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Noise probe for bias-dependent current-path rearrangements in disordered solids

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We present a probe that can distinguish among a large set of physical noisy mechanisms when the current flows in a percolative-like manner, through a disordered material. The measuring technique can determine the existence of a bias-dependent current flow pattern. It is found that there are systems where each bias gives a noise signature which is determined by its special current flow pattern. [S0163-1829(97)50522-4]

The behavior of current flow and current low-frequency fluctuations in disordered materials is still under intensive research.[1] In many physical systems the current is accompanied by low-frequency fluctuations, generally known as the ‘‘$1/f$ noise.’’ This phenomenon is not well understood.[1] In such systems with a variety of morphologies (e.g., amorphous, polycrystalline, porous, granular materials, etc.), there are many possible ways for the current flow to fluctuate: simple scattering events at fluctuating cross-section defects, generation-recombination events, sudden avalanche events at high-field locations, and fluctuating percolating paths of currents between grains. More complicated collective mechanisms, where interactions take place due to long-range forces (like strain, electrostatic, or magnetic forces, etc.) may also determine the fluctuating current flow pattern.

Due to the diversity of physical systems producing $1/f$ noise, it is believed now that each case must be individually investigated,[2] rather than searching for a universal general mechanism that results in a $1/f$ spectrum. Generally the noise spectrum is only a narrow window, giving very little information on the noise mechanism under investigation, and it cannot distinguish between different fluctuation mechanisms. Attempts have been made to distinguish and classify the variety of such systems in order to shed some light on the mechanism responsible for the low-frequency fluctuations. For example: Is the noise an equilibrium process or does the current play a role in creating the fluctuations?[3,5] Are the observed fluctuations a superposition of many local independent microscopic entities or do they come from some collective mechanism due to spatial interactions?[1] If the noise is due to local resistivity fluctuations, can one classify the mechanisms by the various symmetries of the local two-dimensional conductivity tensor?[6,7] Is the noise a reversible mechanism?[4,8,9]

In this paper we present a characterization technique of disordered systems using the noise signature for the classification. Our technique can distinguish between cases where for every dc bias the fluctuations come from the same current pattern flow, and cases where each bias gives a different current flow pattern. This distinction is based on the different noise signature obtained under the application of a different bias. We note that in many available physical systems the current is flowing in a segmentlike manner through a disordered material and the noise is sensitive to fluctuations near the current segments. In such systems it is not clear what happens when the external electric field is increased: if the current of the already existing segment flow increases, the noise signature will not change significantly. If on the other hand, the segments change their location, namely the old ones stop and new ones open, the signature must change, since we probe local fluctuations at different locations.

Our experimental technique consists of applying a fast square-wave bias to the sample, separating the two noise signals generated by the sample under the two bias levels of the square wave, and then computing the low-frequency coherence function between them. Two extreme cases must be considered: (I) If current path locations fluctuate spontaneously through a fixed set of available paths, with no bias dependence, the coherence must be high, since at both bias levels we probe the same slow fluctuations. (II) If on the other hand, each bias level imposes a different set of current paths where we probe local slow fluctuators at different locations, the coherence must drop drastically.

In such a system one must also consider what happens if some local fluctuators are affected by the changing bias: if the fluctuators instantaneously follow the rapid bias changes, then these fluctuators are scrambled and cannot any longer hold their long time memory, thus a significant reduction in the $1/f$ noise magnitude is expected. If only statistical properties of some fluctuators change, the rapid bias changes will affect only the average fluctuators' behavior, thus the coherence function will still remain high.

Following these considerations we applied our technique to a few specific systems which show or do not show bias-dependent noise signatures. These include carbon-loaded polymer bulk resistors, leakage currents in ultrathin silicon-oxide film in metal-insulator-semiconductor (MIS) structures and various amorphous silicon resistors.

