The Maximum Dielectric Strength of Thin Silicon Oxide Films

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Abstract—Thin film silicon oxide capacitors with nonshorting breakdowns were investigated. Breakdowns appear in three forms: single hole, self-propagating, and maximum voltage breakdowns. Single hole and self-propagating breakdowns occur at flaws, and self-propagating breakdowns develop only when the resistor to the source is relatively small, less than 10 KΩ in these experiments. After flaws are burned out by single hole breakdowns, with larger source resistors the maximum voltage breakdown can be observed, destroying the whole capacitor simultaneously. Plotting current against voltage, the current increase is quasi-exponential, but prior to maximum voltage breakdown, the current continues to increase while the voltage decreases slightly below a maximum value Vm. Assuming thermal instability as the cause for this change in the I-V relationship, we have derived an expression for the maximum voltage Vm. Calculated results for fields up to 9.5 MV/cm were found to agree well with measurements for temperatures from -145°C to 65°C and for thicknesses from 3000 Å to 50 000 Å. F, decreases with increasing temperature and thickness of insulation, and is higher for silicon dioxide than for silicon monoxide films. Maximum voltage breakdown occurs when the quasi-exponential increase of leakage current with field produces thermal instability over the whole capacitor area. The maximum dielectric strength is characteristic of the whole capacitor and is determined by its electrical and thermal conductance.

I. INTRODUCTION

Investigations of electrical breakdown in dielectrics have been beset with difficulties which greatly hinder the achievement of systematic results. The most serious difficulty is that test samples usually short out on breakdown and become useless for additional observations. Another difficulty is the occurrence of breakdown at the weakest spots in the dielectric; observations are, therefore, characteristic mainly of defects and much less of the basic properties of the dielectric. Finally, as shorts occur at these weakest spots, the maximum dielectric strength cannot be observed.

Breakdowns, however, need not necessarily cause shorts. This was demonstrated by the Bosch Company in Germany, who have produced capacitors with very thin electrodes since 1936 [1]. On breakdown, the metal evaporates around the breakdown hole, insulating it from the rest of the capacitor. These "self-healing" breakdowns were observed later both in thin film units evaporated on glass substrates and in anodic oxide film units when both, or one, electrodes were less than about 1000 Å thick [2]-[4].

In units with self-healing breakdowns, the quoted difficulties of breakdown investigations can be overcome. Use was made of the self-healing property by Klein et al., to investigate the mechanism of dc breakdown in silicon oxide films 1000 to 10 000 Å thick [5]. These investigations were fruitful because hundreds of breakdown events could be observed on one test sample.

Self-healing breakdowns give, in addition, the key to observations of maximum dielectric strength. Weak spots in the dielectric can be eliminated by self-healing breakdowns and the dielectric strength of the remaining dielectric depends then on bulk properties only.

It is the object of this paper to report on observations of maximum dielectric strength in evaporated silicon oxide films, to calculate this strength, and to draw conclusions with regard to the processes of breakdown. As this treatment is based on results of previous work on breakdown mechanisms [5], it appears useful to describe them briefly in the Section II.

II. BREAKDOWN PROPERTIES OF THIN SILICON OXIDE FILMS ON GLASS SUBSTRATES

Observations were made on capacitors produced by evaporation on microscope glass slides in a vacuum system at 10⁻⁴ to 10⁻⁵ Torr pressure. The electrodes were made of aluminum 400 to 800 Å thick and contact was made to the extensions of the electrodes with silver paste. The dielectrics deposited were silicon oxides with the dielectric constant ε varying from 3 to 7. Low ε silicon dioxide type layers were produced by the evaporation of silicon monoxide in an oxygen atmosphere of about 10⁻⁴ Torr pressure. Dielectric thicknesses varied from 500 to 50 000 Å. The rectangular capacitor areas were 0.2 or 0.02 cm² and the dielectric thickness was usually reinforced by about 50 percent at the edges adjacent to the contacts to prevent preferential breakdown there. The dielectric and electrode thicknesses were measured by multiple beam interference methods.

On applying increasing voltage, breakdown events begin above fields of about 0.5 MV/cm; the frequency of these events increases rapidly with voltage [3]. Figure 1 shows that these breakdowns produce single holes through all three layers of the capacitor. While the holes appear dark in the microgram due to reflected light illumination, they are bright with transmitted light.

