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Conductance fluctuations in undoped hydrogenated amorphous silicon–germanium alloy thin films

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Abstract

We report coplanar conductance fluctuations of device quality, undoped hydrogenated amorphous silicon–germanium alloy thin films (a-SiGe:H) measured from 430 to 490 K. The a-SiGe:H alloys produce noise power spectra similar to coplanar undoped a-Si:H films in the same temperature range. The noise power spectrum S_n does not fit a single $1/f^{\alpha}$ power law but rather has two distinct regions, each accurately fitted by a power law, but with different slopes. The low frequency slope α_1 is similar to that observed in undoped a-Si:H films varying from 1.30 to 1.46 for different Ge concentrations and shows a slight temperature dependence. At higher frequencies, the slope α_2 is less than unity and temperature independent but depends on the Ge content of the film. α_2 decreases from 0.60 for no Ge (pure a-Si:H) to 0.15 for 40 at.% Ge. The noise power at lower frequencies increases and at higher frequencies decreases substantially as the temperature increases from 430 to 490 K. We infer that similar noise mechanisms are operating in undoped a-SiGe:H and a-Si:H films but that the Ge content is influencing the noise, particularly the slope at higher frequencies. In addition, the noise has the expected quadratic dependence on bias current and obeys Gaussian statistics. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Hydrogenated amorphous silicon (a-Si:H) and the alloy hydrogenated amorphous silicon–germanium (a-SiGe:H) have found use in photovoltaic technology due to the low material cost and ease of preparation [1]. To improve the conversion efficiency, a better understanding of the alloy is needed. $1/f$ noise has recently become an additional experimental tool for the characterization of amorphous semiconductors. Several noise studies of hydrogenated amorphous silicon (a-Si:H) have appeared in the literature [2–11]. Despite consistency among the reported work from each laboratory, there are noted differences in the data and explanations between laboratories. Some of these discrepancies might be due to differences in geometry or the type or quality of the a-Si:H samples.

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However, data from samples of nominally the same doping and sample geometry have different reported noise characteristics [4–6]. In particular, some studies of n-type a-Si:H report unexpected phenomena for $1/f^{\alpha}$ noise such as non-Gaussian statistics and a non-linear dependence on the bias current [4,5,7]. Due to the high resistance of undoped a-Si:H, most noise measurements have involved either n-type [4–7,11] or p-type material [12,13] and then mostly with a coplanar geometry. Undoped films have been studied using either a transverse geometry or a coplanar geometry at elevated temperatures. Early studies of undoped a-Si:H in a sandwich structure exhibited $1/f^{\alpha}$ noise spectra with α varying between 0.70 and 1.1 as the temperature increased from 328 to 428 K [8]. A more recent study of undoped a-Si:H with a similar sample geometry finds Gaussian statistics but an α that is frequency dependent, i.e., the spectrum is not a simple power law [10]. Khera and Kakalios [7] and Khera et al. [14] measured coplanar samples and reported $1/f^{\alpha}$ noise with α close to unity and a linear dependence on the bias current, but with strongly non-Gaussian statistics. Our noise studies of coplanar undoped a-Si:H films prepared in several different deposition systems showed the expected dependence on bias current and Gaussian noise statistics [15,16]. However, the spectra do not fit a single $1/f^{\alpha}$ power law but rather consist of two regions each of which fits a power law with different slopes. At low frequencies, α_1 is close to unity, and, at higher frequencies, α_2 is near 0.6. The temperature dependence is such that around 500 K the higher slope region dominates the measured spectrum and around 450 K the lower slope region dominates.

As seen from these studies, noise in a-Si:H, both doped and undoped, requires further investigation using different samples and contact geometries. One potentially fruitful approach is to study noise in alloys of a-Si:H. It is well established that alloying undoped a-Si:H with germanium changes its opto-electronic properties – the bandgap shrinks, the conduction band tails broaden, electron drift mobility diminishes [17], and deep defect states are modified and increased with increasing Ge content [18–21]. As the Ge content increases, characteristic Ge related defect states increase and become dominant controlling the generation, recombination and trapping kinetics [18,20,21]. For this reason, systematic changes in the noise as varying the Ge content could help determine the noise mechanism. However, there has not been any published work in the literature for a-SiGe:H films either in a coplanar geometry or in sandwich structure. In this paper we report, for the first time, noise spectra of undoped hydrogenated amorphous silicon–germanium (a-SiGe:H) alloys with various Ge concentrations.

