Breakdown Transients in Ultrathin Gate Oxides: Transition in the Degradation Rate

S. Lombardo,[1] J. H. Stathis,[2] and B. P. Linder[2]

[1]*Consiglio Nazionale delle Ricerche (CNR)–Istituto per la Microelettronica e Microsistemi (IMM), Sezione di Catania, Stradale Primosole, 50, 95121 Catania, Italy*

[2]*IBM Research Division, P.O. Box 218, Yorktown Heights, New York 10598, USA*

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We report a sharp threshold at 4 V in the growth rate of breakdown spots in thin films of SiO_2 on silicon. This provides some of the first information concerning the electronic structure of the breakdown spot.

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The evolution of complementary metal-oxide-semiconductor (CMOS) devices in Si integrated circuits (IC) has been driven so far by an aggressive device scaling associated with a slower decrease of the supply voltages. This has resulted in an increase of the electric fields applied to the structures, with numerous positive consequences but some drawbacks. Among the negative effects, an important issue is the continuous increase of the tunneling current flowing across the gate oxides under circuit operation. It has been shown that this current is the main origin of the degradation leading to the dielectric breakdown (BD) of the gate dielectric [1], nowadays an ultrathin SiO_2 layer of 1–2 nm of thickness and with a large component of Si nitride at the Si/SiO_2 interface. The increase of tunnel current through the gate dielectric has now reached levels so large that the BD of ultrathin gate oxides has become a major problem, among the issues to be understood in detail to allow further CMOS evolution. Concerning its causes, it is widely recognized that the oxide degradation is due to the buildup, promoted by the transport of carriers through the dielectric, of the concentration of electronic defects in the oxide bulk. This occurs up to a critical defect density correspondent to the threshold for establishing in the whole sample a single percolation path through the oxide joining substrate and gate [1]. The trigger for the final BD event is the completion with the last defect of the percolation path. Then, the BD buildup transient starts, with the gate current showing a continuous and relatively slow increase [2], whose speed has a strong voltage dependence [3]. On the contrary, in the case of relatively high stress voltages the transient appears extremely fast, much below $\approx 1\ \mu s$ in duration. In this case the measured peak power dissipated during the transient is relatively large, from ≈ 5 W on 35 nm oxides down to ≈ 5 mW on 3 nm oxides [4]. Moreover, from three-dimensional heat flow simulations tuned to experimental data, it is estimated that below $\approx$ 1 mW the BD cannot produce complete melting with the formation of a conductive filament continuous through the oxide (hard BD), since the power dissipated in the vicinity of the BD spot can be transferred to the environment at a speed large enough to maintain the temperature below melting [5]. Other estimates for the power threshold, based on the behavior of the post-BD conductance of the BD spot, are, however, much lower. In particular, it has been experimentally observed that as the stress voltage is decreased the post-BD conductance shows a transition from high (hard BD) to low values (soft BD). From this transition a power threshold is estimated, and it results in values from ≈ 10 to ≈ 100 times lower compared to those coming from the heat flow simulation [6,7]. Such extremely large deviation poses the question on the real nature of the transition from hard to soft BD. This is a particularly important issue, not only for the practical implications concerning the real reliability of CMOS circuits in Si ICs, but also for the basic understanding of the BD phenomenon. In particular, the question is what causes the transition from hard BD, i.e., intense and very fast Joule heating of a small volume, to soft BD, or much lighter damage resulting in much lower post-BD conduction.

In order to clarify the physics ruling the degradation of the BD spot, it is therefore particularly interesting to investigate the behavior of the BD transients of ultrathin oxides in the regime from high to intermediate stress voltages. We have studied the behavior of the BD transient from 3.6 to 4.7 V, and in this paper we show evidence of a transition which is driven by the voltage, rather than by the power.