Oscillograms show that on breakdown the voltage V on a 10⁻⁴F capacitor decreases within nanoseconds to 20 to 30 V, followed by recharge from the power source.
Hole diameters from a few microns to nearly 100 microns were observed, and the heat of evaporation of the material removed in a single hole breakdown is found to equal roughly the electrostatic energy stored in the capacitor. These facts were interpreted that single hole breakdown is due to the discharge of the capacitor into a flaw in the dielectric. The discharge is produced when current through the flaw causes thermal instability and increase in conductance by many orders of magnitude. The Joule heat causes evaporation and eruption at high mechanical pressure and formation of the hole.

At high voltages and when the series resistor is 10 kΩ or less in these experiments a second type of breakdown, the propagating breakdown occurs. Figure 2 shows typical destruction, which is large compared with that of a single hole breakdown. Oscillograms show that energy for the propagation is supplied from the external source. Propagating breakdown is triggered by a single hole breakdown and there are several modes of propagation. In one, an arc destroys the upper electrode, the arc burning as long as the supply can maintain it. In a second mode, single hole breakdowns occur at adjacent sites. The temperature increase and possibly mechanical damage at the previous site aid the breakdown at the new site when energy is supplied at a sufficient rate from the supply.

In the investigation described here, a further mode of breakdown propagation was observed in relatively thick dielectrics, when the single hole is produced at voltages above 350 V. This propagation seems to be caused by breakdown of the air in the hole through the dielectric.

The capacitance $C$ decreases during breakdown experiments and the quality of a capacitor is characterized by a $C/C_0$ vs. $V$ curve, $C_0$ being the capacitance before the experiment (see Fig. 3). As breakdown events continue for some time on the application of a voltage, $C$ measured after this period is plotted against $V$. The
distinction of soft and hard characteristics seems self-explanatory. It was found that the voltage at which $C/V_C$ becomes zero decreases considerably when the series resistor to the supply decreases and when the ambient humidity increases. Experiments reported here, unless otherwise stated, were carried out in enclosures dried by molecular sieve, although the results were found to be valid at the humidity of ambient air, too.

III. CURRENT-VOLTAGE CHARACTERISTICS AND THE MAXIMUM DIELECTRIC STRENGTH

A third type of breakdown is reported here, which can be observed in capacitors with hard characteristics. When such capacitors were connected to the source by series resistors larger than about 10 kΩ, propagating breakdown as described above was not observed. Increasing the supply voltage caused single hole breakdowns followed by sudden destruction of practically the whole unit.

For purposes of this work the total destruction was usually avoided. On a second or third slow increase of voltage, single hole breakdowns usually did not occur, and measurement of the leakage current $I$ through the dielectric as a function of the capacitor voltage resulted in typical $I$-$V$ plots as shown in Fig. 4. Accordingly, for increasing supply voltage, the capacitor voltage reaches a maximum value $V_m$ beyond which it decreases, while the current continues to increase. Total destruction occurs for currents larger than $I_m$ observed at the voltage $V_m$. The dielectric thickness of the capacitor of Fig. 4 was $h = 8900$ Å, the dielectric constant was $\epsilon = 5.6$, and the ambient temperature was $T_0 = 27^\circ$C. The power at $V_m$ in these capacitors was of the order of a few watts per cm$^2$ capacitor area. In the bend of the $I$-$V$ curves, current increased on the application of voltage for about a minute. Steady state current values were plotted.

It was found for dielectrics thicker than a few thousand Angstroms that the $I$-$V$ characteristics were repeatable. The maximum voltage was found to depend on a number of parameters.

To investigate the influence of temperature, capacitors were placed between perspex blocks and the package was placed in a customary cryostat. Liquid air or nitrogen was used as cooling media, and heating was obtained electrically by a coil wound around a rod which was attached to the capsule. The current in this coil was regulated by a temperature controller, and fluctuations in the sample temperature were less than 0.25°C.

Figure 5 shows $I$-$V$ curves for a silicon oxide capacitor with a 5200 Å thick insulation of 0.024 cm$^2$ area and a dielectric constant of 5.5. The temperature was changed from 65°C down to $-186^\circ$C. The measured current values include the current through the reinforcements. The latter current is calculated with Fig. 5 and is found to be a few percent of the total current. The current through the reinforcements is subtracted from the total current and Fig. 5 presents the current through the 5200 Å thick capacitor area.

