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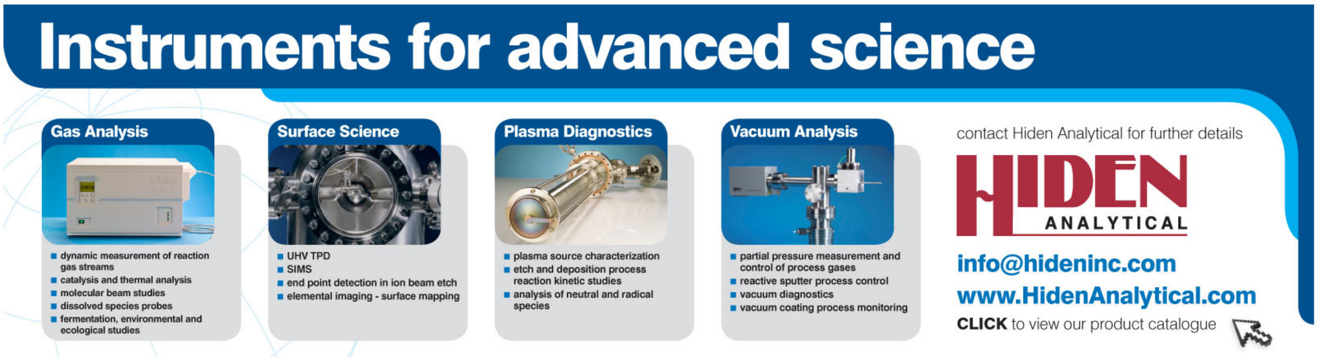

Nondestructive multiple breakdown events in very thin SiO_2 films

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Several breakdown events and multilevel current fluctuations have been observed when ultrathin SiO_2 films are subjected to constant-voltage stresses. These breakdown events are sometimes reversible, and consist in a local change of conduction mechanism. This reversibility shows that no catastrophic thermal effects occur, and that the breakdown is only a local switching between two oxide conduction states of very different conductivities.

The idea that the dielectric breakdown of thin SiO_2 films is a two-step phenomenon is receiving much support.[1–5] High-field electron injection degrades the SiO_2 network generating neutral electron traps[2,4,6] until a threshold degradation is locally reached and a new conduction mechanism is triggered.[2,4,5] This new conduction mechanism is thought to cause an important enhancement of the local current density that during a very fast thermal runaway opens a low-resistance ohmic path between the electrodes.[7–9] The physics of the degradation process can be studied using standard electrical characterization techniques; but since the breakdown is locally triggered in a very small spot,[7,10] the study of the final conduction mechanism requires alternative experimental methods. There are two ways to undertake the study of the physics of the breakdown conduction mechanism: to enhance the relative importance of the conduction of the degraded zones before the catastrophic breakdown (as is being done by means of ultralow noise amplifiers[8,11]), or to get information from the current-voltage (I-V) characteristic after the breakdown event in spite of the probable thermal effects. In ultrathin oxides the energy density dissipated by electron-phonon collisions is lower than in thicker films because the electrons run away from the optical modes, but do not gain enough energy to be thermalized by the acoustic modes of high momentum and low energy.[12] Hence, thermal effects which would hide the signature of the breakdown mechanism in the after-breakdown I-V characteristic might not be present in the breakdown process of films in the 50–70 Å range.

Two-level resistance fluctuations have been observed as low-frequency noise previously to the breakdown of ultrathin oxides.[8,11] This is an indication of the existence of two oxide conduction states of different conductivities. In the literature the highly conductive state has been attributed to either thermally assisted Fowler–Nordheim tunneling through locally reduced injection barriers (0.9 eV),[13] or to resonant tunneling via traps.[9]

All the experiments have been performed on 9×10^{-4} cm^2 square Cr-SiO_2-Si(p) capacitors fabricated on a lightly doped epitaxial p-Si layer (5 Ω cm) of 10 μm which was grown on a degenerated p substrate. The oxide thickness has been determined to be about 55 Å from the capacitance-voltage characteristic. All the measurements have been performed by means of a HP-4145B semiconductor parameter analyzer.

