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Accurate assessment of the time-to-failure of hyper-thin gate oxides subjected to constant electrical stress using a logistic-type model

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Abstract

When a metal-oxide-semiconductor structure with a hyper-thin (≤2nm) dielectric film is subjected to constant voltage stress, after the triggering of the breakdown event, the leakage current increases progressively over time until saturation. In this work, we propose a logistic-type growth model that allows capturing the non-symmetrical features of the trajectory exhibited by the current-time characteristics. It is discussed how the resulting solution could be used to evaluate the time-to-failure under different stress conditions.

Keywords: Progressive Breakdown, Gate Oxide Reliability, Logistic Equation

1. Introduction

Even though the time-to-breakdown (T_{BD}) of an oxide layer in a MOS structure, defined as the time to detection of anomalous current or noise increment, is a parameter of utmost importance in reliability analysis, there is now wide agreement that a new quantity, the so-called time-to-failure (T_F), has to come into play in connection with current integration technologies [1,2]. Basically, the difference between T_{BD} and T_F arises because hyper-thin (≤2nm) oxides enter into the regime of progressive breakdown for gate voltages below 4-5V [3]. In contrast, thicker oxides exhibit an abrupt change of conduction mechanism (from area-distributed to localized current flow), which is often considered the signature of dielectric breakdown. When the device is acting as a circuit component, the partial loss of the gate oxide insulating properties may not affect substantially the circuit operation in an early stage. However, if degradation conditions are persistent, the leakage current may evolve leading the device to operate beyond the circuit tolerance limits. Within this context, T_F is defined as the time required by the current to reach a given level, I_F. T_F is measured with respect to the triggering of the breakdown event (see Fig. 1). Of course, this level may depend on the specific functionality or location of the device within the circuit architecture and can be thought of as a designer-defined parameter. In this work, we extend a

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previous model [4] for the gate current evolution based on the logistic differential equation that, because of the inclusion of a new parameter in the feedback term, allows simulating cases in which the sigmoidal trajectory departs from the symmetric behavior.

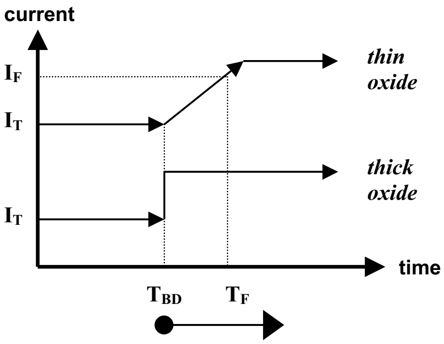

Fig. 1- Schematic representation of the current evolution in thin and thick oxides. The lowest arrow indicates the time origin for the time-to-failure.

2. Experimental

The samples are MOS capacitors with standard SiO_2 films 2 nm-thick and areas of 10^{-6} and 10^{-4} cm^2 on n-Si substrates and p^+ poly-Si gates. The samples were stressed at constant voltage in accumulation conditions. The current flowing through the oxide layer was measured using the configuration described in Ref.[5] with a time resolution up to the nano-second.

3. Models and Simulations

One of the earlier attempts to characterize the progressive evolution of the leakage current in hyper-thin oxides was reported by Linder *et al* [2]. The authors showed that, at the outset of the breakdown event, the current increases exponentially with time. In terms of a dynamical equation, this simple behavior reads:

$$\frac{d\ln I}{dt} = r \qquad I(0) = I_0 \qquad \text{Eq.(1)}$$

where r is the intrinsic growth rate (G^{-1}, the characteristic time according to [2]) and I_0 the initial current. However, this equation cannot account for the saturation of the current observed at larger times. Alternatively, we propose the following differential equation:

$$\frac{d\ln I}{dt} = r\left[1-\left(\frac{I}{I_\infty}\right)^\gamma\right] \qquad I(0) = I_0 \qquad \text{Eq.(2)}$$

where I_∞ is the current for $t\rightarrow\infty$ and γ is a positive constant, which affects the shape of the saturating trend. Notice that for $I \ll I_\infty$ we recover Eq.(1), whereas as I approaches I_∞, the derivative vanishes so that the current levels off. Eq.(2) is a particular case of the so-called generalized logistic model [6] of population growth dynamics and is commonly referred to as the Richardson equation. γ=1 corresponds to the well-known logistic or Verhulst model. The term within the parenthesis represents a feedback mechanism associated with the redistribution of potential drops along the device structure as the degradation proceeds. This particular choice is motivated by the fact that Eq.(2) not only is consistent with the observed exponential and saturating behavior but also because there is simple analytical solution:

$$I(t-T_{BD}) - I_T = I_\infty\left\{1-e^{-\gamma r t}\left[1-\left(I_0/I_\infty\right)^{-\beta}\right]\right\}^{-1/\gamma} \qquad \text{Eq.(3)}$$

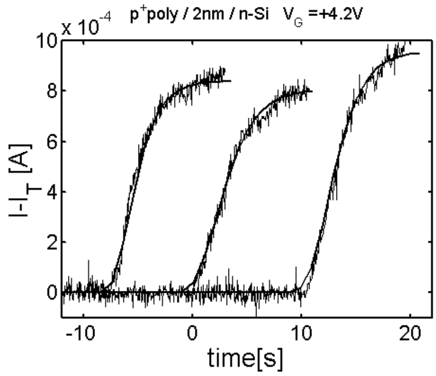

Fig. 2- Experimental and fitting curves showing the initial exponential current increase and saturating behavior. The curves were arbitrarily shifted along the time axis for clarity.

It is worth pointing out that, in order to fit the solution of Eq.(2) to the experimental curves, we have taken into account in Eq.(3) the background tunneling current prior to the breakdown event (I_T) as well as the time-to-breakdown