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Low-k Dielectrics I

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Effect of Trapping on Dielectric Conduction Mechanisms of ULK/Cu Interconnects

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ABSTRACT

Trapping in low-κ dielectric for interconnects was highlighted by voltage shift in IV current-voltage measurements. It is shown that effects of trapping can impact the extraction of conduction mechanisms. Capacitance measurements made on these materials reveal that trapping is at the origin in the increase of capacitance. The creation of dipoles because of this trapping explains this increase in the value of capacitance.

INTRODUCTION

The drastic reduction of intra-level Metal-Metal spacing in advanced interconnects poses concern for reliability linked to the dielectric integrity. The Low-κ dielectric materials which compose the dielectric stack are the site of leakage currents under electric stress. These leakage currents damage the materials to the breakdown. The knowledge of the mechanisms linked to the leakage currents is a key to explain the damaging. Nevertheless the dielectric materials are composed of many defects, which can be active for conduction or just have a role of traps. Characterization of all these defects is an issue to establish the good diagnose of defectivity. Trapping had been already put in evidence in such structures [1]. We propose an analysis of trapping impact through leakage currents and capacitance measurements.

EXPERIMENT

Test structures were fabricated with an advanced Cu/ Low-κ process with 45 nm node processes (Figure 1). Measurements were performed on comb-comb test structures (Figure 2). Leakage currents against field are measured by sweep IV with different speeds of voltage.

Dynamical behavior is studied by impedance spectroscopy for frequencies between 10^{-2} Hz and 10^{3}Hz. A sinusoidal voltage V_{rms}=0.5 V is applied.

Measurements have been performed against temperature (between 100°C and 200°C).

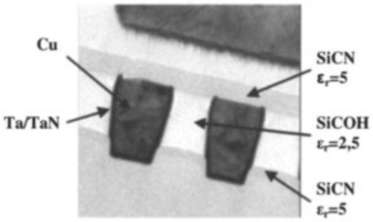

Figure 1. TEM cross sectional view of structures. SiCOH is porous with a porosity of about 30%.

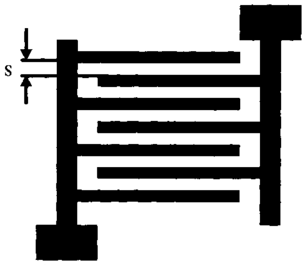

Figure 2. Test structures are interdigited combs structures. Space s between lines is 70 nm.

RESULTS AND DISCUSSION

Measurement of leakage current against applied field and effect of trapping

Trapping takes place in virgin structures from the application of an electric stress. In this part its impact is studied during measurement of leakage currents. If two successive sweeps are performed, a voltage shift to high fields is observed between the two curves (Figure 3). On the other hand, the voltage speed has no influence on the value of the current.

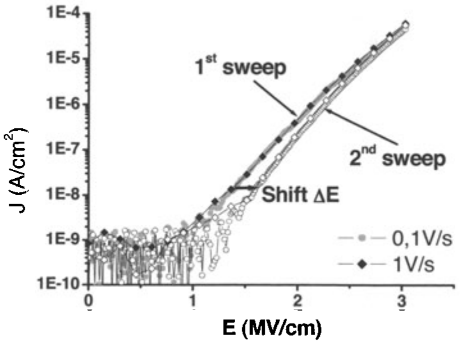

Figure 3. Leakage current measured by two successive sweeps at 125°C to 3MV/cm. Two sweep speeds have been tested: a fast one (1V/s) and a slow one (0.1V/s).

First it is observed that the voltage shift is observed from the base of the curves and decreases with increasing-field. At the base the shift ΔE is about 0.2 MV/cm. Nevertheless, the shape of the curves is strongly impacted after trapping and this will compromise the extraction of the conduction mechanism.

Poole-Frenkel conduction model is detected from the first sweep with the following field-dependence:

$$J(E) \sim \exp\left(-\frac{\phi_{PF}}{k_B T} + \frac{\beta_{PF}\sqrt{E}}{k_B T}\right) \text{ (Eq. 1)}$$

where Φ_{PF} is the activation energy linked to Poole-Frenkel effect and β_{PF} the Poole-Frenkel defined by $\beta_{PF} = \sqrt{\frac{q}{\pi\varepsilon_0\varepsilon_r}}$, with q the electron charge, ε_0 the vaccum permittivity and ε_r the relative permittivity.
A permittivity of ε_r between 2.5 and 3 is obtained from the fit.

