1/f Noise in Doped Hydrogenated Amorphous Silicon

James Kakalios

School of Physics and Astronomy, The University of Minnesota
Minneapolis, MN 55455 USA

Measurements of coplanar current noise in n-type doped hydrogenated amorphous silicon (a-Si:H) are reviewed. The spectral density of tlie conductance fluctuations lias a 1/f frequency dependence for frequency f over the range $1 < f < 10^4$ Hz for temperatures $250 < T < 450$ K. The noise power is itself time dependent, displaying large variations of botli magnitude and f as a function of frequency over long time intervals (several thousaiid seconds). Fourier analysis of tlie conductance noise power fluctuations yields an approximate 1/f frequency dependence, that is, the l/f noise lias 1/f noise. These results indicate that cooperative dynamics, possibly involving hierarchically constrained interactions between tlie fluctuators responsible for tlie 1/f noise, govern the current fluctuations in doped a-Si:H.

I. Introduction

Nearly all physicists focus their attention on optimizing a desired experimental signal and either ignore or mininlize the noise which inevitably accompanies tlieir measurements. A few foolhardy individuals analyze the coise itself, and study the pliysical processes whicli underlie the fluctuations. Such investigations have found that a very wide class of disordered and complex systems display fluctuations whose power spectra varies as the inverse of the frequency f, termed flicker or 1/f noise. Studies of current or voltage fluctuations in semiconductors and metals can reveal important information concerning electronic properties and defect kinetics which are not reflected in bulk transport measurements[1-3]. Recent studies of conductance fluctuations in n-type doped hydrogenated amorphous silicon (a-Si:H) have found that the current noise power is well described by a 1/f frequency dependence for the frequency range of 1 Hz up to 10 kHz over a temperature range from room temperature to 450K[4-5]. However tlie 1/f noise in a-Si:H is anomolous, and displays phenomena typically associated with mesoscopically small spin glasses,[6,7] The 1/f noise in a-Si:H is time dependent, and reveals long time variations and strong correlations between the noise power at differing frequencies which indicate the presence of strong interactions be;ween the fluctuators responsible for the current noise. In this paper we will briefly review our recent efforts to understand the nature of the l/f noise in amorphous silicon.

II. Experimental Methods

The 1/f noise data are collected using a standard two-probe measurement system, as shown schematically in Fig. 1. A constant voltage is applied (using either mercury batteries or an HP 6212C power supply) across the coplanar electrodes, and the fluctuations in the resulting current passing througli the a-Si:H film are amplified using a commercial current pre-amp (Itliaco 564). The current is tlien sent to a spectrum analyzer (HP 3561A) which performs a FFT of the data and calculates the current spectral density S_I for a frequency range of 0 - 1 kHz, with a bandwidth of 2.5 Hz. The amorphous semiconductor sits in a stainless steel measurement chamber under a turbo pumped vacuum, and is in thermal contact with a copper block; resistive heaters and a commercial temperature controller are used to vary tlie sample temperature. All noise measurements are performed in the dark under vacuum following annealing at 450 K to remove any effects of surface adsorbates or prior light exposure;[8] the film is then slowly cooled (2 - 3 C/min) to the measurement temperature. Four probe noise measurements in the van der Pauw geometry using a constant current source and a voltage preamplifier were also preformed to verify that the a-Si:H noise data did not arise from contact effects.

