RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 44, NUMBER 15 15 OCTOBER 1991-I

Random telegraph-switching noise in coplanar current measurements of amorphous silicon

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(Received 27 June 1991)

Resistance fluctuations are reported for n-type doped hydrogenated amorphous silicon (a-Si:H) using a coplanar electrode configuration with effective sample volumes of 10^{-6}–10^{-7} cm^3. Random telegraph-switching noise is observed with fluctuations as large as $\delta R/R \sim 10^{-2}$ for the temperature range $350 < T < 425$ K. Comparison of two-probe and four-probe measurements confirms that these results are not due to contact noise. The switching noise may result from inhomogeneous current paths arising from the hydrogen microstructure in the a-Si:H, which change their resistance value as hydrogen atoms hop from one bonding configuration to another.

Recently, there has been a growing interest in employing noise measurements as a probe of electronic conduction and dynamics in disordered systems.[1–7] Studies of current or voltage fluctuations in small samples can reveal details about electronic properties and defect kinetics, which are not reflected in bulk transport measurements.[3,8,9] In particular, the observation of random telegraph-switching noise (RTSN) in small semiconductor samples has been attributed to the random charging and discharging of individual traps,[8,9] which alters the carrier number and local mobility.[10] RTSN is typically observed in small devices which presumably contain only a few noisy traps,[8,9] such as field effect transistors or tunnel diodes with effective volumes or less than 10^{-10} cm^3. Recent observations of RTSN in relatively large ($\sim 5\times10^{-8}$ cm^{-3}) amorphous silicon-based devices was attributed to the presence of "microchannels" of small cross-sectional area.[6,7] In these experiments, however, the noise was measured transverse to the sample's thickness, which makes it difficult to separate tunneling and contact effects from resistance fluctuations which are intrinsic to the amorphous semiconductor.

In this paper we report the observation of RTSN in the coplanar conductance of n-type doped hydrogenated amorphous silicon (a-Si:H). By comparing two-probe and four-probe measurements we are able to eliminate contact effects as the source of the RTSN. These results are surprising given the large effective volumes (10^{-6}–10^{-7} cm^3) and high free charge-carrier concentrations ($\sim 10^{14}$ cm^{-3}) of the samples studied here. We tentatively suggest that the RTSN is due to hydrogen motion altering the conductivity of inhomogeneous current paths which arise from the silicon-hydrogen microstructure.

The amorphous silicon films studied were synthesized in a rf glow-discharge deposition system. n-type doping is achieved by adding phosphine (10^3 vppm) to the silane; the substrate temperature was 520 K and the incident rf power was 2 W. The films are 1 μm thick, and were deposited onto Corning 7059 glass substrates. Details of the deposition technique, growth conditions, and electronic properties of these samples have been published previously.[11,12]

The resistance measurements were performed using two separate contact geometries. For the electrode configuration shown in Fig. 1(a), (sample 1) electrical contact is made via 100-Å-thick n^+ (1% phosphine in silane) a-Si:H followed by an evaporated chrome layer. The n^+ a-Si:H between the chrome contacts is removed by plasma etching. These coplanar electrodes yield linear current-voltage characteristics for applied voltage of ± 100 V. For four-probe measurements the a-Si:H film and electrodes are scratched with a diamond scribe as indicated in Fig. 1(a), the width of each scratch being ~ 0.1 mm. A current is applied across one diagonal pair of electrodes and the voltage is measured across the other pair. The

