1/*f* noise in hydrogenated amorphous silicon–germanium alloys

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

Abstract: Measurements were made of conductance noise of a-Si:H and a-$Si_{1-x}Ge_x$:H in two different geometries: one where the current flow is transverse to the surface and the other where it is longitudinal to the surface. Because of the large change in sample resistance between the two geometries, it was not possible to measure both geometries at the same temperature. For both geometries, alloyinzg with up to 40% Ge reduces the noise magnitude by several orders of magnitude over that found in a-Si:H. The decrease is incompatible with several popular noise models. Extrapolating the temperature trends for each geometry shows that it is possible that the noise observed in the transverse samples has the same origin as the higher frequency part of the double power law spectra observed in the longitudinal samples.

1 Introduction

In common with most conductors, hydrogenated amorphous silicon (a-Si:H) exhibits fluctuations in conductance whose spectrum is nominally a 1/*f* power law. A variety of noise measurements of a-Si:H have been reported over the past twenty years many of which are contradictory [1]. Working with sandwich structures where the current path is transverse to the surface, Verleg and Dijkhuis measured noise power spectra that deviate from a simple power law [2]; the spectra bend downward in an approximation of a Lorentzian. Other studies of a-Si:H with coplanar electrodes, where the current is longitudinal to the surface, found either simple $1/f^{\alpha}$ power laws with α in the range 0.7–1 or deviations from a power law but in the opposite direction [3, 4], i.e. the spectra are concave upwards. Due to the high resistance of undoped a-Si:H, the measurements with longitudinal currents are usually carried out only at elevated temperatures. If the noise is the result of many sources distributed throughout the bulk of the material then the electrode geometry should not influence the measured noise spectra. To assess whether the discrepancies in reported results might be due to geometry, we have attempted to compare sandwich and coplanar samples of nominally identical material.

Few noise measurements have been reported for alloys of a-Si:H, although we have published some preliminary results on a-$Si_{1-x}Ge_x$:H [5]. a-$Si_{1-x}Ge_x$:H is a well studied material because of its use as a narrow-bandgap intrinsic layer in multijunction solar cells. The motivation for measuring noise of a-$Si_{1-x}Ge_x$:H is to correlate changes in the noise spectra with the known changes in electronic structure that occur with the addition of Ge.

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2 Experimental details

Undoped a-Si:H and a-$Si_{1-x}Ge_x$:H were deposited by RF–PECVD. For longitudinal measurements, glass is used for the substrate; coplanar metal electrodes were evaporated either before or after the sample deposition. For the transverse measurements, stainless steel substrates are used. To improve the ohmicity of transverse samples, thin layers of n-type material were deposited before and after the undoped layer creating an n-i-n structure. Evaporated Cr dots 1.6 mm in diameter form the top electrodes; each dot is isolated from the others by a scribed circle. The Ge content was measured using EDX/SEM. For the transverse geometry, three alloys were studied with Ge contents of 15 at. %, 25 at. % and 40 at. %. The longitudinal samples have similar Ge concentrations of 14 at. %, 26 at. %, and 38 at. %. The thickness of all the alloy samples is 1.5 μm. The thickness of the unalloyed a-Si:H sample studied is 1.0 μm.

The system and procedures used to obtain noise spectra have been described in detail [6]. Essentially, the sample forms a voltage divider with a fixed resistor. A filtered DC voltage is applied to the divider resulting in a bias current, and the current fluctuations at the midpoint are capacitively coupled into a low-noise current-to-voltage converter. After further amplification, the signal is passed through an anti-aliasing filter and digitised. A discrete Fourier transform of the voltage time series yields the noise power spectrum. In order to obtain better coverage over the frequency range of interest, 1 Hz–40 kHz, up to three Fourier transforms with different frequency spacings are applied to each time series. Averaging over 50–100 time-series produces the final noise spectrum. The Johnson noise and amplifier noise are measured with no DC voltage applied to the divider. This background noise is then subtracted leaving only the noise due to conductance fluctuations.