Stepped voltage measurements have been carried out to obtain the I-V characteristic both before and after the breakdown event, which is recorded as a sudden increase in the current, as shown in Fig. 1. In this figure, the pre-breakdown (including the breakdown event) and the after-breakdown characteristics of a typical device are depicted. No conduction is observed with the gate positively polarized either before or after the breakdown event because of the low doping level of the epitaxial layer. This rectifying behavior after the breakdown indicates that the oxide integrity is partially preserved even at the breakdown spot. No ohmic path has been opened between the electrodes, but only smaller changes occurred in the oxide when it suddenly broke up at approximately 19 MV/cm. Also note that a true switching behavior is observed at the breakdown point. In other words, the breakdown event is only a local change of conduction mechanism. The after-breakdown I-V characteristic has been shown to be stable by repeating the measurement procedure between 0 and − 7 V several times and obtaining always the same curve. The after-breakdown conduction is not Fowler–Nordheim tunneling as it is in the pre-breakdown high-field regime and even in the weak spots that appear before the breakdown event.[13]

If a metal-oxide-semiconductor structure is subjected to constant high-voltage stress after the breakdown event, the

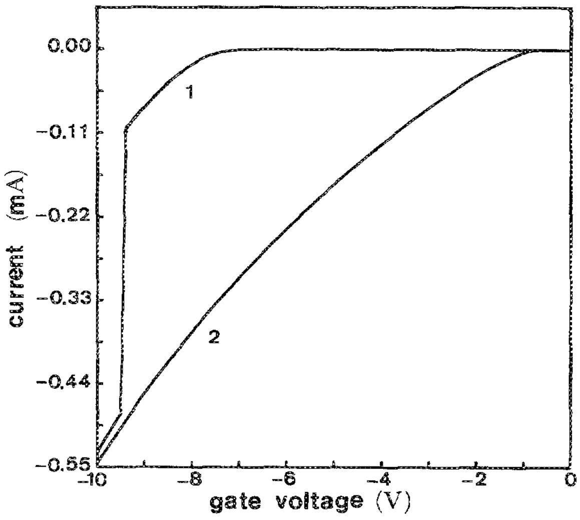

FIG. 1. Current-voltage characteristics before and after the first breakdown event of a typical device. (1) pre-breakdown (including the breakdown event); (2) immediately after the breakdown event.

after-breakdown *I-V* characteristic changes as shown in Fig. 2. Note that when increasing the time of stress, the curve suffers a parallel translation toward higher currents. This behavior indicates that, as found by Olivo *et al.* in the case of the leakage current before the catastrophic breakdown,[13] the highly conductive region increases in area rather than vertically (additional highly conductive regions appear and increase the total "broken" area). In Fig. 3 the evolution of the current under constant voltage stress is depicted. Note that the current changes by steps of almost the same magnitude (~ 0.5 mA in the figures) and that different conduction levels are clearly defined. The existence of these conduction levels, together with the evolution of the *I-V* characteristic presented in Fig. 2, indicates that several breakdown events are observed and that these events correspond to changes of conduction mechanism in different local areas. Together with the degrading steps that cause the total current to increase, backward steps are also observed. This is an indication that the change of conduction mechanism can take place in the reverse direction. A particular case is in which all the breakdown events (three events during a 1000 s stress at 14 MV/cm) are reversible. These "antibreakdown" events are not compatible with irreversible thermal effects. What we have obtained is similar to the pre-breakdown multilevel current fluctuations, but now one step represents a change of several orders of magnitude in the local current density, while before the breakdown the changes could only be detected as noise. Many breakdown events (10^2–10^3) have been registered in only one sample, and the rate of occurrence of these events does not decrease with the stress time, at least during the more than 10 h of stressing at -7 V that were needed to reach the 100 mA compliance current limit of the measuring apparatus. This indicates that the area of the breakdown spots is only a very small fraction of the total capacitor area. A rough estimation has been performed on the basis of an analysis of the breakdown statistics, and an area of 10^{-12} cm^2 seems reasonable in agreement with the estimation made by Olivo *et al.*[13] If the structure is subjected to constant-current stress, only one breakdown event is usually observed. After the occurrence of this event, the applied voltage has to be reduced to extremely low levels (i.e., 2 MV/cm) so that the degradation of the capacitor almost stops.