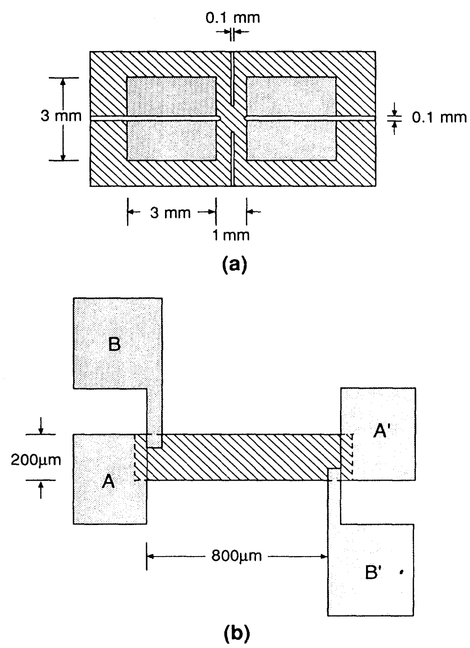

FIG. 1. Coplanar electrode geometries used for the resistance switching measurements. The shaded regions represent the chrome metal contacts and the hatched regions indicate the a-Si:H film, which is also present underneath the metal electrodes. For sample 1 [Fig. 1(a)] a 100-Å-thin n^+ a-Si:H layer lies between the a-Si:H film and the chrome. The open regions in (a) indicate where the metal and semiconductor were removed by scratching with a diamond scribe. No n^+ layer was used in sample 2 [Fig. 1(b)]. Electrodes A-A' are used in two-probe measurements and in four-probe measurements they are the current leads, while B-B' are the voltage leads.

effective volume between the coplanar electrodes in the two-probe configuration is $\sim 3\times 10^{-6}$ cm^3. The electrode patterning in Fig. 1(b) (sample 2) was obtained using photolithography and ion milling, on an n-type a-Si:H film with the same doping and deposition conditions as sample 1, grown in a different deposition run. The area between the voltage leads B-B' is 800 μm long by 200 μm wide, with an effective sample volume of 1.6×10^{-7} cm^3. No n^+ a-Si:H layer was used on this film, and electrical contact is obtained using silver paint directly onto the a-Si:H. These contacts also displayed Ohmic behavior for voltages less than ± 20 V. All of the data reported here for samples 1 and 2 were obtained using voltages within the Ohmic regime.

In the two-probe configuration a constant voltage is applied across the coplanar electrodes and the resulting current is amplified using an Ithaco 564 current amplifier. For the four-probe measurements a constant current is applied to the sample and the voltage fluctuations are measured on a separate pair of electrodes, using a low noise voltage amplifier (SR 560). The output of the current or voltage amplifier is then sent to a spectrum analyzer (HP 3561A) where the resistance against time or the power spectrum are recorded.

In any noise measurement it is important to verify that the noise is not due to a contact effect. We have made both two- and four-probe noise measurements and have found the normalized noise powers to be equal within the normal variations seen from data set to data set. In addition, we have simultaneously measured the current and voltage fluctuations in the four-probe configuration for sample 2 in order to insure that our results are not influenced by changes in the contact resistance affecting the current supplied by the current source. The ratio of the current to voltage fluctuations is less than 10^{-2}, confirming that our results are due to conductivity fluctuations in the a-Si:H. The instrumental background and the Johnson and shot noise are small compared to the RTSN noise of the a-Si:H films. The sample is annealed at 450 K in the dark under a turbo-pumped vacuum to remove any surface adsorbates and effects of prior light exposure before the noise data are taken.[13]

Figure 2 shows a time trace of resistance for sample 1 for increasing temperature. The trace at 425 K was measured using the four-probe configuration, the remaining data were taken using the two-probe technique. Distinct switching from one resistance level to another is evident at all four temperatures, the magnitude of a typical resistance jump is $\delta R/R \sim 10^{-3}$ (curve a) to 10^{-4} (curve d). As shown in Fig. 2(a) a two-state switching process is sometimes observed to modulate other higher frequency noise. Larger spikes are found in the resistance trace at 350 K both before and after the large switch, but not while the system has switched to the higher resistance state. The magnitude of the high-frequency noise is seen to change magnitude after the large switching events near the middle of the trace. Such "switching interaction" effects have previously been observed in very small devices and resistors.[2,3,8]

Clearer switching events are found in sample 2, as shown in Fig. 3. Figures 3(a) and 3(d) are two-probe

