# The Non-Uniqueness of Breakdown Distributions in Silicon Oxides

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## ABSTRACT

Time-dependent-dielectric-breakdown (TDDB) distributions obtained from oxides of the same physical geometry and stressed at the same electric field were found to shift to shorter times when the amount of energy available to flow through electric breakdowns was increased. This paper will show that TDDB distributions are non-unique and that for a breakdown model to accurately describe the reliability of an oxide during actual use conditions, the thermal geometry of the oxide must be taken into account. An accurate method of obtaining electric breakdown distributions will also be presented that allows the use of smaller sample sizes to obtain time-dependent-electric-breakdown (TDEB) distributions which are similar to TDDB distributions.

## INTRODUCTION

To begin the discussion of the non-uniqueness of breakdown distributions requires a semi-formal definition of what an electric breakdown is and the differences between it and a thermal dielectric breakdown. The existence of electric breakdowns is generally accepted, though they may be referred to by many names. Electric (also known as soft, early, quasi, or non-destructive) breakdowns are the creation of a conducting path between the cathode and anode of a stressed oxide during high electric field stressing, that upon further stressing, open circuits and for all practical purposes leaves the oxide in a condition of adequate device operation. Thermal dielectric breakdown is the classical breakdown phenomenon that is used in most discussions of oxide failure. Thermal dielectric breakdown is the creation of a permanent conduction path between the cathode and anode of a silicon oxide. Thermal dielectric breakdown will be shown to be dependent on the thermal geometry of the oxide and the circuitry used to drive the breakdown measurement.

The electric/dielectric breakdown of a silicon oxide has been described as a multi-step event, which can be summarized as follows[1]. During the application of a high electric field, traps are created inside the oxide. As more traps are created, eventually it will be possible to have enough traps communicating between the cathode and anode to actually lower the resistance in a small localized portion of the oxide. This low resistance path results in a local high density current region that is in addition to the normal current flow due to Fowler-Nordheim tunneling. At this point in the wearout/breakdown process, there is a localized short circuit in the capacitor between the cathode and anode. There is a subsequent discharge of the capacitor through the short circuit accompanied by a voltage drop across the oxide. If the balance between the energy stored in the capacitor and the time decay of the current through the external circuit is matched, the breakdown region can be open-circuited. This phenomenon is known as electric breakdown. This process repeats itself many times, at many different locations, until a sufficiently low resistance path has been formed between the cathode and anode to produce a permanent, shorting, thermal dielectric breakdown. This final thermal breakdown is usually referred to as dielectric breakdown.

Electric breakdown would appear to be a relatively benign event and one that has been observed yet dismissed in many papers because a real understanding of the breakdown of silicon oxides is not fully understood. However electric breakdown becomes extremely important when one considers that there is no difference between an electric breakdown and a thermal dielectric breakdown in an oxide other than one is temporary while the other is permanent. The existence of electric breakdowns was noted by James Prendergast in his paper and discussed by several others informally at IRW this year [14]. These electric breakdowns have been known for some time to precede destructive, thermal, dielectric breakdown in silicon oxides[1] [2] [3]. Electric breakdowns have been measured to occur in about 1/10 of the time and at voltages as low as ½ of that required to produce dielectric breakdown[4] [5] [6] [7] [8] [9]. However, when breakdown distributions have been reported and models developed to explain these distributions, thermal dielectric breakdowns have usually been reported, not the electrical breakdowns. It is believed that electric breakdowns have not received as much attention in the past because many of the breakdowns were defect related. The quality of oxide that is commonly being produced is of such quality now that most of the defect dominated breakdowns have been eliminated and breakdowns can now be considered to be largely intrinsic and studied in great detail.

For this paper we have stressed oxides at the same electric field and then by changing the amount of energy that was available to flow through the electric breakdown were able to change the breakdown distributions to shorter times. This change in breakdown times implies that breakdown distributions are not unique and are highly dependent on the test equipment and test conditions present during testing. After a discussion on the formation of electric breakdowns, data will be shown that shows the non-uniqueness of breakdown distributions and the importance of using a model that is robust enough to take into account for electric and dielectric breakdowns to predict the actual lifetime of the device. Finally a new method of extracting breakdown distribution data will be shown that allows the use of smaller sample sizes to get equivalent results compared to TDDB data.

