Localized-State Interactions in Metal-Oxide-Semiconductor Tunnel Diodes

K. R. Farmer, C. T. Rogers,[a] and R. A. Buhrman
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853
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We report on the study of large two-level, low-frequency resistance fluctuations in 1-μm^2 metal-oxide-silicon tunnel diodes, which are due to the strongly correlated emptying and filling of ensembles or clusters of interacting localized states in the oxide. The interaction mechanism is attributed to ionic forces in the strained oxide. It can give rise to complex structure in the switching noise and, under strong electrical stress, can result in the breaking of oxide bonds by the collective action of localized states.

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There have been a number of observations[1-8] of two-level fluctuations (TLF's) in small-area electronic devices, chiefly tunnel junctions and metal-oxide-semiconductor field-effect transistors (MOSFET's). Because of the discrete nature of the phenomena and, in some instances, because the observed resistance fluctuation is of the appropriate amplitude, this telegraph noise has been generally attributed to the trapping and escape of a single electron, either in the tunnel barrier or in the oxide layer adjacent to the active channel of the MOSFET. While interactions between the noise sources were noted in a previous study[1] of metal-insulator-metal tunnel junctions, the general assumption has been that in devices with more than a few active TLF's, the traps act essentially independently.

Here we report on an extensive study of two-level noise sources arising from slowly fluctuating electron trap states in small-area MOS tunnel junctions. We have found that these states do not fluctuate independently; rather, there are quite strong trap interactions. As one result, trap states sometimes empty and fill in synchronization, giving rise to very large amplitude two-level switching. In addition, under high electrical stress, the sudden change of occupancy of a group of trap states can also initiate a complex collective switching process which terminates in the irreversible breaking of oxide bonds and the creation of new localized states in the SiO_2. This last effect represents the first observation of a new, collective mechanism that can be responsible for the onset of electrical breakdown in insulating films.

The devices that have been examined in this study consist of 1-μm^2 Al-SiO_2–p-type Si diodes formed in windows etched through a thick field oxide. The tunnel oxide was grown by a rapid thermal oxidation process,[9] which for the devices discussed here resulted in an approximate oxide thickness of 1.6–2.0 nm as determined by ellipsometry and tunnel conductance measurements. An I-V characteristic of one such MOS tunnel diode taken at 77 K is shown in Fig. 1. This characteristic is in good accord with that expected for a nonequilibrium minority carrier tunnel diode.[10] At low bias voltages, < 1.0 V, the diode characteristic is equivalent to that of an abrupt n-p diode, with the silicon bands in inversion at the Si-SiO_2 interface. At higher bias the surface of the silicon moves from inversion, going to heavy accumulation at 1.2 V. Above this point essentially all the applied voltage is across the oxide barrier. For an ideal diode with no interface states the transition from inversion to heavy accumulation should be accompanied by

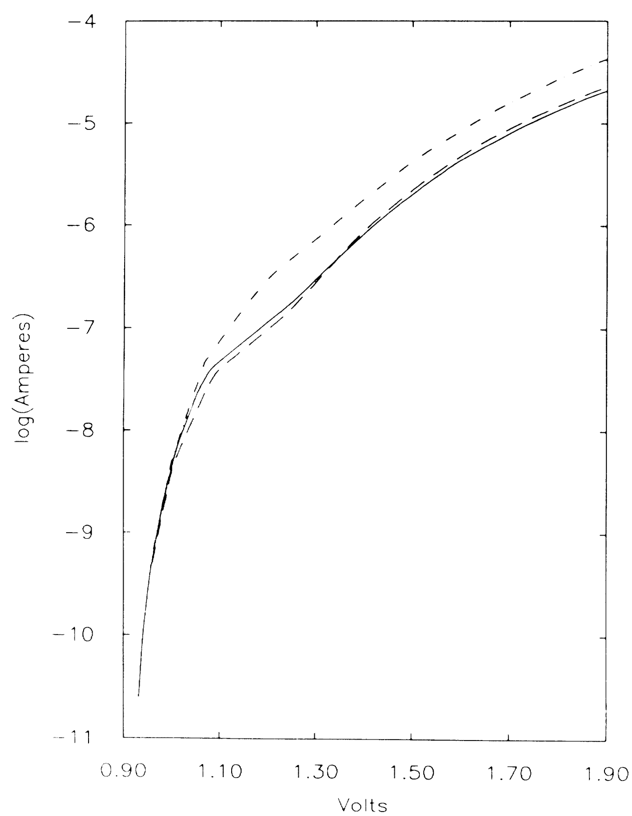

FIG. 1. The I-V characteristic of a 1-μm^2Al-SiO_2–pSi tunnel diode, taken at 77 K. The average oxide thickness is approximately 1.6 nm. The solid line is the I-V taken before electrical stressing, the dashed line is after ten "breakdown" events (see Fig. 4) and the dot-dashed line is after a large number of such events.

only a small increase in diode current, but depopulation of any interface states increases the diode conductance in this region. From measurements of room-temperature I-V characteristics we estimate that these diodes have interface state densities of the order of 10^{12} eV^{-1} cm^{-2}.

