Complete Method for E_{bd} Correction by Series Resistance Characterization

David K. Monroe and Scot E. Swanson

Reliability Physics Department, Organization 1728, MS/108
Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185-1081

Tel: (505) 844-9510 & 844-3729 Fax: (505) 844-2991

Email: dkmonro@sandia.gov & swansose@sandia.gov

RECEIVED
OCT 19 1998

OSTI

Abstract- We have developed a semi-automated method for determining the series resistance profiles of dot capacitors and for obtaining corrected oxide fields at breakdown. This method is based upon a least-squares-fit of IV data, obtained from a voltage-ramp test, to the Fowler-Nordheim leakage model. The profiles provide insight into the general characteristics of series resistance. Certain features of the profiles can be associated with charge trapping and the onset of oxide breakdown.

Keywords- capacitor, MOS, breakdown, leakage, Fowler-Nordheim.

I. Introduction

Monitoring the quality of silicon oxide requires that the oxide field at breakdown, E_{bd} , be reliably determined for the test structures in question. However, series resistance in the test structures can yield values of E_{bd} that are excessively high and this effect can prevent the proper characterization of the oxides.

Series resistance effects have been noted in high-frequency capacitance-voltage (HFCV) testing, and methods of analysis have been developed for determining the effects on the data obtained [1, 2]. Series resistance effects are perhaps most familiar in Vramp testing, in which a ramped stressing voltage is applied to the oxide until breakdown is detected (by JEDEC or ASTM criteria), or until a preset maximum current ("compliance") has been attained [3-7]. The focus of this paper will be on the second type of test.

We routinely test oxide monitor lots, each consisting of eight 6-inch dot capacitor wafers with oxide thicknesses of about 12 nm. Each wafer is processed in a different vertical thermal reactor (VTR) and serves to monitor that VTR for the presence of contaminants. Measurements obtained are high-frequency capacitance-voltage (HFCV) sweeps and wafer-level voltage-ramp (Vramp) tests. Both are based on JEDEC standards [8].

The IV data obtained during Vramp testing show evidence of series resistance. This appears as a leveling or flattening of the IV curve before the test algorithm detects breakdown. Figure 1 illustrates this, with the measured current (I_{meas}) shown in the bold line and the "ideal" or Fowler-Nordheim tunneling current (I_{fnfit}) shown in the thin line. The latter was obtained using the method described below. Both are plotted versus the measured stressing voltage.

Note that the two curves match very closely in the range of about 8 V to 14 V. This corresponds to the region

of the curve that is dominated by FN leakage. The region below 8 V is dominated by noise in the current measuring apparatus. The region above 14 V is dominated by series resistance and its tendency to "clamp" the leakage current. The departure of the bold line from the thin line is interpreted as being caused by series resistance in the test structure. This is indicated by the bold arrow in the plot, which represents the voltage, V_{series} , across that resistance.

Fig. 1. Current versus Voltage (IV Data) for a 12-nm Aluminum Dot Capacitor

Series resistance originates with the materials used to form the test structure, and in the layout for that test structure. The substrate is the most important source, particularly if the doping concentration is low. The use of polysilicon as the top-side contact can also contribute. Series resistance can be reduced by applying metallization to the back side of the wafer, allowing better electrical contact with the prober circuitry. The use of metal rather than polysilicon for the top-side contact can also reduce the effect [6].

The characterization of gate oxides with respect to E_{bd} is nearly universal. Therefore, it is imperative to seek a method of analysis which will result in values of E_{bd} that have been corrected for the effects of series resistance. Likewise, it is imperative to develop a method for characterizing the entire wafer for series resistance, adding to the list of parameters of general interest for wafer-level reliability testing.

