Soft Breakdown in MgO Dielectric Layers

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***Abstract*—In this work, we report on the occurrence of the soft breakdown (SBD) failure mode in 20nm-thick films of magnesium oxide (MgO) grown on Si substrates. To our knowledge, this is the first observation of this failure mechanism in a high-κ gate dielectric with such a large oxide thickness. We show that the I-V characteristics follow the power-law dependence typical of SBD conduction in a wider voltage range than that reported for SiO_2. We pay special attention to the relationship between the magnitude of the current and the normalized differential conductance, and analyze the role played by the injection polarity and substrate type.**

Keywords: breakdown, high-κ, MgO

I. INTRODUCTION

Recently, MgO has been proposed as a serious candidate to replace SiO_2 as gate dielectric in MOS devices both for low [1] and high power applications [2]. The main features of this alternative material are a large band gap in the range 7.3eV [1]-7.8eV [3], ensuring sufficiently large band offsets with Si, a dielectric permittivity κ ranging from 6.7 [4] to 10 [3] depending on the growth method and annealing conditions, high thermal conductivity [2] suitable for large power dissipation, higher breakdown field (12 MV/cm) compared to SiO_2 [2] and significantly, its chemical inertness, which minimizes the formation of an interfacial layer in contact with Si [1]. In this work, we have investigated a specific reliability aspect of the MgO-Si structures, which relates to the modification of low-level leakage currents associated with the post-breakdown conduction mode usually referred to as soft breakdown [5]. As it is well known, this failure mode arises as a consequence of the formation of a single or multiple nanoconstrictions across the oxide layer after reaching a certain threshold density of defects caused by electrical stress. This is a localized conduction mode, independent of the device area, and has been reported to occur not only in SiO_2 but also in a number of high-κ thin films on Si substrates [6]. However, contrary to the widespread opinion that this failure mechanism can only be detected in ultra-thin (t_{ox}<6nm) oxides, we have detected it in MgO films with nominal thickness t_{ox}=20nm. Significantly, our thickness is nearly double the maximum SiO_2 thickness (t_{ox}=12nm) for which SBD has been observed [7]. In order to demonstrate that we are strictly dealing with the same kind of physical phenomenon, we have carried out a thorough analysis of the conduction characteristics starting with the widely accepted function-fit model $I=aV^b$, also known as the power-law model [8]. a and b are constants. This allows us to: firstly, extend the limits of validity of the referred model; secondly, identify SBD events with leakage current levels several orders of magnitude lower than those detected in the past; and thirdly, corroborate the relationship exhibited by the fitting parameters a (I@1V), and b (=$d$lnI/$d$lnV), the normalized differential conductance, over a significantly wider parameter range.

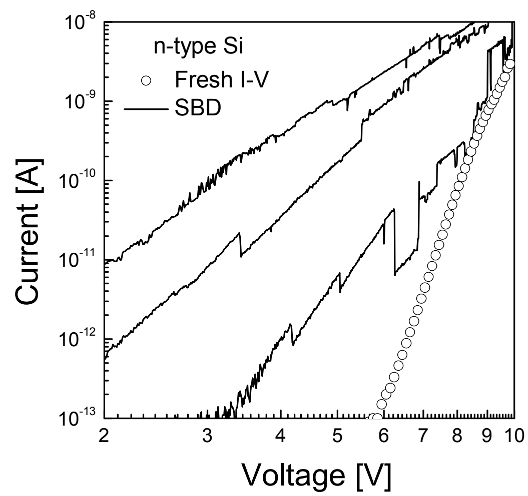

Figure 1. Symbols and lines correspond to the fresh and SBD I-V characteristics, respectively. Notice the use of log-log axis in order to emphasize the power-law dependence.

II. SAMPLE FABRICATION

Hydrogen terminated Si surfaces were prepared by dipping n and p-type (100) Si wafers ($10^{15}cm^{-3}$) in a solution of 5% hydrofluoric acid (HF) for 1 minute, rinsed in D.I. water then dried using nitrogen gas and immediately loaded into the deposition system. MgO films of nominal thickness 5nm (EOT≈2.4nm) and 20nm (EOT≈9.5nm) were deposited by electron beam evaporation from 99.9% MgO pellets at a rate of 0.2Å/s, at 180°C. The samples were capped *in-situ* with 100nm of amorphous silicon (α-Si) using a second e-beam source. For the NiSi gate process, nickel was deposited by e-beam evaporation (~80nm) through a patterned resist mask and subsequent lift-off process. The RTA is a one step process at 500^oC for 30s in N_2. Following excess nickel removal in $H_2O:H_2SO_4$ (1:3), the silicon outside the capacitor area was removed by reactive ion etching using SF_6. The area of the devices tested is $1.6x10^{-7}cm^2$. The permittivity of the MgO film from capacitance-voltage (C-V) analysis is 8.1. The 5nm-thick sample is only used for C-V comparisons since its large leakage current prevents the observation of any SBD event.