Maximum dielectric strengths corresponding to the observed maximum voltages were plotted as circles in Fig. 6.

Regarding the influence of dielectric thickness, the maximum voltage was observed for thicknesses varying from about 3000 to 50 000 Å, as shown in a number of examples in Table I. This table, in addition to columns explained later, lists $h$, $\epsilon$, $T_0$, and the maximum electric field $F_m$ obtained from the measurement of $V_m$. The last line in Table I gives data for a 50 000 Å thick dielectric. $V_m$ could not be measured on this sample at atmospheric pressure, probably due to air breakdown in holes triggering propagation of breakdown (see note in Section II). However, coating the capacitor with a thick layer of epoxy resin made possible the observation of $V_m$. This type of breakdown would have been expected to prevent determination of $V_m$ also for the 21 000 Å thick sample for which a $V_m$ of 434 volts was observed. This, however, was not the case owing to the interesting fact that not one single hole breakdown occurred in two capacitors of this thickness. Some capacitors without any single hole breakdowns preceding maximum breakdown were found also with 4000 Å thick capacitors. $V_m$ has not been found as yet for thicknesses below 2900 Å, because the capacitors produced have been “soft”, with single hole breakdowns destroying the whole capacitor at voltages below $V_m$.

Regarding the influence of composition, silicon dioxide type capacitors were found to have a much higher maximum dielectric strength $F_m$ than silicon monoxide type capacitors, as seen by the comparison of the first two lines in Table I with the remaining lines. $F_m$ for a silicon dioxide capacitor with $h = 2900$ Å was found to be 9.5 MV/cm at room temperature.

In another type of experiment at constant temperature, $V_m$ was measured first with the capacitor in a closed container. The capacitor was then transferred into a furnace with forced ventilation, and Fig. 7 shows that this change produced an increase in $V_m$. The slopes of the two $I$-$V$ curves are slightly different, probably due to changes in the ambient. For this capacitor, $h = 3100$ Å, $\epsilon = 3.8$, and $T_0 = 30^\circ$C.

It will appear in the following paragraphs that a knowledge of the electrical conduction properties is needed for the calculation of the maximum electric field.

The $I$-$V$ curves show that in the high field region of the order of MV/cm the current increases exponentially with voltage. Such behavior was first described by Poole for thin mica sheets [6], and has since been found in many polycrystalline, or amorphous, dielectrics. Often
Fig. 4. Typical current-voltage curves of capacitor; the bend determines the maximum breakdown voltage.

Fig. 5. Variation of $I-V$ curves with temperature.

Fig. 6. Maximum dielectric strength as function of temperature derived from Fig. 5.
TABLE I

<table>
<thead>
<tr>
<th>Sample</th>
<th>$h$ (Å)</th>
<th>$b$ (cm/MV)</th>
<th>$\sigma$ ($\Omega\cdot$cm$^{-1}$)</th>
<th>$\sigma_0$ ($\Omega\cdot$cm$^{-1}$)</th>
<th>$\Gamma$ (W/$^\circ$C)</th>
<th>$F_c$ (calc.) (MV/cm)</th>
<th>$F_e$ (meas.) (MV/cm)</th>
<th>$T_c$ (°C)</th>
<th>$e$</th>
<th>$M$ (MV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3106</td>
<td>1.44</td>
<td>0.023</td>
<td>$0.28 \times 10^{-11}$</td>
<td>0.0065</td>
<td>6.66</td>
<td>5.85</td>
<td>30</td>
<td>3.25</td>
<td>20.1</td>
</tr>
<tr>
<td>2</td>
<td>4900</td>
<td>1.68</td>
<td>0.021</td>
<td>0.8</td>
<td>0.0060</td>
<td>4.6</td>
<td>4.9</td>
<td>30</td>
<td>3.45</td>
<td>19.6</td>
</tr>
<tr>
<td>3</td>
<td>4500</td>
<td>2.67</td>
<td>0.027</td>
<td>1.26</td>
<td>0.0063</td>
<td>2.85</td>
<td>2.94</td>
<td>30</td>
<td>4.00</td>
<td>8.24</td>
</tr>
<tr>
<td>4</td>
<td>7600</td>
<td>3.23</td>
<td>0.029</td>
<td>3.08</td>
<td>0.0079</td>
<td>2.32</td>
<td>2.22</td>
<td>30</td>
<td>3.35</td>
<td>8.21</td>
</tr>
<tr>
<td>5</td>
<td>14 300</td>
<td>2.39</td>
<td>0.037</td>
<td>1.8</td>
<td>0.0059</td>
<td>1.98</td>
<td>1.93</td>
<td>30</td>
<td>8.22</td>
<td>8.29</td>
</tr>
<tr>
<td>6</td>
<td>21 300</td>
<td>2.31</td>
<td>$\Gamma/\sigma \approx 0.16$</td>
<td>1.57</td>
<td>0.0059</td>
<td>1.97</td>
<td>1.98</td>
<td>27</td>
<td>8.22</td>
<td>5.75</td>
</tr>
<tr>
<td>7</td>
<td>50 000</td>
<td>3.35</td>
<td>$\Gamma/\sigma \approx 0.2$</td>
<td>1.57</td>
<td>0.0059</td>
<td>1.95</td>
<td>1.92</td>
<td>27</td>
<td>5.95</td>
<td>8.12</td>
</tr>
</tbody>
</table>