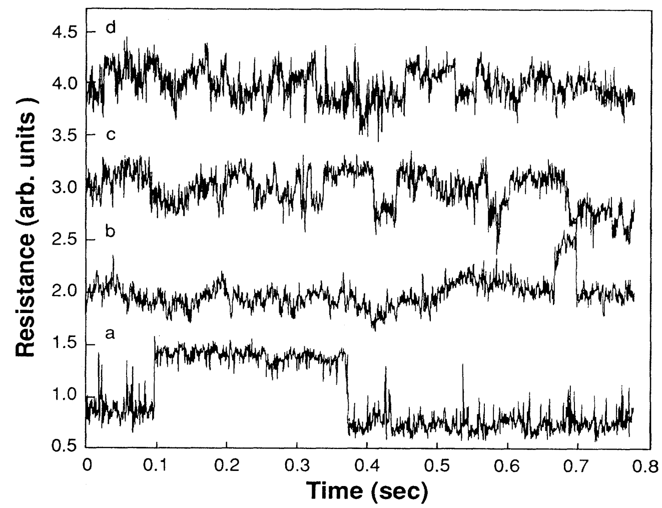

FIG. 2. Plot of resistance against time for n-type a-Si:H with the electrode configuration shown in Fig. 1(a) at 350, 375, 400, and 425 K for curves a–d, respectively. Curve d was measured using a four-probe configuration while curves a–c were obtained by two-probe techniques. The curves are arbitrarily offset and normalized for clarity.

resistance traces while Fig. 3(c) is a four-probe measurement, all performed at 400 K. For both samples 1 and 2 switching events have been observed for time scales ranging from a few milliseconds to several tens of seconds and the fractional resistance changes can vary by several orders of magnitude. On average the fractional resistance changes in sample 2 are larger than for sample 1 and there appears to be a smaller number of fluctuators active at any given time. Both of these results are consistent with the smaller volume of sample 2.

The striking two-state switching in Fig. 3(a) changes abruptly at longer times into a more complicated multistate switching pattern. Frequently a distinct pattern of switching events will disappear or come and go repeatedly [Figs. 3(c) and 3(d)], with a given pattern rarely persisting without change for more than a few traces. These dramatic changes of the switching pattern with time are reflected in the highly non-Gaussian noise statistics observed in these samples, which will be discussed in detail in a later paper.[14]

As a further check that our results are due to bulk fluctuations in the a-Si:H film, Fig. 3(b) shows a resistance time trace of a 5 MΩ metal film resistor at 400 K which has an impedance comparable to that of the a-Si:H. All of the wires, connectors, amplifiers, power supplies, and meters are unchanged from those used to measure the a-Si:H films, yet there is clearly no evidence of RTSN in the metal film resistor. The observed resistance trace is dominated by 60 cycle pickup and was a factor of 10^{-2} smaller (rms) than the RTSN of the a-Si:H.

Many models for resistance noise in semiconductors invoke carrier density fluctuations due to charge trapping.[8,9] Given the size and free carrier density of the sample, 10^5 carriers would have to be trapped simultaneously to give a

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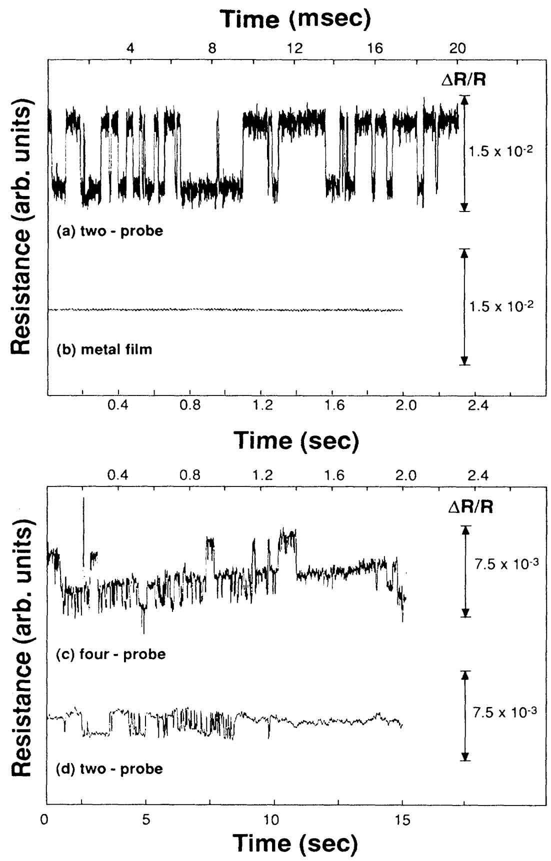