2. Experimental method

Samples of undoped a-Si:H were prepared using several deposition techniques – dc glow discharge (GD) [22] and RF plasma enhanced chemical vapor deposition (PECVD) [23,24] with and without hydrogen dilution – using conditions optimized to produce low defect, ‘device quality’ material. The three samples of undoped a-SiGe:H, deposited in a RF PECVD reactor at United Solar Systems [24], had Ge contents of 14, 26, and 38 at.% as obtained by EDX/SEM analysis. The thicknesses of the samples ranged from 1 to 2 μm. Al, Cr, or NiCr was evaporated either onto the glass substrate before film deposition or onto the film after the deposition to form coplanar electrodes. All measurements used a two-probe geometry. The dark conductivity activation energies of the a-Si:H samples varied from 0.80 to 1.0 eV and of the a-SiGe:H samples from 0.60 to 0.70 eV. Noise and conductivity measurements were carried out under one Torr of flowing helium to reduce the effects of surface contaminants. Some measurements were repeated in a vacuum of 2×10^{-6} Torr to ensure that the He atmosphere was not interacting with the sample to produce spurious noise. Prior to measurements, the samples were annealed for 2–3 h at the highest measurement temperature, which was always less than the deposition temperature. Noise spectra were obtained at the annealing temperature and lower temperatures until the sample resistance reached a value that precluded accurate noise data.

The system and procedures used to obtain noise spectra have been described previously [5]. At each temperature, the ohmicity of contacts was checked and in all cases the bias current was linearly dependent on voltage up to the largest bias current used for the noise measurements. Several noise spectra were obtained for different dc bias currents ranging from 0.5 to 20 μA for the a-Si:H samples and from 2 to 250 μA for the a-SiGe:H samples. The current density was kept below 0.3 A/cm^2 to avoid self heating. The background noise, which consists of Johnson noise and instrumental noise, was measured separately at each temperature and subtracted from each spectrum leaving only the noise due to conductance fluctuations.

3. Results

Typical spectra of the noise power S_n for dc GD undoped a-Si:H are shown in Fig. 1 at three temperatures 443, 474, and 494 K. Similar spectra were obtained for the other samples of undoped a-Si:H films made by the other techniques [15,16]. The spectra have two distinct regions, Region 1 at lower frequencies and Region 2 at higher, each of which fits a power law $S_n \propto 1/f^{\alpha}$ but with different slope parameters α_1 and α_2. The noise power in Region 1 varies only slightly with temperature that results in a small change in α_1, but α_1 varies among the samples from 1.10 ± 0.02 to 1.27 ± 0.02. α_2 shows no temperature dependence for any of the samples but varies between 0.56 and 0.64 among the samples. As temperature decreases, the noise with slope α_2 extends to lower frequencies. At 443 K, the spectra is completely dominated by the single slope of $\alpha_2 = 0.63$. At this temperature, the sample resistance is 100 MΩ, which is at the upper limit for noise measurements. The $1/f$-type noise has the expected quadratic dependence on bias current. The noise of a sample deposited using identical deposition conditions was measured at the University of Abertay Dundee at 442 K producing results in agreement with ours.

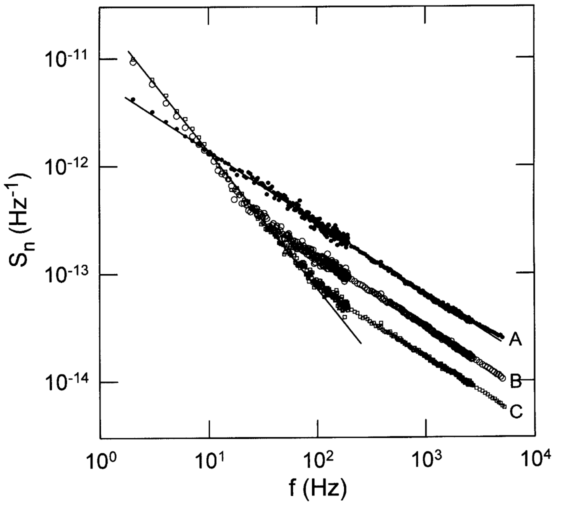

Fig. 1. Noise power density spectra for undoped a-Si:H at A: 443 K, B: 474 K, and C: 494 K.