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## EXPERIMENTAL

Since electric breakdowns appear as a local high current density region in the oxide, it is possible to see them using a fast voltage source in constant current measurements, or a fast current source in constant voltage measurements. Since the time frame of the electric breakdown events is very small, they happen in a few microseconds, and the HP4140B used in our lab is very slow in reacting to current fluctuations due to its ability to measure femto amps. It was necessary to use a digitizing oscilloscope to capture each electric breakdown and its corresponding waveshape. The test station setup at Clemson allowed constant voltage stressing through an HP4140B while a Tektronix TDS-520 digitizing oscilloscope recorded the electric breakdown waveshape. Since the breakdown waveshape is caused by the collapse of the voltage across the oxide, the oscilloscopes' triggering mechanism worked nicely to capture the waveshapes and record the electric breakdown times. Still and video cameras were also setup to allow the viewing of the breakdowns as they occurred, which on 40 nm through 80 nm oxides, were visible to the naked eye since the energy stored across the capacitor and the voltage were sufficiently high to discharge enough energy through the capacitor to cause the localized heating which would actually melt the polysilicon and aluminum surface. By utilizing different voltage sources, other than the HP4140B, that had lower internal resistances, it was possible to simulate the differences that test equipment could have on breakdown distributions, and the differences different actual use conditions could present, and also the dependency of the dielectric breakdown on the thermal geometry of the oxide.

For all of the experiments, a series of oxides were fabricated using high quality commercial local-oxidation-of-silicon (LOCOS) processes on both n-type and p-type substrates. The oxide thickness' were 3 nm, 5 nm, 10 nm, 20 nm, 40 nm, and 80 nm. Constant voltage TDDB testing was applied to areas ranging from 5E-5cm$^2$ to 2E-3 cm$^2$ using different testing equipment but at the same electric field. In the first set of experiments the constant voltage was applied using the relatively high impedance HP4140B pAmeter. In another set of experiments the constant voltage was applied using a low impedance, VIZ WP 711 voltage source. The voltage across the oxide was measured using a Tektronix TDS-520 oscilloscope both to ensure that identical fields were applied and to detect electric breakdowns when they occurred. Using customized software through a general-purpose-interface-bus (GPIB), it was possible to apply a constant stressing voltage, record the current information, while at the same time recording both the waveshape and time of each individual electric breakdown as they occurred during the entire stressing period of the oxide up to the time at which thermal dielectric breakdown occurred. It must be stressed that we are capable of recording each and every electric breakdown that occurs up until the final thermal dielectric breakdown. This allows the plotting of two different types of breakdown statistics, time-dependent-electric-breakdown (TDEB), and time-dependent-dielectric-breakdown (TDDB) distributions.

## ELECTRIC BREAKDOWNS AND DIELECTRIC BREAKDOWN

For the analysis of oxide quality and reliability, the TDDB test is one of the most commonly used. During TDDB testing, an oxide is stressed at a constant high electric field, or constant current density until thermal dielectric breakdown is detected. The thermal dielectric breakdown is detected commonly in the form of a sudden permanent increase in the current flowing through the oxide Fig. 1. The formation time of this permanent short between the cathode and anode of the oxide is taken as the time of thermal dielectric breakdown, and when taken from many samples allows a distribution to be formed that is used to predict oxide reliability under normal operating conditions. This is the classical view of what is happening in the oxide and the view that most have used to develop breakdown models and statistics. Since we have the ability to measure more than the final thermal dielectric breakdown of the oxide, the picture that is seen is greatly changed. Because electric breakdowns can be viewed occurring very early in the lifetime of the oxide and reoccurring up until thermal dielectric breakdown, it is more correct to view the oxide lifetime as a series of electric breakdowns. These electric breakdowns occur until a certain oxide quality and energy state is reached that makes it impossible to open circuit the electric breakdowns. When this type of local wearout has occurred, the last electric breakdown becomes dielectric breakdown. Figure 2 shows the electric breakdowns occurring before thermal dielectric breakdown as current spikes on an current versus time graph.

