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New method of probing barrier integrity and low-k stabilityChoong-Un Kim^{1,2}, D. M. Meng¹, W.-H. Bang¹, N. Michael¹, Y.J Park³, and L. Matz³¹Materials Science and Engineering, The University of Texas at Arlington, TX 76019, USA²Phone: 01-817-272-5497 email: choongun@uta.edu³Silicon Technology Development, Texas Instruments, Inc., Dallas, Texas 75243**1. Introduction**

With the continuing thrust toward nanoscale technology nodes for microelectronic devices, the realization of reliable interconnects is becoming increasingly difficult and poses critical technological challenges. In these technology nodes, the interconnects are required to be integrated with ultralow-k dielectrics yet allowed only a minimal thickness protective barrier layer. Such requirements, compounded by more aggressive processing conditions, makes the interconnect more susceptible to failures of various origins [1].

Equally challenging to the realization of reliable interconnects is the characterization of the structural stability of ultralow-k dielectrics and barriers. Even a small change in the stability of the ultralow-k or the barrier can have a significant impact on interconnect reliability. However, at this time, detection of such changes is extremely difficult, if not impossible, due to a lack of suitable characterization methodology. There is a host of metrologies currently practiced in the microelectronic industry to detect such changes and failures. Unfortunately, these metrologies, developed for interconnects with dense dielectric and a thick barrier layer, are ineffective and time-consuming. In particular, they are not designed to exclusively examine the barrier integrity and the low-k stability, increasing the potential for false diagnosis. It is, therefore, imperative to develop a characterization method that yields needed information with speed and accuracy.

For the past few years, we have been developing a new method that is simple but effective in characterizing the barrier integrity, as well as the structural stability of ultralow-k in as-processed conditions. Our method is drastically different from the conventional methods as it utilizes ions in a liquid electrolyte as probes. Their reaction with interconnect materials and their motion is modulated and monitored by a way of voltammetry [2]. The voltammetry characterizes the barrier integrity by monitoring reaction current specific to barrier defects and also characterizes the pore structure in ultralow-k dielectrics by monitoring the kinetics of the ion migration. An added benefit is that it can be implemented without major investment, because it works with standard interconnect test structures and common instruments already available. In order to demonstrate its effectiveness, we carried out a series of developmental investigations. This paper presents some of the results along with the explanation of its working principle.

2. Principle of Voltammetry

The working principle of the characterization method develop in our study is simple and straightforward. It utilizes the fact that liquid, including an electrolyte, can infiltrate the ultralow-k dielectric layer through the open pore structure or the open space in the molecular bond network. When an electrolyte infiltrates the area between two barrier/Cu interconnect structures, such as in a comb pattern, it creates a situation essentially the same as an electrochemical cell. The two interconnects act as the electrodes, and they are electrically connected through ions in the electrolyte. When external bias is applied to these two electrodes, the ions can drift from one electrode to the other, creating current that is proportional to the speed and the number of moving ions. In case when the electrodes contain materials that are reactive with the ions, the resulting current indicates the condition of the interconnects.

Our study determines that the two forms of voltammetry can be utilized depending on the characterization target. The first form is cyclic voltammetry which applies cyclic bias while monitoring current. We found that cyclic voltammetry is an effective method for characterization of barrier integrity. When the barrier is defective, the Cu interconnect is exposed to the electrolyte through the defects. Unlike the common barrier materials like Ta and TaN, Cu undergoes redox reactions at around $\pm 0.3V$. The reaction current can be monitored best using continuously cycling bias because it produces peak in the currents near at $\pm 0.3V$. The absence of defects results in a simple hysteresis in current, similar to the behavior of a capacitor because ions in the electrolyte simply move back and forth.

The second form of the voltammetry is "step-mode" voltammetry [3]. It involves application of a static bias for attaining full polarization of ions, followed by removal of the bias. The current that flows after removal of the bias is result of ion diffusion to restore chemical equilibrium. When the barrier is defect free, the ions involved in this current are due only to the diffusion of infiltrated ions and their motion can be modeled by a simple diffusion law and the simple boundary conditions of impermeability. The current produced in this process takes the form of an exponentially decaying function, with kinetics affected by ion diffusivity for a given geometry. Fitting the experimental data to the model equation yields the effective ion diffusivity. Since ion diffusivity is affected greatly by pore structure, it can be used as a mean for characterizing pore structure in ultralow-k layer and also its stability during processing.

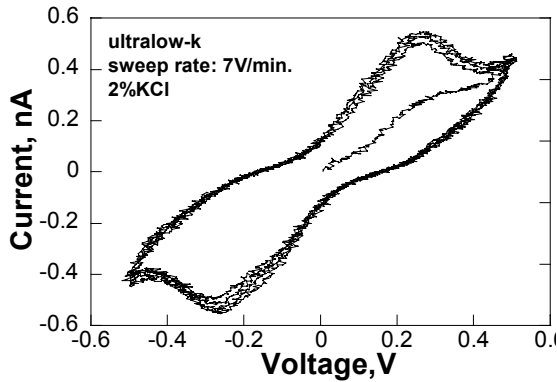


Fig.1 Cyclic voltammetry result showing the presence of reaction current peaks near at $\pm 0.3V$ due to defects in 25nm thick Ta diffusion barrier. It is tested at room temperature.