As seen from Fig. 1, the noise power in Region 2 decreases with increasing temperature with the result that more of the measured spectrum is composed of Region 1. Fitting the noise power in Region 2 to a power law $S_n \propto T^d$ results in $d = -20$. The other samples produced similar values for d. The dependence of noise power on dc bias current $S_n \propto I^b$ was checked in both regions and we find $b = 2.0 \pm 0.03$ as expected. In addition, the noise signal was tested for non-Gaussian components by measuring the correlation between the noise power at separated frequencies and the second spectrum. The distribution of correlation coefficients was centered on zero and was in agreement with that expected for Gaussian noise. Also, the second spectrum measured for several frequency bands was white which again is consistent with Gaussian noise.

The noise spectra of the undoped a-SiGe samples are qualitatively similar to the unalloyed material. As illustrated in Fig. 2, the spectra still divide into two regions with different α's. Region 1 is similar to that observed in a-Si:H; α_1 varies from sample to sample ranging from 1.20 ± 0.02 to 1.48 ± 0.02 and varies slightly with temperature. The slope in Region 2 varies systematically with Ge content; α_2 decreases from 0.63 for the pure a-Si:H samples to 0.44 for 14 at.% Ge, 0.27 for 26 at.% Ge, and 0.15 for 38 at.% Ge.

The temperature dependence of the noise power also depends on Ge content (Fig. 3). In Region 1, the noise power density at 5 Hz is almost

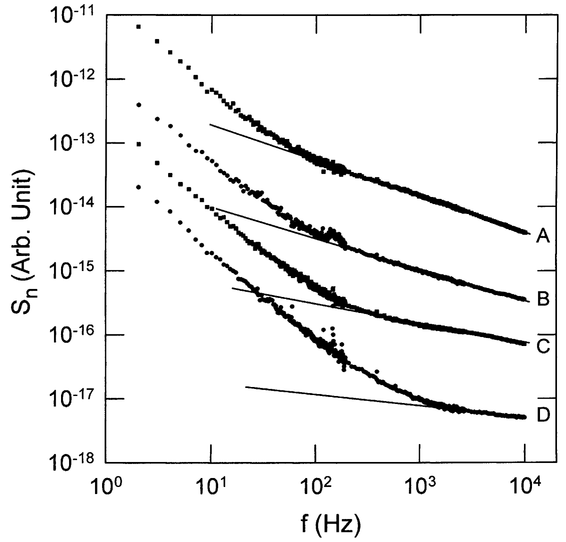

Fig. 2. Noise power density spectra for a-Si:H (A) and a-SiGe:H with B: 14, C: 26, and D: 38 at.% Ge. The curves have been shifted vertically for clarity.

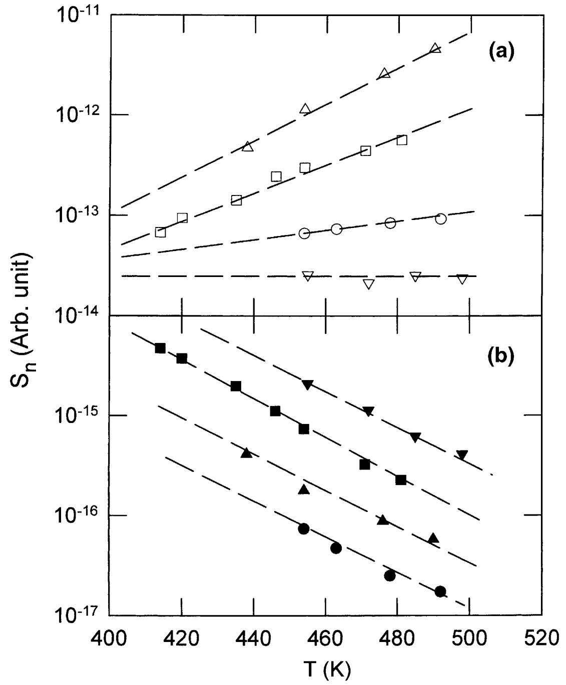

Fig. 3. The dependence of the noise magnitude on temperature at (a) 5 Hz and (b) 3 kHz for a-Si:H (inverted triangle) and a-SiGe:H with 14 (circle), 26 (square), and 38 (triangle) at.% Ge. The spectra are shifted vertically for clarity.