Particular attention was paid to the ohmicity of contacts for the transverse samples. The I–V relation was measured at each temperature. Figure 1 shows the I-V relation for the four transverse samples at typical measurement temperatures. The samples of a-$Si_{1-x}Ge_x$:H are ohmic up to the largest voltage applied. However, the sample of a-Si:H becomes superohmic above 0.1 V. The bias current used

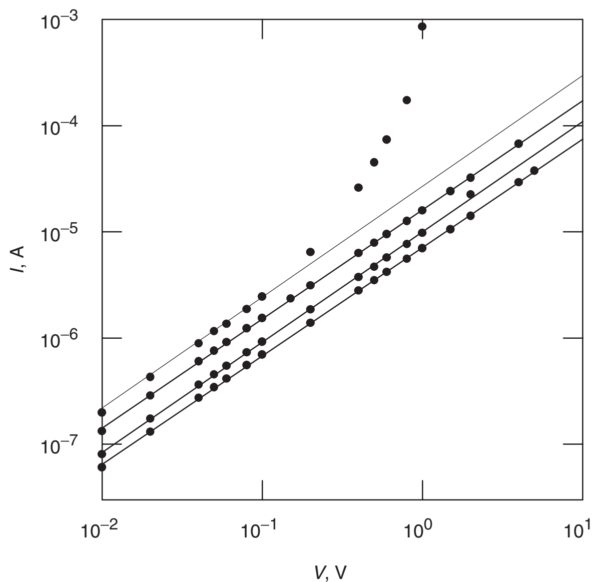

Fig. 1 *I–V relation for the four samples with transverse geometry*
Top to bottom: unalloyed a-Si:H at 375 K, 25% Ge at 350 K, 15% Ge at 343 K, and 40% Ge at 332 K

during noise measurements was restricted to the linear region of the I–V curve. At each temperature, noise spectra were obtained for a range of bias currents in order to check the dependence of the noise magnitude on bias current. For all the samples, the noise power scales as the square of the bias current as expected. The dependence on the bias current is removed from the spectra presented in this paper by dividing the noise power by the square of bias current resulting in normalised noise power spectra.

Given a sample with a certain level of intrinsic conductance fluctuations, the ability to measure those fluctuations is limited by the maximum DC bias current, the sensitivity of the amplifiers, and the level of background noise, especially Johnson noise. All three criteria are affected by the sample resistance; for a given measurement technique, the resistance must fall within a certain range. For the level of noise found in a-Si:H, our apparatus is restricted to sample resistances from about 10 kΩ to 50 MΩ. The limitation on the high end is due to the sensitivity of the current amplifier and the maximum voltage that can be applied to the sample to establish a bias current. The limitation on the low end is due to the excessive Johnson current noise and Joule heating in the sample. Due to the large internal stress in high-quality a-Si:H, samples with thicknesses larger than several microns tend to peel off the substrate. Since the film thickness is limited to be of the order of a micron and electrode dimensions are typically several mm in size, the resistance of a sample with electrodes in the transverse geometry will be a factor of 10^6 less than the same sample with coplanar electrodes. Thus, it is not possible for us to measure noise for the two geometries at the same temperature and make a direct comparison. Instead we measure over as wide a temperature range as possible and in particular to as high a temperature as possible with the transverse electrodes and as low as possible for the longitudinal electrodes.

3 Results and discussion

3.1 Influence of Ge

Before discussing the noise measurements, it is helpful to review the changes in electronic structure that occur when a-Si:H is alloyed with Ge. The most notable change is a narrowing of the bandgap with increasing Ge content. The mobility gap of a-Si$_{1-x}$Ge$_x$:H, that is the energy region containing localised states between the conduction and valence bands, decreases linearly with x from 1.8 eV for a-Si:H to 1.0 eV for a-Ge:H [7]. As the mobility gap narrows, the Fermi level does not maintain the same relative position between the bands, but instead tracks the conduction band mobility edge for x in the range 0.1–0.7 [7, 8]. Since electrons are the majority carrier, the conductivity activation energy remains at 0.75–0.7 eV for a wide range of alloy compositions despite the changes in the mobility gap. Effectively, the Fermi level moves downwards with respect to the centre of the bandgap and with respect to the defect energy levels. The density of localised states also changes with the addition of Ge. The density of midgap defects increases exponentially with x and is typically about two orders of magnitude higher in a-Ge:H compared to a-Si:H [9]. Time-of-flight studies of electron transport show that the electron drift mobility decreases due to an increase in the width of the conduction band tail states [10]. The electron microscopic mobility inferred from these studies is not significantly changed. Optical studies show that the Urbach edge is not affected by alloying; Ge seems not to significantly alter the valence band tail states.

We discuss first the samples with a transverse electrode geometry. The noise spectra produced by the transverse samples fit well to a $1/f^{\alpha}$ power law; however, the exponent α changes with Ge concentration (Fig. 2). The a-Si:H sample has $\alpha = 0.96$. But adding Ge systematically reduces α (see the inset to Fig. 2); α for the 40% Ge sample is only 0.56. In addition to becoming less steep, the spectra decrease in magnitude as Ge is added. Increasing the Ge content from 15 at. % to 40 at. % decreases the noise magnitude by about a factor of 50.