This paper will describe an analytical method for determining the series resistance profile of a single gate oxide test site. From the resistance profile it is possible to estimate E_{bd} corrections and to obtain a proper characterization of the site. Single-site characterization can be readily extended to wafer-level characterization, in which a wafer map of series resistance can be obtained. The authors are currently pursuing this application.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

II. Purpose

This paper describes a semi-automated method of analyzing and modeling series resistance in gate oxide test structures. It applies to V-ramp testing of polysilicon or aluminum dot capacitor structures with oxide thicknesses in the "thin" range, that is, with thicknesses greater than about 4 nm. This specifically excludes "ultra-thin" oxides, as well as any other insulating layers for which Fowler-Nordheim leakage does not dominate for the range of stressing voltages applied.

The method consists of performing a Fowler-Nordheim (FN) least-squares fit routine to an IV data set and estimating the series resistance as a function of applied voltage. The function $R_{\text{series}}(V_{\text{app}})$ is referred to as the series resistance profile, and can be used to estimate the corrected oxide field at breakdown. Examining many such profiles provides insight into the general characteristics of series resistance. It is of particular interest that certain features in the series resistance profile can be associated with the onset of oxide breakdown. This will be discussed in more detail at the end of the paper.

A number of assumptions underlie the analysis presented here. Largely they are based upon the current understanding of leakage current mechanisms in insulators. Some are assumptions made to simplify the analysis required to obtain the series resistance from experimental data:

(1) Fowler-Nordheim (FN) leakage dominates over other types of leakage. This is generally true for oxides in the thickness range being considered and for stressing voltages normally applied to such oxides in a V-ramp test [9].

(2) The test structure is electrically equivalent to an ideal capacitor in series with a resistor. Figure 2 illustrates the equivalent circuit. This is a simplification, because the resistance is actually distributed, in a non-uniform way, across the area of the test structure [6].

(3) The series resistance depends only upon the leakage current and takes the form of a simple function, $R_{\text{series}}(I_{\text{fn}})$. In fact it will be seen that R_{series} is time-dependent, as well, due to the effects of charge trapping in the oxide.

Fig. 2. Equivalent Circuit Assumed for MOS-Capacitor Showing Applied Voltage, Oxide Voltage, and Series Resistance Voltage.

In the Fowler-Nordheim tunneling or leakage regime, the leakage current density, J_{fn} , resulting from an applied oxide electric field, E_{ox} , is given by the following model:

$$J_{\text{fn}} = \alpha E_{\text{ox}}^2 \exp(-\beta/E_{\text{ox}}).$$

This model has both a theoretical and an empirical basis. The Fowler-Nordheim leakage current can be obtained from the leakage current density by

$$I_{\text{fn}} = J_{\text{fn}} A_{\text{ox}},$$

where A_{ox} is the area of the oxide. The resulting expression for the leakage current in terms of the oxide electric field is then given by:

$$I_{\text{fn}}(E_{\text{ox}}, \alpha, \beta) = A_{\text{ox}} \alpha E_{\text{ox}}^2 \exp(-\beta/E_{\text{ox}}).$$

The variables α and β are the Fowler-Nordheim model parameters. Theory indicates that they should be derivable from the following expressions:

$$\alpha = [q^3/(8\pi h)]/(\Phi_B m^*),$$

$$\beta = [(8\pi 2^{1/2})/(3qh)](m^*/m)^{1/2} \Phi_B^{3/2}.$$

Here q is the charge of the electron, h is Planck's constant, Φ_B is the barrier height in eV, and m^* is the effective mass of the electron [7].

The values of α and β which are obtained empirically, by fitting the FN model to experimental data, are in general agreement with the theoretical values, but show some departure due to the local field factor. An enhanced version of the theory has been proposed, which has the same general form as the theoretical version [10]. Thus, the model still takes the same form

$$J_{\text{fn}} = \alpha E_{\text{ox}}^2 \exp(-\beta/E_{\text{ox}}),$$

but the values of α and β are assumed to absorb the field factor, as well as other factors not appearing explicitly in the model.