FIG. 3. Plot of resistance against time for n-type a-Si:H with the electrode configuration shown in Fig. 1(b) at 400 K. Figures 3(a) and 3(d) were measured using the two-probe configuration, while Fig. 3(c) is a four-probe resistance trace. Figure 3(b) was measured by replacing the a-Si:H film with a 5 MΩ metal film resistor. The curves are offset for clarity. The time scale that describes each resistance trace is adjacent to each curve.

fractional resistance change as large as 10^{-2}. An alternative model suggests that the conduction is dominated by current filaments, making the resistance sensitive to a small number of carrier traps or defects.[6,7] As mentioned earlier RTSN has been observed previously in a-Si:H but only in device structures where the current fluctuations are measured transverse to the film's thickness. Rogers *et al.*[5] observed discrete resistance switching in Nb/a-Si:H/Nb devices at 6 K, with $\Delta R/R = 4\times10^{-4}$. The electrode area was 4.2×10^{-7} cm^2 and the effective volume of the sample was $\sim10^{-11}$ cm^3. Acre and Ley[6] observed telegraph noise in a-Si:H/a-SiN$_x$:H double-barrier structures with electrode areas of 2.5×10^{-3} cm^2. In order to reconcile the large current fluctuations with the size of their structures, Acre and Ley suggested that "microchannels" occur where the tunneling barrier through the nitride layer is a relative minimum. These authors estimated that the cross-sectional area of these microchannels was on the order of 1 μm^2. The current through the microchannels would then be sensitive to trapping and release of single charge carriers. Similarly, Choi *et al.*[7] report RTSN with $\Delta I/I \sim 0.1\%$–10% in the temperature range of $300 < T < 373$ K in Cr/p^+ a-Si:H/Cr structures with a-Si:H films several thousand angstroms thick and electrode areas of 10^{-6} cm^2. These authors suggest that their results may be due to breakdown in the thin thermal oxide at the metal contact–semiconductor interface, perhaps due to weak spots with a higher relative conductivity, which cause a large fraction of the total current to be carried in a small filament. The filling and emptying of a localized trap near the conducting pathway could modulate the height of the tunneling barrier, making the current in such a filament sensitive to a single trap.

Studies of the noise power spectrum for n-type a-Si:H films by our lab also reflect a sensitivity to the fluctuations of a small number of conduction paths.[15] The noise spectral density S_I obeys a $1/f$ frequency dependence and displays a power-law dependence on the coplanar dc current passing through the sample, that is $S_I \propto I^b$. The power-law exponent b was temperature dependent, ranging from ~ 1 at 300 K to 2–2.5 at 450 K, and was also found to be strongly dependent on thermal cycling. Previous observations of nonlinear (that is $b \neq 2$) $1/f$ noise have been ascribed to the influence of inhomogeneous current paths. Both the observation of RTSN in the large effective volume coplanar geometries reported here, and the nonlinear current dependence to S_I, supports the proposal that electronic transport in a-Si:H occurs, at least in part, through conducting filaments.

We now address possible origins of inhomogeneous current paths in nominally homogeneous amorphous silicon. Doping in amorphous semiconductors leads to the introduction of positively charged donor atoms and compensating negatively charged dangling-bond defects.[16] It has been argued that potential fluctuations from these charged defect states influences the location of the conduction-band mobility edge.[17] However, reconciling the observed magnitude of the resistance switching with the known charged defect density of 3×10^{17} cm^{-3} present in 10^3 vppm phosphorus doped a-Si:H (Ref. 16) requires a statistically improbable clustering of defects in order to achieve a significant localization of the current into a microchannel.[18] An alternative source of structural heterogeneities is the known microstructure of the ~ 10 at.% bonded hydrogen in the amorphous silicon. Recent studies have suggested that in addition to the dilute and clustered phases observed in nuclear-magnetic-resonance studies,[19] the hydrogen displays a complex morphology.[20] While the influence of the hydrogen microstructure on the electronic properties of a-Si:H is not known, it has been suggested that electrical conduction in amorphous silicon proceeds via classical percolation, with regions of high hydrogen concentration serving as insulating barriers or traps.[21] It is therefore possible that the conduction noise in a-Si:H films is dominated by a few conducting paths which carry a large fraction of the current. Those few current paths would than have a disproportionate influence on the noise measurements. Moreover, it is well known that hydrogen atoms change their bonding configurations and diffuse throughout the a-Si:H film at the temperatures studied here.[22] The motion of hydrogen atoms, either singly or collectively, could dramatically change the connectivity of a current filament and could also account for the changes in the noise pattern [Figs. 3(c) and 3(d)] as different current filaments are turned on and off. Alternatively, charge trapping at a defect near the current filament could be responsible for turning the channel on and off. We can make a crude estimate of a lower limit of the characteristic volume dominated by a single current filament (which is not necessarily the same as the size of a filament) by assuming that the fractional resistance change is approximately equal to the fractional volume affected. For the fractional resistance changes of 1% found in sample 2, we find a characteristic volume of 10^{-9} cm^3, giving a 30-μm cross-sectional characteristic length. We do not presently understand the mechanism by which charge trapping or the motion of hydrogen atoms can strongly influence the conductivity of a filament this large, or how a smaller filament could dominate conduction over such a large length scale. Clearly, further studies are necessary in order to determine the origin of the RTSN in a-Si:H.

