Characterization of individual electron traps in amorphous Si by telegraph noise spectroscopy

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We have used telegraph noise spectroscopy to study the properties of individual localized electron traps of a particular type in thin layers \((t < \sim 6 \text{ nm})\) of rf sputtered amorphous Si and amorphous Si:H. The results indicate that these traps have bistable ionic configurations: The trapping kinetics are dominated by transitions between two different ionic configurations with an associated change in trapped charge. Above \(\sim 20 \text{ K}\), configurational transitions are by thermally activated hopping; below 20 K, transitions appear to be induced by zero-point oscillations.

Recently,1-3 Rogers and Buhrman described how to use the resistance fluctuations of small area tunnel junctions to study the charge transfer kinetics of individual electron traps in the dielectric which forms the tunneling barrier. Here, we apply this new spectroscopic technique, telegraph noise spectroscopy (TNS), to study the individual electron traps in thin layers of amorphous Si (a-Si) and amorphous Si:H (a-Si:H).

The devices which we have studied are Nb/a-Si/Nb, Nb/a-Si:H/Nb, and Nb/a-Si/a-Si:H/a-Si/Nb tunnel junctions. All the barriers were deposited by rf sputtering in either 8 mTorr of pure Ar (for a-Si) or in 8 mTorr of Ar with 0.5 mTorr of H\(_2\) (for a-Si:H). Further details of device and barrier fabrication have been described elsewhere.4-6 The device cross-sectional areas were in the range \(35 \mu\text{m}^2 < A < 120 \mu\text{m}^2\). Nominal barrier thicknesses were 5.6 nm with a thickness ratio for the films of approximately 1:5:1. Our temperature range was \(2 \text{ K} < T < 300 \text{ K}\).

TNS is based on the fact that variations of localized charge configurations (e.g., trapping of electrons or rotation of dipoles) within the tunnel barrier material can distort the local shape of the energy barrier and thus cause the tunnel junction resistance \(R_j\) to change.7 For devices of sufficiently small area \((A < \sim 100 \mu\text{m}^2)\) the resistance change due to trapping of a single electronic charge is easily resolved with conventional low noise electronics. As single charges are captured and emitted by traps in the barrier, \(R_j\) changes in sudden, discrete jumps. This telegraph noise in \(R_j\) yields direct information about the single-trap charge transfer rates.

Figure 1 inset shows a time record of the resistance for a Nb/a-Si/Nb tunnel junction of \(A = 42 \mu\text{m}^2\) at \(T = 6.0 \text{ K}\) biased with a mean voltage of 17 mV. This trace shows resistance switching typical of what we find for all of our a-Si and a-Si:H layers. In this particular trace, only one active noise source is dominant causing the resistance to cleanly switch between two distinct levels.

Figure 1 shows the resistance power spectral density \(S_R(f)\) which results from averaging 1000 time traces such as in the inset. As shown, \(S_R(f)\) is largely given by a single Lorentzian contribution to the spectrum. We find that each active trap contributes one Lorentzian spectrum to the total spectrum \(S_R\). Machlup6 calculated the expected power spectrum for a single telegraph noise source with pulse height \(\delta R_j\) within a relaxation time approximation where the times between state transitions are exponentially distributed about the mean times \(\tau_1\) and \(\tau_2\). He found that \(S_R(\omega) = \text{then a Lorentzian, as observed, with the following properties:}\)

\[
S_R(\omega) = P_0 \left[ \tau_{\text{eff}} (1 + \omega^2 \tau_{\text{eff}}^2) \right],
\]

\[
P_0 = \delta R_j^2 \left[ \frac{\tau_{\text{eff}}}{\tau_1 + \tau_2} \right],
\]

\[
1/\tau_{\text{eff}} = 1/\tau_1 + 1/\tau_2.
\]

We find that these equations provide an excellent quantitative connection between the real time behavior and the measured \(S_R\).