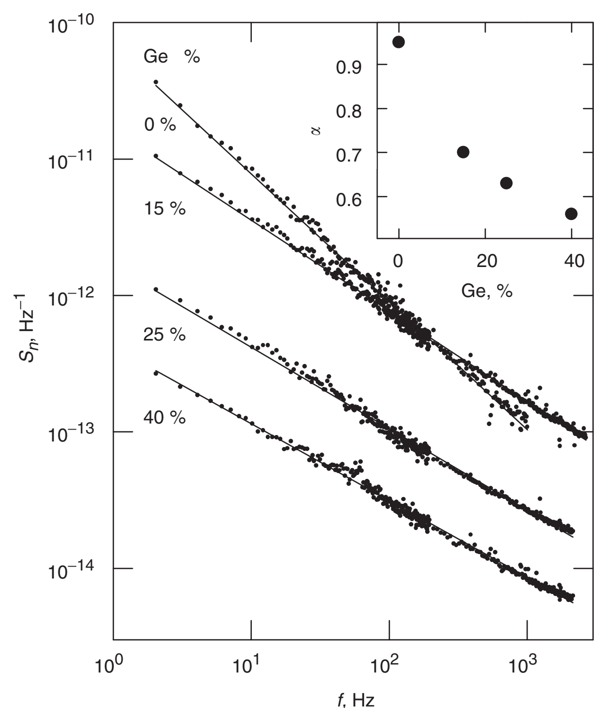

Fig. 2 *Normalised noise power spectra for the four samples with transverse geometry*
Measurement temperatures are 375 K for unalloyed a-Si:H, 343 K for 15% Ge, 336 K for 25% Ge and 332 K for 40% Ge. The lines are fits to a $1/f^{\alpha}$ power law
Inset: the exponent α as a function of Ge concentration

Because of the large density of localised states in amorphous semiconductors, it is natural to apply a generation–recombination noise model to explain conductance fluctuations. Localised states trap mobile carriers reducing the conductance, and thermal excitation from the localised states to the mobility edge increases conductance. It is well known that traps at a single energy level produce a Lorentzian noise spectrum $S(\omega) \propto /1(1+\omega^2/\omega_0^2)$; ω_0 is the sum of the trap and release rates. Deeper states have lower ω_0. Since the localised states in amorphous semiconductors are distributed in energy, a more complicated noise spectrum results. The tendency in the literature is to calculate the spectrum by simply adding the Lorentzians for each trap level although theorists will say that, strictly speaking, this is not correct since correlations can exist between the occupancies of traps at different energies [11]. But, qualitatively, one expects that deep traps tend to contribute to the noise spectrum at lower frequencies because of the low ω_0; whereas shallower states contribute to the higher frequency parts of the spectrum. Given this albeit rather crude understanding of generation–recombination noise, do the changes we observe in the noise spectra for a-$Si_{1-x}Ge_x$:H fit the model? The conclusion has to be no, they do not. The addition of Ge increases the numbers of deep states and broadens the conduction band tail. The net effect of both changes is to increase the relative number of deeper traps with respect to shallower ones. Yet the opposite is observed in the spectra where a decrease in α with increasing Ge means more relative weight at higher frequencies.

Another popular model for $1/f$ noise links conductance noise to temperature fluctuations. The idea is straightforward; because the conductance is activated and varies significantly with temperature, any fluctuations in temperature should produce conductance noise. However, our data do not support this model. The conductivity activation energy for the three alloyed samples are close to one another at 0.7 eV. Since all samples would experience the same magnitude of temperature fluctuations, the conductance noise should be the same for these samples in contradiction to what is observed.

The noise power of a-$Si_{1-x}Ge_x$:H decreases with increasing temperature. Figure 3 shows the decrease in the noise power density at 500 Hz for the three alloyed samples.

