Analysis of the Impact of Linewidth Variation on Low-K Dielectric Breakdown

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Abstract— Low-k time-dependent dielectric breakdown (TDDB) has been found to vary as a function of metal linewidth, when the distance between the lines is constant. Modeling requires determining the relationship between TDDB and layout geometries. Therefore, comb test structures have been designed and implemented that vary pattern density and linewidth independently in 45nm technology. Models are computed to estimate TDDB as a function of linewidth, and the cause of variation in TDDB behavior is investigated.

I. INTRODUCTION

Low-k time-dependent dielectric breakdown is considered to be one of the most important reliability issues during Copper/Low-k (Cu/low-k) technology development and its qualification. Lower breakdown field strengths of porous low-k materials, the susceptibility of low-k materials to mechanical damage by chemical mechanical polishing (CMP), contamination due to photoresist poisoning, and copper drift are some of the reasons Cu/low-k interconnects systems are vulnerable to breakdown. Reduced supply voltage scaling with respect to feature size scaling compounds the problem and results in exponentially increasing electric fields among interconnects every technology generation. Time-dependent dielectric breakdown (TDDB) of damascene structures has to be assessed as a system of a dielectric, diffusion barrier, cap layer, and copper interconnect. An example of this system is shown in Fig. 1(a).

Backend dielectric reliability testing relies on comb structures, shown in Fig. 1(b). The comb structures create a lateral stress across the dielectric between the fingers of the comb, which are separated by the minimum distance design rule. A voltage difference, V , is applied to the comb, which creates a lateral electric field through the intra-layer dielectric.

Figure 1. (a) Cross-section of an example copper/low-k interconnect system (b) Comb test structure.

Figure 2. Example Weibull plot for comb test structures with four areas: 1X, 3X, 4.5X, and 9X.

Data are collected for a sample of comb structures. The data are ordered from shortest to longest breakdown time. Each time point is assigned a probability point, P_i , by partitioning the probability scale equally. An example is shown in Fig. 2.

The data is fit by a distribution, either the Weibull distribution or the Log-Normal distribution [1], in order to enable extrapolations to lifetimes at low percentiles [2]. The resulting data is then scaled to use conditions [3]-[5] and to the vulnerable area corresponding to the chip [6].

This paper looks at the variation in low-k dielectric breakdown times as a function of metal width, a parameter that is not supposed to impact failure rates. Metal width is the width of the Cu interconnect lines drawn on the mask. Any change in the actual linewidth on chip, from the linewidth drawn on the mask, will also cause a change in actual linespace between the interconnects. Note that in this work we use the term metal width and linewidth interchangeably. Similarly, we use the terms space and linespace interchangeably. We refer to the fraction of the area of interconnect lines on the mask to the fraction of the area of the mask as pattern density.

This paper begins with a summary of prior work on modeling variation in failure rates as a function of linewidth in Section 2. Section 3 describes the test structures that were used in this work, which were implemented on a 45nm test chip, and summarizes the TDDB measurement results. In Section 4 we consider several possible explanations of the observed variation in characteristic lifetime as a function of linewidth. Section 5 uses the results in Section 4 to create a model of characteristic

lifetime as a function of linewidth. Section 6 concludes the paper with a summary.

II. PRIOR WORK ON THE IMPACT OF LINWIDTH ON LOW-K DIELECTRIC BREAKDOWN

The two dominant models of dielectric lifetime, the E Model [3] and the $\sqrt{E}$ Model [4], [5], relate time-to-failure (TF), to electric field. In both models, the only factor that determines TF for structures manufactured using the same low-k dielectric is the electric field (E). Electric field in backend structures is a function of the distance between the interconnect lines, termed linespace (S),

$$E = \frac{V}{S}. \quad (1)$$

In our test structures and in prior work on this topic, S is constant, and only the linewidth is varied. In prior work, with 180nm technology, experimental data indicated that time-to-breakdown was a function of linewidth [7]. Analysis found that the difference in time-to-breakdown was due to a physical difference in the distance. The data was analyzed to determine an explanation for the difference in distance. The explanation that best matched the data was microloading in etch [7]. The microloading effect was explained as a sensitivity of etch rate to pattern density [8], [9].

The SEM results were then used to model variation in distance between the lines as a function of etchable area. Using the data, a model of lifetime as a function of linewidth that matched the data well was found [7]. However, the test structures used to analyze the impact of metal linewidth confounded the impact of linewidth with pattern density, as can be seen in Fig. 3. Fig. 3 shows that whenever linewidth is increased, while keeping linespace constant, the pattern density also increases.