The samples used for the experiments are *n*-channel MOS field effect transistors (nMOSFETs) with oxides of 2.25, 1.55, or 1.50 nm of thickness, with a channel width of 20 μm and channel lengths of 0.4 and 0.3 μm. We have performed constant voltage stresses at room temperature and as a function of temperature up to 140 °C, in inversion, with gate at high voltage and with source, drain, and body all short circuited at ground potential or at low voltage. To monitor the BD transient three different measurement configurations have been used. The first employs a current preamplifier and a digital oscilloscope to bias the sample and to record the amplified current trace, respectively. This permits sensing the BD current without using a resistance in series with the sample, and it allows a time resolution of the order of a few

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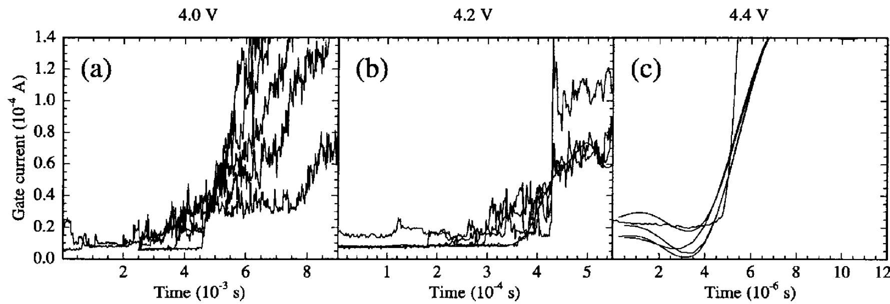

FIG. 1. Examples of BD transients on FETs with 1.55 nm oxides and channel lengths of 0.4 μm, during stresses at 4.0 V (a), 4.2 V (b), and 4.4 V (c). Five transients, measured by using a current preamplifier, are reported in each figure. Note the change of the time scale among the various figures.

microseconds. The second way [4] allows a time resolution of a few nanoseconds, though with the drawback of using a 100 Ω resistor in series with the sample. The third configuration is based on a semiconductor parameter analyzer (HP4156B) providing no series resistance but a limited time resolution, of a few milliseconds.

Figure 1 reports BD transients on MOSFETs with 1.55 nm oxides, and channel lengths of 0.4 μm, during stresses at 4.0 V 1(a), 4.2 V 1(b), and 4.4 V 1(c), measured by using the current preamplifier. Only the final BD phase is reported. The time origin has been arbitrarily chosen in order to align all the transients at a fixed current level. In some cases at $t = 0$ the current is the one due to tunnel through the oxide before BD (very close to the current measured in the fresh oxide); in others it is much higher since before the final BD event a pre-BD phase with higher current is observed. In all cases there is evident a final phase in which the current, though generally very noisy, increases with time. Though under the same stress voltage conditions the BD transient duration shows fluctuations, an overall decrease of the BD transient duration is observed as the voltage increases. Note, in particular, the change in the time scale on going from 4.2 V [Fig. 1(b)] to 4.4 V [Fig. 1(c)]. In the latter case the apparent BD duration reaches times of the order of 1 μs, i.e., below the time resolution allowed by the bandwidth of the current preamplifier. The transition to a very fast BD transient is evident in Fig. 2, where we report the average increase of BD current (dI_{BD}/dt) as a function of stress voltage. The dI_{BD}/dt values are estimated by linear best fit to data, for BD currents in the range between $\approx$ 10 μA and $\approx$ 100 μA. It is evident that in the range $\approx$ 4.1–4.2 V the dI_{BD}/dt values have almost a discontinuity below which the rates drop down dramatically. We now discuss main features of the transients in these two regions and show evidence concerning the nature of the discontinuity.

At low voltage dI_{BD}/dt shows two main features: first, it has a strong dependence on voltage, with a slope of about 3 decades/V, estimated by linear best fit to the data (Fig. 2). This observation fits nicely with other reports showing a progressive BD effect taking place at lower stress voltages [2,3]. The second characteristic of dI_{BD}/dt in the low voltage region of Fig. 2 is a small dependence on temperature (not reported here).

At high stress voltage the BD rates are indeed much larger than the values reported in Fig. 2, which are measured with a time resolution limited to about 1 μs. By using high time resolution, we observe transient durations of a few ns (Fig. 3). Even in this case the transient duration is close to the time resolution of the system, but, in any case, the data of Fig. 3 demonstrate that at stress voltages of $\approx$ 4.5 V the dI_{BD}/dt values are indeed much larger than those reported in Fig. 2, at least 10^5 A/s. It is worth noting that, with the same set of samples and measurement configuration, the BD transient durations increase by about 5–6 orders of magnitude by decreasing the stress voltage down to 4.0 V.