In conclusion, random telegraph-switching noise has been observed in coplanar current measurements of n-type a-Si:H with effective sample volumes of 10^{-6}–10^{-7} cm^3 for temperatures ranging from 350 to 425 K. Comparison of two-probe and four-probe measurements confirms that the switching noise is due to bulk changes in the resistance of the a-Si:H. These results are discussed in terms of a model whereby variations in the bonding microstructure of the hydrogen in the amorphous silicon lead to conduction filaments which can change their resistance when hydrogen atoms hop from one bonding configuration to another.

We gratefully thank C. C. Tsai of Xerox-Palo Alto Research Center for providing the a-Si:H samples, and acknowledge stimulating and helpful discussions with M. B. Weissman, B. Shklovskii, R. A. Street, H. Fritzsche, E. D. Dahlberg, and J. W. Halley. This research was supported by the University of Minnesota and NSF Grant No. DMR-9057722. One of us (J.K.) was also supported in part by the McKnight Foundation, and N.E.I. was supported by NSF Grant No. DMR-9001874.

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

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

[3]G. A. Garfunkel, G. B. Alers, M. B. Weissman, and N. E. Israeloff, Phys. Rev. B **40**, 8049 (1989).

[4]Neil Zimmerman and Watt W. Webb, Phys. Rev. Lett. **65**, 1040 (1990).

[5]C. T. Rogers, R. A. Buhrman, H. Kroger, and L. N. Smith, Appl. Phys. Lett. **49**, 1107 (1986).

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

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

[8]K. S. Ralls, W. J. Skocpol, L. D. Jackel, R. E. Howard, L. A. Fetter, R. W. Epworth, and D. M. Tennent, Phys. Rev. Lett. **52**, 228 (1984).

[9]C. T. Rogers and R. A. Buhrman, Phys. Rev. Lett. **53**, 1272 (1984).

[10]R. D. Black, P. J. Restle, and M. B. Weissman, Phys. Rev. B **28**, 1935 (1983).

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

[12]J. Kakalios and R. A. Street, Phys. Rev. B **34**, 6014 (1986).

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

[14]C. E. Parman, N. E. Israeloff, and J. Kakalios (unpublished).

[15]C. Parman and J. Kakalios, Phys. Rev. Lett. (to be published).

[16]R. A. Street, Phys. Rev. Lett. **49**, 1187 (1982).

[17]R. A. Street, J. Kakalios, and M. Hack, Phys. Rev. B **38**, 5603 (1988); H. Overhof and W. Beyer, Philos. Mag. B **43**, 433 (1981).

[18]B. Shklovskii (private communication). Details of this argument will be published in Ref. 14.

[19]J. A. Reimer, R. W. Vaughan, and J. C. Knights, Phys. Rev. Lett. **44**, 193 (1980).

[20]S. B. Zhang and W. B. Jackson, Phys. Rev. B **43**, 12142 (1991); R. A. Street, Phys. Rev. B **43**, 2454 (1991).

[21]M. H. Brodsky, Solid State Commun. **36**, 55 (1980).

[22]R. A. Street, C. C. Tsai, J. Kakalios, and W. B. Jackson, Philos. Mag. B **56**, 305 (1987); J. Kakalios, R. A. Street, and W. B. Jackson, Phys. Rev. Lett. **59**, 1037 (1987).