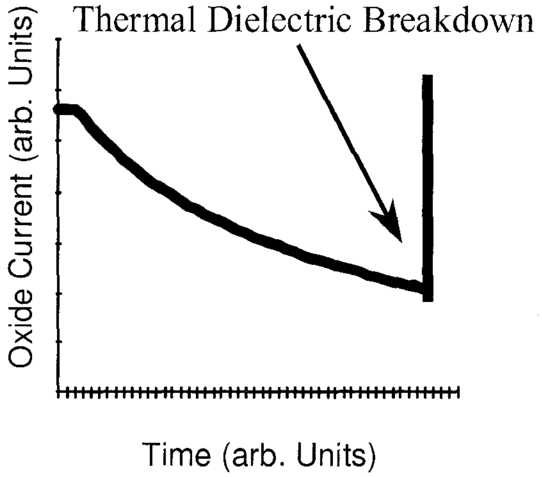

Fig. 1: The current vs. time characteristics of an oxide being stressed at a high constant voltages as during a TDDB test. The I-t characteristic shown is typical of oxides stressed using the HP4140B pAmeter.

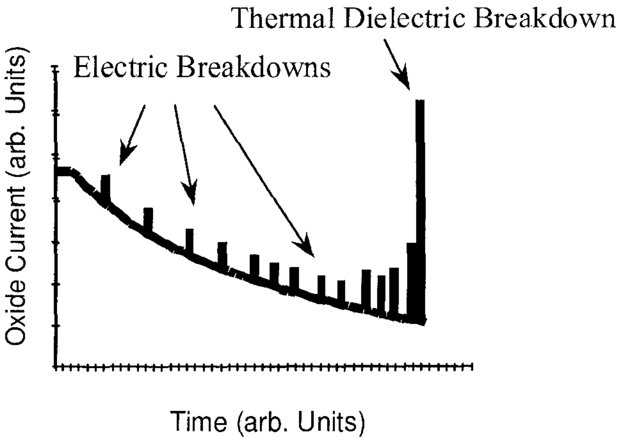

Fig. 2: The I-t characteristics of an oxide stressed under high constant voltage with the times of the electric breakdowns, recorded by the TDS520, superimposed on the I-t data.

A typical electric breakdown, that we are graphically showing as a current spike during the stressing of an oxide, can actually be viewed in Fig. 3. Because electric breakdowns cause a temporary short circuit and voltage collapses across the oxide, an oscilloscope can be used to detect when the voltage has collapsed. This waveshape is from a 80 nm oxide where it is relatively easy to determine when any voltages have changed due to the high voltages used during stressing. It is important to note that there is both a voltage collapse and a subsequent recovery of the circuit as the electric breakdown is blown open. It is believed that the ringing that accompanies an electric breakdown waveshape is from the measurement circuit itself. The voltage source overcharges the oxide prior to restoration of the steady state currents and voltages. It was possible to observe many, in some cases hundreds, of these electric breakdowns occurring prior to dielectric breakdown. The frequency of the electric breakdowns increased with time up until the thermal dielectric breakdown event. The times of the occurrence of these waveshapes was used to plot the current spikes in Fig. 2. The shape of the electric breakdowns does not seem to change in a significant manner up to the final thermal dielectric breakdown.

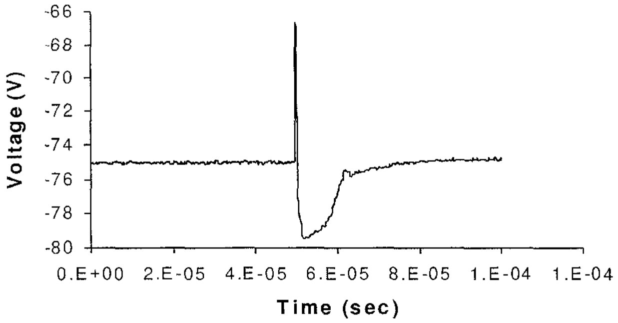

Fig. 3: The characteristic waveshape associated with an electric breakdown occurring on an 80 nm oxide stressed in accumulation at 75 volts as recorded by the TDS520.

