H is perhaps stating the obvious, given the unusual and often conflicting work reported to date by different groups of researchers. While most find spectra that fit to a $f^{-\alpha}$ power law, which is probably the only agreement, there have also been reports of nonlinear behaviour, that is noise power scaling with other than the expected quadratic dependence on bias current, non-Gaussian statistics and RTN. Of these unusual phenomena, RTN is the most widely observed; yet its appearance in some samples and not others and its intermittent and unstable nature has prevented a definitive study. There is a clear need for further analysis of RTN and the factors that control or generate it. The experiments carried out at our laboratories on doped and undoped a-Si:H samples, as well as a-SiGe:H alloys, show no evidence for nonlinear behaviour or non-Gaussian statistics.

Models of generation–recombination noise, e.g. trapping and release of carries from a distribution of localised energy gap states, have had some success in certain cases but not others. One study of undoped a-Si:H sandwich structures was successful in explaining the observed temperature and frequency dependence of the noise in terms of a DDH model. However, we were unable to explain our results on undoped a-Si:H with coplanar electrodes with the same model. In these samples there appears to be two mechanisms at work, one generating the temperature dependent noise seen at higher frequencies and another producing a spectrum with greater slope seen at lower frequencies. Also, we have argued that the $1/f$ noise spectrum of doped a-Si:H cannot be explained by a generation–recombination model based on majority carrier trapping and release from localised states.

Filamentary conduction in a-Si:H is proposed to explain the RTN and computer simulations bear out the possibility. The existence of filaments of current may provide a way of reconciling the disparate results. If for certain samples, the network of filaments has a dominant link say because it is close to a percolation threshold then one is likely to see RTN and perhaps other unusual effects. But if the network is well connected and has many paths contributing to the overall conduction then fluctuations in the many filaments add incoherently and standard $1/f$ noise is produced. More work to experimentally establish the existence and topology of filaments is clearly needed.

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