Reliability Challenges with Ultra-Low k Interlevel Dielectrics


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The adoption of ultra-low k dielectric materials in the pursuit of greater performance will pose reliability challenges quite unlike what we have previously experienced. The ultra-low k (ULK) dielectrics are completely different from the materials we have traditionally used. Unfortunately, the properties that make them desirable from an electrical point of view make them undesirable from a mechanical and environmental point of view. Low mechanical strength, low elastic modulus, rapid diffusion and susceptibility to dielectric breakdown are all characteristic of the ULK dielectrics. In this paper we review work we have performed in our laboratory to understand and characterize these new and temperamental materials.

1. Introduction

In order to obtain the performance gains that have been customary in the industry (Moore’s Law and derivatives), physical scaling or shrinking of the critical dimensions has been employed. However, it has become increasingly difficult if not impossible to continue on this path, and may not be feasible at all beyond the 65 nm “node”. Therefore, if we are to increase performance, we will need to rely on advances in materials, rather than aggressive geometry, to achieve our goals.

The first major effort in this direction was the introduction of Cu as a conductor material. It was not without its problems and surprises in both the areas of integration and reliability, and it took considerable time to incorporate into the industry. New fabrication techniques requiring entirely new concepts for semiconductor technology (electroplating for example) were necessary to make this a reality. After considerable trial and tribulation, we are now in a position to enjoy the fruits of our labor, but once again we have been stalled. Further advances will require the use of interlevel dielectrics (ILD) with a lower dielectric constant. (1)

It is important to realize that ultra-low k (ULK) dielectric materials are completely different from the SiO$_2$ based dielectrics we have used in the past. Perhaps most importantly, low-k dielectrics have much lower breakdown field strengths than traditional ILD materials. For instance, SiO$_2$ has an intrinsic breakdown strength of greater than 10 MV/cm, whereas the vast majority of the newer materials have breakdown strengths generally on the order of 5 or 6 MV/cm. There is a relationship between reliability and field strength, and the
dependence is closer to exponential than to linear.

(2) With use conditions climbing towards 1 MV/cm, the probability of there being a problem is raised considerably. Interlevel and intralevel time dependent dielectric breakdown (TDDB), never a problem in the past, now becomes something to consider.

In addition to lower breakdown strength, low k is associated with poor mechanical properties. The lower the k the lower the ultimate strength, and the lower the stiffness of the material (lower modulus of elasticity). Not only that, but these materials are prone to brittle fracture. (3)

The open structure of the low-k dielectrics also make them particularly susceptible to diffusion of the ambient into and through the dielectric. (4) By ambient, we mean whatever is in the immediate environment, particularly atmospheric. Water vapor and oxygen, both components of the ambient environment, are of interest because of the effect they can have on the properties of the dielectric and on the enclosed metal conductors. This can lead to a new class of failure mechanisms that were not important previously.

In this paper, reliability work performed in our laboratory will be reviewed with an emphasis on the special problems associated with the low-k dielectrics as compared to traditional ILD materials. TDDB, electromigration (EM), cracking and diffusion of water and oxygen will be discussed.

2. TDDB

Time dependent dielectric breakdown (TDDB) has, in the past, been a problem for gate dielectrics only. When SiO₂ based ILDs were employed, the breakdown strength was so high and the ILD thicknesses were so great that breakdown had never been a problem except in those cases where severe mis-processing may have compromised the structure. However, recent advances in chip design, made possible by advances in processing technology, have required the use of low-k ILD materials, coupled with Cu metallization with very aggressive design rules. Even though the operating voltage has been reduced significantly, to less than 1.5 volts in recent designs, the dimensions have been reduced to a point where much higher electric fields are now used that would never have been considered previously. For instance in the past when 3.3 volts may have been used with metal lines 1 μm apart embedded in glass with a breakdown strength of 10 MV/cm or more, now we can have 1.5 volts across a spacing of only 100 nm of ULK with a breakdown strength of perhaps 5 MV/cm.

One of the challenges is that none of the proposed low-k dielectrics behave anything like the previous SiO₂ based materials. In addition, each of the materials acts in a unique and peculiar manner. Therefore, not only can we not apply what we know from previous technologies to the new materials, but we cannot even use what we learn from studying one dielectric to learn about another.

One of the first things we learned is that intralevel behavior is quite different than interlevel behavior. Intralevel leakage is significantly higher than interlevel leakage for the same electric fields and TDDB performance is significantly worse. Additionally, the statistics of breakdown are quite different. The variance in the lifetime in intralevel breakdown is much greater than that for interlevel breakdown.

Such behavior strongly suggests that the leakage and the breakdown characteristics are both determined by interfaces that connect the metal conductors by an “imperfection”. One indication of the importance of these interfaces is that changing hard mask material has been shown to alter the initial leakage between combs and affect the lifetime significantly.