Note: 1) Samples 1 and 2 are silicon dioxide type capacitors; the rest are silicon monoxide type capacitors.
2) Sample 7 was measured in ambient air.
3) $M = (1/b) \log (1/\sigma)$ is a figure of merit for the films.
4) Samples 1 and 2 are silicon dioxide type capacitors; the rest are silicon monoxide type capacitors.
5) Sample 7 was measured in ambient air.
6) $M = (1/b) \log (1/\sigma)$ is a figure of merit for the films.

Fig. 7. Influence of forced ventilation on the maximum voltage.

Fig. 8. Linear part of some curves of Fig. 5 replotted against $1/T$.

Fig. 9. $\sigma_0$ as function of temperature.

Fig. 10. $\sigma$ and $b$ as functions of temperature.
a linear relation between $\log I$ and $V^{1/2}$ was found, e.g., with Al$_2$O$_3$ [7], impregnated paper [8], tantalum pentoxide [9], to quote a few examples. This relationship was interpreted that the conduction is due to a Schottky type of emission mechanism.

Considering thin silicon oxide films, one of the $I$-$V$ curves in Fig. 4 shows a good linear fit for $\log I$ as a function of $V^{1/2}$ over a wide range. However, at the highest fields preceding breakdown the current curve bends somewhat upwards. It appears, with the aid of calculations described in Section IV, that the start of this upward bend is not caused by Joule heating. As a matter of fact, in this high field region a better linear fit is found for the second curve of Fig. 4, where $\log I$ is plotted as a function of $V$.

Experience with capacitors varied. Some gave for $\log I$, or $\log \sigma$, a good linear fit as a function of $V$ and others as a function of $V^{1/2}$ in the high field region. Here $\sigma$ is the electrical conductivity.

Interesting additional information about the process of conduction is obtained by reploting the typical results of the linear portion of Fig. 5 as $\log I$ vs. $1/T$, with $V$ as a parameter (Fig. 8). The relationship is found not to be linear. On the other hand, relatively small departure from linearity is obtained when $\log I$ is plotted vs. $T$.

Although it is of primary interest to find an interpretation for these high field conduction observations, this is not the purpose here, and it suffices to realize that the conduction processes through silicon oxide cannot be described by simple models. For this reason, and also to achieve simplicity in analysis, it turned out to be convenient to represent the conductivity $\sigma$ of silicon oxide by the relation

$$\sigma = \sigma_0 e^{(T - T_o) \beta F}.$$  

Such a relation is a good approximation when $T - T_o$ is not large compared with $T_o$, and (1) was found suitable for the calculation of the maximum dielectric strength. The relation was determined for varying ambient temperatures $T_o$ in the high field region preceding maximum breakdown. The parameter $\sigma_0$ was found to be a quasi-exponential function of $T_o$, as shown in Fig. 9 for the $I$-$V$ curves of Fig. 5. The coefficients $a$, $b$, and $\Gamma$ were found to vary relatively little with temperature as seen in Fig. 10, also calculated with the results of Fig. 5.

The factor $\sigma_0$ is only a fictitious “zero field” conductivity at $T = T_o$: the real low field conductivity is smaller by several orders of magnitude (see Fig. 4). It may be remarked that the $\log \sigma$ vs. $F$, or vs. $T$ curves turned out to be nearly linear for the capacitor of Fig. 5.