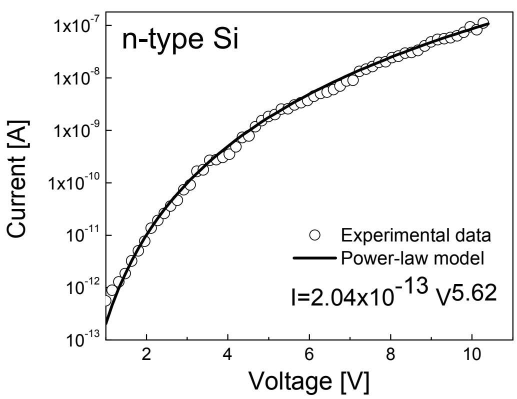

Figure 2. Fitting to a typical SBD I-V characteristic using the power-law model.

III. Experimental Results and Analysis

Figure 1 shows three SBD I-V characteristics measured in an n-type sample after ramped voltage stress starting from 10V. This end voltage is progressively increased in order to induce additional damage. Notice the switching behavior typical of digital SBD conduction [9]. Because of the 20nm MgO thickness of the investigated sample, the fresh I-V is only measurable for V_G>6V. This allows a large voltage window for the observation of the SBD I-V curves [10]. Moreover, this window becomes even wider for larger damaged areas and it can extend up to 10-12V. The I-Vs cannot be associated with a single SBD event and it is more likely that they correspond to the contribution of multiple spots distributed over the device area. Regarding the voltage dependence of the post-breakdown curves, notice that the linear relationship between log(I) and log(V) supports the use of the power-law model. It is also clear from this plot that as the current increases, the slopes of the different I-Vs become shallower. This behavior was already reported for SBD in SiO_2 after electrical stress (with $t_{ox}\approx 3.8$-4.3nm) [8] and after heavy ion irradiation (with $t_{ox}\approx 4$nm) [11]. Figure 2 shows a typical fitting to a SBD I-V characteristic in MgO using the power-law model. In case of a switching I-V, the fitting parameters were extracted from the average curve.

The relationship between the magnitude of the current and its normalized differential conductance cannot be explained by any of the existing physical models [5] except by the quantum point contact model [12]. Figure 3 explicitly shows the correlation between the parameters *a* and *b* obtained from a large number of I-V characteristics. It is worth pointing out that the points cannot be considered as a statistically independent data ensemble since some of them were extracted from I-Vs measured in the same sample after further degradation. On the contrary, in [8], the parameters were extracted from independent measurements. However, what is importantly addressed here is that both data sets (MgO and SiO_2) follow similar linear trends. Figure 3 also shows that the correlation between the parameters *a* and *b* in MgO nearly covers ten orders of magnitude of the parameter *a*. In SiO_2 this correlation holds in a narrower range. In addition, the figure reveals that many of the SBD events occurring in MgO are softer than those taking place in SiO_2. This can be a matter of the sample thickness, which because of the lower tunneling current permits the observation of softer events, or of the particular features of the conducting spots, *i.e.* the microscopic arrangement of the defect sites within the insulator.

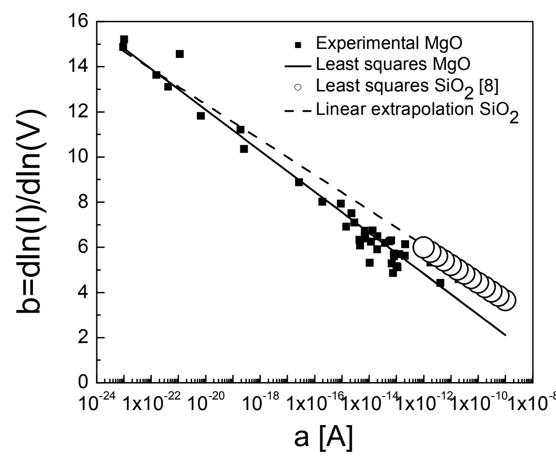

Figure 3. Relationship between the parameters *a* and *b* in the power-law model. The circles correspond to the region of SiO_2 experimental data.
MgO: b=-0.90·log(a)-6.05, SiO2: b=-0.78·log(a)-3.27

