Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp36-37

Mean time to failure distribution in thin oxide film: Observation at nano and devices scale and modelling using a filamentary growth model

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1. Introduction

Atomic Force Microscope in Conduction mode (C-AFM) current measurement is a promising, direct and quantitative way to study dielectric breakdown without patterning a device [1]. In this work we have studied the cumulative failure distribution of time to dielectric breakdown (TDDB) at different voltage on standard MOS devices and on the exact same SiON oxide layer but unpatterned one using C-AFM tip in ultra high vacuum (UHV) as a top electrode. The mean time to failure (MTTF) was then extracted from those data and an analytical model based on a filamentary growth approach similar to [2] is developed. The MTTF evolution with surface or voltage variation can be well reproduced by the model with coherent parameter.

2. Experiments

C-AFM measurement were performed with an Omicron AFM/scanning tunnelling microscopy system under UHV (<10^{-9} torr) in contact mode (20nN) with conductive diamond tips (B doped). The AFM tip served as a top electrode and voltage was applied to the substrate. The current was recorded by a Keithley 6430 equipped with a sub femtoamper sourcemeter. The 2.6nm thick SiON layers investigated in this study were formed by performing a pulsed RF decoupled plasma nitration process. The SiO_2 base layer was formed by thermal oxidation at 980°C in O_2 flow. Finally, samples were annealed at 1100°C under O_2 flow to stabilize N atoms in the oxide. Samples for C-AFM measurements were outgased at 150°C for 3h at $4x10^{-8}$ torr.Devices measurements were done on NMOS with surfaces from 0.04µm² to 4µm² using a HP4156 Semiconductor parameters analyzer at 125°C

A constant voltage stress (CVS) is applied until the detection of a sharp increase in the current. This hard breakdown can be detected at devices scales or at nanoscale.

Those CVS measurements were repeated at least 40 times on different location and the cumulative failure distribution of the TDDB were plotted in fig.1 and fig.2 for measurments on devices and at nanoscale respectively.

For the three different areas and for all voltages, the TDDB distribution can be fitted with a weibull distribution with a slope (β) close to 1.2.

The area scaling of the TDDB distribution has been successfully done in [3] on the same data and has validated the C-AFM as a characterization tool to do reliability measurements. In the next we will focus on the MTTF evolution.

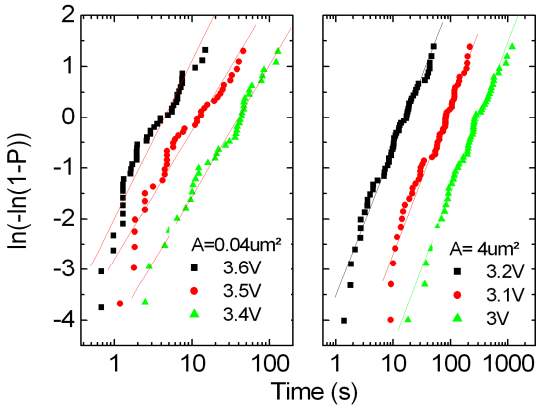

Figure 1. Cumulative failure distribution obtained by device measurements on SiON for two different surfaces (0.04µm² and 4µm²) .

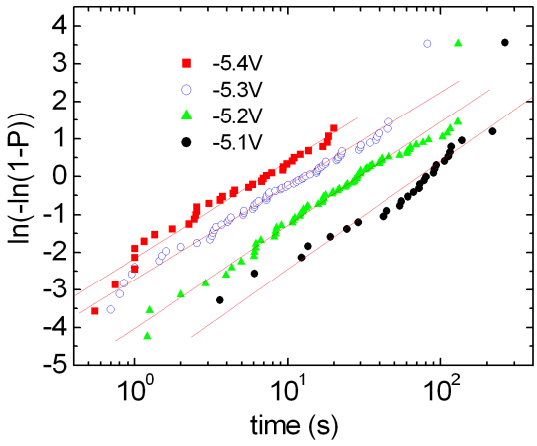

Figure 2. Cumulative failure distribution obtained by C-AFM on SiON.

3. Model and conclusions

Filament field assisted nucleation has been used to describe switching in phase change memory devices [4,5], Dielectric Breakdown [2] or more recently a pre-breakdown phenomena [6] (on the exact same dielectric layer that the one used in this paper). By tuning the ramp speed (RS) and the current compliance a negative differential resistance (NDR) has been reported at nanoscale [6] and is presented here in

fig.3 bottom. This pre-breakdown phenomenon has been quantitatively explained by a filamentary model. Under certain condition when the voltage ramp is reversed the filament continue his growth. So the current can still increases even if the voltage decreases. We will attempt to model the MTTF distribution with a filamentary model similar to the one used in [2] for dielectric breakdown and to compare the extracted value from the different experiment. In [2,6] it has been shown that the filament radius is in the range of several Å. Due to the very small conductive area of this filament a very high current density is flowing through the filament. This can lead to electro-migration as reported in [7,8]. The free energy F_{cyl}, considering a cylindrical filament with a radius R and a length h has been slightly modified from the expression given in [4] by adding a term proportional to h ,to the effective charge of the ions eZ*, the electrical conductivity ρ, the current j and the temperature T, to take into account the electro-migration effect on the filament growth.

$$\alpha = jeZ^{*}\rho T$$

$$F_{cyl} = 2\pi Rh\sigma - \pi R^{2}h\mu - \frac{E^{2}\varepsilon\varepsilon_{0}\pi h^{3}}{2} + \alpha h \qquad (1)$$

Increasing E, the applied field, leads to a smaller F_{cyl} and to an easier growth of the filament. In eq.1 σ is the surface tension and μ the chemical potential between the conductive cylinder and dielectric.