An accurate analysis of the after-breakdown conduction is out of the scope of this letter, but trap-assisted resonant tunneling[9,14,15] is a plausible hypothesis. This mechanism would explain the fundamental role of the injecting interface in the breakdown,[16] the observed after-breakdown fluctuations, and the coupling of these fluctuations (see Fig. 4) since several resonances can be coupled by Coulombic interactions. This mechanism would also be compatible with previous models based on the generation of neutral trapping

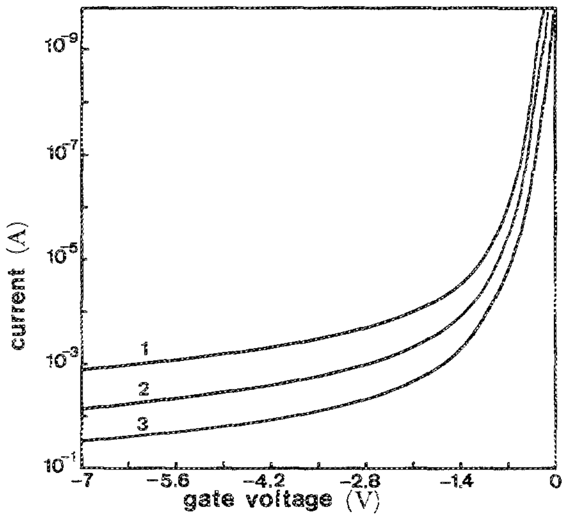

FIG. 2. Evolution of the after-breakdown *I-V* characteristic with the time of constant-voltage stress (-7 V) (1) Just after the first breakdown event; (2) after 20 min of stress; (3) after 6 h of stress.

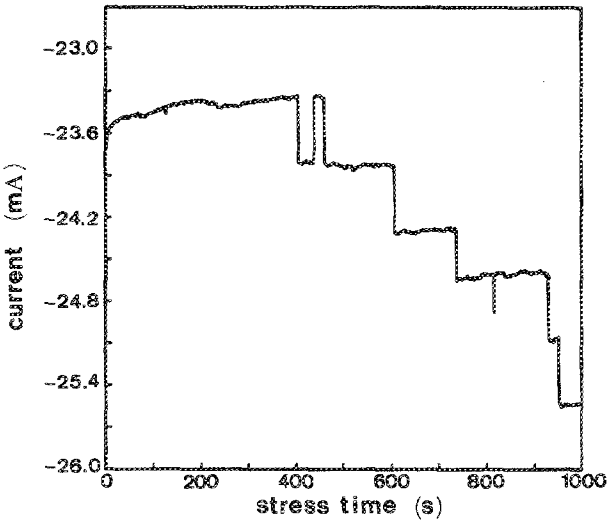

FIG. 3. Evolution of the current of a typical device subjected to constant voltage stress (-7 V) during 1000 s. The high conduction level indicates that several breakdown events occurred before the beginning of this test (during previous stresses).

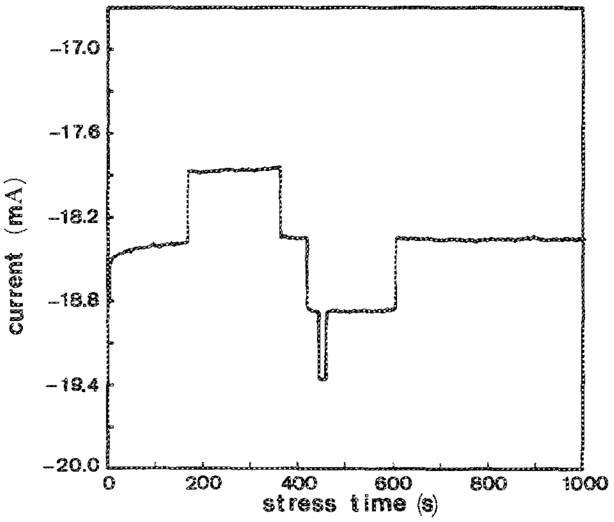

FIG. 4. Evolution of the current under constant bias in one particular case in which the same current level is reached after three breakdown events and three "anti-breakdown" events. Irreversible thermal effects are not responsible for the breakdown. Again, as in Fig. 3, several breakdown events had been registered during previous stresses, and this is the cause for the high initial current level.

sites,[2,4,5] and would explain the reversibility of the breakdown events, which is the most striking feature of the presented results.

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