Drift, Diffusion and Dielectric Breakdown

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1. Introduction

Premature breakdown of dielectrics in copper interconnects due to copper contamination is a serious problem and limits future device performance and cost scaling. Such contamination may occur from an excess of oxygen at the dielectric surface [1], from an increase in the moisture content of the dielectric [2], or from other forms of damage suffered during processing such as occurs with chemical-mechanical polishing [3]. The statistical models used to project the end-of-life from accelerated test conditions do not provide much insight for improving the properties of barriers/dielectrics necessary to meet industry targets and extrapolating these models to predict lifetime at normal operating conditions may result in large error. We have presented a material physics based drift/diffusion model, as a first step, which accurately matches existing experimental time to fail data on SiO_2 dielectrics with and without barriers [1, 4-6]. The model identified the diffusivities and solubilities of copper ions in the dielectric and barrier as the important parameters in determining the lifetime of the dielectric. We also hypothesized that the transport of oxidizing species necessary for the copper ion formation and the injection and removal of electrons and holes plays an important role in dielectric reliability and this effect is accounted for by the field acceleration parameter in current models.

The models are successful at correlating the time-to-failure for SiO_2 and SiCOH dielectrics with and without diffusion barriers. In this talk I will discuss how metal ion solubility affects lifetime and how we are using conventional current-time testing as well as variable voltage ramp rate and variable frequency bipolar testing to assess failure and understand how electron, hole, and ion transport affect the lifetime of a dielectric.

2. Results

The model is based on two equations. The continuity equation for Cu ions,

$$\frac{\partial C_d}{\partial t} = -\nabla \cdot \left\{ -D_d \left[1 + \left(\frac{\alpha_d}{k_B T} \right) C_d \right] \nabla C_d - \mu_d C_d \nabla V \right\} \tag{1}$$

and Poisson's equation for local electric field.

$$-\nabla \cdot \left(\varepsilon\varepsilon_{\nwarrow}\nabla V\right) = qC_d \tag{2}$$

Equations (1) and (2) apply in the dielectric. The initial and boundary conditions that must be satisfied are:

$$t = 0 \qquad C_b = C_d = 0 \qquad V = 0 \tag{3}$$
$$x = 0 \qquad C_d = C_{de} \qquad V = V_o \tag{4}$$
$$x = L_d \qquad D_d\left[1+\left(\frac{\alpha_d}{k_B T}\right)C_d\right]\nabla C_d + \mu_d C_d \nabla V = 0 \qquad V = 0 \tag{5}$$

We use the Einstein relation to couple the copper ion diffusivity, D_d, to the ion mobility, μ_d, via the thermal voltage, V_e.

Figures 1 and 2 show results from the simulation compared with experimental data. The first figure shows that we can use this model to predict the time to failure for SiO_2-based dielectrics over a wide range of electric fields and temperatures.

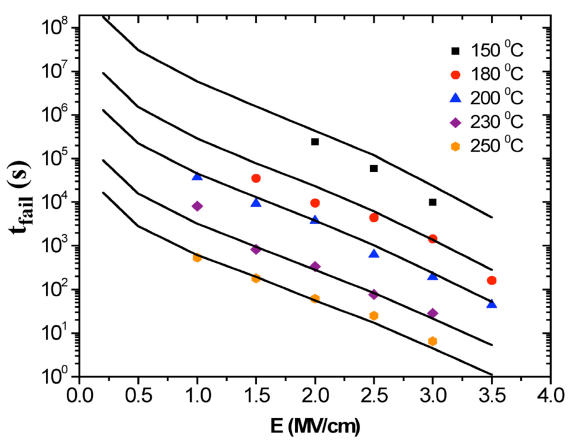

Figure 1 Comparison of experimental time to failure data for SiO2 dielectrics using equation (1) and the data of Hwang et al [7].

Figure 2 shows the time to failure for a SiCOH-based dielectric as a function of voltage ramp rate and metallization type. This mode of testing allows us to separate the metallization into two types, reactive and non-reactive. Thus, reactive metals like copper exhibit a different slope and time to failure from unreactive or inert metals like gold. Aluminum, which forms a self-limiting oxide in contact with the dielectric, exhibits a higher breakdown strength and longer lifetime as a result of the development of this oxide layer.

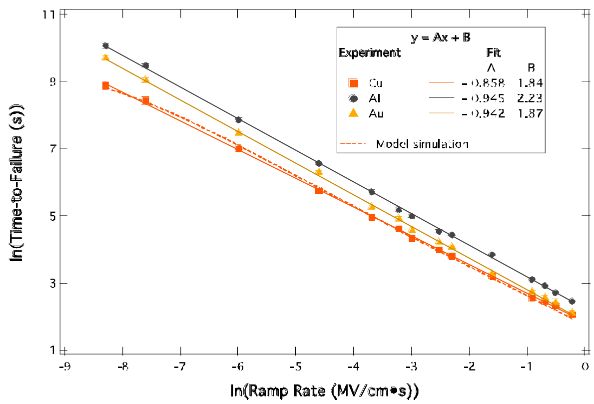

Figure 2 Experimental data plotted as the time-to-failure versus applied electric field ramp rate. Model parameters include: T = 200 ˚C, Ce = 4.2×1026 atom/m3, DCu = 1.86×10-21 m2/s, a = 1.8×10-44 J/atom.

3. Conclusion

We have developed a series of diffusion-based models to describe the breakdown of dielectrics and predict their useful lifetime. The models work for SiO_2-based dielectrics with and without metal diffusion barriers. In addition we have developed a series of alternative testing methods that allow us to categorize and study the effect of metallization and hopefully understand the roles of electron, hole, and metal ion transport on the failure of dielectrics.

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