Empirical values for α and β can be obtained from any set of IV data for which FN behavior is evident and for which a good fit is achievable. The parametric model above is assumed and numerical fitting routines are applied. The values obtained are usually found to be near [11]:

$$\alpha = 1.6 \times 10^{-6} \text{ A/V}^2, \quad \beta = 2.2 \times 10^8 \text{ V/cm}.$$

III. Method of Analysis

The method of analysis being used can be applied to any IV data set showing the characteristics of FN leakage. The FN model is assumed to apply to the entire voltage range, as long as the current exceeds the noise threshold, I_{thresh} (typically above 1×10^{-9} A). All other effects are assumed to be due to series resistance [3-6, 9].

The applied voltage is assumed to be distributed across a leaky capacitor and a series resistor:

$$V_{app} = V_{ox} + V_{series}$$

In the low-current region ($I_{fn} \approx I_{thresh}$) the voltage across the series resistance is negligible, so this reduces to:

$$V_{app} \approx V_{ox} = t_{ox} E_{ox}$$

where t_{ox} is the thickness of the oxide.

By direct substitution, the FN model for the leakage current density, J_{fn} , can be expressed in terms of the oxide field, $E_{ox} = V_{app}/t_{ox}$. The resulting expression can then be modified to take the form:

$$\ln(J_{fn}/E_{ox}^2) = -\beta/E_{ox} + \ln(\alpha).$$

Defining the variables $x = 1/E_{ox}$ and $y = \ln(J_{fn}/E_{ox}^2)$ converts this to the linear expression:

$$y = -\beta x + \ln(\alpha).$$

Thus, a least-squares-fit analysis of the IV data will yield estimates of the FN model parameters, α and β . Using these values in the FN model allows the "ideal" IV curve to be plotted along with the actual data.

The process of performing the fit involves the selection of an initial voltage (current) at which the fit is to begin and a final voltage (current) at which the fit is to end. The initial voltage must be chosen so as to correspond to a value of the leakage current which is above the noise threshold, I_{thresh} . The final voltage should be chosen to include as many of the IV data pairs as possible, without extending into the region where the actual IV data departs from the FN model. This region is usually evident from the IV plot itself.

The selection of the initial and final voltages, as well as the quality of the fit, can be checked by a visual inspection of the plot of actual and "ideal" data. This is illustrated in Figure 1, where the bold line (actual data) and thin line ("ideal" data) are plotted together and show very good overlap between about 8 to 14 V.

Most importantly, the quality of the fit can be monitored by checking the value of the coefficient of determination, r^2 , which is obtained as part of the least-squares-fit routine. This value indicates how well the FN model fits the actual IV data. For a perfect fit the value of r^2 should be unity, while for a very good fit it should be greater than 0.9. For the IV data files forming the basis of this report it is often possible to obtain values of r^2 that are better than 0.99 and sometimes better than 0.999.

At higher currents, the series resistance is no longer negligible, so the FN model must be combined with a series resistance model. The distribution of the applied voltage must then be represented by:

$$V_{app} = V_{ox} + V_{series}$$

where V_{series} is given by:

$$V_{series} = I_{fn} R_{series}$$

The latter equation is the defining relationship for series resistance.

With these results in hand, V_{series} can be found using:

$$V_{series} = (V_{app} - t_{ox} E_{ox}),$$

and R_{series} can be found using:

$$R_{series} = (V_{app} - t_{ox} E_{ox}) / I_{fn}.$$

The corrected value of E_{bd} is then obtained using:

$$E_{bd,corr} = (V_{app} - V_{series}) / t_{ox}.$$

Note that the leakage current, I_{fn} , and the applied voltage, V_{app} , are measured directly. The oxide thickness, t_{ox} , is assumed to have been obtained independently (typically using HFCV data). The oxide field, E_{ox} , is calculated by numerically inverting the FN model equation for a given value of J_{fn} . The parameters α and β are assumed to have been obtained independently, using the least-squares-fit method for the low-current region, as described earlier.