Measurement Chamber

Spectrum Analyzer
HP 3561A

Current Amp
Ithaco 564

Metal Electrodes
a-Si:H
Glass Substrate
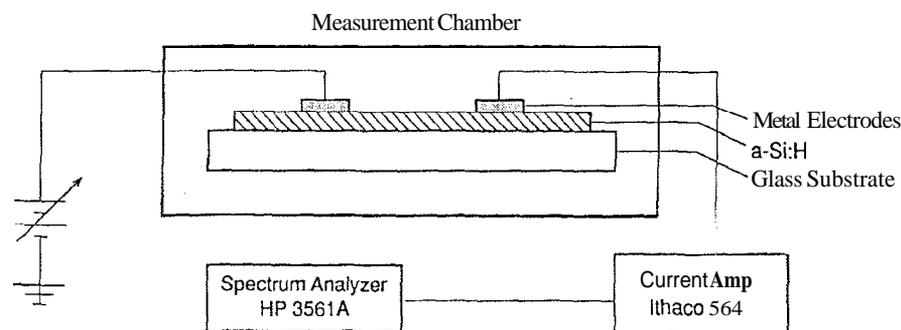
Figure I: Sketch of tlie experimental apparatus used to perform two probe current noise measurements. The sample is in thermal contact with a Cu block in which resistive heaters are used to vary the film's temperature, and resides in a stainless steel turbo-pumped measuremeiit cliainber.

B

200μm

A

A'

800μm

B'
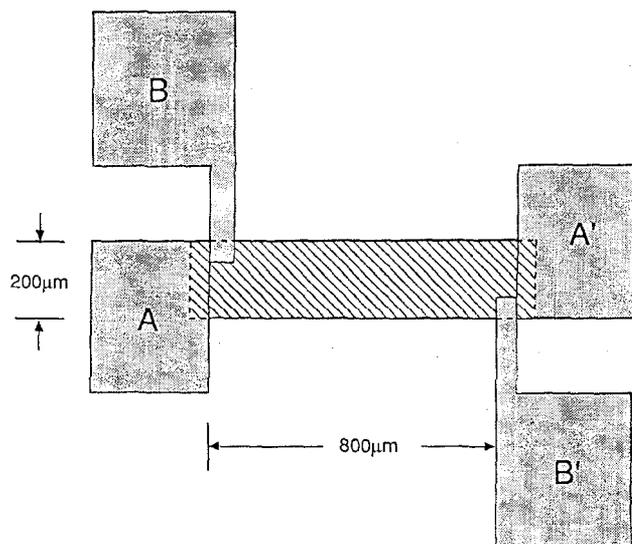
Figure 2: Coplanar electrode configuration used to perform tlie iioise measurements. Tlie film was patteined using conventional pliotolitliograpliy and ion milling; tlie a-Si:II extends into tlie sliaded regions labeled A-A' and B-B'. Tlie electrodes A-A' were used for two probe noise measurements, for four probe measurements A-A' were tlie current leads and tlie resulting voltage fluctuations were measured across electrodes B-B'. Tlie a-Si:H film is 1 μm tliick and tlie doping level is 1000 p.p.m. PH_3.

Tlie a-Si:H films ineasured here are grown using pure silane (SiH_4) in a capacitively coupled r.f. glow discharge deposition reactor. N-type doping is achieved by the addition of phosphine (PH_3) at a gas phase doping level of 1000 p.p.m. Tlie films are 1 μm thick and are deposited onto Corning 7059 glass substrates. Tlie data described in this review were obtained from an amorphous silicon film which was patterned as shown

in Fig. 2, using conventional photolithography and ion milling. Tlie a-Si:II film extends into tlie shaded regions labeled *A-h'* and B-B' in Fig. 2. Electrodes A-A' are used iii two-probe noise measurements, and in four probe measurements they are tlie current leads while electrodes B-B' are the voltage contacts. The area between the leads B-B' is 800 μm long by 200 μm wide, with an effective sainple volume of $\sim 1.6 \times 10^{-7}$ cm^3. Electrical contact is obtained using silver paint directly onto tlie a-Si:II film; these contacts displayed Ohmic current-voltage characteristics for applied voltages less than 20 V. Details of tlie sample preparation[9] and measurement technique[5] are published separately.