Applying a method similar than in [2] we can obtained the nucleation barrier W_{cyl} by minimizing the free energy and

$$W_{cyl} = \frac{1}{E}\sqrt{\left(\frac{W_{0}}{R_{O}} + \frac{2\alpha}{3}\right)^{3} \times \frac{1}{\pi\varepsilon\varepsilon_{0}}} \qquad (2)$$

$$\text{With } W_{0} = \frac{2\pi R_{0}^{3}\mu}{3},\ R_{0} = \frac{\sigma}{\mu} \text{ and } Eh = \sqrt{\frac{2\mu}{3\varepsilon\varepsilon_{0}}} \qquad (3)$$

This leads to a nucleation time of

$$\tau = \tau_{0}\exp\left(\frac{EhW_{0}}{kTE}\right) \qquad (4)$$

Where τ_0 is a pre-exponential factor which has the order of magnitude of lattice vibration (10^{-13} s). In the case of a filamentary growth the MTTF [2] distribution is expressed as:

$$MTTF = \exp\left[\ln(-\ln(1-Fg)) + \beta\ln\left(\frac{\sigma\cdot Sf}{Sd}\right) + \beta\cdot\frac{W_{cyl}}{W_{0}}\right] \qquad (5)$$

Fg is a fixed proportion of failed devices and is taken as 67% in our case Sd is the surface of the device under test which is unknown for the C-AFM measurement and Sf is the filament area. Using formula 1 to 5 we attempt to fitt our MTTF for the 3 different Surfaces. MTTF of fig 1 and 2 are reported on fig.3 and the computation results of the MTTF using formula 4 are also plotted. Note that all the data have been translated to room temperature. The fitting parameter Eh and Sf were first found by fitting the two MTTF distributions with known surface. Then using the same set of parameter for Eh and Sf, the surface under the C-AFM tip was fond to be $10x10^{-18}m^{2}$.

The surface S_d for C-AFM is consistent with [3,6 9,10], $(Eh*W_0)/kT \sim 72V/nm$ for all the devices that have been tested which corresponds to a thermal nucleation radius of ~2.5nm and a nucleation barrier of 4.1 eV close to published data [2,11], S_0 ~0.3 nm² which corresponds to a filament diameter of about 6Å the same surface that the one estimated in [6].

The dependence of the MTTF respect to the applied voltage, the voltage acceleration factor, can be reproduced well by the model. Increasing the applied voltage leads to a decrease of the nucleation barrier and so the filament can growth more rapidly leading to a smaller MTTF.

NDR and MTTF are fitted with the same parameters indicating that dielectric breakdown and NDR can be understood together in the framework of a conductive filament growth.

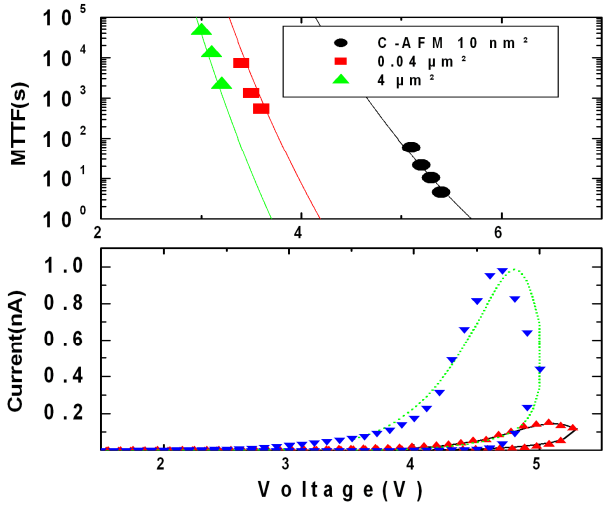

Figure 3. Top: MTTF obtained for 3 differents surfaces at different voltage on a 2.6 nm SiON layer. Square and circle are experimental data and line are the model computation for different voltage and surface. Bottom: Current Voltage characteristics simulation and experiment comparison of a SiON oxide stress with two ramped voltage stress. ▲1: Experiment RS=2V/s, Vmax = 5.3V; ▼ 2 Experiment RS=0.062V/s, Vmax =5V; ▬ 3: Simulation RS=2V/s, Vmax =5.3V; - - 4: Simulation RS=0.062V/s, Vmax =5V.

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