PERGAMON

Microelectronics Reliability 39 (1999) 171–179

MICROELECTRONICS RELIABILITY

Electric breakdowns and breakdown mechanisms in ultra-thin silicon oxides

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Received 30 March 1998; received in revised form 4 July 1998

Abstract

It was found that the breakdown times measured using time-dependent-dielectric-breakdown (TDDB) distributions could be shifted to shorter times when the amount of energy available during the breakdown event was increased. The TDDB distributions were non-unique and breakdown models must account for both electrical breakdowns and dielectric breakdown. A novel approach for obtaining breakdown distributions will be presented. This approach uses a small number of oxides to obtain a time-dependent-electric-breakdown (TDEB) distribution, which will be shown to provide complementary information to that obtained from (TDDB) distributions. While the observation of dielectric breakdown in ultra-thin dielectrics may be difficult using standard test conditions, it will be shown that electric breakdowns are relatively easy to observe.

Introduction

In order to understand the discussion of oxide breakdown that follows, it is important to define the differences between electric breakdowns and thermal breakdown. Electric breakdowns have been referred to as soft, early, quasi, non-destructive or type A–B breakdowns and are associated with the creation of a *temporary* conducting path between the cathode and anode. The conducting path causes a discharge of the oxide voltage, dissipation of the oxide stored energy through the conducting region, rapid heating of the region to high temperatures, followed by at least partial, if not full, recovery of the oxide voltage as the breakdown region open-circuits. Many electric breakdowns are usually observed prior to a destructive, thermal, dielectric breakdown. Thermal breakdown, usually referred to as dielectric breakdown, is associated with the creation of a *permanent* conducting path between the cathode and anode. Thermal or dielectric breakdown will be shown to depend on the circuitry used to drive the breakdown measurement.

Electric breakdowns have been known for some time to precede destructive, thermal, dielectric breakdown in silicon oxides [1–3]. Electric breakdowns have been measured to occur in about a tenth of the time and at voltages as low as half that required to produce dielectric breakdown [4–9]. However, when breakdown distributions have been reported and models developed to explain these distributions, thermal dielectric breakdowns have usually been reported and analyzed. One reason electric breakdowns have not received much attention in the past is because many of the breakdowns were thought to be defect related. However, the

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0026-2714/99/$ - see front matter
PII: S0026-2714(98)00236-4

quality of modern oxides is so high that most of the defect dominated breakdowns have been eliminated and almost all breakdowns, electric and thermal, can now be considered to be intrinsic. Recently, it has been shown that electric breakdowns produce different breakdown distributions from thermal breakdowns, and thermal breakdown distributions are not unique [10].

In the work reported here we will describe how electric breakdown distributions and thermal breakdown distributions are different. We will describe techniques for triggering electric breakdowns into thermal breakdowns. We will also describe some post-breakdown current measurements that show the size of the breakdown region depends on the techniques used to trigger breakdown. A new method of extracting breakdown distribution data will be described that uses smaller sample sizes to get equivalent results to TDDB data. Electric breakdowns in ultra-thin oxides will be described. In this paper it will be shown that, while the time-to-breakdown of electric breakdowns is different from time-to-breakdown of thermal breakdown, there is no fundamental difference between an electric breakdown and a thermal dielectric breakdown event, other than one is temporary while the other is permanent.

Experimental

Electric breakdowns occur in a few microseconds and integrating ammeters, such as the HP4140B pAmeter used for most TDDB measurements, are unable to respond to or measure electric breakdowns. It is necessary to use a high-speed electric breakdown detection system. The test station used to measure both electric and thermal breakdowns reported here used a HP4140B pAmeter to measure the oxide dc current and voltage with a Tektronix TDS-520 digitizing storage oscilloscope placed across the sample. Every electric breakdown event, the thermal breakdown event, and the waveshape of these events were recorded in the memory of the TDS-520 or on a zip drive. Still and video cameras were used to view and photograph the local breakdown regions as they occurred, which on 40 and 80 nm oxides, were easily visible under the microscope.