A time record of the resistance R of one such device is shown in Fig. 2(a). The low-frequency behavior of R is dominated by abrupt transitions between two distinct levels. This is the simplest type of behavior that is observed. Depending on the particular bias point and temperature chosen, a given diode exhibits none, or one, or more than one of these low-frequency TLF's. An example in which there are two, apparently independent TLF's active at the same time is shown in Fig. 2(b). The change in tunnel resistance that occurs during these fluctuations ranges from less than 0.1% to greater than 10%. These latter values are surprisingly large for a 1-μm^2 device. The R increase that would be expected to occur for the capture of a single electron in an otherwise uniform

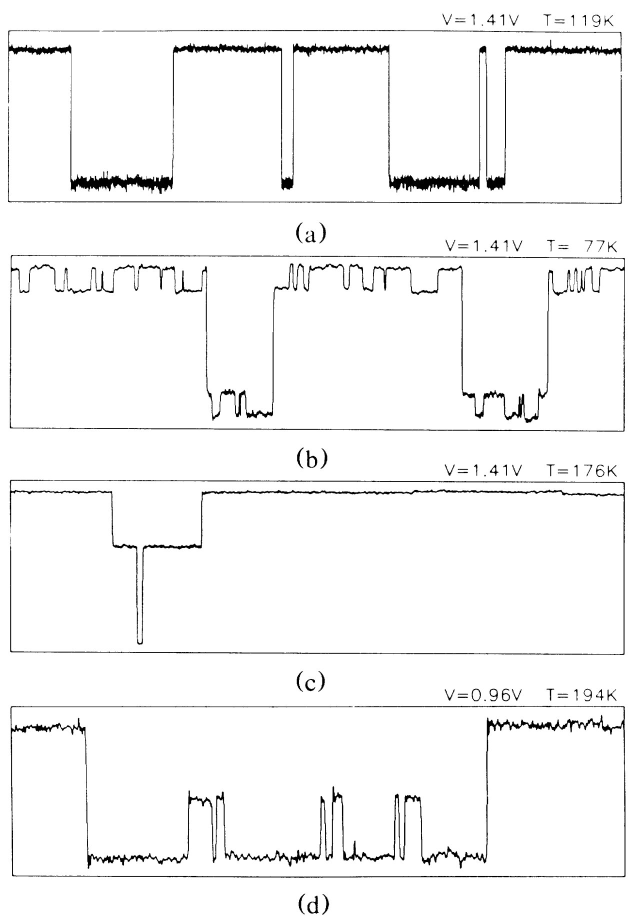

FIG. 2. Time records of MOS tunnel-diode resistances showing some of the different types of discrete, low-frequency fluctuations that have been observed at moderate bias. (a) Clean TLF. (b) Two independent TLF's. (c) Three-level "attractive" fluctuation. (d) Three-level "repulsive" fluctuations.

SiO_2 tunnel barrier is of the order of 0.01% for a 1-μm^2 diode.[11,12] (We note that very large TLF's have also been recently reported[8,13] in Al_2O_3 and AlGaAs tunnel barriers.)

The statistics of the TLF's can be examined by measurements of the probability of transition from one level to the other. As usual the lifetime of each state is found to be exponentially distributed, with the mean lifetimes invariably changing with T as expected for both thermally activated electron capture and electron emission:

$$\omega_{\text{em,cap}} = \omega_{0\,\text{em,cap}} \exp(E_{a\,\text{em,cap}}/kT).$$

We have measured a very wide range of activation energies and attempt rates, with E_a varying from 7 to 450 meV and $\omega_{0,i}$ from 10^2 to 10^{12} sec^{-1}.