III. Results

Fig. **3** shows a log-log plot of 1000 rins averages of tlie spectral density S_I against frequency at 310 K. The data is well described by tlie frequency dependence $S_I \propto f^{-\gamma}$ where $\gamma \sim 1.1$ over tlie frequency range 10 to 10^4 Hz. Similar results are obtained over the temperature range 250 K < T < 450 K, and for n-type films for which tlie gas phase doping level is 10 p.p.m.[10] While tlie average noise power is consistent with a 1/f frequency dependence, a more interesting story emerges upon examining tlie 1000 individual FFT's which comprise tlie data of Fig. **3.** Tlie resulting time record of tlie noise power, shown in Fig. 4, is generated as follows.[2,11] A single power spectrum is calculated by

Fourier transforming a 1024 point current time series. This is then repeated a large number of times, of order 10,000, which takes ~ 3 hours to complete. To reduce the amount of data to be stored, and to simplify tlie data analysis tlie noise pomer spectra are summed into seven octaves, with tlie lowest octave ranging from 5-10 Hz and containing two power spectra points and tlie liigliest octave, from 320 - 640 Hz consisting of 128 power spectra points. By choosing frequency bins tliat increase by a factor of two from tlie lower to tlie upper frequency the 1/f noise power per octave is tlie same for all seven octaves. Tlie iioise power time traces in Fig. 4 have consequently been offset for clarity. Tlie data in Fig. 4 was taken at 400 K, comparable time traces are observed froin room teinperature to 450 K.
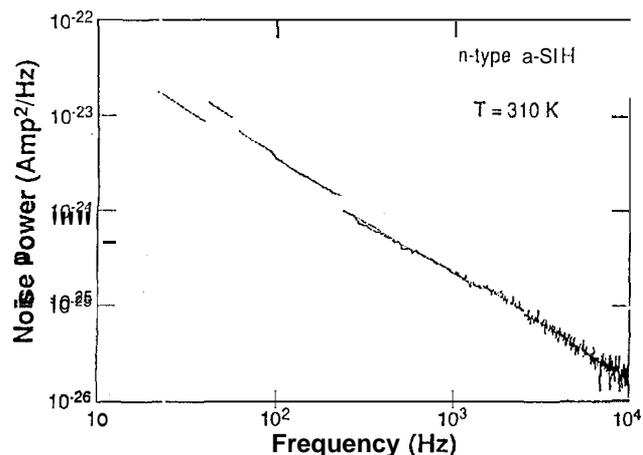
Figure 3: Log-log plot of the coplanar current noise power density S_I against frequency for n-tgpe a-Si:H measured at 310 K. Tlie data is tlie result of 1000 rms averages.

Tlie fluctuations in the noise power in eacli octave are inucli larger than the expected variations due to tlie sampling of a 1andoin signal. There are large variations as a function of time in the iioise power in a given octave (octave 7 for example). In addition, there are several events, marked by tlie arrows in Fig. 4, for which a sudden change ill tlie iioise magnitude ill a giveii octave is strong y correlated witli the changes in noise power extending over several octaves. These correlated clianges in tlie time dependence of tlie noise power

are not observed in Johnson noise measurements when the amorphous semiconductor sample is replaced with a metal film resistor of impedance comparable to the a-Si:H film.[10] Analysis of the correlation coefficients which characterize tlie noise power variations across differing frequency octaves[11,12] finds tliat tlie correlatioiis are much stronger tliaii would be expected for a suin of statistically independent Lorentzian power spectra, whose amplitudes are independently modulated.[6] That is, tlie data in Fig. 4 cannot be accounted for if tlie properties of tlie fluctuators responsible for the current noise are varied in parallel. In fact, spectral analysis of tlie data in Fig. 4, described below, clearly indicates that tlie current noise sources in a-Si:H interact on long time scales through some forin of cooperative dynamics.