We now discuss the transition in the BD duration. The explanation in terms of a power threshold appears difficult. In fact, by taking as examples the data of Fig. 1(a) (stress at 4 V), the power dissipated through the BD spot

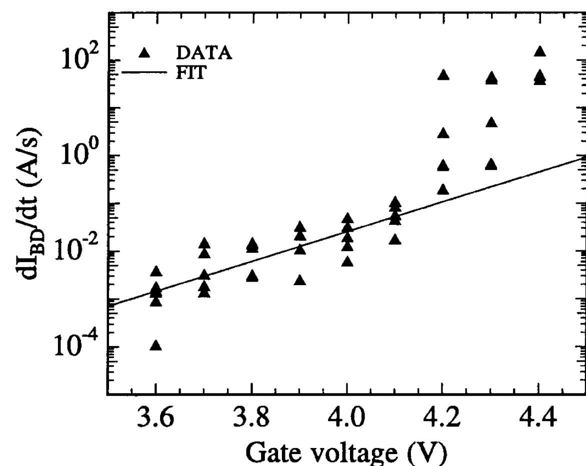

FIG. 2. Rate for the BD current increase, dI_{BD}/dt, as a function of the stress voltage measured in 1.55 nm oxides by using a current preamplifier.

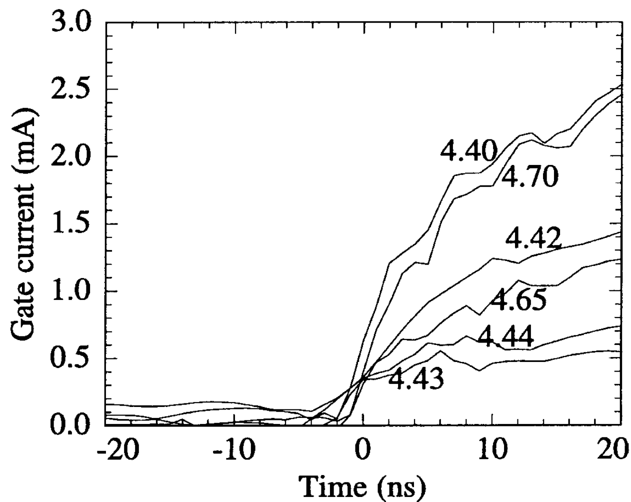

FIG. 3. Transient durations measured with high time resolution under stress voltages of ≈ 4.5 V. Through the larger bandwidth, the dI_{BD}/dt values are much larger than those reported in Fig. 2, and, in particular, equal to or larger than 10^5 A/s.

during the transient can vary as much as by a factor of about 10 (from $\approx 4 \times 10^{-5}$ W to $\approx 5 \times 10^{-4}$ W, but, nevertheless, the transients are relatively slow with no transition to a fast BD. On the contrary, at 4.4 V [Fig. 1(c)], though the power varies in the same range, the transients are much faster. So the transition in the BD mode is likely to be due to other parameters: good candidates appear to be the electric field or the voltage applied to the oxide. To distinguish among these two possibilities we have performed measurements on oxides of different thickness in the same voltage range. Figure 4 reports the BD transients measured at 4.1, 4.3, and 4.5 V in 2.25 nm oxides [4(a)–4(c)] and in 1.50 nm oxides [4(d)–4(f)], respectively. From such data it is evident that for the two thicknesses the transition to the fast BD mode occurs at the same voltage (between 4.1 and 4.5 V). This indicates that the transition among fast and slow BD transients is driven by the stress voltage rather than by the field. The threshold appears around 4 V.

A reasonable explanation for the threshold is a microscopic mechanism involving the electrons emitted by the cathode, in this case the inversion layer. When these carriers have enough energy ($>$ 4 eV), they are able to trigger the generation of some atomic motion in the BD spot forming in the oxide. It is important to point out that the charge or time to BD does not show any discontinuity at 4 V; i.e., the defect buildup leading to BD does not exhibit the same threshold energy. Below 4 V, both the initial generation of defects leading to BD and the degradation rate after BD have similar voltage dependence, suggesting that both processes have the same origin related to the generation of defects by energetic carriers impinging on the anode [3]. Thus, the observed threshold in the BD transient around 4 V cannot be related to the same process which leads to the initial defect generation, but must be related to some aspect of the newly formed BD spot itself. Indeed, in correspondence with an energy threshold of about 4 eV the Si-SiO_2 system shows a number of transitions. Internal photoemission experiments show an edge at this energy, identified as the electronic transition from the Si valence band edge