The simplest interpretation of these TLF's is that an independent defect in the barrier, whose behavior can be described in terms of a single generalized coordinate Q, fluctuates about an equilibrium position. If a fluctuation is of a sufficient amplitude Q_c it can bring, for example, an occupied localized electron energy level near the Fermi level of one of the two electrodes, at which point a transition can occur through electron tunneling to the electrode. As a result of this event, the defect relaxes to a new equilibrium position Q_0 for which the associated unoccupied electron energy level lies well above the electrode Fermi level and from which it eventually makes the reverse transition. E_a is then the amount of energy that the Q fluctuation must have to bring either the occupied or unoccupied electron level to the point where electron tunneling is favorable, while the attempt rates are set either by the vibrational frequency of the trap state or by the electron-tunneling rate, whichever is the lower. Previous results[1,6] have been consistent with this model. But here the smaller values of $\omega_{0,i}$ are many orders of magnitude too low to be the rate for electron tunneling completely through a 1.5- to 2.0-nm SiO_2 barrier. This could be a result of barrier inhomogeneity with the lower attempt rates being associated with tunneling to and from traps in a much thicker than average part of the oxide. But a change of occupancy of such traps would have little effect on the overall junction resistance and thus could not cause the large ΔR that is observed. Indeed, we have seen no correlation between the size of a TLF and its attempt rates. We conclude that electron tunneling cannot always be the rate-limiting step in the capture and emission process.

While the behavior illustrated in Figs. 2(a) and 2(b) is most common, we have often observed different types of switching. Two examples are shown in Figs. 2(c) and 2(d). Here the switching is between three well-defined levels, not two or four. There are a number of possible explanations for this behavior. One, which is consistent with all the observations, is that an ionic, strain-related interaction occurs between, presumably, nearby defect states such that the occupancy of one trap, or one group of traps, strongly affects the probability of electron capture or emission by another trap or group of traps. Since the ionic reconfiguration that accompanies the capture or emission of an electron at a slow trap site will cause a localized strain in the tunnel barrier, such an interaction is plausible. The behavior in Figs. 2(c) and 2(d) is then described as the tuning on or off of fluctuations of one TLF by another. The proposed strain interaction also allows both the attractive effect illustrated in Fig. 2(c) where the filling of one state permits the filling of the other state, and the repulsive effect shown in Fig. 2(d) where the emptying of one state permits the filling of the other. If this strain interaction model is adopted, then we must also conclude that the interaction energy can be relatively high. For example, in Fig. 2(d) not one of the small transitions was observed over a two-hour period when the large fluctuator was in its up state. If we simply assume that only the activation energy is affected by this interaction then this corresponds to at least a 0.3-eV shift in $E_{a,\mathrm{em}}$ for the small TLF.

This trap-trap interaction model is supported by the behavior of some of the large amplitude TLF's as a function of temperature T. An example is shown in Fig. 3. At the lowest T we see that R is characterized by very sharp two-level switching. As T increases R begins to make transitions to intermediate values between the two extrema. At still higher T, R switches randomly between a number of distinct levels, but with the extrema still being present. The obvious conclusion is that the low-temperature TLF is caused by ensembles of strongly interacting traps emptying and filling simultaneously, within the time scale of the measurement. The effect of increasing T is to weaken the interactions so that some traps can change their charge while others do not. Since the amplitude of the intermediate resistance steps is still quite large compared to that calculated for single-electron capture and emission, it appears that even these intermediate steps are due to the collective action of more strongly interacting subensembles of traps.

If the large TLF's are due to the collective fluctuations of trap states we then have a straightforward explanation for the low values of $\omega_{0,i}$. The attempt rate for such a fluctuation would be set not by an electron-tunneling time nor by the vibrational frequency of a single ion, but by either the net fluctuation rate of the strongly interacting ensemble of traps or by the probability of the simultaneous tunneling of all the electrons into and out of the traps whenever a sufficiently large fluctuation is made.

Final evidence for strong and complex localized-state interaction effects is found by biasing the tunnel diodes at high electrical fields (and currents). An example of what is observed under such conditions is given in Fig. 4, which shows R versus time taken at 77 K for a diode biased at 2.99 V (E_{bias}=18 MV/cm). Typically R is very stable for long periods of time, but at random intervals it makes an abrupt transition to a lower level