The long time (low frequency) variations in tlie iioise power per octave for the data in Fig. 4 are inost clearly seen by generating second spectra S_2 which cliaracterizes the conductance noise power fluctuations. Tlie second spectrum is tlie Fourier transform of the time record of tlie noise power in a given octave.[11] For each octave, which is identified by tlie logarithmic center frequency f_1, a power spectrum $S_2(f_1, f_2)$ is calculated iii the usual manner at a frequency f_2 which is determined by the time scale of tlie noise power fluctuations in Fig. 4. Noise power fluctuations due to Gaussian processes, such as thermal variations in tlie fluctuators properties would have a frequency independent S_2, that is, the second spectra would be "white". As shown ia Fig. 5, the second spectra for n-type a-Si:H has a strong frequency dependence for all seven octaves. Tlie data iii Fig. 5 lias been normalized, sucli tliat if tlie noise power fluctuations arose froin uncorrelated variations (i.e. Gaussian processes) then S_2 would be unity at all frequencies. Tlie second spectra for a-Si:H lias an approximate power-law frequency dependence for all octaves, witli magnitudes well above unity. The frequency dependent second spectra in Fig. 5 is observed over tlie entire temperature range iiivestigated here, for gas-phase doping levels 10 and 1000 p.p.m. PH_3 in SiH_4, and in four-probe as well as two-probe measurements.[10]
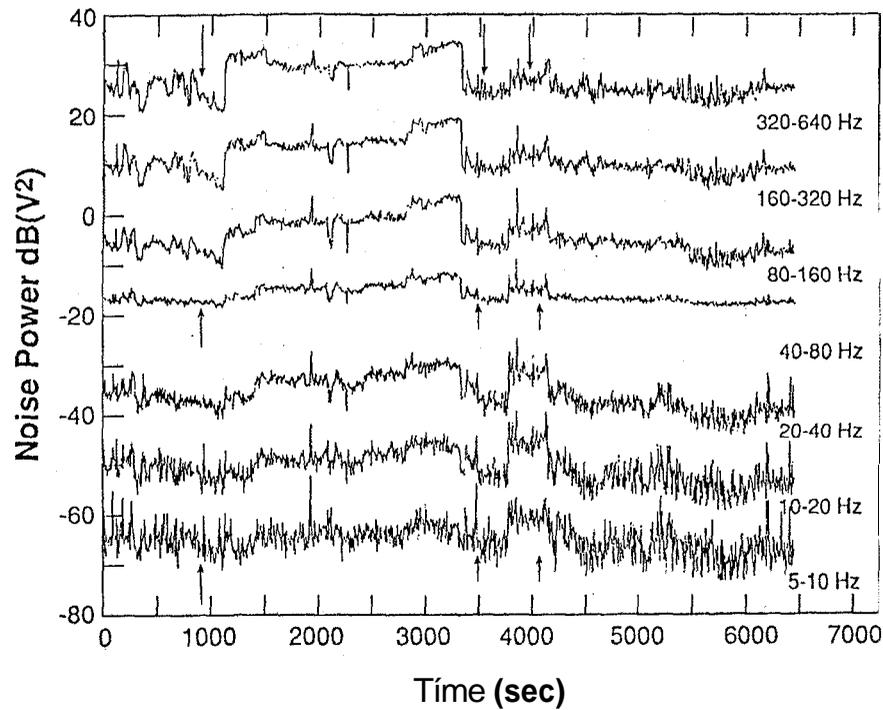
Figure 4: Plot of the noise power as a function of time for seven octaves for tlie n-type a-Si:H film shown in Fig. 2 at 400 K. Eacli data point is tlie result of 4 rms averages. Tlie curves have been offset vertically for clarity.
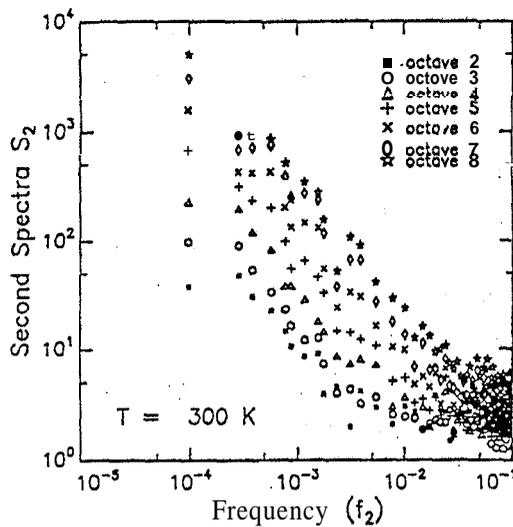
Figure 5: Log-log plot of tlie Fourier transform of the noise power fluctuations, termed "second spectra" S2 against frequency for the n-type a-Si:H film in Fig. 2 at 300 K.