The oxides used in these studies were fabricated by four separate integrated circuit manufacturers using high quality LOCOS processes using both *n*-type and *p*-type substrates. Oxides with the thicknesses 1.5, 3, 4, 5, 10, 20, 40 and 80 nm were measured. Oxide areas ranged from 5×10^{-5} to 2×10^{-3} cm^2. Using customized software through a general-purpose-interface-bus (GPIB), it was possible to simultaneously apply a constant stressing voltage, record the oxide current, record both the waveshape and time of each individual electric breakdown during the entire stressing period of the oxide up to the time at which thermal breakdown occurred, and in the thicker oxides, view and photograph every electric and thermal breakdown region. It was possible to record the waveshape associated with the thermal breakdown. Recording of the times of both all electric breakdowns and the thermal breakdown allowed the plotting of two different types of breakdown distributions, time-dependent-electric-breakdown (TDEB) distributions associated with all of the electric breakdowns, and time-dependent-dielectric-breakdown (TDDB) distributions associated with the final thermal breakdown. The measurements were all made with the substrate in accumulation.

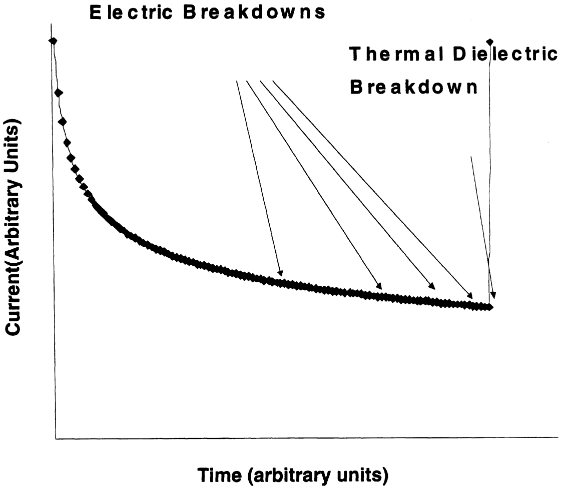

Fig. 1. The current–time characteristics of an oxide stressed at a constant voltage with the time of the thermal breakdown, as recorded by the HP4140B pAmeter, and the times of the electric breakdowns, as recorded by the TDS-520 oscilloscope, shown. At low oxide fields hundreds of electric breakdown events were recorded sometime before thermal breakdown occurred.

Electric breakdowns and dielectric breakdown

During TDDB testing, an oxide is stressed at a constant high electric field or at a constant current density until thermal dielectric breakdown is detected. The time of the thermal breakdown is recorded when either a precipitous increase in the current through the oxide or a drop in the voltage across the oxide occurs. The breakdown times measured on many oxides are used to generate a TDDB distribution. In order to record a significant number of early failures a very large number of oxides must be destructively tested. With the use of the high-speed oscilloscope it is possible to record the times at which all electric breakdowns occur, up to

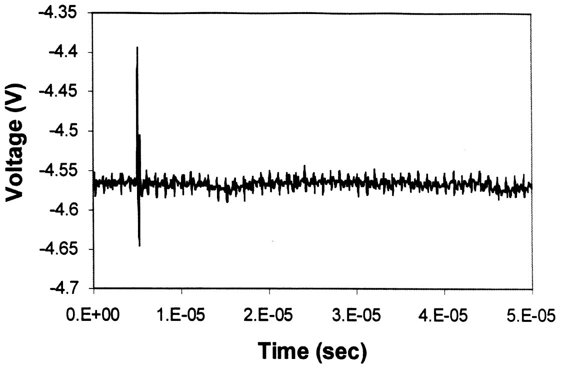

Fig. 2. The characteristic waveshape associated with an electric breakdown occurring in a 3 nm oxide stressed at 4.7 V as recorded by the TDS-520.

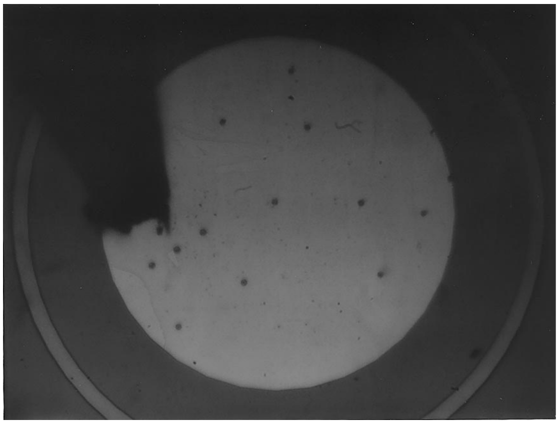

Fig. 3. Spots on the surface of an 80 nm oxide stressed in accumulation at 75 V. Each thermal melt spot on the surface of the oxide could be directly correlated to the detection of an electric breakdown by the TDS-520. Detection of electric breakdowns on oxides thinner than 40 nm relied solely on detection by the TDS520 since the energy dissipated was not sufficient to cause thermal melt spots.