independent of temperature for a-Si:H, but is increasingly temperature dependent as Ge is added as shown in Fig 3(a). Fitting to $S_n \propto T^d$ yields for d 4, 12, and 18 for 14, 26, and 38 at.% Ge, respectively. In Region 2 at 3 kHz, the noise power density decreases with temperature similar to the behavior observed for unalloyed a-Si:H (Fig. 3(b)). Ge content has no effect on the temperature dependence with d almost equal for all samples with a value around −18. As with the a-Si:H samples, the noise power of the a-SiGe:H alloys varies quadratically with bias current, $b = 2.0 \pm 0.03$. Likewise, the noise signal was tested for non-Gaussian components and in all cases was found to be Gaussian.

4. Discussion and conclusion

There are similarities and differences in the noise spectra of a-Si:H and a-SiGe:H. The shape is similar in all samples consisting of two regions each of which fits a power law. α_1 in the low frequency region is larger for the SiGe alloys ranging from 1.20 to 1.50 whereas α_1 is closer to unity for a-Si:H. α_2 in the high frequency region depends on the Ge content, decreasing as Ge is added. Ge content also changes the temperature dependence of the noise power but only for Region 1. As was shown previously [15,16], S_n in Region 1 is almost temperature insensitive for a wide range of a-Si:H samples. However, S_n increases with temperature for a-SiGe:H and to a greater degree for larger Ge content. The decrease of S_n with temperature in Region 2 is unaffected by adding Ge. All these results indicate that similar noise mechanisms are functioning in both a-Si:H and a-SiGe:H thin films with a coplanar geometry.

We infer from the different dependencies on temperature and Ge content that the noise spectra we observe for both a-Si:H and a-SiGe:H arise from two separate noise generating mechanisms. Because of the different characteristic slopes one mechanism dominates the spectrum at lower frequencies and the other at higher frequencies. Because the noise produced by each mechanism differs in temperature dependence, the temperature range over which both can be seen in the experimentally accessible frequency range is limited. However, at this time the natures of the mechanisms causing this type of noise spectrum are not known. Previous reports using modulated photocurrent and ESR measurements on a-SiGe:H with varying Ge content have shown that deep defect states attributed to both Si and Ge are present in the alloy. These defect states are found to be in both neutral and charged forms. Perhaps as the Ge content and Ge associated traps increases, free carrier trapping is altered leading to the observed changes in the noise.

We mention that other noise measurements on undoped a-Si:H reported in the literature show differences from those reported here. Khera and Kakalios [7] and Khera et al. [14] carried out a noise study on undoped a-Si:H films with coplanar geometry at elevated temperatures. Their spectra had a single slope and quadratic dependence on bias current, but the noise signal had strongly non-Gaussian statistics. Most other reported studies on undoped a-Si:H films were on sandwich structures [2,8–10] and at temperatures much below the ones used here. No sharp kinks or unusual features at higher frequencies have been observed for the sandwich samples. Verleg and Dijkhuis [10] found curved spectra reminiscent of a Lorentzian frequency dependence and found good agreement with their data using a Dutta–Dimon–Horn (DDH) model [25] involving generation and recombination through distributed trap levels. The model yielded a distribution of activation energies peaked around 0.85 eV below the conduction band edge that was identified with defect levels. However, we were unable to fit our results on undoped a-Si:H films using the DDH model [16]. Recently, the noise-detected magnetic resonance experiments on intrinsic a-Si:H samples with a sandwich geometry identified, for the first time, a microscopic state involved in the noise namely a hole in the valence band tail [26]. However the measurements could only be carried out under illumination which may not be relevant for noise produced in the dark. The noise mechanisms in intrinsic a-Si:H films and those in a-SiGe:H alloys with coplanar geometry are still unknown.

Acknowledgements

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