Hence, although the theory associates the time-to-breakdown difference with pattern density, we could not conclusively verify that pattern density, rather than linewidth, produced the time-to-breakdown difference. This paper aims to distinguish between these two factors.

Figure 3. Test structures that vary both linewidth and density concurrently (top view). Both the test structures have the same line space.

Figure 4. A test structure pair that can distinguish between the impact of density and linewidth (top view). Both the test structures have different linewidths but the same pattern density.

III. TEST STRUCTURE DESIGN AND RESULTS

We have designed test structures that vary metal linewidth and density separately, with the aim to distinguish the impact of linewidth and density. Two of the test structures are shown in Fig.3. Two other test structures have the same density and are shown in Fig. 4. One has non-uniform linewidth, with thin and wide lines that match those in Fig. 3.

We use the following terminology. The structure with minimum linewidth is referred as 1X, since the drawn width of the lines is 1X. The structure with linewidths that are N times the minimum linewidth is referred as NX. We have 3X and 5X test structures. The test structure with non-uniform linewidth is referred as 1X/5X, since one of the combs has 1X linewidth and other has 5X linewidth. Note that 1X, 3X and 5X test structures have different linewidths, but the same linespace on the mask. Test structures 3X and 1X/5X have the same pattern density.

If TF is a function of density, then TF should be the same for the two test structures in Figure 4. On the other hand, if linewidth is the cause of the TF difference, then there will be a difference in TF distributions for the two structures. Furthermore, TF of the non-uniform structure in Fig. 4 should be predictable using TF distributions of the two test structures in Fig. 3 that match the linewidths of the fingers of the non-uniform structure, using area scaling, combined with the method we have proposed to predict the failure rate when there are two independent failure mechanisms [10], [11].

Fig. 5 shows the failure rate distribution for the test structures with 1X, 3X, and 5X linewidths. These test structures vary both linewidth and density.

Figure 5. Time-to-failure distributions for test structures with 1X, 3X, and 5X linewidths. 90% confidence bounds are added for the 1X test structure.

Note that for the test structures in Figure 5, only the linewidth and the pattern density are varied and the distance between the lines has remained constant. The characteristic lifetime (x-intercept in Figure 5) increases with an increase in linewidth, with the structure with 5X linewidth showing the largest characteristic lifetime.

Fig. 5 also shows a model and confidence bounds for the 1X linewidth data set, indicating that the changes in the characteristic lifetime cannot be attributed to random variation. The model was computed based on data from 1X, 3X, 4.5X, and 9X area test structures, using area scaling to find slope of Weibull curve, β , and an analysis of the Weibull curves to extract random die-to-die variation [10],[11]. The improvement in characteristic lifetime for wide lines is statistically significant.

Fig. 6 compares data from the non-uniform 1X/5X structure with the 3X structure, which matches its density. Their failure rate curves do not match. Consequently, density does not appear to be a major factor causing a difference in lifetime. We also checked if the data from the 1X and 5X models can be combined to predict the results for the non-uniform 1X/5X structure. As can be seen from Fig. 7, the model and the data do not match. For more information on Fig. 7, see the Appendix and [10],[11].

Figure 6. Failure rate distribution comparison for structures with equal density.

Figure 7. Predicted failure rate for the 1X/5X structure, based on data from the 1X and 5X structures.

Figure 8. The manufactured shift in linewidth as a function of linewidth on the mask. The light grey dots correspond to the non-uniform test structure and the black dots correspond to the uniform test structures. The model is computed with regression.

IV. ANALYSIS OF POTENTIAL CAUSES OF VARIATION

In this section, we consider some possible explanations for variation in characteristic lifetime as a function of either linewidth or density.

A. Variation as a Function of Printed Geometry

Manufactured geometries were collected for our structures using scanning electron microscopy. The data is shown in Fig. 8.

In this graph, we define the linewidth difference as

$$\Delta W = W_{ACTUAL} - W_{DRAWN} \quad (2)$$

In Fig. 8 grey dots correspond to the non-uniform test structure and give the ΔW for the 1X comb and the 5X comb on the 1X/5X test structure. The black dots correspond to the uniform test structure with 1X, 3X, and 5X linewidths. The graph indicates that the narrow lines are wider than drawn, and the wide lines are narrower than drawn. We now turn to two potential explanations for variation in the printed linewidth: lithography and etch.