IV. CALCULATION OF THE MAXIMUM DIELECTRIC STRENGTH

Several interpretations could be considered for the occurrence of a maximum voltage. As the Joule heat produced at $V_m$ is considerable, calculation of $V_m$ due to this effect was attempted first.

The temperature rise in the capacitor due to Joule heat can be assumed to be uniform because the capacitor is very thin. The equilibrium temperature $T$ of the thin film capacitor can then be determined simply by equating the Joule heat with that lost by heat transfer

$$\sigma \frac{A}{h} V^2 = \Gamma (T - T_0).$$

In this relation $\sigma$ denotes the effective capacitor area, $h$ the dielectric thickness, and $\Gamma$ the thermal conductance of the capacitor unit. With the use of (1) and the relation $V = Fh$, we can write (2) as

$$\sigma_0 A h F^2 e^{b F} e^{(T - T_o)} = \Gamma (T - T_o).$$

It is assumed that $T - T_o$ is relatively small and that $a$, $b$, and $\Gamma$ is constant over the temperature range from $T_o$ to $T$.

Solutions and physical meaning of an equation similar to (3) but without the factor $e^{b F}$ was treated by Wagner for the interpretation of thermal breakdown in insulations [10].

This equation can be solved graphically for the equilibrium temperature $T$ as shown in Fig. 11, where the Joule heat and the heat loss are plotted against temperature. The parameter for Joule heat is the electric field, with $F_1 < F_2 < F_1$. The lower intersection of the Joule heat curve for $F_1$, with the heat loss line determines the steady state temperature in this case. There is no intersection with the heat loss line for the field $F_2$, and when a field of this magnitude is applied to the capacitor the temperature increases continuously until destruction of the capacitor occurs. The field $F_m$, for which the Joule heat curve is tangent to the heat loss line, is assumed to represent the maximum field which can be applied to the capacitor without destruction. $F_m$ and the corresponding temperature $T_m$ can be determined by equating at $T_m$ the derivatives of the two sides of (3) with respect to $T$.

$$a \sigma_0 A h F^2 e^{b F} e^{(T_m - T_o)} = \Gamma.$$  

Dividing (3) by (4) we find

$$1/a = T_m - T_0.$$  

A relation for the maximum field $F_m$ is obtained by substituting (5) into (3)

$$F_m = \frac{1}{b} \log \frac{\Gamma}{a \sigma_0 h e^{F_m}}.$$  

In this relation $\epsilon$ is the basis of natural logarithms. Equation (6) can be rewritten for the maximum voltage

$$V_m = \frac{h}{b} \log \frac{\Gamma}{a \sigma_0 h V_m^2}.$$  

286 IEEE TRANSACTIONS ON ELECTRON DEVICES FEBRUARY
For the calculation of $F_m$ and $V_m$, the factors $a$, $b$, and $\sigma_0$ are determined from the current-voltage measurements with the aid of (1). The thermal conductance can also be obtained from the $I$-$V$ measurements. Equation (2) can be rewritten for the thermal conductance as

$$\Gamma = IV/(T - T_0)$$

(8)

where $T - T_0$ is the steady state temperature rise as a result of Joule heat. $T - T_0$ can be determined by measuring the current $I_1$ at the instant when the voltage $V$ is applied to the capacitor ($T = T_0$), and the current $I_z$ when the temperature has increased to the steady state. From (1), for a constant field $F,$

$$T - T_0 = \frac{1}{a} \log \left( \frac{I_z}{I_1} \right)$$

(9)

so that (8) becomes

$$\Gamma = \frac{I_z V}{T - T_0} = \frac{a I_z V}{\log (I_z/I_1)}.$$ 

(10)

The thermal conductance was usually determined graphically with the aid of $I$-$V$ curves (see Fig. 5), when neighboring curves were plotted for ambient temperature differences of 20°C to 30°C. Denoting by $T_i$ the temperature for the lower curve and by $T$ the temperature for the higher curve, the intersection of the extended higher line with the lower curve determines the power $I_z V$ which causes the temperature increase $T - T_0$. This is shown on an example in Fig. 5. $T$ should be chosen for the calculation of $\Gamma$ so that the intersection occurs in the vicinity of $V = V_m$.

Values of $\Gamma$ determined in this way are tabulated in Table I and are plotted vs. ambient temperature in Fig. 12 for the capacitor represented by the $I$-$V$ curves of Fig. 5. Table I also shows values of the coefficients $a$, $b$, and $\sigma_0$.