the time of the thermal breakdown, using only a small number of oxides. Thus, an alternative way of describing breakdown is as a series of electric breakdowns, culminating in a final, permanent, thermal, electric breakdown, that is recorded as dielectric breakdown. Depending on the oxide field, hundreds of electric breakdowns can occur prior to thermal breakdown. It will be shown that in oxides thinner than about 5 nm, where the stored energy in the oxide is small and detection of thermal breakdown is difficult, electric breakdowns are an easier technique for detecting breakdown. In Fig. 1 a typical current–time characteristic measured during a constant-voltage TDDB measurement is shown. Both the time at which the thermal breakdown occurred, as recorded on the HP4140B pAmeter, and the times at which electric breakdowns occurred, as recorded by the TDS-520, have been shown.

The waveshape of a typical electric breakdown, in this case measured on a 3 nm thick oxide fabricated on *p*-type silicon, has been shown in Fig. 2. The voltage across the oxide collapsed as the temporary short-circuit formed and then recovered when this region open-circuited. It is believed that the ringing that accompanied the electric breakdown was caused by the measurement circuit. After electric breakdown the voltage source overcharges the oxide prior to restoration of the steady-state currents and voltages. In general, the frequency of occurrence of the electric breakdowns increase with stress time up to the final thermal breakdown event. The times of the occurrence of these waveshapes are graphically shown in Fig. 1. The waveshapes of the electric breakdowns did not seem to change in a significant manner up to the final thermal dielectric breakdown. The waveshapes were relatively independent of oxide thickness over the complete range of oxide thicknesses, from 1.5 to 80 nm.

On the thicker oxides it was possible to see thermal melted regions appear on the surface of the oxide every time an electric breakdown occurred, as shown in Fig. 3. On the oxides thicker than 40 nm the capacitive stored energy, $1/2CV^2$, was high enough to melt the polysilicon and aluminum on top of the oxide during an electric breakdown event. Through the use of still and video cameras it was possible to show a one-to-one correlation between the thermal melting on the surface of the oxide and the voltage spike on the oscilloscope. On thinner oxides, the visual effects are less visible under normal stressing conditions, since the energy dissipated is much smaller. However, if a large auxiliary capacitor was placed across the thinner oxides or if a low impedance voltage source was used to make the measurements, the thermal melt regions were often observed, due to the larger energy stored in the auxiliary capacitor or the larger current available during the electric breakdown. For ultra-thin gate oxides electric breakdowns are easier to see using the TDS-520 oscilloscope, in the form of voltage collapses across the oxide. If the oxides were observed in the dark, light was observed to accompany every physically observed breakdown region. It was assumed that this light was incandescence caused by the high temperatures accompanying the melted regions of the oxide and silicon.

A model of the breakdown process has been shown in Fig. 4 [11]. During the stressing of the oxides at high electric fields, randomly distributed traps are generated in the bulk of the oxide. The existence of these traps was obvious from the current decay in Fig. 1, which was caused by the trapping of electrons in the traps near the cathode. When enough traps are formed

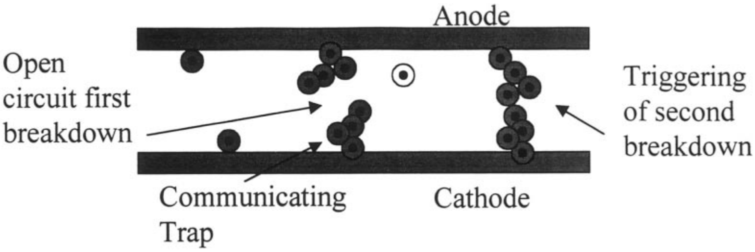

Fig. 4. Illustration of electrical breakdowns by the formation of communicating traps within the oxide.

close enough together to form a conduction path between the cathode and anode, breakdown occurs. This view of oxide breakdown doesn't take into account the electric breakdowns that can occur in the oxide. That is, the shorted regions can be open-circuited, as shown in Fig. 4. The open circuiting of the previous short circuit region probably involves local heating of the oxide and local rearrangement of the silicon and oxygen atoms. The model described above was presented by Sune et al., in a modified form [12], and in the form described in Fig. 4 by Degraeve et al. [11], and has been supported experimentally [13]. It should be noted that the formation of short-circuit regions that subsequently open-circuit was first observed by Klein in 1966 on thick oxides [1]. The early work of Klein appears to have been subsequently forgotten, since electric breakdowns have generally been dismissed as non-destructive and, as such, do not affect the reliability of the device. Also, many problems in oxide quality at the time of Klein's work were process and defect related.