We have carried out our measurements in the following setup: the sample is connected to two bias voltages V_1 and V_2 alternately, using a 2 KHz oscillator that controls two commercial electronic switches, alternately. The switches do not add any noise to the system since they act as a short or as a break in the circuit. The noise is then amplified using a low noise preamplifier. The amplified fluctuations are diverted into two different channels by using two additional electronic switches that are synchronized with the alternating bias, at the 2 KHz rate. Each channel transmits fluctuations coming from the device under a different bias, i.e., either V_1 or V_2. After further amplification and low-pass filtering of each channel, the two signals are connected to a two-channel spectrum analyzer for accumulating time traces of the noise and computing the power spectral density (PSD) of each channel, as well as the coherence function (normalized cross PSD) at the 1–800 Hz frequency band. In our measurements the actual bias applied depends on the sample's impedance: for samples of low impedance the bias is applied to a balanced bridge (applying a current to the sample) and a voltage preamplifier is used, while for samples of high impedance the bias is directly applied to the sample and a transimpedance preamplifier is used for measuring current fluctuations.

The system has three modes of operation: in mode 1, V_1 is applied to the sample and in channel 1 we observe fluctuations under dc conditions. In mode 2, V_2 is applied to the sample and in channel 2 we observe fluctuations under dc conditions. In mode 3, the 2 KHz oscillator controls the four switches using two complementary digital signals, so that the bias is alternating between V_1 and V_2, and both noise signals are measured—both time traces, PSD_1 and PSD_2, and the coherence function between the two channels at the frequency range of 1–800 Hz. The measurement setup was carefully tested using all three modes of operation, in order to assure that the main noise in our experiments comes from our samples. Although some samples showed complicated fluctuations with intermittency in the short time range, PSD and coherence measurements were averaged over many traces to ensure accurate and reproducible results. We found no drifts that might lead to misinterpretations.

The first system we tested was a carbon loaded polymer resistor[10–12] near the percolation threshold: a five probe device was prepared, each arm showed a linear I-V curve with 6 kΩ resistance. The PSD of the device noise under dc conditions (mode 1) showed a simple $1/f$ dependence, though time traces of the noise showed sometimes large discrete jumps indicating that the sample is small enough to enable us to observe discrete microscopic events of the noisy mechanism. Second spectra[1] of the noise showed $1/f$-like frequency dependence of most octaves, as shown in Fig. 1(a). Such results were interpreted by others as a current redistribution phenomenon,[13] where slow spontaneous current paths rearrangements occur at a fixed bias, causing slow changes of the PSD magnitudes at higher frequency bands. No bias dependence of the paths was considered in Ref. 13.

Applying our technique in mode 3, and computing the average coherence function at a 1–100 Hz range, for a constant V_1 value and for different V_2 values, we obtained the result shown in Fig. 1(b). All data points have values close to 1, indicating that the fluctuations for different bias voltages are highly correlated, i.e., current fluctuations come from the *same current pattern* for different bias voltages (case I). Obviously, for $V_1 = 4$ V and $V_2 = 0$ V the coherence is less than 0.1, since there should be no correlation between the $1/f$ resistance fluctuations and thermal noise at zero bias.[5]

The second system tested was an MIS structure, made by cleaning a bare p-type silicon substrate and then applying a small drop of a silver paste on the low-quality thin (approximately 25 Å) native oxide that always forms on such a substrate. The metal gate made of metallic silver grains (which typically have a diameter of 3 μm), is expected to have a discrete number of contact points to the oxide, rather than a continuous contact surface. Even fewer contact points coinciding with oxide defects are expected to carry the leakage current from the silver paste through the oxide to the silicon substrate. We found that the PSD of the leakage current noise had approximately a $1/f$ shape, though the noise was found to be highly non-Gaussian, showing discrete events, intermittency, random telegraph signals (RTS's) etc., similar to the findings in Ref. 14, though no drift or other nonstationary behavior was found. The I-V curve showed an exponential behavior, typical of a Schottky barrier interface.