The voltage shift corresponds to the internal field introduced by a uniform density of trapped charges n_t and given by:

$$E_{trap} = -\frac{qn_t}{2\varepsilon_0\varepsilon_r} \text{ (Eq. 2)}$$

During the measurement, E_{trap} increases whereas the applied field increases. The measured conduction current settled according to the total field $E+E_{trap}$ and consequently according to the establishment speed of the total field. Therefore the establishment speed of the total field is a competition between establishment of the applied field and the internal field due to trapped charges. The measured current settles according to the faster establishment.
Thus the second curves in figure 3 correspond to partially trapped states, and since the applied field settles faster than the internal field, the curve is distorted.
Measurements have been performed to higher fields (Figure 4).

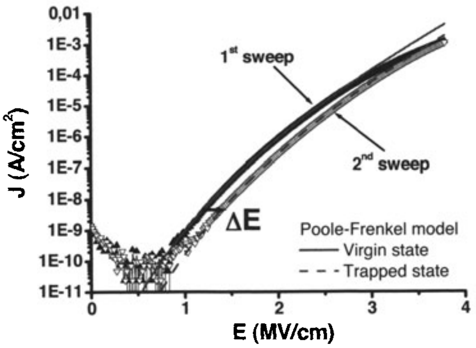

Figure 4. Two successive measurements at 125°C to high fields (about 4MV/cm).

At about 3MV/cm, the first sweep diverges from the Poole-Frenkel conduction model.
Moreover, the Poole-Frenkel model is recovered at the second sweep, with a voltage shift.
On the first sweep, the divergence from Poole-Frenkel conduction model takes place when the internal field due to trapped charges settles faster than the applied field [2], since it opposes. The recovering of Poole-Frenkel model at the second sweep means that most of the traps have been

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filled. We can extract the total traps density from the voltage shift and Eq. 2, at about $n_t \approx 5.10^{11} cm^{-2}$. Since all traps are filled, measurements of leakage currents are not anymore impacted by trapping. The conduction mechanisms can be studied against temperature (Figure 5).

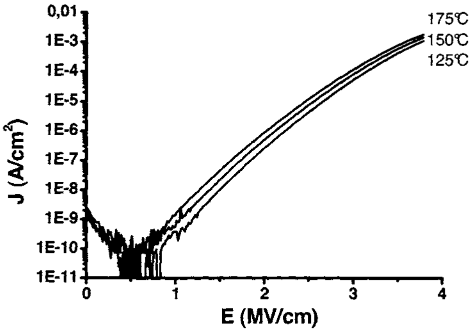

Figure 5. Leakage currents against temperature at trapped state to 4MV/cm.

Conduction currents correspond to Poole-Frenkel conduction with an activation energy Φ_{PF} of 0.8 eV.
Consequently, two types of defects have been set in evidenced: traps which are filling during electric stress and defects active for Poole-Frenkel conduction.

<u>Trapping during stress: characterization by CV measurements</u>

From the previous observations, trapping can be monitored during a stress, by the evolution of voltage shift between measurements of leakage currents. In addition, CV measurements have been performed simultaneously (Figure 6).

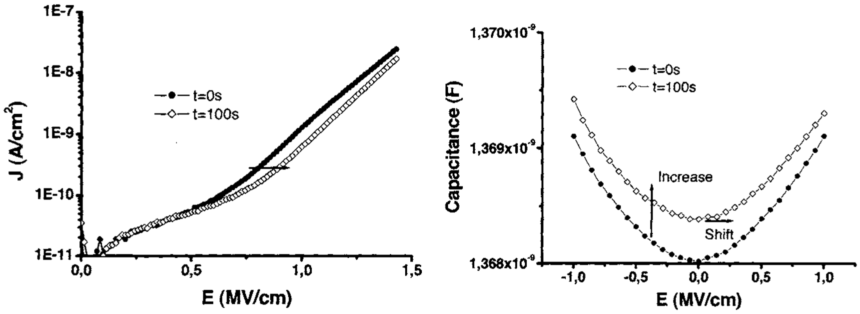

Figure 6. Leakage currents and capacitance (at 1 kHz) measured at 125 °C during a stress at

constant voltage (10V i.e. 1.43 MV/cm).