Table I Median initial leakage and median time to failure for interdigitated comb structures with ULK dielectric and two different hard masks

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Median Leakage</th>
<th>Median Lifetime</th>
</tr>
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<tbody>
<tr>
<td>Nitrided Oxide Hard Mask 0.1225 mm Space Wafer 1</td>
<td>30.3 nA</td>
<td>46 minutes</td>
</tr>
<tr>
<td>Nitrided Oxide Hard Mask 0.1225 mm Space Wafer 2</td>
<td>34.8 nA</td>
<td>2.5 hours</td>
</tr>
<tr>
<td>Nitrided Oxide Hard Mask 0.1400 mm Space Wafer 1</td>
<td>8.25 nA</td>
<td>8.67 hours</td>
</tr>
<tr>
<td>Nitrided Oxide Hard Mask 0.1400 mm Space Wafer 2</td>
<td>10.2 nA</td>
<td>6.68 hours</td>
</tr>
<tr>
<td>C Doped Oxide Hard Mask 0.1225 mm Space</td>
<td>5.58 nA</td>
<td>1.44 minutes</td>
</tr>
<tr>
<td>C Doped Oxide Hard Mask 0.1400 mm Space</td>
<td>1.54 nA</td>
<td>11.5 minutes</td>
</tr>
</tbody>
</table>
Since the ILD material itself was identical regardless of the hard mask, it is only logical to conclude that the interface made the difference in performance. Curiously, higher initial leakage was associated with better TDDB reliability, contrary to expectations although not unprecedented. (5) Samples with nitrided oxide exhibited approximately 6 times the initial leakage as those using the carbon doped oxide hard mask, yet the lifetimes were ~50 times longer.

This is contrary to “Common Sense”. One would expect that higher leakage should lead to shorter lifetimes. Therefore, it is common practice to use leakage measurements to evaluate the suitability of a material for use as an interlevel dielectric. Clearly, with ULK ILD materials, this cannot be done.

Reconciling this unusual behavior with commonly accepted models for TDDB is a challenge. It is one that need be met, since, unless we do so, we will be in the unenviable position of trying to control a very important property of a component of perhaps the most important contributor to the world’s economy without understanding it. This is a formula for surprises, which no reliability engineer wants to have. Furthermore, if we can understand in detail what determines the behavior of ULK dielectrics, we can then design procedures to accommodate it.

As an example, let us examine the possibilities in terms of the present uncertainty we have in predicting gate dielectric behavior, the well-known E vs. 1/E controversy that has raged for decades, although it has become somewhat overtaken recently by percolation models. (6) If the data we have obtained is extrapolated according to the E model, we find ourselves at the edge of acceptability, if not occasionally predicting dire consequences. If we apply the data to extrapolations according to the 1/E model, we find ourselves predicting lifetimes that rival the solar system in longevity. Clearly it is in our interest to resolve this issue.

Recently a simple model has been proposed based on the probability of a ballistic electron gaining enough energy before interacting with the dielectric to cause damage that will lead to breakdown. (2,7) It seems to account for much of what we observe and fortuitously predicts very long lifetimes at use conditions of a few volts. However, we cannot adopt such models without being more than just reasonably convinced of its correctness.

The results of our research in this area are presented in another paper in this conference (2) and will not be repeated here. Selfishly, there is great opportunity for scientific discovery and invention in this field as well as many unknowns that need to be resolved in order to use these materials with confidence. We are looking forward to the debates that will undoubtedly ensue.

3. Electromigration

At first thought there should not be any new issues concerning electromigration with ultra-low k dielectrics. Perhaps a case could be made that the weaker strength of the ULK dielectrics would provide less in the way of Blech Effect diffusion back force, but there is no clear indication that this has happened. Where things do become important, however, is in the adhesion of materials inherent in the ULK integration scheme to the upper surface of a conductor. (8)

In the damascene processing schemes necessary for the use of ULK materials, there is a problem where the top surface of a metal conductor cannot be covered with liner. Cu metal electromigration proceeds by interfacial diffusion. (9) The adhesion of the conductor (presumably Cu) to the liner is good, and this interface does not provide a pathway for electromigration. The top interface, however, is covered, in most schemes, with some kind of cap layer, or with a layer of ILD. (10) The adhesion across this interface is seldom as good as the adhesion of the metal to the liner. In some cases, it is actually quite poor.

![Fig.1 Schematic of conductor line indicating fast diffusion interfacial pathway](image)

Our research has shown that the rate of electromigration-induced void growth and lifetime, and therefore, the rate of interfacial diffusion is
determined by the adhesive strength across the interface. This is a relationship that just makes common sense, but it can also be arrived at more formally. In fact, we can see both theoretically and experimentally that the activation energy for diffusion as determined from electromigration experiments is linearly dependent on the “energy release rate” obtained from adhesion measurements. Both quantities can also be estimated from our knowledge of the chemistry of the interface. (8)

Electromigration can be effectively eliminated if this top interface is no longer active as a diffusion pathway, providing that we have a near-bamboo structure and, therefore, no opportunity for grain boundary transport. One way this can be accomplished is to deposit a suitable metallic cap that would tie up the interface. (11) We have experimented with a variety of metallic caps, and they all improve lifetime considerably over non-metallic caps. In particular the use of Ta/TaN (often employed as a liner material) and CoWP increase electromigration lifetime by more than an order of magnitude and increase the activation energy as compared to SiN.