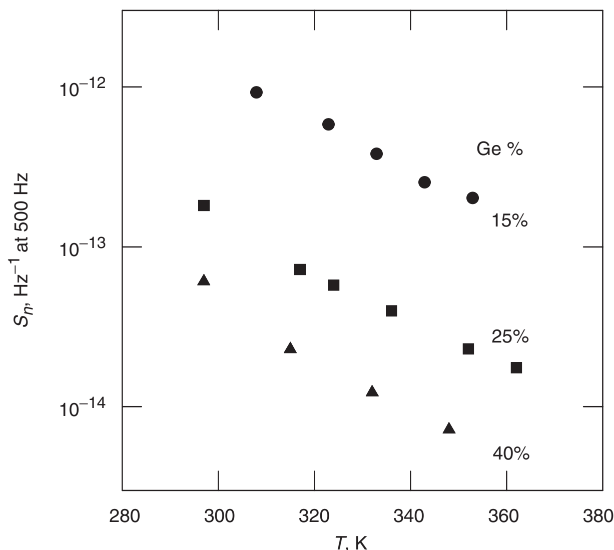

Fig. 3 *Temperature dependence of the normalised noise power at 500 Hz for the three a-$Si_{1-x}Ge_x$:H samples with transverse geometry*

Due to the nonohmicity of the contacts for the a-Si:H sample, reliable data could not be obtained over a range of temperature. The spectra shift downward, maintaining approximately the same values of α at all temperatures. According to the Hooge relation, one expects a decrease in noise power as the number of free charge carriers N increases; $S_n = \alpha_H/fN$ where α_H is a parameter characterising the noise magnitude. If the only effect of temperature on the noise is to increase N then $1/S_n$ should follow the conductivity (the change in microscopic mobility with temperature is a minor effect). Assuming $1/S_n$ is activated (the temperature range is too small to prove activated behaviour based on the data) and replotting on an Arrhenius plot yields an activation energy of 0.33–0.37 eV, considerably smaller than the conductivity activation energy of 0.7 eV; N increases faster than $1/S_n$. Thus, in order to fit the Hooge relation, α_H must increase with temperature. α_H is useful as a measure of the magnitude of the noise for a material. The value is limited for the alloy material because α_H depends not only on temperature but also on frequency, since the Hooge relation assumes a $1/f$ noise spectrum, which is not true for the alloys. Nevertheless, a range of values can be calculated once N is determined. Given that the calculation is only approximate, N can be estimated from the conductivity by assuming a value for the electron microscopic mobility of 3 cm^2/Vs. For the 40 at. % Ge sample, α_H is in the range 3×10^{-7}–3×10^{-6}. For many materials, α_H is of the order of 10^{-3} so the magnitude of the noise is relatively small in the alloys. The samples with lower Ge concentrations have larger α_H, since the noise level is greater. The a-Si:H sample at 375 K has a noise spectrum close to $1/f$, so the noise is characterised by the single value $\alpha_H = 4 \times 10^{-5}$.

3.2 Influence of geometry

Turning now to the longitudinal samples, we find qualitatively different noise spectra for these samples. As shown in Fig. 4, the spectra do not fit a power law over the measured frequency span, but rather are steeper at lower frequencies and very shallow at higher frequencies. We have observed similar spectra for many a-Si:H samples with the same electrode geometry [4]. In common with the transverse samples, adding Ge decreases the magnitude of the noise by a factor of 20–50, depending on frequency, from 14–38 at. % Ge. The reduction is similar in magnitude to that observed for the transverse samples. If the data are fit to power laws separately well above and below 100 Hz, the exponent α at low frequencies is in the range 1.2–1.5 whereas at high frequencies the value is 0.6 for a-Si:H and decreases with Ge concentration reaching 0.15 for the 38 at. % Ge sample. Another difference with the transverse samples is the change in the shape of the noise spectrum with temperature. As shown in Fig. 5 for the 24 at. % Ge sample, as the temperature increases the noise magnitude below 100 Hz increases while above 100 Hz the magnitude decreases. The different dependence on temperature for the two regions and different frequency dependence suggest that the spectrum is a result of two disparate noise sources.

For reasons explained in Section 2, the longitudinal samples were measured at higher temperatures than the transverse samples so a direct comparison is not possible. If the trends exhibited in Fig. 5 are extrapolated to lower temperatures, the resulting spectrum for the longitudinal sample would be dominated by the low α region because the noise power in this region increases strongly with decreasing temperature. The magnitude of the noise power for the transverse samples also increases with decreasing temperature. A linear extrapolation to lower temperatures of the