Experimental results

It was decided to determine the extent to which an electric breakdown degraded the performance of a capacitor. The low-level leakage currents were measured on an oxide (a) before stressing, (b) after the first electric breakdown, (c) after many electric breakdowns, and (d) after the final thermal dielectric breakdown. The current–voltage characteristics of this oxide are shown in Fig. 5 as the oxide degraded. After the electric breakdowns the oxide was still functional and only had an increase in low-level leakage currents that was attributed to either the formation of traps within the oxide or residual damage left after the electric breakdown. These low-level leakage currents were, in most cases, indistinguishable from stress-induced-leakage-currents (SILCs). However, in some cases these currents occasionally dropped with subsequent stresses. These drops were attributed to the opening of temporary short-circuits caused by residual damage left in the oxides. After the thermal breakdown the low-level

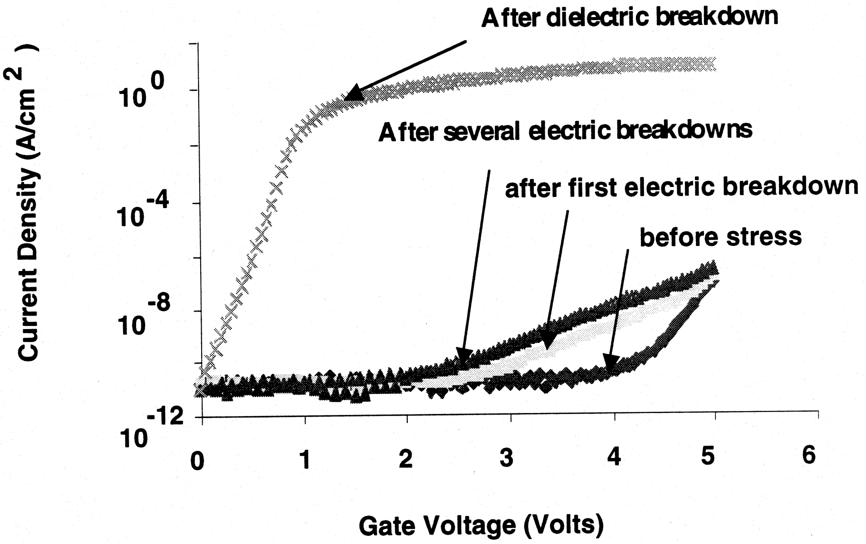

Fig. 5. Current–voltage characteristics of a 5 nm thick oxide measured before stress, after 7.25 V stressing with no electric breakdowns recorded, and after subsequent 7.25 V stressing until thermal dielectric breakdown was recorded.