It was argued above tliat tlie correlations of tlie noise power between differing frequency octaves are much stronger than would be expected for an ensemble of statistically independent Lorentzian noise sources, tlie magnitude of each of wliich is independently modulated in parallel. An alternative explanation for the noise power time dependence is that the interactions between tlie fluctuators are governed by some form of serial kinetics. Tlie second spectra in Fig. 5 further constrains the type of series interactions between tlie fluctuators, namely they must be such tliat lead to a power-law time dependence of higher moments of the current-current correlation function. One such form of cooperative dynamics which lias tlie necessary properties to account for our observatioris would be if me fluctuations responsible for the $1/f$ noise interact through hierarchically constrained kinetics.[2,13] A hallmark of hierarchical interactions is tlie scaling dependence of the second spectra.[13] The fractal nature of a hierarchical tree implies that tliere is no characteristic time scale for the second spectra, and tliat all of the $S_2(f_1, f_2)$ should be identical when plotted against a scaled frequency f_2/f_1. This scaling property simply reflects tlie self-similar nature of the hierarchical tree, tliat is, tlie S_2 for the 5-10 Hz octave has a certain magnitude at a frequency f_2, while for tlie 320-640 Hz octave one finds that same S_2 magnitude at a higher frequency f_2', and the ratio of f_2'/f_2 is determined by tlie ratio of tlie two

octave's center frequencies.

When the second spectra of Fig. 5 are replotted against scaled frequency f_2/f_1, the resulting plots are indeed scale invariant, as shown in Fig. 6. There are no adjustable parameters in the scaling of the data in Fig. 6; rather the data in Fig. 5 was replotted by simply dividing the horizontal axes for each curve in Fig. 5 by the center frequency of each octave. While there is some scatter to the data in Fig. 6, nonetheless all seven curves are consistent with a single frequency dependence given by

$$S_2 = S_2(0) + \alpha_2(f_2/f_1)^{-\gamma_2},$$

where $S_2(0)$ and α_2 are constants and γ_2 is the S_2 spectral slope. For the data in Fig. 6 the power law exponent $\gamma_2 \sim 1.13$, $S_2(0) \sim 2$ for scaled frequencies above 10^{-3} Hz and α_2 is of the order of 10^{-3}. The above expression describes the second spectra over the temperature range of $250 < T < 450$ K with $S_2(0)$ ranging from 2 to 10, while $10^{-4} < \alpha_2 < 10^{-1}$, with no systematic temperature dependence.