First it is observed the same voltage shift both in IV curves and CV curves. Moreover it is observed the increase of the capacitance and the decrease of the curvature of the parable. Consider a medium which contains *N* dipoles of polarizability α and dipole moment μ, with the assumption of low density so that interactions between dipoles are neglected. In the most general case concerning the intrinsic properties of the medium, the permittivity ε against applied field is [3]:

$$\varepsilon(E)=\varepsilon_r(E,T)+N\left(\alpha+\frac{\mu^2}{3k_BT}-\left(1-4u-2u^2\right)\frac{\mu^4E^2}{45k_B^3T^3}\right)$$

where *u* is the term for anisotropic polarization linked to the polarization of the *N* dipoles. In the case of isotropy, the permittivity becomes:

$$\varepsilon(E)=\varepsilon_r(E,T)+N\left(\alpha+\frac{\mu^2}{3k_BT}-\frac{\mu^4E^2}{45k_B^3T^3}\right) \text{ (Eq. 3)}$$

$\varepsilon_r(E,T)$ is the intrinsic permittivity of the medium.
Equation 3 allows us to speculate that the increases of the capacitance and the decrease of the curvature can be explained by the addition of a low density of N_{add} dipoles of dipole moment μ_{add}, whom the polarizability is neglected, compared to the steady-state dipole. With this assumption, the total permittivity according to the initial permittivity ε_{virg} of the virgin dielectric stack (measured before stress at t=0s) and the addition of N_{add} dipoles is given by:

$$\varepsilon(E)=\varepsilon_{virg}(E,T)+N_{add}\left(\frac{\mu_{add}^2}{3k_BT}-\frac{\mu_{add}^4E^2}{45k_B^3T^3}\right) \text{ (Eq. 4)}$$

A dipole moment μ_{add} of about 35 Debye is extracted using Eq. 4. In the case of a dipole between charges e and –e, the length of the dipole is about 8 Å. Then we obtain N_{add} of the order of 10^{16} cm^{-3}. With the assumption that dipoles were uniformly distributed between Cu lines, we extract the corresponding surface density, to be compared to the density of filled traps, at the same time during the stress (Figure 7).

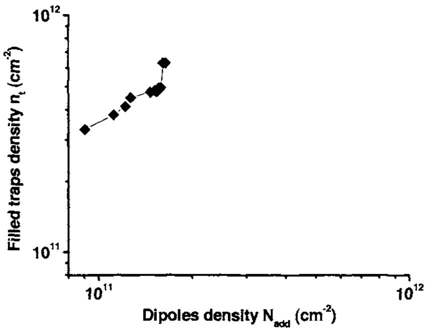

Figure 7. Correlation between dipoles density and filled traps density during stress at constant voltage (1.43MV/cm) and 125°C.

Surface densities of created dipoles and filled traps are well correlated. Thus capacitance can be used to monitor trapping during stress. From this observation, we proposed to characterize the state during stress, by measurement of capacitance versus frequency with zero bias.

Dynamic behavior by impedance spectroscopy and monitoring of stress

Since we have linked increase of capacitance with trapping, we have characterized and studied the stress by measurement of the capacitance against frequency non-destructively. To perform this, the impedance spectroscopy allows probing the dynamic behavior without bias on a large range of frequencies.
First we have characterized the capacitance at virgin state (Figure 8) before any stress.

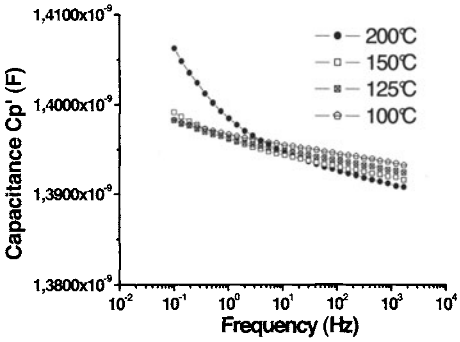

Figure 8. Capacitance against frequency and temperature at virgin state (before stress).

For each temperature, capacitance increases at low frequencies. At high frequencies, capacitance is decreasing with increasing temperature, and at low frequencies, the temperature-dependence is opposing. At high frequencies the temperature-dependence corresponds to the dipolar contribution of dipoles.
With the same assumption established for Eq.3, the permittivity can be written:

$$\varepsilon_S(T) = \varepsilon_r(T) + \frac{N\mu^2}{3\varepsilon_0 k_B T} \text{ (Eq. 5)}$$

$\varepsilon_r(T)$ is the intrinsic permittivity at zero bias, N the density of dipoles present at low density in the virgin stack and μ the corresponding moment.
Capacitance has been fitted according to Eq. 5, with the assumption that the temperature-dependence of $\varepsilon_r(T)$ was neglected (Figure 9).