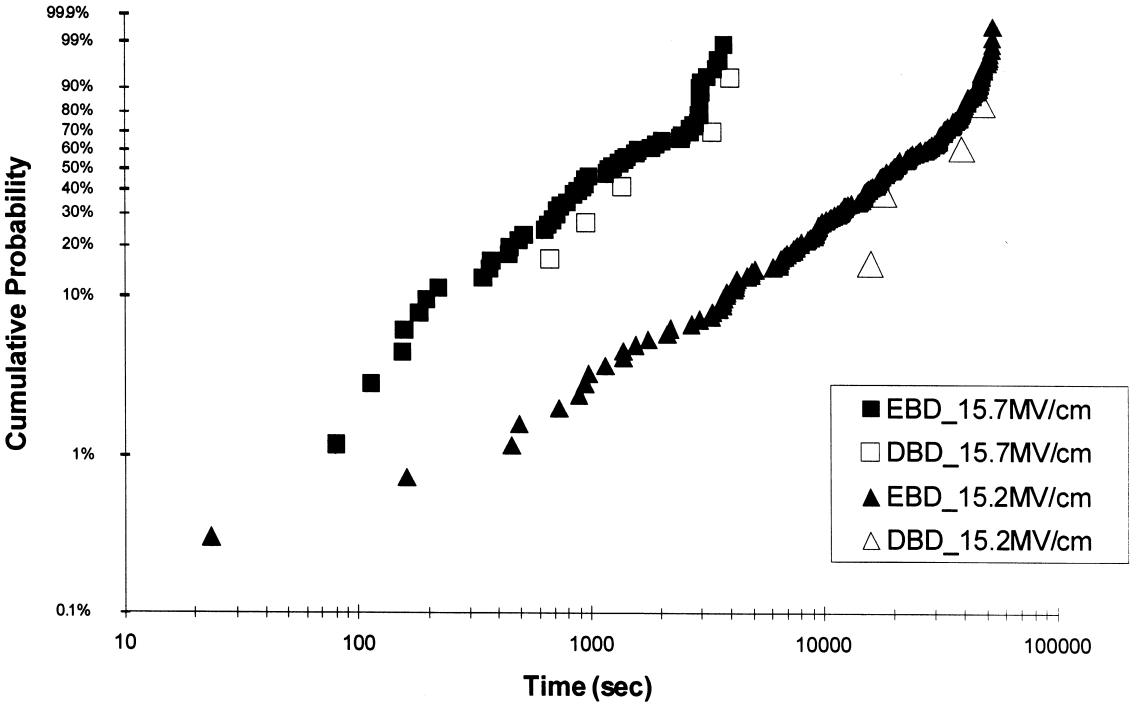

Fig. 6. TDEB distributions obtained from stressing five identical 3 nm thick oxides at 15.7 and 15.2 MV/cm. The thermal dielectric breakdown times have been shown as DBD, along with every electric breakdown time recorded as EBD. Notice the strong correlation between the TDEB distributions and the TDDB distributions. The five dielectric breakdowns have been shown as open symbols and the many electric breakdowns have been shown as filled symbols.

leakage current was quite high. This high current could be lowered by open-circuiting the thermal breakdown region using techniques similar to those previously described [1,3].

Since these electric breakdowns could be triggered into thermal breakdown by increasing the amount of capacitive stored energy or lowering the impedance o the test circuitry [10], and, as such, represented all possible times for possible thermal breakdown, quantifying the times of the electric breakdowns provided a useful way of accessing oxide quality and reliability. By plotting all of the recorded electric breakdown times measured on only a few oxides in a TDEB distribution, it was possible to obtain a distribution quite similar to TDDB distributions that had been obtained using many oxides. Fig. 6 shows two TDEB distributions obtained on five different oxides on the same wafer at two different electric fields, along with the TDDB distribution obtained from these five oxides. The electric fields were determined from the current–voltage characteristics using previously described techniques [14]. Both the TDEB and TDDB distributions had similar slopes; however, there are more data points obtained in the TDEB distribution at shorter stress times. When measuring TDDB distributions it is often necessary to obtain several hundred breakdowns in order to see the early failures. One of the most useful concepts to be derived from the data presented in Fig. 6 is to note that every electric breakdown is a potential

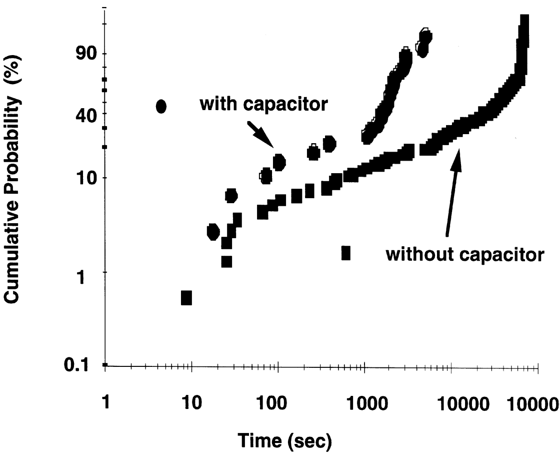

Fig. 7. TDEB distributions obtained from 3 nm oxides stressed at a constant field of 15.6 MV/cm with and without an auxiliary energy storage capacitor placed in parallel with the test oxide. As the energy available to flow through the electric breakdown region was increased, the time to thermal dielectric breakdown decreased.

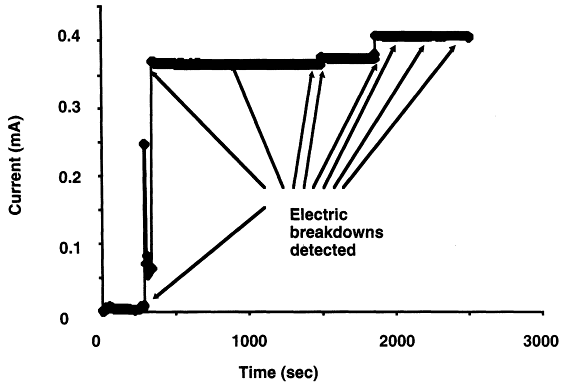

Fig. 8. The current–time characteristic of a 1.5 nm thick oxide fabricated on *n*-type silicon stressed at 16 MV/cm showing step current increases and "noisy" current levels. Electric breakdown times are shown.