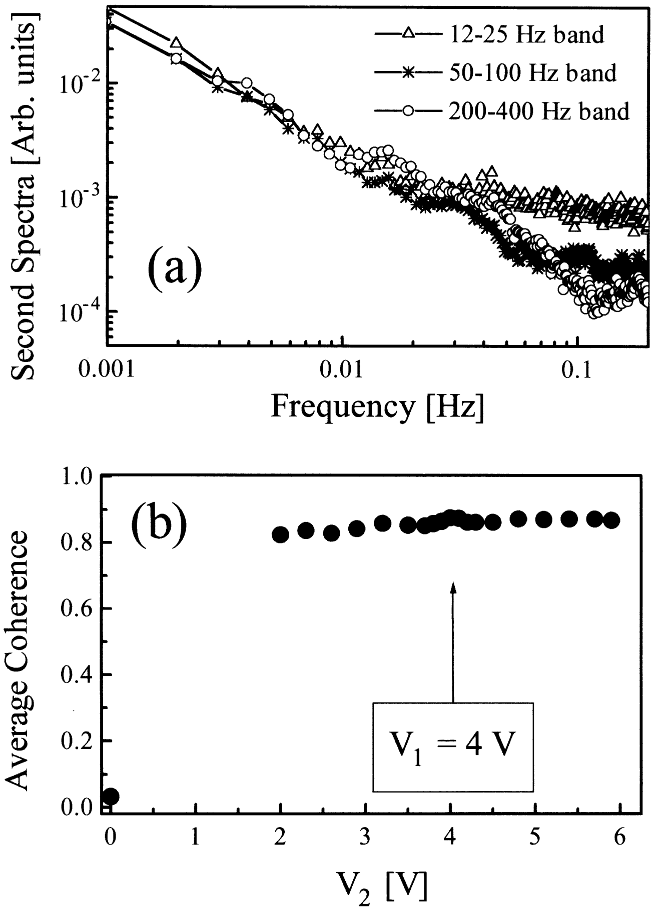

FIG. 1. (a) Second spectra of three octaves, for a carbon-loaded polymer resistor under dc conditions. (b) Average coherence function, in 1–100 Hz range, vs sample's bias V_2, for a constant $V_1 = 4$ V. This measurement was carried out using the setup described in the text, under ac conditions (mode 3).

The average coherence function between fluctuations due to two different bias voltages, measured with our new technique (in mode 3), gave surprising results: the coherence decreased dramatically to about 0.2 when the difference $|V_1 - V_2|$ was increased [Fig. 2(a)]. Furthermore, there was no significant difference between PSD's measured at dc conditions with $V = -0.5$ V and -0.8 V in comparison with ac conditions (mode 3) where the square-wave bias alternated between the above voltages [Fig. 2(b)]. In some instances, a slow RTS was clearly observed in one channel, while none was observed in the second channel, as shown by the time