Because of the simplicity of the kinetic equations, either the time record or \(S_R(f)\) can be used to measure the electron capture and emission rates. For cases where only one trap is active in our bandwidth the rates can be determined directly by compiling a histogram of the times between transitions. However, when several states are active in the same bandwidth, we find that the rates are most easily determined...
by measuring $S_R$, fitting the spectrum to a sum of several Lorentzian components, and using Eqs. (1b) and (1c) to determine $\tau_1$ and $\tau_2$ for each trap from the measured $\Delta R_1$, $\tau_{\text{eff}}$, and $P_0$ of the corresponding Lorentzian. Repeating the measurements at different temperatures and voltages gives information on the type of dynamics involved in charge transfer. Because of the relatively large areas of the devices we have studied, there are often several traps active at a given $T$ and $V$; we have primarily used the power spectrum approach.

Figure 2 shows the typical temperature dependence of $\tau_{\text{eff}}$ and $P_0$ for a Lorentzian associated with a single trap at $T > 20$ K. In this temperature range, $1/\tau_{\text{eff}}$ increases in a thermally activated manner. However, the total area under the Lorentzian, $P_0$, is a much more slowly varying function of $T$. Equations (1b) and (1c) suggest that this temperature dependence arises when both $1/\tau_1$ and $1/\tau_2$ are thermally activated, but in a manner which keeps their ratio nearly fixed. The solid lines in Fig. 2 show a fit to the data assuming Eqs. (1b) and (1c) with

$$1/\tau_1 = (1/\tau_{01})e^{-E_g/k_BT}.$$  

For the ensemble of individual noise sources we have studied in both a-Si and a-Si:H, we find $10^{-10} \lesssim \tau_{01} \lesssim 10^{-12}$ s with a median value near $10^{-11}$ s [$\langle \ln (\tau_{01}) \rangle = 10.95$, standard deviation = 0.54]; the activation energies $E_g$ are in the range $10 \text{ meV} < E_g < 120 \text{ meV}$. The limits on $E_g$ are largely determined by the observed $\tau_{01}$, the range of $T$ over which we can see individual switching events ($T < 100$ K) and our bandwidth; it is likely that activation energies outside the range above exist and would be observed for temperatures and frequencies outside our experimental range. For a given trap, the attempt frequencies for electron capture and emission usually differ by less than a factor of 3 and the activation energies are within 20% of each other.

A model has been described which yields thermally activated rates for both electron emission and capture for traps in amorphous Nb$_2$O$_5$; the same model can be applied to the particular traps we observe in a-Si. The main concept is that the thermally activated rates imply a shift of the energy position of the electronic state from one side of the electrochemical potential, $\mu$, to the other upon charging or discharging. Thus, while the trap is occupied, it is located below $\mu$; while it is empty, it is located above $\mu$. Several interactions exist which can cause major shifts in the state energy depending on occupation: Interactions between the trapped charge and the nearby ions lead to lattice distortions and consequence energy level shifts. The existence of a Stokes shift in photoluminescence spectra of a-Si$^{9}$ is direct evidence for lattice deformation effects. Similarly, Coulombic and exchange interactions with other electrons are also likely to play a role in shifting the state energy. Regardless of the particular mechanisms involved, our essential point is that the energy of the electronic trap state must shift with changes in electron occupation. Likewise, we emphasize the converse: Only trap states which significantly shift in energy upon change in occupation will be observed in the low-frequency noise.

An extremely simplified trapping model which explains the data described above assumes that a trap has two spatial ionic configurations with rather similar total energies, but which differ by having the energy of one particular localized-electron orbital shifted through the chemical potential. Such an energy shift could arise simply because of differences in the orbital bonding distance in the two configurations. Then, as the ions make thermally activated transitions between the configurations, the trap will charge or discharge; the emission and capture kinetics are then dominated by the reversible ionic configurational hopping and both rates will be thermally activated.