IV. Evaluation of the Inverse Function

The model for Fowler-Nordheim leakage can be expressed as a function of oxide field, E_{ox} , with two fitting parameters, α and β :

$$I_{fn} = F(E_{ox}; \alpha, \beta) = A_{ox} \alpha E_{ox}^2 \exp(-\beta/E_{ox}).$$

Its corresponding inverse function can be defined by

$$E_{ox}(I_{fn}) = G(I_{fn}; \alpha, \beta),$$

which is also parameterized with respect to α and β . For a given I_{fn} , it can be evaluated to obtain the corresponding E_{ox} .

Because of the nature of the function for I_{fn} , it is not possible to obtain a closed-form expression for the inverse function $G(I_{fn}; \alpha, \beta)$. Instead, for any given value of the current I_{fn} , an iterative numerical method must be used to obtain the corresponding value of E_{ox} . As a check, this value of E_{ox} can be substituted into the original equation modeling the Fowler-Nordheim leakage current to verify that the original value of I_{fn} is recovered.

Newton's method can be used to numerically evaluating $G(I_{fn}; \alpha, \beta)$. This begins with defining the function:

$$f(E_{ox}) = A_{ox} \alpha E_{ox}^2 \exp(-\beta/E_{ox}) - I_{fn}.$$

Obtaining the value of E_{ox} corresponding to a given value of I_{fn} is equivalent to finding E_{ox} such that $f(E_{ox})$ equals zero. Newton's method requires the derivative of $f(E_{ox})$ with respect to E_{ox} :

$$df/dE_{ox} = \alpha (2E_{ox} + \beta) \exp(-\beta/E_{ox}).$$

With these two expressions, the numerical iteration can be represented by:

$$E_{ox} \leftarrow E_{ox} - f(E_{ox}) / (df/dE_{ox}).$$

For any given value of E_{ox} , the right-hand side of the relation above is evaluated to obtain the next value of E_{ox} , as indicated by the arrow ($\leftarrow$). This iterative method can be applied repeatedly to any degree of convergence desired. In this way the value of the oxide field, E_{ox} , corresponding to a given value of the leakage current, I_{fn} , can be obtained for assumed values of the parameters α and β .

An alternative method also uses iteration, but is much simpler to use, because it does not require the derivative. The first step is to define the parameters:

$$z = \beta/E_{ox},$$

$$\xi = I_{fn}/(A_{ox} \alpha \beta^2).$$

Then the Fowler-Nordheim equation can be written as

$$\xi = z^{-2} e^{-z}.$$

This can be transformed to obtain

$$z = -\ln(\xi z^2).$$

The iteration is performed on the variable z as follows

$$z \leftarrow -\ln(\xi z^2),$$

for any given value of ξ (or, equivalently, I_{fn}). After z converges to its final value, z^* , to any specified degree of accuracy, the corresponding value of E_{ox} can be recovered:

$$E_{ox} = \beta/z^*.$$

V. Results of Analysis

The computer code we have developed to implement this procedure allows the user to perform off-line analysis of the IV data set obtained during Vrampt testing on a capacitor test structure. The code provides a series resistance profile and E_{bd} corrections for the data set. Human oversight and intervention are very useful in screening the data sets and assessing their usefulness for R_{series} analysis.

We have examined the IV data files for almost 70 oxide monitor lots with $t_{ox} \approx 12$ nm. There are eight 6-inch wafers per lot, so the total number of wafers is well over 500 in number. It has been observed that there are three general categories of IV plots to consider, those for which (1) breakdown occurs below I_{thresh} ; (2) breakdown above I_{thresh} is correctly detected by the algorithm, with no apparent series resistance; and (3) the current does exceed I_{thresh} , but breakdown is not properly detected by the Vrampt algorithm, with clear evidence of significant series resistance in the test

structure. For the first case, the breakdown is aberrant and no correction is possible. These occurrences are rare. For the second case, the breakdown is "nominal" and no correction is appropriate. These occurrences are fairly common.