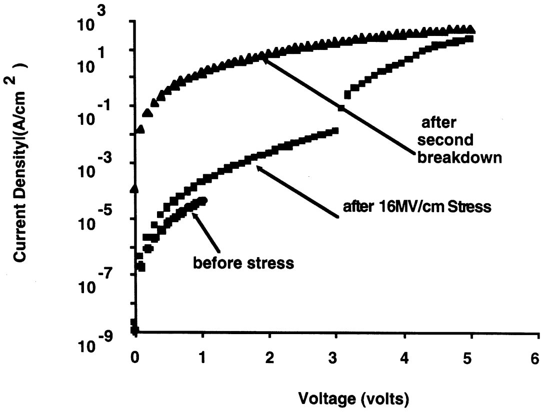

Fig. 9. Current–voltage characteristics of a 1.5 nm thick oxide recorded: (1) before stress; (2) after stressing at 16MV/cm as shown in Fig. 8; and (3) second voltage sweep performed after apparent dielectric breakdown at 21 MV/cm.

thermal dielectric breakdown. If the local conditions in the oxide and the driving circuitry are matched, then an electric breakdown can be triggered into a thermal breakdown. Since there were often hundreds of electric breakdowns occurring during an electric breakdown test and every possible breakdown was recorded, it was found that in many cases the *TDEB* distributions were multi-modal. Multi-modal *TDDB* distributions were usually only obtained when many hundreds of oxides were destructively measured.

In previous work we have shown that, on thicker oxides, it was possible to shift the time of the dielectric breakdown to shorter times (a) by increasing the capacitive energy available to discharge during an electric breakdown, or (b) by using a low impedance voltage source [10]. Similar experiments were conducted on oxides as thin as 3 nm. Two TDEB distributions obtained on 3 nm thick oxides have been shown in Fig. 7. One of the distributions was obtained from the oxides and one of the distributions was obtained from the oxides that had the additional 330 μF capacitor placed in parallel with the test oxide. The TDEB distribution obtained with the parallel capacitor was shifted to shorter breakdown times. It is important to note that the electric breakdowns recorded under both conditions began at approximately the same time and only the final thermal dielectric breakdowns were different. The multi-modal nature of the TDEB distribution is clearly seen in these data. In order to obtain a similar measurement using TDDB testing, several hundred breakdowns would have been needed.

It has been reported that thin oxides appeared to undergo dielectric breakdown as recorded by step increases in current flow and the appearance of "noisy" current-versus-time plots during a constant voltage stress [6]. Similar data taken on 1.5 nm thick oxides has been shown in Fig. 8. Each current step was accompanied by detection of an electric breakdown event. These measurements were consistent with the model of communicating traps forming a short-circuit and then partially open-circuiting. Since the oxide current never completely relaxes to its original value, it appeared that the short circuit was unable to completely open-circuit and residual damage from melted oxide, the polysilicon, or the substrate remained in the oxide throughout the measurements. Evidence for residual damage has been reported in studies of stress-induced-leakage-currents [15]. On several of these 1.5 nm thick oxides many electric breakdowns were recorded prior to the first current step increases. Therefore, even the time at which the first current step increase occurs is suspected to be a thermal breakdown and recording that time as the breakdown time overestimates the breakdown time. Recording the voltage fluctuations across the oxide with the TDS-520 provided a more complete means of quantifying oxide breakdown and quality.

For ultra-thin oxides in the 1.5 nm range there is difficulty defining breakdown, largely because the energy available to trigger thermal breakdown is limited and the oxides have significant conduction prior to stressing [16]. A series of current–voltage characteristics measured on 1.5 nm thick oxides have been shown in Fig. 9, illustrating a problem of defining breakdown in these thin oxides. A voltage sweep was performed on a fresh 1.5 nm oxide. The oxide was then stressed at 16 MV/cm and the current–voltage characteristic was remeasured. The low-level current increased somewhat and would have been attributed to SILC. However, during the high-voltage stress, many electric breakdowns were observed as well as many current step increases and noisy current. However, the oxide never appeared to undergo thermal dielectric