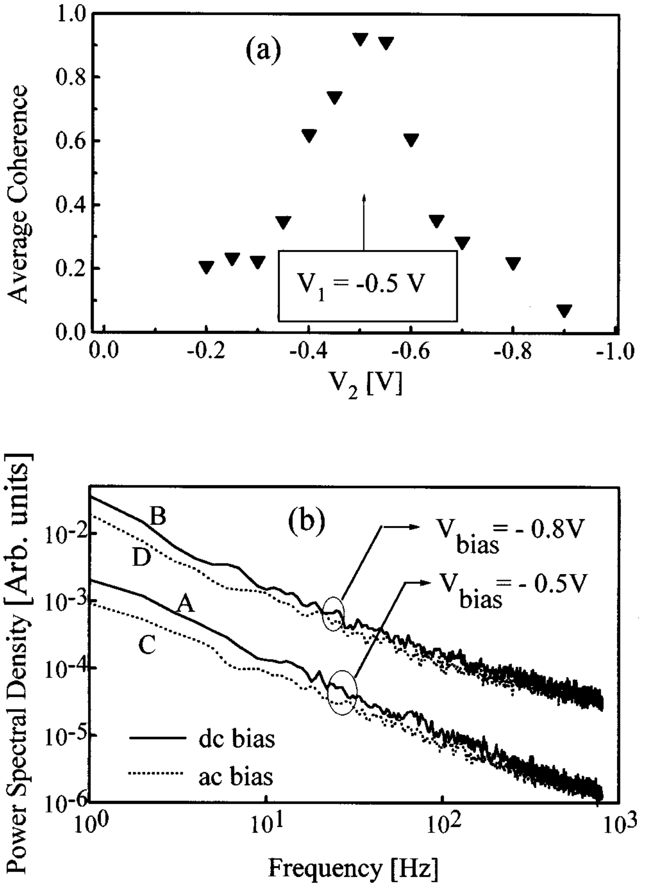

FIG. 2. (a) Average coherence function, in 1–100 Hz range, vs sample's bias V_2, for a constant $V_1=-0.5$ V, measured on a metal-insulator-semiconductor sample using the setup described in the text, under ac conditions (mode 3). (b) Spectra of the current fluctuations of the sample: trace *A* and *B* were measured under dc conditions where $V_1=-0.5$ V and $V_2=-0.8$ V using mode 1 and 2 of the setup (see text). Traces *C* and *D* were measured simultaneously under ac conditions using mode 3, where sample bias was alternating between the two bias voltages.

traces of Fig. 3, respectively. The RTS in channel 1 under V_1 comes from some large two-state fluctuations in one path, that cannot be probed in channel 2, since this current path stops and another current path starts somewhere else under V_2. This behavior, shown in Figs. 2 and 3, indicates that different electric fields impose different current flow paths that resulted in a completely new noise signature. In each bias we observe slow fluctuations happening at a different location, with little correlation between them.

The behavior presented in Fig. 1 shows a bias-independent noise signature while the behavior shown in Fig. 2 exhibits a strongly bias-dependent noise signature. To demonstrate an intermediate case we also studied two different amorphous silicon devices: (1) metal/*p*-type *a*-Si:H/undoped *a*-Si:H/metal, and (2) metal/thin silicon oxide/ *n*-type *a*-Si:H/metal.[15] The first one showed a linear *I*-*V*, no discrete events in the noise, and a coherence function close to 1, for all combinations of V_1 and V_2, indicating a bias-independent current flow pattern. The second sample showed a parabolic *I*-*V* curve, discrete jumps and RTS's in the current noise. The coherence measured in mode 3 of our setup dropped from ~1 to 0.7 when increasing $|V_1-V_2|$, as shown in Fig. 4.

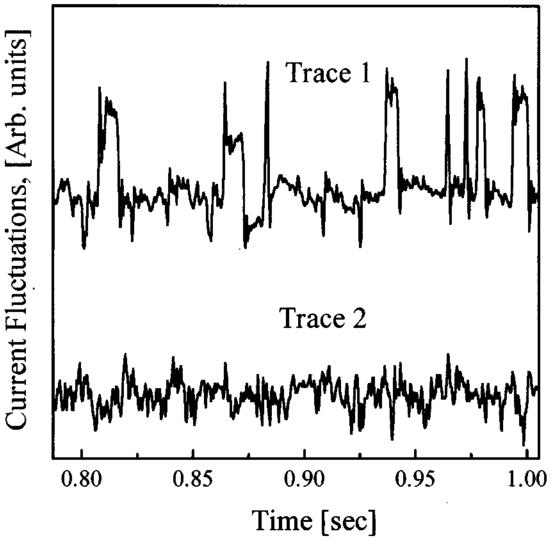

FIG. 3. Time traces of the low-frequency fluctuations, collected simultaneously at the two channels, using the new technique in mode 3: trace 1 and 2 correspond to $V_1=-1.1$ V and -0.5 V, respectively. Trace 1 exhibits a large RTS while trace 2 does not.