It is the third case that is the focus of the analysis presented here. Figure 1 illustrates the effect of series resistance on the IV curve for a wafer ($t_{ox} = 12$ nm) in a typical lot. The bold curve represents the actual test data from a large aluminum dot capacitor on that wafer. The thin curve represents the corresponding "ideal" IV plot that would occur without the effects of series resistance being present. This curve was obtained from the actual data by performing a least-squares fit to the FN model, beginning at I_{thresh} (1×10^{-9} A) and extending for a voltage change of about 3 V.

Note that the actual data (bold line) falls short of the "ideal" data (thin line), because at higher currents the applied voltage is distributed across the oxide and the series resistance, as well. Comparing the two curves, and assuming that the discrepancy (illustrated by the bold arrow in Figure 1) is caused by series resistance in the test structure, provides the series resistance profile. This can be used to correct the oxide field at breakdown.

Table 1. shows the compiled results of detected and corrected fields at breakdown, for one site on each of the eight wafers in the selected lot. Note the presence of several abnormally high detected fields in the middle column. These are notably reduced by E_{bd} correction, as shown in the right-hand column.

Wafer Number	$E_{bd,detect}$ (MV/cm)	$E_{bd,corrected}$ (MV/cm)
2	16.7	10.1
4	9.2	9.2
6	10.5	10.5
8	17.4	11.1
10	12.5	11.7
12	12.2	11.2
14	5.1	5.1
16	14.2	12.8
Mean	12.2	10.2
Std dev	4.0	2.3

Table 1. Detected and Corrected E_{bd} Values

The mean values and standard deviations of the columns of oxide field values appear at the bottom of the table. The mean is adjusted from just above 12 MV/cm to just above 10 MV/cm, while the standard deviation is adjusted from 4 MV/cm to almost 2 MV/cm. Thus, the E_{bd} correction process tends to shift the distribution downwards, as expected, but also tends to tighten the distribution, as well.

A very high quality oxide would be expected to have a value of E_{bd} higher than 10 MV/cm. However, the oxides

being tested for this study did not begin as "prime" wafers, because they are produced for the purpose of monitoring VTRs for the presence of contaminants.

As a rule, the characteristic E_{bd} values for all such monitor wafers are comparable to the ones indicated above. The method for correcting breakdown voltage and field gives results which are consistent with direct observations of the IV plots and which yields values of oxide field that fit a much tighter distribution.

The series resistance profiles are interesting in their own right. Figure 3 illustrates two profiles (for wafers 2 and 8) from the lot being considered. In general it has been observed that R_{series} initially increases with applied voltage, usually in a ramp-like fashion. It then attains a maximum value, which generally occurs before the breakdown voltage is reached.

The maximum value of R_{series} , which is in the range of 150-200 ohms for the two curves in Figure 3, could be regarded as a characteristic series resistance for the test structures in question. However, as noted above, it generally occurs before breakdown voltage is attained. Therefore, it is not the value used for correcting the value of E_{ox} at breakdown.

Another observation pertaining to the maximum value of R_{series} has an interesting implication. This maximum generally occurs just before the voltage at breakdown is attained. It could therefore be considered a precursor to oxide failure. This is likewise suggested by numerous other test results for similar test structures. Whether this is of any practical value for a capacitor which is a component in a complex circuit remains to be seen.

After the value of R_{series} reaches a maximum, it then begins to decrease rapidly. This coincides with the occurrence of increasing leakage current in the oxide. The two series resistance profiles shown in Figure 3 suggest that this decrease is approximately exponential. In general it is observed that R_{series} approaches an asymptotic value. (This

value is just below 100 ohms for both of the curves shown in Figure 3.) This asymptote could be regarded as a characteristic value of R_{series} for the test structure under consideration. However, it is attained well after the breakdown voltage has been reached and is not the value required for correcting E_{bd} .