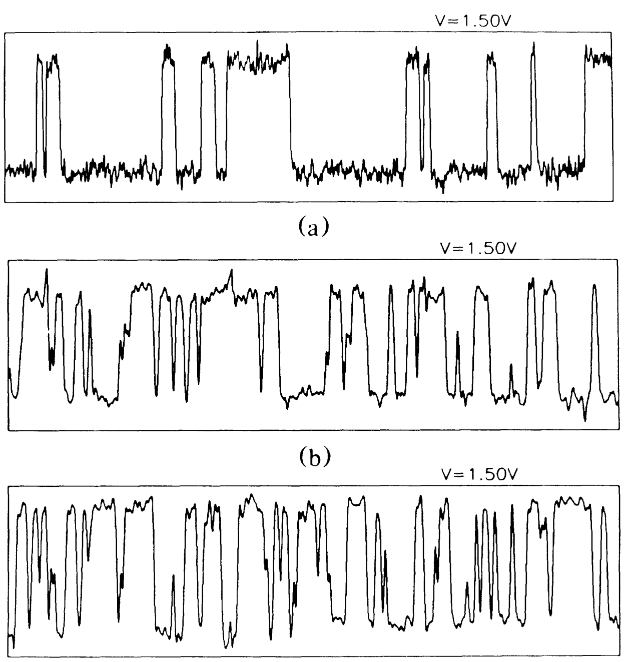

FIG. 3. R vs time for a large TLF taken at three different temperatures. (a) At T=77 K, R switches sharply between two very well defined levels. (b) At T=174 K, R pauses at a few well defined intermediate values. (c) At T=226 K, R switches between still more levels.

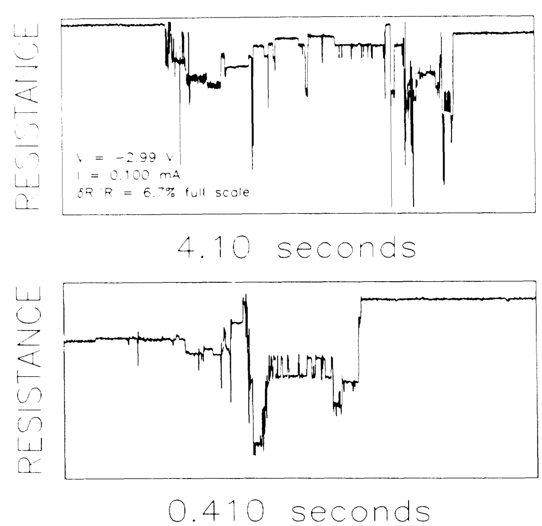

FIG. 4. R vs time for a MOS diode based at high voltage (V=2.99 V, E_{bias}=18 MV/cm). The upper half shows the record of a single breakdown event. The resistance after the event is noticeably lower than before. The lower half, an expanded portion of the complete time trace, shows that the switching is discrete and quasistationary for brief periods of time.

($\Delta R/R > 1\%$) which marks the beginning of a very complex switching phenomenon that eventually terminates in a permanently lower, but again low noise, resistance level. As can be seen in the figure, these "breakdown" events still involve clear switching between discrete levels. But now these levels, and the switching rates, rather than remaining constant, keep changing with time. At still higher bias, the time between these breakdown events decreases until they occur continuously. At this point the discrete switching is still clearly resolvable.

The *I-V* of a diode at 77 K taken before and after it has undergone ten such breakdown events is shown in Fig. 1. On the scale of the figure the main effect is to slightly decrease the diode conductance in the 1.0- and 1.2-V portion of the *I-V*. Such a decrease is consistent with the creation of donor states at the Si-SiO_2 interface. If these newly created states are distributed fairly uniformly over the interface, this corresponds to the creation of $\sim 10^3$ additional interface states. The *I-V* characteristic taken after a very large number of these breakdown events is also shown in Fig. 1. Now the conductance has increased very significantly for all bias voltages above 1.0 V. This increase is consistent with the creation of a large density ($> 10^{13}\ \mathrm{eV}^{-1}\ \mathrm{cm}^{-2}$) of positive states in the oxide barrier.

Several studies[14,15] have shown that strong electrical stress can cause the creation of interface states and positive oxide states in SiO_2 layers, a process that eventually results in the abrupt electrical breakdown of thicker oxide layers. Our interpretation of the results shown in Fig. 1 is consistent with this work. The essential new result is that the mechanism for the formation of these states has as its basis a sudden, collective change in the occupancy of a group of traps, presumably induced by the strong electrical stress. This collective event sets up a strong strain in the oxide, which in turn causes an unstable situation in which ensembles of trap states empty and fill abruptly as a configuration is sought which will minimize the overall energy of the system. Eventually such a stable configuration is reached, apparently by the breaking of additional oxide bonds which serves to reduce the local strain and relax the system. The crucial point is that here the energy necessary to break a bond is provided not by a single electron process, but by the collective action of groups of trap states.

In summary, we have found that two-level resistance fluctuations can be due to correlated, *multielectron* capture and emission in a strongly interacting cluster of localized trap states. The interactions can result in quite complex low-frequency noise behavior. This points to an explanation of some of the diverse noise behavior found in many electronic systems. At high electrical stress we find that the correlated switching of ensembles of trap states can result in the breaking of oxide bonds and the creation of positive oxide and silicon interface states.

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[a]Present address: Bell Communications Research, Red Bank, NJ 07701.

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