Metastable and bistable ionic configurations (i.e., those which differ in spatial configuration or in spatial configuration and in total charge) have been used to explain data in a variety of systems. Ionic reconstructions have often been invoked to explain the low-temperature thermal properties of bulk amorphous materials.$^{10,11}$ Recent results on photoconductivity of $p$-$i$-$n$ diodes formed from a-Si have also been interpreted by assuming localized states in the mobility gap which appear at two distinct energies depending on the type of radiation applied to the device.$^{12}$ Interpretation of deep level transient spectroscopy signals from the EL2 center in GaAs$^{13}$ as well as recent theoretical work$^{14}$ also implies that this defect is likely to be bistable. While the measured activation energies are considerably lower than those calculated for bistable systems in crystalline environments, we note that the amorphous nature of the Si barrier is expected to produce a range of local environments resulting in a variety of activation energies. Our measured activation energies are consistent with those assumed to explain low-temperature properties of bulk glassy systems.

We also find evidence that ionic motion is important in...
charge transfer for $T < 20$ K. In this lower temperature region, we find strong deviations from thermal activation in both $\tau_r$ and $\tau_a$. Figure 3 shows a typical $\tau_{\text{eff}}$ and $P_0$ vs $T$. The fact that $P_0$ is only weakly temperature dependent again shows that both the rates have the same basic $T$ dependence. However, that dependence is clearly not described by a thermal activation form below 20 K. The saturation of the rates at the lowest temperatures implies that some other means of configurational transition becomes important as thermal activation freezes out; it is very similar to the saturation observed for Nb$_2$O$_5$ barriers. However, the peak in $\tau_{\text{eff}}$ at $\sim 9$ K is a new effect which we do not find for Nb$_2$O$_5$. As yet we have no detailed explanation for it.

Previously, we attributed the deviation of the rates from thermal activation as an indication of transitions between ionic configurations via ionic tunneling or, equivalently, zero-point motion. This picture still seems to be a satisfactory explanation of the general properties shown in Fig. 3. The values of $E_a$ and $1/\tau_0$ for the traps, determined from the thermally activated region, along with Wentzel-Kramers-Brillouin tunneling rate estimates suggest that ionic tunneling should dominate below $\sim 10$ K. Furthermore, we observe that the low $T$ rates increase nearly exponentially with increasing voltage, consistent with an ionic tunneling argument.

Another important observation is that we see no statistically significant difference between the number of noise sources in a-Si barriers and the number in a-Si:H barriers. This observation implies that the number of bistable traps is essentially independent of hydrogen concentration, $C_H$. Thus, the number of bistable trap states does not appear to be correlated with the number of singly occupied dangling bond states which are generally believed to be responsible for the majority of traps in a-Si.

A similar observation has been made for the nuclear magnetic resonance energy relaxation rate $1/T_1$ of protons in thick glow discharge deposited a-Si:H layers at low $T$. $1/T_1$ in this material has been shown to be dominated by interactions with bulk two level tunneling systems (TLS). It was also shown that, although the paramagnetic electron signal is strongly dependent on $C_H$, the proton $1/T_1$ is not, implying that the number of TLS is independent of $C_H$. Thus, we have an indication that the observed bistable traps in our thin a-Si and a-Si:H tunnel barriers are directly correlated with the TLS found in bulk a-Si:H which again indicates the importance of ionic motion as a basic property of these particular traps. Gibson and Meservey also have inferred the existence of TLS in very thin films of thermally deposited a-Si. Thus, the existence of TLS may well be a property of a-Si, largely independent of the method of preparation.

Finally, we note that bistable trap states involving ionic reconfiguration have now been identified in two distinct systems (Nb$_2$O$_5$ and a-Si) by telegraph noise spectroscopy. Similar results are now being obtained with SiO$_2$ layers. Thus, it is becoming apparent that bistable trap states are rather ubiquitous, and constitute the dominant source of 1/f noise in many electronic systems.

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FIG. 3. Typical $\ln(\tau_{\text{eff}})$ and $\ln(P_0/R_0^2)$ vs $1/T$ for $T < \sim 20$ K showing the low $T$ deviation of the rates from thermally activated behavior.