Q. *How fast are these electric breakdowns?*
A. Electric breakdowns typically occur in less than 10 micro-seconds on oxides thicker than 5 nm as we record them on the oscilloscope. On 5 nm and thinner it is possible for an oxide to have an electrical breakdown that lasts for longer periods of time, as long as 10-20 seconds because there is not enough energy to cause an open circuit immediately.

Q. *How large are the voltage drops across the oxide?*
A. The Tektronix TDS-520 typically only registers that there has been a change in the voltage below a certain level. The line capacitance and inductance will cause the actual signal that we record to be distorted from what actually is happening at the surface. The important thing is that we are recording temporary shorting paths across the oxide.

When an electric breakdown occurs as a short circuit between the cathode and anode, and the subsequent oxide charge and voltage from the source is discharged through the capacitor, it is possible to see thermal melted regions on the surface of the oxide as shown in Fig. 4. This visual melting occurs under normal conditions during the stressing of thick oxides of 40 nm and greater. Since the energy stored, which is represented by $\frac{1}{2}CV^2$ is very high, a localized short circuit will cause a great amount of heat to be generated which can melt the poly and aluminum on top of the oxide. Through the use of still and video cameras it was possible to draw a positive one to one correlation between thermal melting on the surface of the oxide and a voltage spike on the oscilloscope. On thinner oxides it should be noted that the visual effects are not visible under normal stressing conditions since the energy dissipated is much smaller. However as will be shown later, by increasing the energy that is stored through the addition of an external capacitor, it is possible to force enough energy to be dissipated during the electric breakdown event to cause a thermal melting of the surface. The use of a low impedance source, which effectively lowers the RC time constant of the circuit and allows a larger instantaneous current to flow, will allow a more rapid discharge of the charge stored on the oxide. It is important to note that on thicker oxides it is possible to see hundreds of shorts forming on the surface of the oxide and the subsequent waveshapes up until the formation of a permanent thermal dielectric breakdown. Since the thinner oxides do not normally show surface melting it is necessary to rely on the viewing of the waveshapes alone to determine when an electric breakdown has occurred. On thinner oxides hundreds of electric breakdowns have been observed prior to dielectric breakdown.

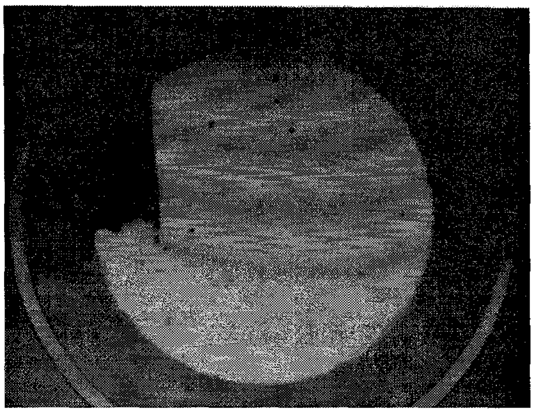

Fig. 4: Spots on the surface of an 80 nm oxide stressed in accumulation at 75 volts. Each thermal melt spot on the surface of the oxide could be directly correlated to the detection of a electric breakdown by the TDS520. Detection of electric breakdowns on oxides thinner than 40 nm relied solely on detection by the TDS520 since the energy dissipated was not sufficient enough to cause thermal melt spots.

Q. *What oxide thickness are you using to see these electric breakdown effects?*
A. We have seen electric breakdowns physically and electrically on the surface of oxides thicker than 40 nm. Oxides thicker than 40 nm have a higher $\frac{1}{2}CV^2$ energy available for discharge through the oxide causing localized heating to melt the top layer of poly and aluminum. We have observed electric breakdowns on oxides as thin as 3 nm as voltage spikes, but unless an additional capacitor is added in parallel to the test oxide to raise the stored energy, the thermal melts on the surface are usually not observed.

Q. *What is the gate material and thickness?*
A. Poly with aluminum on top, and approximately greater than 400 nm thick.

It becomes important now to discuss the models that have been developed that allow for the electrical breakdown event and ultimately the non-uniqueness of TDDB distributions. During the stressing of oxides at high electric fields, randomly distributed traps are formed in the bulk of the silicon oxide Fig. 5. The existence of these traps is obvious from the current decay in Fig. 1 which is caused by the trapping of electrons near the cathode. The classical accepted sequence of events for silicon oxides is that randomly distributed traps are formed until at some point, enough traps are formed close enough together to form a permanent conduction path between the cathode and anode. It is also assumed that the time of the formation of these permanent shorting event is unique.