We interpret our results in terms of bias-dependent current paths rearrangements as follows: tunneling currents through a junction are proportional to the product of three factors: the density of electrons available on one side of the junction, tunneling transition coefficient, and the density of unoccupied states available on the other side. All three factors are strongly bias-dependent. Since defects candidates for carrying tunneling currents have a random nature with a variety of structures, one can expect different and even opposite *I*-*V* behavior at each defect location. (A simple example of a reduction of current with increasing bias is well known

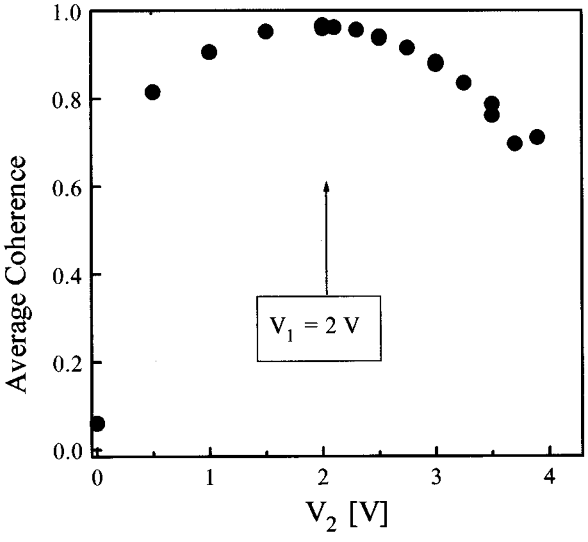

FIG. 4. Average coherence function, in 1–100 Hz range, vs sample's bias V_2, for a constant $V_1=2$ V, measured on a metal/thin oxide/ *n*-type *a*-Si:H/metal structure, using the setup under ac conditions (mode 3).

to take place in a simple tunnel diode.) Thus, for two nonidentical weak points in the oxide, it is possible that for a certain bias one defect point will allow a current segment to flow, while at a different bias the other one will. By changing the bias between the two voltages we alternately probe the two segments, each of which contains a different set of fluctuators located along its path. This mechanism results in the different noise signatures, as discussed above.

In some of our MIS as well as *a*-Si:H samples we observed that some fluctuators' characteristics, like duty cycle or amplitude of RTS's, were bias-dependent.[14,16] Also, there was a difference between time traces of these fluctuators under dc and ac conditions. It was suggested by others that trapping/detrapping of charge near a current segment caused the RTS's in the noise.[14] Since a trapped charge can alter the local barrier, a fluctuating occupancy of a defect can show up as noise in a nearby current segment. The different characteristics of the RTS are caused then by the bias dependence of the trapping/detrapping mechanism. Nevertheless, this feature alone cannot explain the fact that fluctuators are observed under ac conditions in one channel and do not show up in the second one (Fig. 3). If the current path always passes near the fluctuator's location (a trapping/detrapping site[14]) then the slow RTS must be observed in both channels (perhaps with different characteristics than under dc conditions). The fact that we observed a slow RTS under a rapid square-wave bias only in one channel clearly states that the current path must alternate its location according to the bias and hence it probes the fluctuator's state only when the current path is close to it.

So far we have found bias-dependent current paths rearrangements only in samples containing leakage currents in oxide layers. One cannot *a priori* expect such a behavior in the variety of disordered materials, although some predictions can be made if one knows something about the current flow and current fluctuation mechanisms. Our technique can shed some light on such systems.

We believe that the thin oxide plays an important role in the results shown, since in both cases of the MIS and the *a*-Si:H samples the I-V curve as well as the noise features found above, are mainly determined by this layer.

In conclusion, we have demonstrated an interesting probe that uses low-frequency noise measurements under square-wave ac conditions to detect the bias dependence of current path rearrangements in disordered solids. We have tested three different systems and we have shown that in a case where bias-dependent barriers are involved, as in thin silicon oxide, changing the bias causes rearrangements of the current paths, resulting in changes of the noise signature.

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