The cap must do more than just slow down the diffusion of Cu. The cap material itself must not diffuse away, and it must also adhere well to the ILD. If it has a substantially higher resistivity than the conductor (almost a certainty) it cannot be too thick, lest the composite resistivity become too high for the application.

It has been demonstrated that a thin layer of CoWP satisfies these conditions admirably. Cu conductors covered with as little as 8 nm of CoWP essentially do not fail in experimentally accessible time frames at normal accelerated test conditions. Tests at extreme accelerations, where you can actually obtain data, have revealed an activation energy for diffusion of 2 to 2.4 eV which is suggestive of lattice diffusion. Extrapolations to any reasonable use condition indicate that if we were to employ a CoWP cap layer, electromigration failure ceases to be a reliability issue. In fact, the current density limitations will not be determined by electromigration, but by Joule heating only. It remains for a manufacturing process incorporating CoWP to be developed.

4. Mechanical Integrity

One of the cruelest tricks Mother Nature has played on us is that the mechanical strength and the dielectric constant appear to have a strictly inverse relationship. The elastic modulus appears to have a similar relationship. (13) As the electrical properties become more desirable, the mechanical performance suffers correspondingly.

The ULK ILD materials also tend to exhibit brittle fracture, even though they have very low elastic moduli. This leads to serious problems with dielectric cracking both during the processing and in applications that are subject to repeated thermal excursions.
The major reliability concern is cracking of the dielectric leading to possible rupture of the conductor as well as providing an entry for corrosive ambientssuch as moisture and oxygen. The driving force for cracking is a quantity known as the Energy Release Rate (ERR), \( G \), given for a soft film on a stiff substrate by

\[
G = \frac{\sigma^2}{E} h
\]  

(1)

where \( \sigma \) is the film stress, \( h \) is the thickness and \( E \) is the elastic modulus of the film. From Eqn. (1) we can see that the energy release rate is increased as the elastic modulus is reduced. Soft low-k dielectrics are, therefore, especially prone to cracking.

The propensity for cracking is highly dependent on geometry. One feature that is especially prone to cracking is a gap in between large plates of metal in a mode known as channel cracking. We have performed extensive experimental and theoretical modeling of relevant structures and have discovered that the worst case, the maximum value for \( G \) occurs when the gap width is approximately twice the metal film thickness.

The presence of softer dielectrics underneath the cracking layer will also increase \( G \), but the effect is much enhanced by the presence of the gaps. For instance, if the underlying dielectric is thickened, the maximum increase in \( G \) is about 100\%, whereas the presence of the optimum sized gap can increase \( G \) by nearly a factor of 30.

This knowledge should be used by designers to avoid layouts with similar features. On the other hand, such structures can be used to experimentally determine the relative resistance of various
materials under consideration to this potential failure mode by ensuring failure at a precise location and in a standard configuration.

5. Environmental Effects

There are two important features of low-k dielectrics that determine the response to the environment. For one, low-k dielectrics are generally quite permeable to ambient gases, most notably oxygen and water vapor. Diffusion of oxygen into the dielectric can cause oxidation damage to the enclosed Cu conductors, especially if the liner is imperfect. Water vapor has the added problem of severely weakening the dielectric and promoting insidious stress corrosion cracking.

Stress corrosion behavior for a glassy material is characterized in Fig. 8. Regions II and III are of little importance to reliability, since if we are in these regimes, the crack has nucleated and is propagating. We’re already in trouble. It is more important to eliminate the cracks altogether. The important quantity here is \( G_{th} \) or the threshold energy that is required to initiate a crack. This energy can be reduced significantly by the presence of water vapor. (15)

As water molecules are absorbed into the strained bonds at the crack tip, they reduce the cohesive strength of the dielectric which promotes cracking. In some cases, size constraints determines that the water molecules cannot reach the crack tip producing a condition known as steric hindrance which can significantly mitigate stress corrosion. However, with the open structures of low-k dielectrics, diffusion of water is generally quite rapid through the dielectric and we lose this possible advantage.

![Fig. 8 Schematic of a typical stress-corrosion cracking curve for glasses](image)

![Fig. 9 Threshold energy plotted as a function of the partial pressure of water vapor for different dielectric constant materials](image)
6. Concluding Remarks

The competing requirements of reliability and electrical performance have provided challenges in incorporating ULK ILD materials into high performance integrated circuit technologies. Furthermore, the properties of ULK dielectrics are completely different from the SiO$_2$ based materials traditionally used. Therefore, the learning we have gained over the past decades will not serve us in the near future. In the past we never had to deal with concepts such as TDDB of interlevel dielectrics, whereas now it is a significant problem. Most importantly, the predictive reliability models must be generated that can relate performance gained from accelerated tests to actual use conditions. In addition, these modeling and kinetic studies must be performed for each new material being considered as an ILD. This is a challenge that must be met.

7. Acknowledgements

The authors of this paper are all from one small group at the research facility in Yorktown Heights. We are but a small part of the large team that has worked to develop the materials that includes participants from East Fishkill, Burlington and other groups here at Yorktown. Unfortunately time and space do not permit acknowledging individual efforts, but thanks to these many contributors is in order.

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