Fig. 7 shows the spectral slope γ_2, along with the spectral slopes of the original 1/f noise. There are two noteworthy aspects of Fig. 7: first, at all temperatures the S_2 spectral slope is less than the slope of the original 1/f noise. This simply indicates that higher order current moments are less correlated (contain less information) than lower order moments (a lower slope indicates that the second spectra is closer to white noise, i.e. uncorrelated) Secondly, the temperature dependence of γ_2 is consistent with the expression $\gamma_2 = (1 + \beta)/2$ where $\beta = T/T_0$ with $T_0 = 600$ K. While there is no theoretical justification whatsoever for such a temperature dependence of γ_2, the connection between γ_2 and the temperature dependence of β from stretched exponential relaxation[14] of the defect structure, which has been associated with hydrogen motion[14] and hierarchically constrained kinetics provides encouragement that a common physical process may describe both nonlinear dynamical phenomena in amorphous silicon.
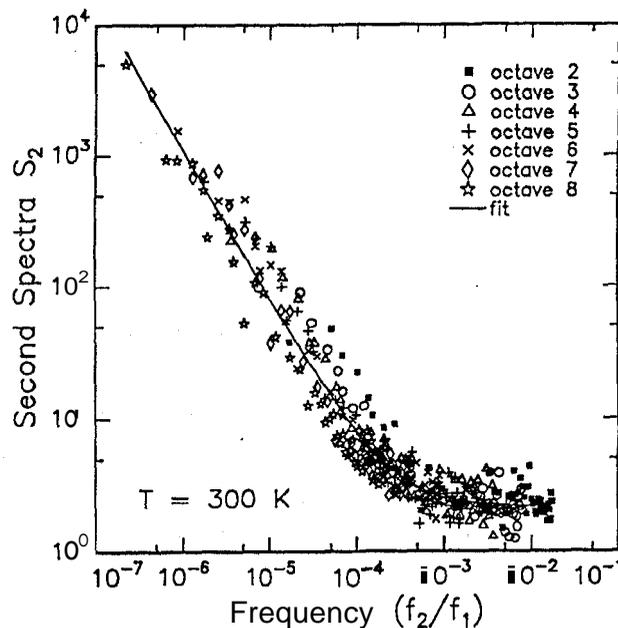
Figure 6: Log-log plot of the second spectra against scaled frequency f_2/f_1, as described in the text.
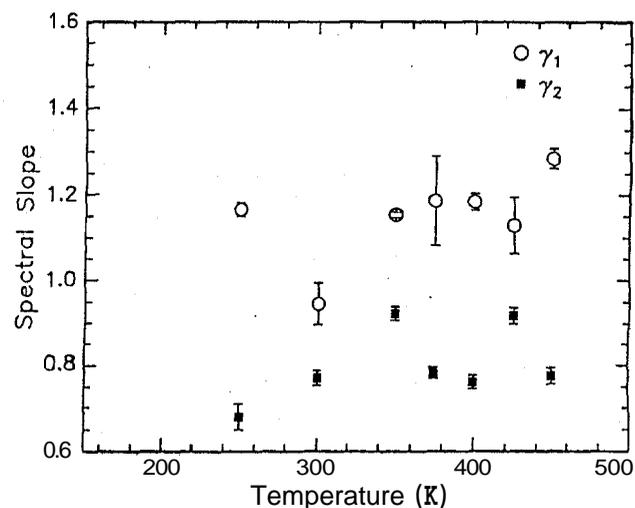
Figure 7: Plot of the spectral slope $\gamma_1[= -d(\log S_I)/d(\log f)]$ (open circles) for the current noise and $\gamma_2[= -d(\log S_2)/d(\log (f_2/f_1))]$ (closed squares) for the second spectra as a function of temperature.

IV. Discussion

The striking non-Gaussian nature of the conductance noise power fluctuations is not the only anomalous feature of the current noise in doped a-Si:H. We have recently reported[16] observations of random telegraph switching noise at and above room temperature

in coplanar current measurements for tlie sample iii Fig. 2, that is across electrode separations as large as 1 mm. Tlie switcliing noise is too large to be accounted for by cliarge trapping at a single defect, and lias been interpreted as reflecting tlie presence of inliomogenous current filaments in the a-Si:H, tlie conductance of which are time and temperature dependent. The scale invariant second spectra described in tliis paper clearly indicate tliat tliere are strong interactions between these filaments.

These microchannels could originate from either long-ranged potential fluctuations induced by tlie charged dopants and oppositely charged dangling bond defects which are introduced by tlie doping process in n-type a-Si:H, from tlie intrinsic disorder of tlie silicon network or from the known bonded liydrogen microstructure. Tlie fact that the second spectra are essentially tlie same for 10 p.p.m. and 1000 p.p.m. PH_3 doped a-Si:H films,[10] for which the charged defect concentrations vary by an order of magnitude, makes it unlikely that the current filaments arise from potential fluctuations. Experimental investigations of the non-Gaussian nature of tlie current noise are in progress for a-Si:H films for which the band tail slopes (which reflects tlie intrinsic disorder of tlie silicon network) and tlie liydrogen content (influenced by changing tlie deposition conditions under which tlie film is grown) are systematically varied.