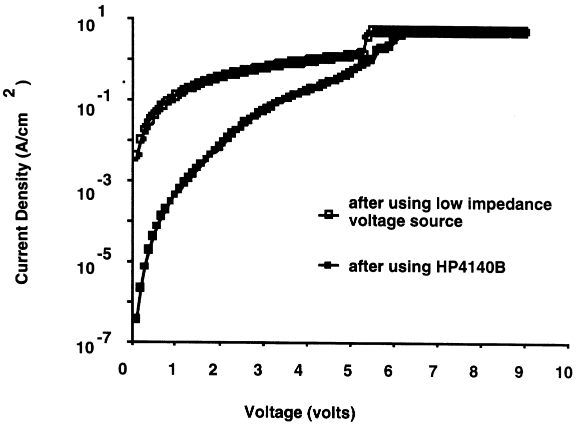

Fig. 10. The differences in oxide current–voltage characteristics of a 3 nm thick oxide stressed at 15.7 MV/cm with two different voltage sources. Lowering voltage source impedance caused more damage during thermal breakdown and more low-level leakage current after breakdown.

breakdown. The increased SILC was probably due both to trap generation and residual damage inside the oxide. As the voltage was swept to higher fields, the oxide appeared to undergo a second breakdown, as indicated by the jump in the current that occurred at voltages above 3.3 V. A subsequent voltage sweep confirmed that a very low resistance shorting path had formed between the cathode and anode. Thus, this oxide might not have been described as having undergone breakdown after the first stress, when in fact, many electric breakdowns were measured. These results are consistent with the recent paper at IEDM in which the oxides in the 2 nm range never appeared to undergo dielectric breakdown [16]. However, since electric breakdowns still occur, measurement of the electric breakdown times provide a convenient means of quantifying breakdown in ultra-thin oxides.

Since the dielectric breakdown event in an oxide is largely dominated by thermal events, changing the amount of energy that is available for discharge through a shorting path should cause the temperature of this path to vary and should produce varying final states of the oxide. Since the final state of the oxide depends on the details of the triggering of breakdown and maintaining the current though the breakdown region, the complexity of defining the true dielectric breakdown of an oxide is quite complex. In Fig. 10 the current–voltage characteristics of a 3 nm oxide have been shown after stressing to dielectric breakdown at 15.7 MV/cm. One characteristic was obtained using the HP4140B pAmeter to trigger breakdown and one characteristic was obtained using a low-impedance voltage source. In the case involving the low impedance voltage source, more energy was available to flow through the electric breakdown regions and, thus, more heating occurred and more damage was done to the oxide. This increased damage resulted in a lower resistance path forming in the oxide. On occasion, it was possible to see the damage spot in the oxides thinner than 5 nm thick if the low-impedance voltage source was used to produce breakdown. It was not possible to see the breakdown spot in these thin oxides if the HP4140B pAmeter was used. In many cases dielectric breakdown was not detected using the HP4140B pAmeter, but was detected using the low impedance voltage source, particularly in the thinner oxides.

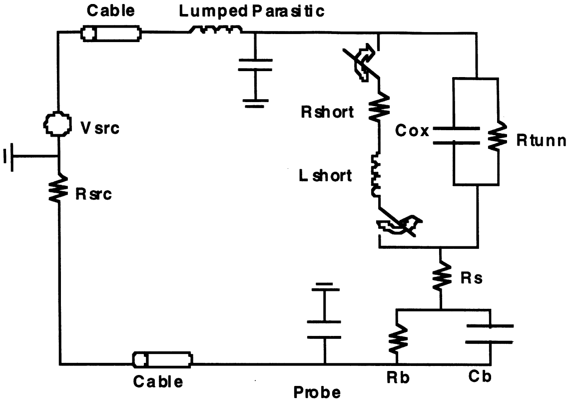

Fig. 11. Electrical breakdown equivalent circuit used for PSPICE simulations, containing the model of the electric breakdown. The two switches were used to simulate the short-circuiting and open-circuiting of the breakdown region.

A PSPICE model of the breakdown was developed to simulate the electric breakdown waveshapes that were measured. An equivalent circuit that simulated the voltage and current sources and the impedances of the cabling was connected to the test oxide, as shown in Fig. 11. Two switches were used to represent the electric breakdown region. Initially, one switch was closed and one switch was open. When an electric breakdown occurred the open switch became closed and a short time later the closed switch became open, simulating the formation and evaporation of a short circuit. Included in this circuitry was an equivalent circuit for the electric breakdown region [17]. The breakdown was simulated by the two switches that generated the short-circuit of the breakdown region and the open-circuit region that followed and a short-circuit oxide resistance and inductance, along with resistances and capacitances associated with the substrate and back contacts [17]. The two switches were sufficient to handle the breakdown event. By varying the values of the short-circuit region it was possible to accurately simulate an electric breakdown as shown in Fig. 12. The measured waveshapes could be matched