Maximum fields were calculated using (6) and results for $F_m$ are also given in Table I and in Fig. 6 where they are plotted as crosses. Measured and calculated values of $F_m$ agree within a few percent.

Roughly linear increase of maximum dielectric stress is found with decreasing temperature, $A$ linear rise is obtained for $F_m$ with (6) when $a$, $b$, and $\sigma_0$ are constant. If the ambient temperature changes by $\theta$, $\sigma_0$ changes roughly to $\sigma_0 e^{\theta}$, and using this replacement in (6) we get

$$F_m = \frac{1}{b} \log \frac{\Gamma}{a \delta \Delta \sigma_0 F_m^2} - \frac{\theta}{b}.$$ 

(11)

It should be noted that if the thermal conductance, could be kept constant, the low temperature $F_m$ would be higher than in Fig. 6, and the curve would appear more linear. The method described for the calculation of $F_m$ can be equally well applied for conductivity relations different from that of (1), e.g., when $\sigma$ or $I$ are proportional to $e^{-V_{1/2}}$, $c$ being a coefficient. Calculations become involved, however, when $\sigma$ is represented by an expression proportional to $e^{-B/1}$ where $B$ is a coefficient.

Maximum voltages were calculated with conductivity relations different from that of (1) and good agreement was found between measurements and calculations when the conductivity relation fitted well the high field region adjoining the bend of the $I$-$V$ curves.

V. Discussion

An alternative interpretation to thermal instability for the occurrence of maximum voltage could be a change in the conduction mechanism at the bend. While the results of the previous section negate this possibility, there is additional evidence against this interpretation. Experiments represented by Fig. 7 show that forced ventilation increases $V_m$. As ventilation increases the thermal conductance, the increase found in $V_m$ is in agreement with (6). When the $I$-$V$ curve with ventilation is corrected with (2) and (1) for the effect of temperature increase, it is found that this curve is still linear where the bend occurs in the $I$-$V$ curve of the experiment without ventilation. The mechanism of conduction,
The measurements involved in the experimental determination of conductivity $\sigma$ and maximum dielectric strength $F_m$ are those of voltages, currents, temperatures, capacitances, and the dimensions of the capacitor samples. The errors in the magnitude of $F_m$ are caused by the limited accuracy of the measurements, by the limited constancy of ambient temperature, and by the current measurements in the bend of the $I-V$ curves where steady state values of the current are needed. It should be remarked regarding the latter point that it is not desirable to extend the duration of the current measurements because sometimes destruction of the electrodes occurs, possibly by electrolysis.

Agreement of the calculated values of $F_m$ with the measured ones depends on the magnitudes of these errors. Additional errors enter the calculation of $F_m$ because $\Gamma$ is determined graphically, and because the assumed constancy of $\alpha$, $b$, and $\Gamma$ in the temperature range from $T_0$ to $T_m$ is an approximation only. Fortunately, with the exception of $b$, the factors in the relation for $F_m$ occur in the logarithmic argument. The influence of the inaccuracies in the factors is, therefore, considerably diminished, values of the argument varying from about 500 to about 10$^8$.

The curves of Figs. 10 and 12 for $\alpha$, $b$, and $\Gamma$ were drawn to fit calculated values at the ambient temperature of Fig. 5, and there is some scatter of the points around the curves. Inspection of the graphs for $\epsilon$ and $\Gamma$ shows that both are increasing with temperature. Thus, as by $F_m \alpha \log (\Gamma/\alpha)$, the effect of these changes is decreased. It was found that, considering all the sources of error, not much could be gained by correcting (6) for changes in $\alpha$, $b$, and $\Gamma$ in the range $T_0$ to $T_m$ when $T_0$ was larger than $-150^\circ$C. It appears from additional experiments now in progress that below this temperature the simple relation for $F_m$ must be corrected, as the nature of the conductivity changes. However, in the temperature range discussed here, the accuracies represented by Fig. 6 and in Table I were found generally for silicon oxide films.

By (10), $\Gamma$ is proportional to $\alpha$, and $\sigma$ is proportional to $h/A$ when calculated with Ohm's law; further, $b$ is proportional to $h$ when calculated from measurements of $I$ and $V$. Equation (6) can therefore be transformed into a relation for $F_m$ which does not contain $\alpha$, $b$, $\Gamma$, $A$, and $h$, but measured values of $I$ and $V$ only. Errors are then smallest in the calculation of the maximum dielectric voltage $V_m$.