We have also investigated the role played by the substrate type and polarity injection. Fig. 4.a shows that similar SBD currents can be found both for n (+VG) and p-type (-VG) substrate samples in accumulation conditions. Identical results arise for an n-type Si sample biased with both polarities (Fig. 4.b). Notice that this is not the case for the fresh I-Vs. These plots indicate that the injecting electrode does not play any significant role as long as there is sufficient charge available. The current seems to be limited by the breakdown path itself, so that its transmission properties become a key element for the description of the phenomenon [5]. For higher breakdown events the current at inversion conditions is indeed limited by the charge available at the injecting electrode (not shown here).

Finally, Fig. 5 demonstrates that our samples exhibit very abrupt interfacial properties. The ratio between the maximum capacitances measured at accumulation conditions coincides with the ratio of the nominal thicknesses. This indicates that, if any interfacial layer exists, it is not significant or has a similar

κ value to that of MgO, a result that is supported by XPS analysis [13]. This also poses a question as to whether the breakdown of the interfacial layer oxide between the high-κ and the silicon substrate plays a significant role in the breakdown of high-κ thin films on silicon, as recently suggested in [14].

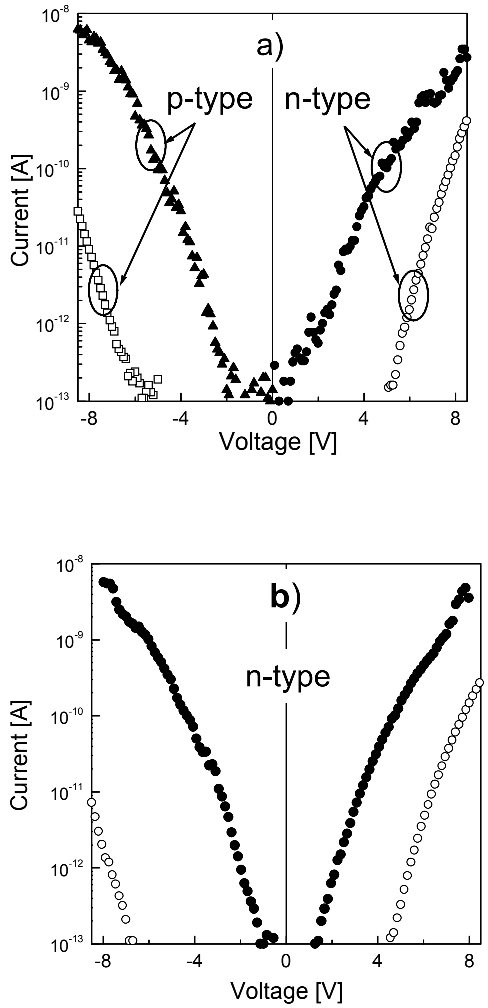

Figure 4. (a) Effect of substrate type and (b) injection polarity on the SBD curent. Hollow and filled symbols correspond to the fresh and SBD I-V characteristics, respectively.

IV. CONCLUSIONS

The post-breakdown electrical behavior of MgO layers in MOS structures was investigated. It was shown that soft breakdown conduction can be detected in a relatively thick high-κ film and that the connection between the charge transport mechanisms in MgO and SiO_2 goes beyond the fact that they share the same power-law model. The correlation between the model parameters and therefore the simplicity of the underlying physics, perhaps, should be regarded as a sign of the low dimensionality of the involved conducting structures.

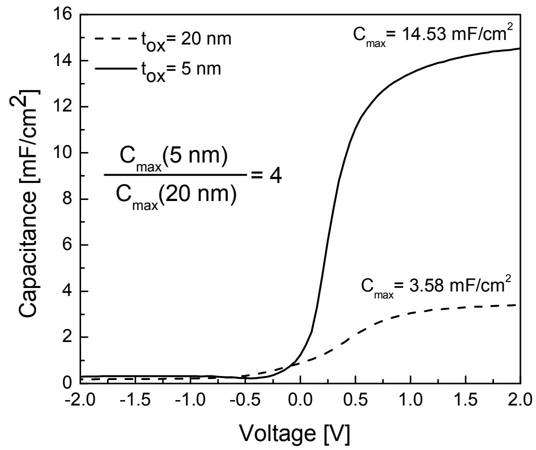

Figure 5. C-V plots for two samples with different oxide thickness.

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