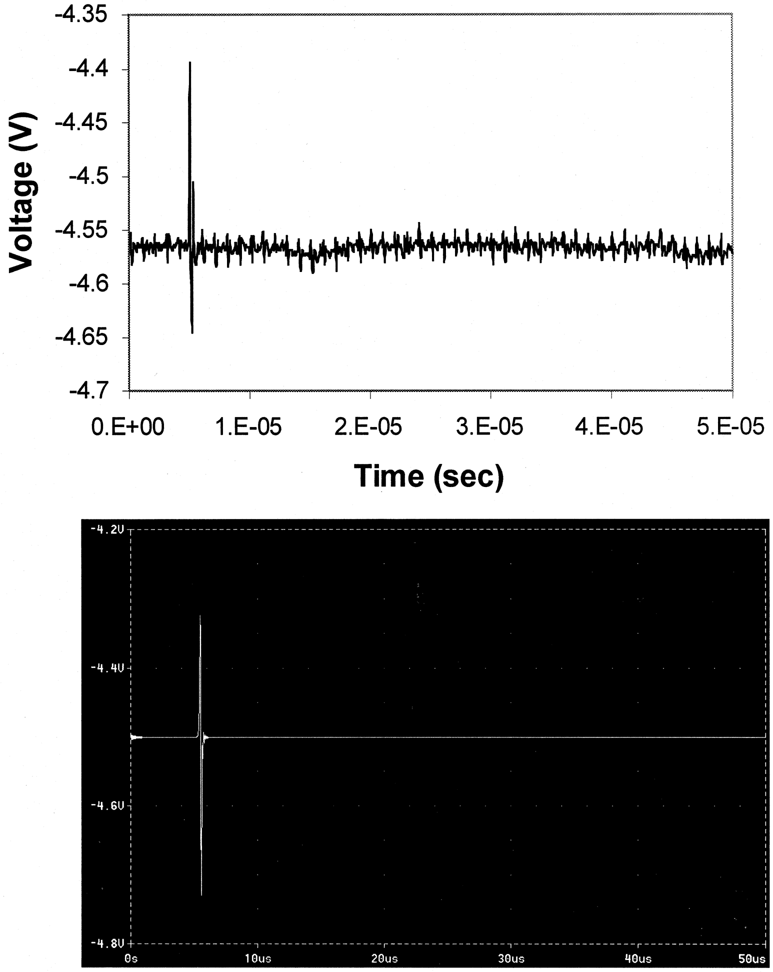

Fig. 12. Waveshapes obtained using the PSPICE model shown in Fig. 11 along with the measured wavelength. The PSPICE model was able to simulate the measured waveshape quite accurately. The measured waveshape is on the top. Both plots have the same vertical and horizontal scales.

quite accurately using different breakdown region values. It is important to note that this simulation was only qualitative and quantitative simulation would require extensive knowledge about the sizes of the breakdown regions, where they occurred, and details of the circuitry used to make the measurements [17]. Work is continuing to further define the values of resistance and inductance associated with each breakdown event.

Conclusion

Since electric breakdowns occur before final thermal dielectric breakdown, and since they can be triggered into dielectric breakdown by modifying the test circuitry, it is important to study both electric breakdowns and thermal breakdown. Several experiments coupling these two breakdowns were described. It appears that the information obtained in a TDEB distribution, taken using only a small number of oxides, is a good representation of a TDDB distribution taken using a large number of oxides. The amount of measurement time required to obtain a TDEB distribution is significantly less than that required to obtain a TDDB distribution. The models of Sune et al. and Degraeve et al. both appear to be sufficiently robust to take into account either the electric breakdowns or dielectric breakdown in oxides, just by modifying the number of traps required to trigger breakdown [11,12]. However, both of these models do not completely describe the breakdown process. In order to accurately describe dielectric breakdown, thermal events associated with the melted regions in the oxide must be taken into account. The TDEB distributions define all the possible times for oxide failure. The TDDB distribution only provides the time of the final failure. Every electric breakdown is a possible dielectric breakdown. Whether this electric breakdown becomes a thermal breakdown is often determined by the test circuitry, and not the oxide itself. For ultra-thin gate oxides the final state of the oxide after breakdown is dependent on the test conditions present during an electric breakdown. We believe that TDEB distributions provide a method of looking at early failures within an oxide and are a good complement to or even a replacement for the TDDB distribution.

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