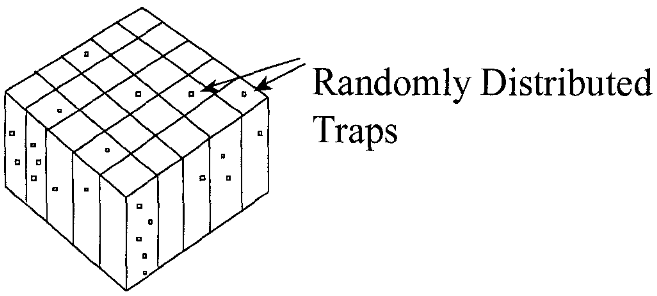

Fig. 5: Statistical model of breakdown that is dependent on the generation of traps within the oxide.

The problem with this classical view of oxide lifetime is that it doesn't take into account the fact that electric breakdowns can occur in the oxide. That is, the shorting regions can be open circuited. As an oxide is stressed at a high electric field and traps are formed within the oxide, it is possible for enough traps to form between the cathode and anode that a conduction path will appear. This model was presented by Sune and Degraeve and has been supported by work at Clemson[11] [12] [13].

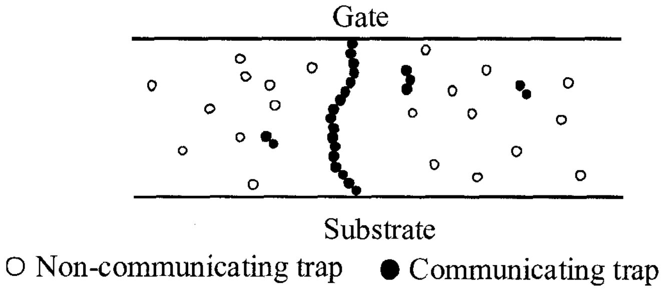

Fig. 6: Illustration of electrical breakdowns by the formation of conducting traps within the oxide.

This conduction path can do one of two different things depending on the thermal geometry of the oxide: 1) It can form a permanent shorting path, a thermal dielectric breakdown, or 2) it is possible for the short-circuit to open circuit, as is known to happen during an electrical breakdown. Fig. 4 shows electric breakdowns on the surface of an oxide occurring before final thermal dielectric breakdown. This phenomena was first observed by Klein in 1966 and excellent work was done to characterize this effect on thick oxides[3]. That work appears to have been subsequently forgotten since electric breakdowns have generally been dismissed as non-destructive. It was assumed that, since the device appeared to recover after the electric breakdown, that the breakdowns were non-destructive and did not affect the reliability of the device. Also most problems in oxide quality at the time of Klein's work were related to process problems and it was hard to look at the intrinsic breakdown of the oxide when extrinsic breakdown was a severe problem.

Q. *What was the cause of the first short circuit and the high current through it?*
A. We believe that the shorting during an electric breakdown could be caused by band to band tunneling, trap to band tunneling, Bohr orbital overlap, and/or residual damage in the oxide. Nearer to the dielectric breakdown of the oxide, the residual damage will be a large contributor to stress-induced-leakage-currents (SILC).

## Experimental Results

Since it was clear that electric breakdowns were occurring before final thermal dielectric breakdown, it was decided to try to trigger some of the early electric breakdowns into thermal dielectric breakdowns. The techniques used were to couple the $\frac{1}{2}CV^2$ energy stored in the oxide to the electric breakdowns by a) lowering the internal impedance of the voltage source used to drive current through the oxide or b) making more energy available to the capacitor during electric breakdown by adding an external capacitor in parallel with the test capacitor.

Q. *What size was your external capacitor?*
A. Several external capacitors were placed in parallel with the test oxide. The sizes were varied from .1μF to 10μF

Q. *When you say high impedance what are you talking about?*
A. The HP4140B is capable of resolving extremely low currents(femto Amp) and therefore has a high input impedance that restricts the amount of current that will be dissipated through an electric breakdown. The HP4140B has an internal impedance of about 40 kΩ. The low impedance drivers that we used as an alternate voltage source had impedance's that were 3-4 orders of magnitude lower in resistance than the HP4140B, therefore allowing more current to flow through an electric breakdown and forcing it to become a dielectric breakdown.