B. Lithography

The aerial image of a test structure varies with pattern density because of the optical proximity effect. The optical proximity effect is a function of focal depth and pitch. The radius of influence is around 400nm for an illumination system with a wavelength of 193nm. Hence, the optical proximity effect can influence the narrow lines, but is less likely to influence the wider ones. It tends to increase the linewidths of dense structures, depending on exposure dose. The narrow linewidths are the least dense structures, and therefore the manufactured linewidth difference (in Fig. 8) should be the most negative. Our data is the opposite, and inconsistent with the optical proximity effect.

Figure 9. The manufactured line height as a function of linewidth. The black and grey dots correspond to the uniform and non-uniform test structures, respectively. The model is computed with regression.

C. Etching

Etch rate and etch selectivity have been shown to be strongly dependent on pattern density. Previous models have established a link between the line space, linewidth, etch rate, and mean-time-to-failure (MTTF) [7]. These models use Mogab's model [8] that predicts a decrease in etch rate with an increase in linewidth. However our dataset shows variation in the height of the structures. This is summarized in Figure 9. This is because the process uses a timed etch, rather than an etch stop layer. The data in Fig. 9 shows a correlation between linewidth and line height. Based on this data we can assume that the line height is proportional to the etch rate. A model was computed for etch rate, and is shown in Fig. 10.

Pattern density causes spatial variation in etch rate by changing the concentration of reactants in areas with different pattern densities, as different features compete for reactants over short distances [12]. Taylor *et al.* [13] and Abrokwhah *et al.* [12] report a decrease in etch rate with increasing pattern density. Our test structures show an increase in etch rate with increasing pattern density, as in [14], [15], if there is any relationship at all, opposite to the trend reported in [12], [13].

Aspect ratio dependant etching (ARDE) manifests itself in submicron feature sizes having high aspect ratios (feature height/feature width). In the presence of ARDE, higher aspect

Figure 10. The etch rates for test structures were found to vary as a function of aspect ratio, showing ARDE. The aspect ratio is computed using measured data. The black dots and grey dots correspond to the uniform and non-uniform structures, respectively. The model is computed with regression.

Figure 11. The variation in linewidth in the fabricated chip as a function of aspect ratio. The black dots and lines correspond to the uniform test structures, and the grey dots correspond to the non-uniform test structure. The model is fit by regression.

ratio trenches etch slower [16]. Fig. 10 shows the etch rates for our test structures, along with their aspect ratios.

When the etch rate increases with trench size, this indicates that the process is chemically-controlled. Ion bombardment is not controlling the etch, but rather the concentration of etchant species entering the trench increases with increasing trench width. Therefore, as the trench width increases, more etchant can enter the trench (since etchant arrives at random angles), thereby increasing the etch rate [12], [16].

Hence, it appears that the etch rate is composed of two different etch rate components, the lateral etch rate and the vertical etch rate, both of which depend on aspect ratio. The impact of the lateral component on line width as a function of aspect ratio is as illustrated in Fig. 11.

The trend observed in the actual linewidths can be attributed to the lateral component of etch rate. If we take the line heights as an indicator of vertical etch rate, then the line heights indicate that the vertical etch rate decreases with increasing aspect ratio, while the lateral etch rate increases. The difference in linewidths, attributed to ARDE, partly explains the data in Figure 8 and the increase in TF with linewidth.

D. Variation as a Function of Electric Field Enhancement

A potential cause of variation in characteristic lifetime is electric field enhancement due to fringing effects.

Finite element simulations were carried out using ANSYS to determine the effect of geometry on electric field. Finite element simulations show that high electric field intensities are observed at bends and tips. This is consistent with results in the literature [17].

The locations of high electric field in finite element simulations coincide with vulnerable locations in the Cu/Low-k dielectric structure. Specifically, after formation of the trench, barrier metals are blanket deposited, followed by the deposition of a Cu seed layer and Cu deposition via electroplating. After Cu deposition via electroplating, CMP is carried out to remove the excess Cu covering the dielectric. The difference in hardness between the barrier layer, the soft Cu layer, and the

Figure 12. Maximum electric field at the midpoint between the lines vs. the scale factor that accounts for the difference in distance line space between actual and ideal structures. The black dots and grey dot correspond to the uniform and non-uniform structures, respectively. The model is computed with regression.

softer low-k dielectric layer, can lead to an uneven profile along the top edge of the trench. This uneven profile, along with high electric fields at the corners of the trench, can trigger Cu diffusion and lead to breakdown. In the literature, breakdown sites have been observed around the corners of the trenches [18], [19].