Both the switching noise and the time dependent noise power indicate that the resistance of these current filaments, regardless of their origin, must change with time. We have previously suggested tliat tlie motion of hydrogen underlies tlie changes in the properties of tlie inhomogeneous current filaments.[5,6,16] Tlie strong interactions between the filaments responsible for the $1/f$ noise described here, wliose dynamics may be hierarchically constrained, suggest that tlie rearrangements of tlie hydrogen bonding configurations may involve many hydrogen atoms moving collectively.

We close with a speculation on tlie possible origin of the cooperative interactions between liydrogen atoms in doped a-Si:H. It has been known for some time that the motion of hydrogen can cause variations in the electronic properties of a-Si:H. Recent detailed studies of hydrogen diffusion have found tlie tlie liydrogen diffusion coefficient is, in turn, sensitive to the

local electronic properties near the moving hydrogen atom.[17] It is known tliat hydrogen relieves strain in tlie amorphous silicon film by breaking highly strained Si-Si bonds, creating new Si-H bonds. It is plausible tliat when one (or possibly two) liydrogen atoms reside on a strained Si-Si bond, they modify tlie local strain fields and consequently the electronic states in tlie vicinity of tlie strained bond, and tliat tliis alteration in tlie strain fields extends a considerable distance from the bond. These distortions in tlie strain fields will then alter the ability of another liydrogen atom to diffuse into tliis region, and will introduce correlations in tlie electronic properties of one region of the a-Si:H with another. We are investigating, both experimentally and using computer simulations, tliis suggestion that hydrogen-hydrogen interactions, mediated by tlie Si strain fields, underlie tlie conductance fluctuation phenomena observed in a-Si:H.

Acknowledgments

References

1. P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).

2. M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988).

3. Sh. M. Kogan, Usp. Fiz. Nauk **145**, 285 (1985) [Sov. Pliys. Usp. **28,** 170 (1985)].

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

5. C. E. Parman, N. E. Israeloff and J. Kakalios, Phys. Rev. B **47** (in press).

6. C. E. Parman, N. E. Israeloff and J. Kakalios, Pliys. Rev. Lett. **69**, 1097 (1992).

7. N. E. Israeloff, G. B. Alers and M. B. Weissman, Phys. Rev. B **44**, 12613 (1991).

8. M. Tanielian, Philos. Mag. B **45**, 435 (1982); D. L. Staebler and C. R. Wronski, Appl. Phys. Lett. **31**, 292 (1976).

9. R. A. Street, J. C. Knights and D. K. Biegelsen, Pliys. Itev. B **18**, 1880 (1978).

10. C. E. Parman, N. E. Israeloff, J. Fan and J. Kakalios, to be published.

11. P. J. Restle, M. B. Weissman, G. A. Garfunkle, P. Pearah and H. Morkoc. Phys. Rev. B**34**, 4419 (1986).

12. P. J. Restle, M. B. Weissman and R. D. Black, J. Appl. Phys. **54**, 5844 (1983).

13. G. A. Garfunkle, G. B. Alers, M. B. Weissman and N. E. Israeloff, Pliys. Rev. B **40**, 8049 (1989).

14. J. Kakalios, R. A. Street and W. B. Jackson, Pliys. Rev. Lett. **59**, 1037 (1987).

15. A. T. Ogielski and D. L. Stein, Phys. Rev. Lett. **55**, 1634 (1985).

16. C. E. Parman, N. E. Israeloff and J. Kakalios, Phys. Rev. B **44**, 8391 (1991).

17. P. V. Santos, N. M. Johnson, R. A. Street, M. Hack, R. Thompson and C. C. Tsai, Phys. Rev. B (in press); W. B. Jackson, C. C. Tsai and P. V. Santos, J. Non-Cryst. Solids **137 & 138**, 21 (1991).