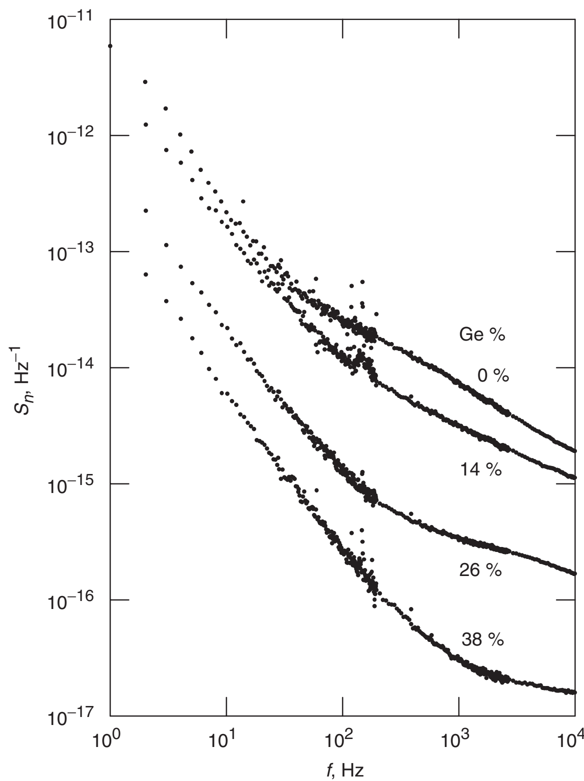

Fig. 4 *Normalised noise power spectra for the four samples with longitudinal geometry*
Measurement temperatures are 460 K for unalloyed a-Si:H, 454 K for 14% Ge, 446 K for 26% Ge and 454 K for 38% Ge

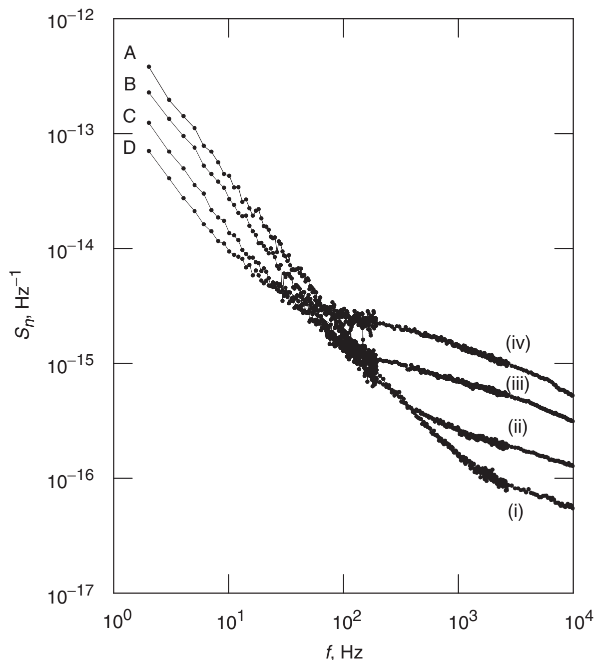

Fig. 5 *Normalised noise power spectra for the 26% Ge sample with longitudinal geometry at four temperatures*
(i) 471 K; (ii) 454 K; (iii) 435 K; (iv) 420 K

noise power for the longitudinal sample at 1 kHz results in values that are within a factor of five of those observed for the transverse sample. Thus, it is possible that the noise observed for the transverse samples is the lower temperature continuation of the high-frequency branch of the spectra of the longitudinal samples. Such an extrapolation is subject to error since the shape of the spectrum also must change with temperature since the α values for the two geometries are so different.

If the noise spectra for the two geometries do have different origins then the noise source cannot be a collection of independent fluctuators distributed randomly throughout the volume of the material. Three alternatives are possible. First, there is a significant noise contribution from the metal–semiconductor interface. Contact noise would dominate in the transverse samples since the interfacial area is substantially greater. Secondly there is a noise source at the surface. In this case, the longitudinal samples would be most affected as the transverse samples have essentially no free surfaces. Thirdly, there is nonuniform conduction through the bulk of the sample by current filaments. In the transverse geometry, the observed noise would result from an average over many filaments that connect the two electrodes. However, since the path between the electrodes in the longitudinal geometry is larger, much of the current might be carried by a small number of filaments. The observation of random-telegraph noise in doped a-Si:H supports the premise of filamentary conduction [12]. Although experimentally difficult, a comparison between the two geometries at the same temperature is clearly necessary.

4 Conclusions

We have expanded noise measurements to the alloy system a-$Si_{1-x}Ge_x$:H in order to better understand the origin of conductance fluctuations in a-Si:H. The changes that occur upon addition of Ge are not consistent with noise models based on trapping into localised states or temperature fluctuations. We have also tried to compare the noise for two electrode geometries, sandwich and coplanar, in order to resolve discrepancies in the literature between the noise spectra measured in different laboratories. A direct comparison at a single temperature was not possible, but the trend indicates that the noise seen in transverse samples might be identified with the higher-frequency branch of the double power law spectra seen for the coplanar geometry at higher temperatures.

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