It was first necessary to determine whether or not an electric breakdown degraded the performance of a capacitor enough to render it useless. The stress-induced-leakage-currents (SILC) were measured on an oxide a) before stressing to get the base leakage current level, b) after stressing but without the detection of an electric breakdown, c) after the detection of the first electric breakdown, d) after many electric breakdowns, and e) after the final thermal dielectric breakdown was detected. As can be seen in Fig. 7 after each subsequent stressing the oxide was still functional and only had an increase in SILC's that can be attributed to either the formation of traps within the oxide or residual damage left after the electric breakdown. After each subsequent stressing the oxide contained more traps and/or more damage. Therefore, the stress induced leakage current rose. It should be important to note that we believe the SILC is made up of several components as you get closer to thermal dielectric breakdown. SILC is generally thought of to be comprised of trap tunneling within the oxide, but the presence of electric breakdowns shorting between the cathode and anode, and the subsequent open circuiting is thought to leave residual damage within the oxide as poly is drawn down into the oxide during the high heating at the localized shorting location. This silicon is believed to cause higher stress induced leakage currents.

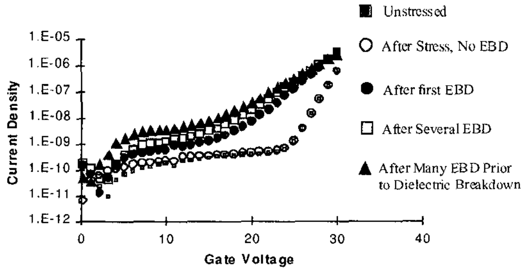

Fig. 7: Stress-induced-leakage-currents on a 40 nm thick oxide measured before stress, after 40.5 volt stressing with no electric breakdowns recorded, and after subsequent 40.5 volt stressing until electric breakdowns were recorded.

Once it was determined that electric breakdowns did not significantly degrade the device performance, other than increasing the SILC present within the oxide, TDDB tests were carried out on oxides that were from the same wafer, with the same physical geometry, and at the same electric field. Since we were trying to determine the effects of the energy available to flow through the short circuited electric breakdown region, TDDB tests were conducted to determine a baseline of where a normal TDDB distribution would lie. Capacitors were then placed in parallel with the oxide under test in order to increase the ½$CV^2$ energy available at breakdown. Then a low impedance voltage source was used to allow the full capacitor charge to be discharged as quickly as possible. Finally, the first electric breakdowns using the HP4140B pAmeter were noted. Under each different situation the voltage across the oxide was carefully monitored by the oscilloscope to ensure that the same electric fields were being applied and to monitor for electric breakdowns. It is clear from Fig. 8 that by increasing the amount of energy available to discharge through the short circuited electric breakdown region, that different breakdown distributions can be obtained, even when oxides are stressed at the same electric field, have the same physical geometry, and are even from the same wafer. It becomes clear from Fig. 8 that TDDB distributions are not a unique event, meaning that, depending on your measurement circuitry and the thermal geometry of your oxide, wildly different TDDB distributions can be obtained.

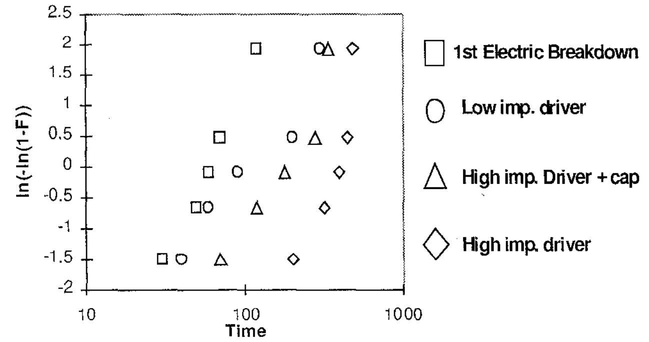

Fig. 8: TDDB measurements obtained from identical 40 nm oxides stressed at a constant voltage of 40.5 volts in accumulation. As the energy available to flow through the electric breakdown region was increased the time of thermal dielectric breakdown decreased.