The good agreement of measured and calculated values of $V_m$ and $F_m$ leads to the following interpretation of the observations.

Silicon oxide capacitors, which at voltages lower than $V_m$ were cleared by self-healing breakdowns from randomly distributed weak spots, present a quasi-homogeneous behavior under the conditions of the above experiments. The high field leakage current increases exponentially with electric field, and when the Joule heating becomes sufficiently large destruction of the whole capacitor occurs due to thermal instability. This breakdown caused by the leakage current determines a maximum dielectric strength which the entire dielectric can support for the given conditions.

As the thermal instability determines the value of $V_m$, a basic aspect of this breakdown is common with that of thermal breakdown treated many years ago by Wagner [10]. Thermal breakdown as described by Wagner, however, differs in other aspects from the breakdown at maximum voltage. Accordingly, thermal breakdown occurs at the weakest spots in the insulation, hence, the dielectric strength determined in this way is very much lower than $F_m$. Further, as mentioned previously, Wagner was originally not considering in his analysis an exponential $I-V$ relationship which was found so important for the development of maximum breakdown. His relations for thermal dielectric strength, as quoted in the literature, are therefore quite different from those for $V_m$ [11]. In addition, geometry and the properties of the weak spots are not known. Therefore, their thermal dielectric strength cannot be calculated in contrast to $V_m$ and $F_m$, which can be calculated with good accuracy.

It is interesting to ask here whether the single hole breakdowns occur by similar processes as breakdown of the whole capacitor at $V_m$. The flaws in the dielectric where single hole breakdowns arise can be of a geometrical nature or can be material inhomogeneities. When the flaw is of the first type, the breakdown field can be determined by (6) as long as (1) for the electrical conductivity remains valid at the flaw. The difference in the value of $F_m$ for the whole capacitor and for the flaw is found in the expression $\Gamma/(hA)$. $\Gamma/A$ is somewhat larger at the flaw and $h$ is somewhat smaller. The argument of the logarithmic expression increases therefore, which generally results in a small increase of $F_m$ at the flaw. Assuming that for small increase in $F_m$, the nature of the electrical conductivity does not change, single hole breakdowns at geometrical flaws appear to arise by processes similar to those at $V_m$.

Considering (6) and typical values of the factors in Table I, it is seen that the dominant factors determining the maximum dielectric strength are the rate of current increase with field, expressed by $b$, and the conductivity, expressed by $\sigma$. As a matter of fact, relative maximum dielectric strengths may be characterized by a "figure of merit" $-(1/b) \log \sigma$, also included in Table I. Difference in properties in electrical conduction explains the superiority of $F_m$ for silicon dioxide over that for silicon monoxide.

The influence of thickness variations cannot be well ascertained, because capacitors of unequal properties are produced in subsequent evaporations. In spite of this, it appears from Table I that for dielectric thicknesses
above 7000 Å the decrease in $F_p$ is not caused by a change in the conduction properties, but only by the increase in the thickness of the dielectric. This is checked by calculations with (6).

It is of great interest to know the limits for the observation of the maximum field, and in a continuation of this project insulations of thicknesses far exceeding 50 000 Å are being investigated in vacuum. The existence of a maximum breakdown voltage due to heat produced in the dielectric was stipulated and calculated previously by Whitehead for thick insulations [12]. This maximum so-called “thermal” voltage has not been observed on dc owing to breakdown at the weakest points.

Summing up, investigations in capacitors with self-healing breakdown result in the observation of a maximum dielectric strength. This strength can be calculated with data of thermal and electrical conductance of the capacitor, and agreement with observations is good. Breakdown fields nearing 10 MV/cm were observed in silicon dioxide on glass substrates. Maximum dielectric strength has been observed from -190°C to 70°C, for thicknesses from 2900 Å to 50 000 Å and for silicon oxides of varying composition.

Self-healing capacitors make possible simple and reliable investigation of thin film conduction up to the maximum field. These capacitors make it possible also to probe at low voltages into the basic nature of breakdown processes. In silicon oxide thin films, the quasi-exponential leakage current increase with voltage and thermal instability caused by Joule heating explain the destruction on breakdowns, and the two separate effects are connected by a simple theory.

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References