In some cases, irregularities are observed in the series resistance profiles. These appear as zig-zags upon otherwise smoothly varying R_{series} curves. One of the curves in Figure 3 shows this effect. Previous studies have associated these with charge trapping and the resulting degradation of the oxide [6]. This is the time-dependent effect in the series resistance that was referred to earlier.

VI. Summary and Conclusions

We have described a semi-automated method for analyzing IV data obtained from Vramp testing of dot capacitors. This method uses least-squares fitting to the Fowler-Nordheim model to determine the series resistance profile of the capacitor, and the corresponding correction to the oxide field at breakdown.

The profiles provide some insight into the nature of oxide breakdown. The forms and shapes of these profiles are reasonably consistent and provide at least three characteristic values of R_{series} that may be of significance in better understanding the oxide breakdown.

The value of R_{series} at breakdown is the most immediately useful of all, because it is used to correct the oxide field at breakdown. The asymptotic value of R_{series} is clearly important as a property of the post-breakdown phase. It has received the attention of at least one previous study [6]

Finally, the maximum value of R_{series} is also an important property, but for the pre-breakdown phase. Numerous series resistance profiles suggest the possibility that attaining this value could serve as precursor to oxide breakdown. However, it is not apparent how this effect could be utilized outside the testing environment. This will be the topic of additional study.

Acknowledgments

The authors would like to acknowledge the assistance of Danelle Tanner, from whom the original least-squares fit approach was obtained. They would also like to acknowledge William Miller and William Filter, as well as Danelle Tanner, all of whom provided tremendous assistance in editing this paper.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

References

- [1] K. Iniewski, A. Balasinski, B. Majkusiak, R. B. Beck, A. Jakubowski, "Series Resistance in a MOS Capaci-

tor with a Thin Gate Oxide", *Solid-State Electronics*, Vol. 32, No. 2, 137 (1989).

[2] K. Iniewski, A. Balasinski, A. Jakubowski, B. Majkusiak, R. B. Beck, K. Grigorov, "Series Resistance Influence on High-Frequency C-V Characteristic of MOS Structure", *Electron Technology*, 20, 3/4, 101 (1987).

[3] J. S. Neely, "Measurement and Analysis of Breakdown Field on Thin Oxide MOS Capacitors with High Series Resistance", 1991 WLR Final Report, 111 (1991).

[4] F. Pio, L. Ravazzi, C. Riva, "Influence of series resistance in oxide parameter extraction from accelerated tests data", *Microelectronics Journal*, 24, 445 (1993).

[5] F. Pio, L. Ravazi, C. Riva, "Series Resistance Effects in Thin Oxide Capacitor Evaluation", *IEEE Electron Device Letters*, Vol. 13., No. 10, 544 (1992).

[6] F. Pio, "Sheet resistance and layout effects in accelerated tests for dielectric reliability evaluation", *Microelectronics Journal*, 27, 675 (1996).

[7] E. Wu, S. H. Lo, W. Abadeer, A. Acovic, D. Buchanan, T. Furukawa, D. Brochu, R. Dufresne, "Determination of Ultra-Thin Oxide Voltages and Thickness and the Impact on Reliability Projection", 1997 IRPS, 184 (1997).

[8] Sandia National Laboratories and Hewlett-Packard Company, "SWORD, Sandia Wafer-Level Reliability Software for HP4062UX Parametric Test Systems", Sandia Corporation, 1996.

[9] S. M. Sze, *Physics of Semiconductor Devices*, Second Edition, John Wiley & Sons, New York (1981).

[10] H. A. Schwettman, et al., *Journal of Applied Physics*, 45, 914 (1974).

[11] R. Degraeve, J. L. Ogier, R. Bellens, Ph. Roussel, G. Groeseneken, H. E. Maes, "On the field dependence of intrinsic and extrinsic time-dependent dielectric breakdown", 1996 IRPS, 44, (1996).