If there are still doubts that electric breakdowns are occurring and that TDDB distributions are indeed unique, the following experiment can be done. Grow a 12 nm thick high quality LOCOS oxide, run a conventional TDDB test on the oxide using conventional equipment and a stress voltage of 12 volts (10 MV/cm). Then run the same test as before except instead of a high impedance voltage source, use an extremely low impedance source such as a battery from a car to provide the 12 volts. This same experiment using an extremely low impedance voltage source was carried out at Clemson on 80 nm oxides at a high voltage around 10 MV/cm, with the voltage monitored on an oscilloscope. At the time of the first electric breakdown enough current was able to flow through the shorting path that caused the probe and a few millimeters of the test wafer to be vaporized. This thermal dielectric breakdown occurred not at the time predicted by the classical TDDB distribution but at a much shorter time that was consistent with the formation of electric breakdowns predicted by TDEB distributions.

From Fig. 8 is clear that as the capacitance stored energy, ½$CV^2$, that is available to flow through the electric breakdown is increased, the time to dielectric breakdown is reduced. In fact by using a sufficiently low impedance source it was possible to trigger the first electric into the dielectric breakdown. Therefore, oxides that are stressed at the same electric field can have TDDB distributions that wildly vary. Since these electric breakdowns are occurring and can be triggered to become dielectric breakdown by increasing the amount of stored energy, quantifying the electric breakdowns should provide a more useful way of accessing accurate reliability data on an oxide. By plotting all of the recorded electric breakdown times, recorded during the stressing of 6 different oxides, it was possible to obtain a useful distribution that mirrored the TDDB distributions obtained through classical testing methods. Fig. 9 shows a breakdown distribution that we have called the time-dependent-electric-breakdown (TDEB) distribution plotted along with the classical TDDB distribution obtained from these six oxides. There is an extremely good fit between the intrinsic TDDB data and the main EBD distribution.

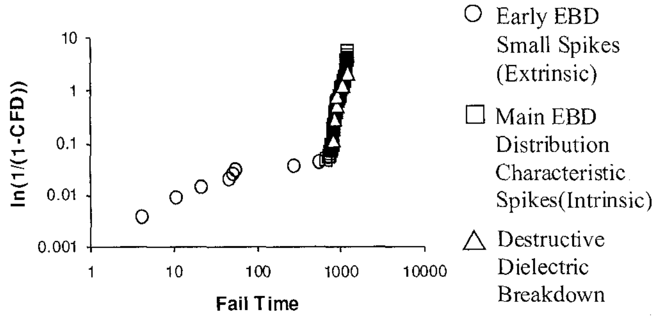

Fig. 9: TDEB distribution obtained from stressing 6 identical oxides at 75 volts in accumulation. The thermal dielectric breakdown is plotted as well as every electric breakdown time recorded. Notice the strong correlation between the main electric breakdown population and the thermal dielectric (TDDB) distribution.

Fig. 9 shows far more of what is happening to the oxide under stressing conditions than the normal TDDB test distribution. With the TDEB distribution it is possible to see all the times that the oxide could have failed. This is in contrast with the TDDB test which shows only the intrinsic breakdown time of each individual oxide. As we have shown above, varying the energy available at an electric breakdown event will give varying breakdown distributions. We have been able to note that the breakdown distributions obtained by recording the electric breakdown events typically show a definite multi-modal distribution. This multi-modal distribution is consistent with the actual breakdown of the oxide including early failures. We believe it is possible to correlate the early electric breakdown to the extrinsic breakdown of the oxide. In some cases it was possible to correlate some of the early electric breakdowns with a different type of voltage spike than the main population of electric and dielectric breakdowns shown in Fig. 10. Though we do not yet know what information can be explained from the shape of the breakdown spikes, due to the parasitic resistances, inductances, and capacitances in the measurement circuit, it is possible to note that the early breakdowns all seem to have a breakdown signature that recovers remarkably faster than the main electric breakdown signature. The implications of the different voltage waveshapes during electric breakdowns are unknown at this time and further work is being done to differentiate intrinsic and extrinsic breakdown populations.