The electric field distribution should indicate the potential defect sites in the dielectric. However, the exact value of the maximum electric field is determined by the corner rounding at the corners, as noted in [19]. Our simulation results show that the maximum electric field at the corners does not follow any particular trend as linewidth increases. Hence, the role of the maximum electric field at the corners is excluded in this analysis. We compute the peak electric field intensities in the bulk of the dielectric (along a line centered between the interconnect lines) as a function of linewidth.

In these simulations, the physical dimensions of the lines were used. If the distance between the lines were to determine the maximum electric field for a fixed applied voltage, then the maximum electric field, E_{FEM} , would relate to the change in width, ΔW , as follows

$$E_{FEM} = \frac{S_{DRAWN}}{S_{DRAWN} - \Delta W}. \quad (3)$$

S_{DRAWN} is the drawn linespace and $S_{DRAWN} - \Delta W$ is the actual linespace. This relationship is shown in Figure 12. Figure 12 shows that the maximum electric field in FEM simulations is primarily a function of distance between the lines for the uniform structures. It is not a function of distance for the non-uniform structure, because the wide lines are not equally spaced between the narrow lines. Therefore, the maximum electric field is a function of the minimum spacing between the lines. If we take into account the non-uniform spacing between the lines, there is a direct relationship between electric field and (3), as illustrated in Figure 13. This shows that there is no unexpected field enhancement.

Figure 13. Maximum electric field at the midpoint between the lines vs. the scale factor for the shift in distance between the lines, accounting for the fact that the non-uniform structure has non-uniform line space. The black dots and grey dots correspond to the uniform and non-uniform structures, respectively. The model is computed with regression.

V. MODELING CHARACTERISTIC LIFETIME

Variation in width can potentially explain the observed difference in lifetime caused by ARDE.

Characteristic lifetime is assumed to be a function of electric field, E , in the dielectric. The electric field is a function of the distance between the lines. For a pitch, P , then the space, S_{ACTUAL} , is

$$S_{ACTUAL} = P - W_{ACTUAL}. \quad (4)$$

Since,

$$P = W_{DRAWN} + S_{DRAWN}, \quad (5)$$

we have that

$$S_{ACTUAL} = S_{DRAWN} - \Delta W. \quad (6)$$

The electric field is proportional to $1/S_{ACTUAL}$, as noted in (1). Using (1) we have,

$$\ln \eta = A + \frac{B}{S_{DRAWN} - \Delta W} \quad (7)$$

for the E model, and

$$\ln \eta = A + \frac{B}{\sqrt{S_{DRAWN} - \Delta W}} \quad (8)$$

Figure 14. Model of the characteristic lifetime as a function of the measured value of characteristic lifetime using regression based on (a) $1/(S_{DRAWN} - \Delta W) = 1/S_{ACTUAL}$ for the E Model and (b) $1/\sqrt{S_{DRAWN} - \Delta W} = 1/\sqrt{S_{ACTUAL}}$ for the $\sqrt{E}$ Model. The black dots correspond to the uniform test structure, from which the model is constructed. Based on this model, the 2σ confidence bounds are computed. The grey dot corresponds to the non-uniform test structure.

for the $\sqrt{E}$ model.

We use the characteristic lifetime data to find the best fit for A and B using only the data from the uniform structures. The results are shown in Fig. 14.

We now use the models, and computed constants, A and B, to determine a predicted lifetime for the non-uniform structure, which has non-uniform actual linespace. This structure is equivalent to two structures in parallel, with the measured linespace, and half of the area.

To do this we know that for the Weibull distribution, the cumulative probability density function is

$$P(t) = 1 - \exp\left(-\left(\frac{t}{\eta}\right)^\beta\right). \quad (8)$$

From the Poisson distribution, the cumulative probability density function is related to defect generation as follows

$$P(t) = 1 - \exp(-\lambda(t)A). \quad (9)$$

Combining (8) and (9), we have a computed defect generation function:

$$\lambda(t) = \frac{1}{A} \left(\frac{t}{\eta}\right)^\beta \quad (10)$$

which produces $d(t) = \lambda(t)A$ as a function of time.