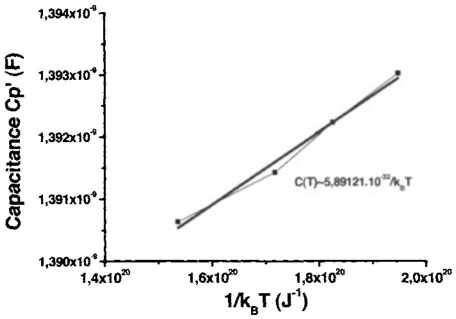

Figure 9. Capacitance against temperature at 1kHz.

From Eq. 5, we obtain $N\mu^2 \approx 5.10^{-33}\,C^2m^{-1}$ that corresponds to a density $N \approx 6.10^{20}\,cm^{-3}$ for a dipole moment of around 1 Debye unit. From this, we can estimate dipole-dipole interaction energy given by $E_{dip} = \frac{\mu^2}{4\pi\varepsilon_0 d^3}$ with $N \approx \frac{1}{d^3}$, with d is the dipole-dipole space, and then approximately $E_{dip} \approx \frac{N\mu^2}{4\pi\varepsilon_0}$. We obtain $E_{dip} \approx 0.3$meV that is much lower than the thermal energy $E_{th} \approx 25$meV at 300K. Thus the assumption of a low density of dipoles in the dielectrics at virgin state is well verified.

Concerning the capacitance in low frequencies, the increase to low frequencies has not yet been studied in details, but has to be linked to the contribution of hopping of charges carriers in amorphous dielectrics [4].

From this, the capacitance measured by impedance spectroscopy has been used to characterize the state during a stress.

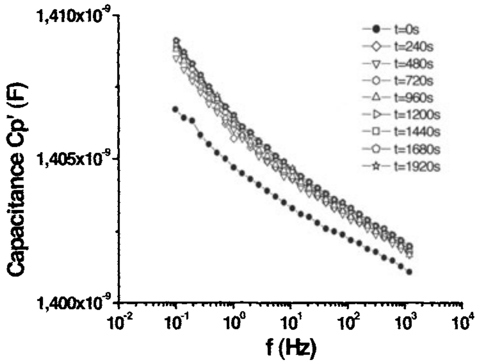

Figure 10. Capacitance against frequency measured by impedance spectroscopy at 125°C and during a stress at 1.43MV/cm.

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As previously capacitance increases. Using Eq. 4, the increase ΔC of capacitance is then:

$$\Delta C = \frac{N_{add}\mu_{add}^{2}}{3k_{B}T}\frac{\Sigma}{s}$$

On figure 10, at 1920s from the start of the stress, we can extract about 2 $10^{11}cm^{-2}$ created dipoles.

Concerning the physical mechanism explaining the link between trapping and creation of dipoles, model has been already proposed in the case of charge trapping in SiO_2 [5]. A simple model describes the increase of the polarization in the vicinity of the trapped charge, by interaction of the trapped charge with the components of the medium. The model of creation of dipoles by charges trapping is similar to the concept of crystalline dipole developed for crystalline defects [3]. As it is described for a crystalline dipole, created dipoles correspond to charges e and –e spaced by a length of the order of magnitude of a bond. The model described by Eq. 4 applies the Langevin-Debye model that is likewise recovered in the concept of crystalline dipole. It highlights the relevance of capacitance as a monitor of trapping.

CONCLUSIONS

The effect of trapping has been studied on leakage currents and on capacitance. It has been shown that during trapping, measurements of leakage currents against applied field are strongly modified by the local field created by trapped charges. The extraction of conduction mechanisms is thus compromised. The trapping has been linked to the increase of capacitance measured by CV. With the assumption of low density, creation of dipoles has been proposed as interpretation to explain the increase of capacitance. The good correlation obtained between dipoles densities and filled traps densities show that capacitance is a good monitoring for trapping. This justifies the use of impedance spectroscopy as a non-destructive technique for characterization of trapping. Moreover this technique is promising to probe the behavior of the dielectric stack, non-destructively and close to use conditions, i.e. at low fields.

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