3. Characterization of barrier integrity

In our study, fully executed Cu interconnects are used. These interconnects are integrated with various types of low-k dielectrics, having different porosity, dielectric constants, and processing conditions. In addition, various types of barrier materials (Ta, TaN, TiSiN) with varying thicknesses are also examined. Our research reveals that cyclic voltammetry works extremely well for all types of interconnects used in our study. Fig.1. presents an example of cyclic voltammetry results for interconnects with barrier defects. Notice that the hysteresis shows a distinctive reaction peak during both forward and reverse sweeps. Such peaks are absent when the barrier is defect free. Ideally, the defect density can be quantified from the intensity of the peak current because more defects should produce higher reaction peaks. However, the needed model for such quantification remains as future work. Nevertheless, detecting the presence of defects, which is of engineering importance, can be a simple matter of conducting cyclic voltammetry and finding the peak current.

4. Characterization of pore structure

Our study also finds that step voltammetry is very effective in characterizing the pore structure of low-k dielectrics because the effective ion diffusivity is sensitively affected by the pore size and porosity. Fig.2a shows the example of the effective ion diffusivity measured with three different dielectric conditions: no dielectric layer, dense low-k ($k \sim 2.9$) and ultralow-k ($k \sim 2.2$). The no dielectric case (two mating electrodes separated by electrolyte) is studied in order to examine the accuracy of the method because the effective diffusivity is also available from other measurement methods. Two facts are noteworthy from the data in Fig.2a. The first is that the bulk diffusivity (no dielectric) determined from our method matches reasonably well with the known values. Secondly, the effective ion diffusivity correctly reflects the pore structure of the low-k materials. The diffusivity in low-k materials is far smaller than that in bulk state, more than 7 orders of magnitude. Furthermore, the data shows that the diffusivity in dense low-k is smaller than that in the ultralow-k. The dense low-

k is nearly free of pores and diffusion is likely to take place through the open space within the bond network rather than pores. This makes the diffusivity lower in dense low-k than in ultralow-k.

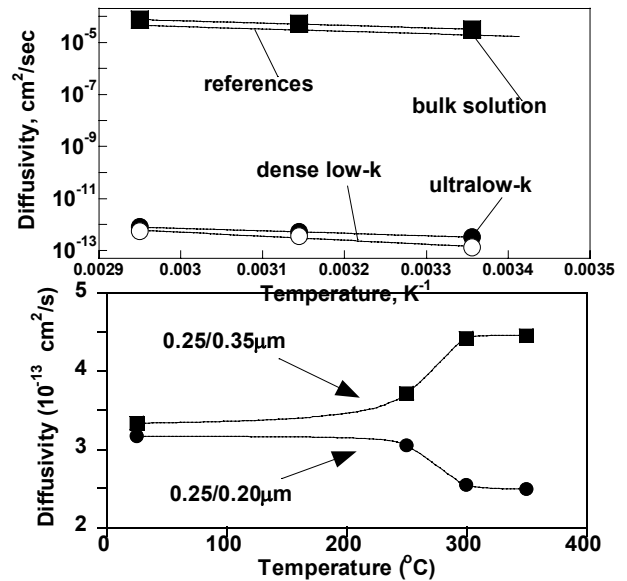


Fig.2. a) The determined effective diffusivity of KCl ions in 3 different dielectric materials, and b) the diffusivity change in ultralow-k dielectric after 1 hr treatment at various temperatures. The results from two different low-k layer widths (0.35 and 0.2 μm) are compared.

Although the method for determining pore size from the diffusivity is still under development, the developed method is already proven to be useful for engineering applications because it provide a way to trace the change in the pore structure. The data shown in Fig.2b shows an example of the change in diffusivity as a function of annealing temperature for interconnects with varying dielectric layer width ($k \sim 2.2$) in comb structure, i.e varying pitch. Note that the diffusivity does not remain constant but varies with annealing. More interesting is the result that the pitch affects the direction of the change. Since the diffusivity reflects the pore structure, the result indicates that the pore structure either collapses or coalesces during annealing depending on pitch. We believe that the competition between thermal diffusion for pore growth and compressive stress for pore collapse is responsible for the result.

Acknowledgement

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- [1] N. L. Michael and C.-U. Kim, *Appl. Phys. Lett.*, **83**, 1959 (2003).
- [2] C.-U. Kim, J.-Y. Park, N. Michael, Y.-J. Park, S. H. Kang, and S. Satyanarayana, *Proc. 2004 Adv. Metal. Conf.* (MRS, Warrendale, PA, 2005), p.679.
- [3] D.M. Meng, N. Michael, C.-U. Kim, and Y.-J. Park, *Appl. Phys. Lett.*, **88**, 261911 (2006).