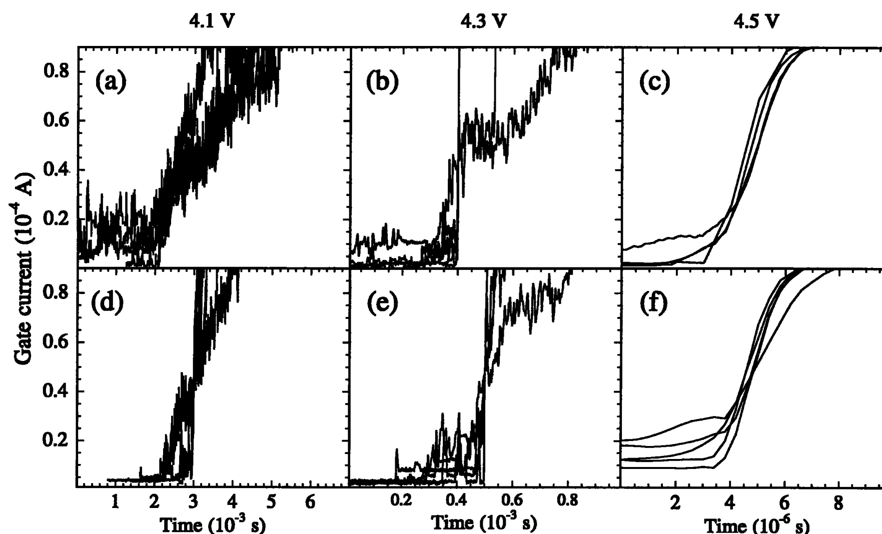

FIG. 4. Top figures: BD transients measured on FETs with 2.25 nm oxides during stresses at 4.1 V (a), 4.3 V (b), and 4.5 V (c). Five transients are reported in each figure. Bottom figures: same as top but in FETs with 1.50 nm oxides during stresses at 4.1 V (d), 4.3 V (e), and 4.5 V (f). By comparing top and bottom figures, though the oxide thicknesses are different, note that the transition to the mode with a fast BD transient takes place at about the same voltage.

(Si VBE) to the SiO_2 conduction band edge (SiO_2 CBE) [8]. This implies that under our experimental conditions (voltage drop of about 4 V across the oxide) we are in a transition region where the tunneling of electrons from the Si VBE to the SiO_2 CBE passes from the direct to the Fowler-Nordheim regime. The latter compared to the former implies a much stronger dependence of the current on the voltage which may be related to the observed threshold. Another possible candidate may be connected to the photoluminescence band observed in SiO_2 at about 4.3 eV, attributed to the oxygen vacancy [9]. The relationship with the present finding appears, however, problematic since this transition requires from 5 to 7.6 eV to be excited. In oxidized porous Si, however, a sharp edge at about 4.3 eV has been found by photoluminescence excitation spectroscopy [10]. This was attributed to the absorption of defects at the Si-SiO_2 interfaces of the oxidized porous Si and, in particular, of SiOH groups. Under our experimental conditions such transitions may be excited either via high energy photons produced by the *bremsstrahlung* at the anode of the electrons injected through the oxide or through some Auger process.

Another possibility is that directly such electrons, without the mediation of photons or of an Auger process, reversibly excite specific defect sites. Previous density-functional theory calculations [11] have given values for the relaxation energies for inelastic tunneling via various defects in silica. The hydrogen bridge was identified as a likely candidate for the defect responsible for the low-field stress-induced leakage current observed in SiO_2, because it has a small relaxation energy as required for tunneling at low voltages. Following the same line or argument, a defect which undergoes a structural relaxation of ≈ 4 eV upon charge capture can explain the sudden transition in the rate of BD. If the applied voltage difference is less than the relaxation energy, an electron captured by the defect remains trapped there. For higher applied voltage, the electron can tunnel out of the defect into empty states in the anode, exciting local phonon modes and cycling the defect back to the initial configuration where it can repeat the process. Calculations show that atomic hydrogen in SiO_2 has appropriate transition states [11], cycling between the positive state bound to oxygen and the negative state bound to silicon, and it is therefore a likely candidate. Other possibilities, perhaps related to internal electronic structure of the nanometer-sized defect spot itself, might also explain the observed threshold energy.

In summary, we have observed a sharp voltage (energy) threshold in the growth rate of BD spots in thin films of SiO_2 on silicon. This provides some of the first information concerning the electronic structure of the BD spot.

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