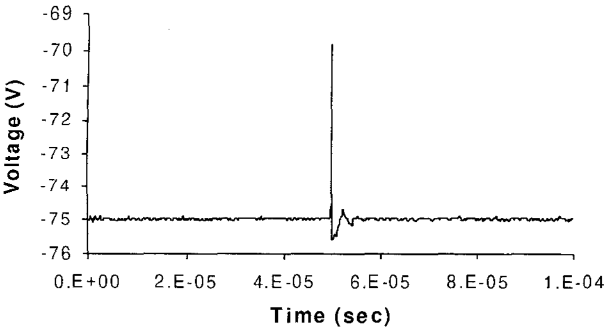

Fig. 10: Electric breakdown detected before the main electric/dielectric breakdown population on a 80 nm oxide stressed at 75 volts. Possible extrinsic breakdown indicator in an oxide.

As we noted earlier, the thermal melting on the surface of the oxide is greatly dependent on the amount of energy available to flow through an electric breakdown. If the $\frac{1}{2}CV^2$ is low, then a thermal melt will not occur. Below 40 nm the energy available for discharge is decreased to the point that electric breakdowns can only be detected electrically, but are usually hard to see optically. However, by increasing the amount of energy available at the electric breakdown event by adding a capacitor in parallel with the test oxide, it was possible to see visually thermal melts on the surface of the oxide as shown in Fig. 11. This observation of breakdown spots provides further proof that, in order to provide a robust model of electric breakdown, the thermal geometry of the oxide must be considered.

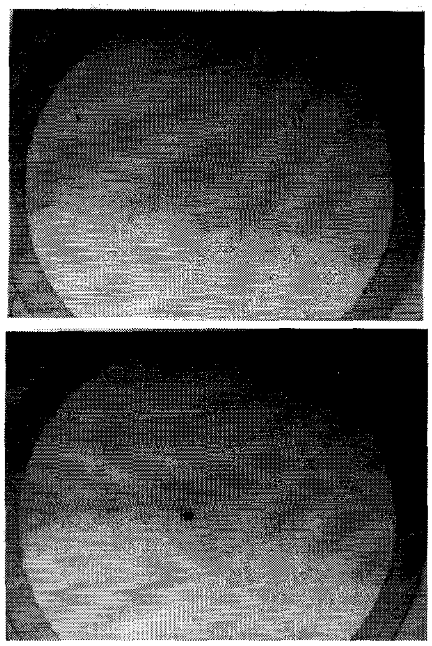

Fig. 11: Identical oxides stressed at 23 volts to thermal dielectric breakdown. Top photo taken after oxide was stressed using a HP4140B while the bottom photo was stressed with a HP4140B and an additional 10µF capacitor.

## CONCLUSION

Since electric breakdowns are occurring before final thermal dielectric breakdown, and since they can be triggered into dielectric breakdown by increasing the energy available, it is important to look at electric breakdowns to determine the events that are occurring inside the oxide in the time leading up to thermal dielectric breakdown. The models of Sune and Degraeve are robust enough to take into account for either the electric breakdowns or dielectric breakdown in oxides[11] [12]. However, these models are not complete. It has been shown that to completely account for the effects that take place during high voltage stressing, it is necessary to understand the thermal geometry of the oxide. It is necessary to know what is happening inside the oxide as shorting paths are forming between the cathode and anode during electric breakdowns. Even without a complete model that takes into account all of the different variables, it is possible to use electric breakdown analysis to allow the creation of TDEB plots that mirror the TDDB distribution and show all the possible times for oxide failure instead of just the intrinsic population with a smaller sample size. We believe that TDEB distributions provide a method of looking at early failures within an oxide and is a good complement or even replacement to the TDDB test.

## QUESTIONS DURING THE VIDEO

Q. *Why are all of the breakdown regions on the edge of the capacitor?*
A. These capacitors were designed to accentuate the edge effect problem due to bird's beak. Since there exists a localized lower thickness of oxide around the edge of the capacitor the field across the edge is higher and subsequently electric breakdowns occurred there before the main area of the capacitor started experiencing electric breakdowns. When the stress voltage polarity was reversed, the breakdowns occurred uniformly across the main oxide area. This shows how bird's beak only affects one interface, not both.

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