For each of the measured linespaces, the model can be used to compute characteristic lifetimes η_1 and η_2 for the test structures with area A. The two test structures have the same shape parameter, β , which was computed in [10],[11]. The

combined defect generation function, $d(t) = \lambda_1(t)A/2 + \lambda_2(t)A/2$, is

$$d(t) = \frac{1}{2} \left[\left(\frac{t}{\eta_1}\right)^\beta + \left(\frac{t}{\eta_2}\right)^\beta \right]. \quad (11)$$

Substituting into (9), we have the following joint cumulative probability density function

$$P(t) = 1 - \exp\left(-\frac{1}{2} \left[\left(\frac{t}{\eta_1}\right)^\beta + \left(\frac{t}{\eta_2}\right)^\beta \right]\right). \quad (12)$$

The characteristic lifetime, η , of the joint structure is

$$P(\eta) = 62.5\%. \quad (13)$$

Combining (12) and (13), we have

$$\left(\frac{\eta}{\eta_1}\right)^\beta + \left(\frac{\eta}{\eta_2}\right)^\beta = 2. \quad (14)$$

which results in

$$\eta = \left[\frac{2}{\frac{1}{\eta_1^\beta} + \frac{1}{\eta_2^\beta}} \right]^{1/\beta}. \quad (15)$$

Figure 14 shows the predicted values of the characteristic lifetime based on (15) for both the E and $\sqrt{E}$ models. It can be seen that the model matches the data reasonably well.

VI. CONCLUSIONS

Test structures have been designed to model the impact of metal linewidth and pattern density on the behavior of TDDb. The test structures vary both pattern density and linewidth independently to enable separation of the impact of these factors. TDDb behavior is found to be dependent on aspect ratio dependent etching, which modulates the linewidths in printed structures and causes the distance between fingers of a comb structure to be non-uniform. Characteristic lifetime has been modeled as a function of the line space, and for the case where the line space is non-uniform. A good fit was obtained for the experimental data.

APPENDIX

In order to generate a Weibull plot for the combination of the two structures, we need to compute a defect generation function, $\lambda(t)$. We use the cumulative Weibull distribution in (8) and the cumulative Poisson model in (9) to obtain $\lambda(t)$ in (10).

Let's suppose that the test structure area is A . Then the defect generation functions for the 1X and 5X structures are

$$\lambda_{1X}(t) = \frac{1}{A} \left(\frac{t}{\eta_{1X}} \right)^{\beta_{1X}} \quad (16)$$

and

$$\lambda_{5X}(t) = \frac{1}{A} \left(\frac{t}{\eta_{5X}} \right)^{\beta_{5X}}. \quad (17)$$

The total number of defects at any time is $\lambda(t)A$. Therefore, the number of defect for the combined structure with $A/2$ of 1X and $A/2$ of 5X is

$$\lambda(t)A = \lambda_{1X}(t) \frac{A}{2} + \lambda_{5X}(t) \frac{A}{2}, \quad (18)$$

and the cumulative probability density function is

$$P(t) = 1 - \exp \left(-\frac{1}{2} \left(\left(\frac{t}{\eta_{1X}} \right)^{\beta_{1X}} + \left(\frac{t}{\eta_{5X}} \right)^{\beta_{5X}} \right) \right). \quad (19)$$

This equation is converted to Weibull format, as follows

$$\ln(-\ln(1-P(t))) = \ln \left(\frac{1}{2} \left(\left(\frac{t}{\eta_{1X}} \right)^{\beta_{1X}} + \left(\frac{t}{\eta_{5X}} \right)^{\beta_{5X}} \right) \right). \quad (20)$$

Note that we have Weibull plots for 1X and 5X structures and for these plots

$$\ln(-\ln(1-P_{1X}(t))) = \ln \left(\left(\frac{t}{\eta_{1X}} \right)^{\beta_{1X}} \right) \quad (21)$$

and

$$\ln(-\ln(1-P_{5X}(t))) = \ln \left(\left(\frac{t}{\eta_{5X}} \right)^{\beta_{5X}} \right). \quad (22)$$

Hence

$$\begin{aligned} \ln(-\ln(1-P(t))) &= \\ \ln \left(\frac{1}{2} \exp(\ln(-\ln(1-P_{1X}(t)))) + \frac{1}{2} \exp(\ln(-\ln(1-P_{5X}(t)))) \right). \end{aligned} \quad (23)$$

Figure 7 is computed by interpolation at each point, t , in the Weibull plots for the 1X and 5X structures. Let

$$y_{1X} = \ln(-\ln(1-P_{1X}(t))) \quad (24)$$

be y-axis values from the Weibull plot for the 1X structure. Similarly, let

$$y_{5X} = \ln(-\ln(1-P_{5X}(t))). \quad (25)$$

Then, at any time point we compute

$$\ln(-\ln(1-P(t))) = \ln \left(\frac{\exp(y_{1X}(t))}{2} + \frac{\exp(y_{5X}(t))}{2} \right). \quad (26)$$

to generate Figure 7.

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