Formation and characterization of electrically induced nanodiodes in thin oxide films

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The application of a high voltage to the gate electrode of a MOS structure generates traps or defects within the insulating material that eventually leads to its dielectric breakdown. This final state consists in the formation of localized leakage current paths between the electrodes which exhibit conductance levels close to the quantum conductance unit $G_0=2e^2/h$, where e is the electron charge and h the Planck's constant. In this work, we extend a previous model for the I-V characteristic of a single spot [1] to the case of multiple parallel leakage paths. The model is based on the so-called generalized diode equation (diode + series resistance) and is solved in terms of the Lambert W function, *i.e.* the solution of the transcendental equation $we^w=x$. Within this framework, the diode-like behavior is ascribed to the formation of the band bending at the semiconductor electrode and the series resistance to the constriction effect. We show that by means of electrical stress, we are able to control the conductance level of the device simply by adding intentionally generated leakage sites.

For the experiments we used MOS capacitors grown on n-type Si (10^{15} cm^{-3}), with 3 nm-thick SiO_2, poly-Si gate and area of $1.96\text{x}10^{-5}$ cm^2. Initially, the spots are generated using a high voltage sweep from 5V to 13V as shown in Fig. 2. The curves were measured in different samples. The considered region of the I-Vs corresponds to the linear conduction regime (also known as hard breakdown) and each jump in the characteristic can be associated with the creation of a new spot in a different location over the device area. For one of the I-Vs plotted in Fig. 1, Fig. 2 reveals that the conductance of the whole characteristic spans over a few quantum units. If instead of a complete sweep, the measurement is stopped after each jump and a low voltage I-V is performed (this time from 0V to 4V) a set of I-Vs like the one shown in Fig. 3 (linear axis) and Fig. 4 (log axis) is obtained. After the low voltage I-V, the high voltage stress is resumed until the detection of a new jump. Fig. 5 shows the differential conductance of such curves in units of G_0. Notice that at least the first six curves exhibit conductance levels close to integer values of G_0. These features are indicative of the mesoscopic nature of electron transport after dielectric breakdown.

In what follows, the model proposed to account for the conduction in the nanodiodes system is described. According to [1], the current flowing through one of the nanodiodes can be modeled using the expression:

$$I_i = I_{0i}\left\{\exp\left[\alpha_i\left(V - I_i R_i\right)\right] - 1\right\} \tag{1}$$

where I_{0i}, α_i and R_i are fitting constants. Considering the equivalent circuit model depicted in Fig. 6, the total current that flows through the structure reads:

$$I = \sum_i I_i = \sum_i \left(\frac{1}{\alpha_i R_i} W\left\{\alpha I_{0i} R_i \exp\left[\alpha_i\left(V + I_{0i} R_i\right)\right]\right\} - I_{0i} \right) \tag{2}$$

Figures 3 and 4 show the same experimental data (symbols) and simulation results (red lines) in two representations. Notice that the model is able to capture the behavior of the experimental I-Vs both for low (exponential increase) and high (linear regime) applied voltages. A thorough analysis of the model parameters will be presented in the final submission.

[1] E. Miranda, IEEE Electron Dev Lett 26, 673 (2005)

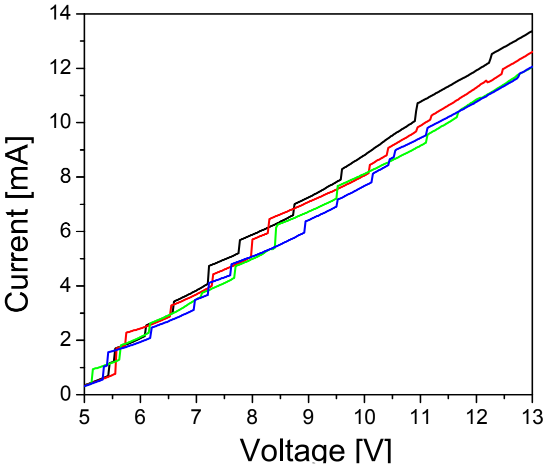

Fig. 1. Formation of breakdown spots by means of a high voltage sweep. Each curve was measured in a different device.

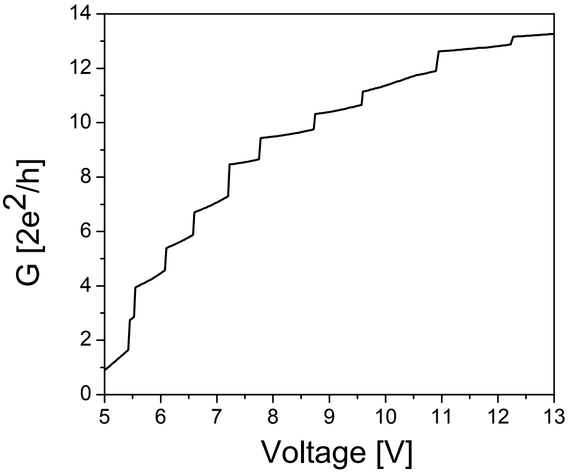

Fig. 2. Evolution of the conductance-voltage characteristic during the generation of spots.

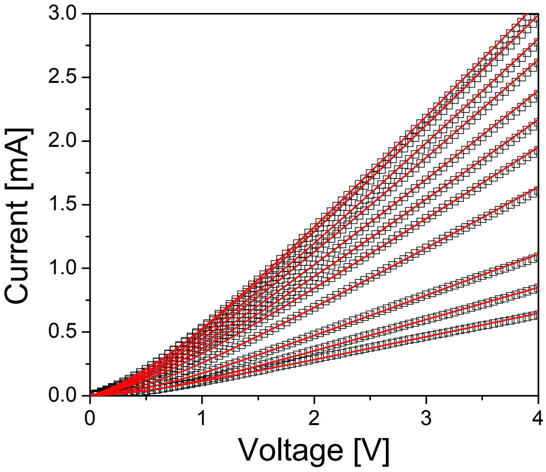

Fig. 3. Current-voltage characteristics after the detection of multiple breakdown events. (Linear axis to emphasize the high voltage region)

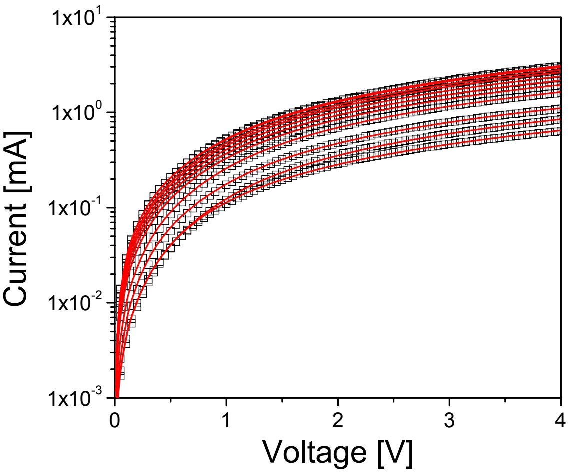

Fig. 4. Current-voltage characteristics after the detection of multiple breakdown events. (Log axis to emphasize the low voltage region)

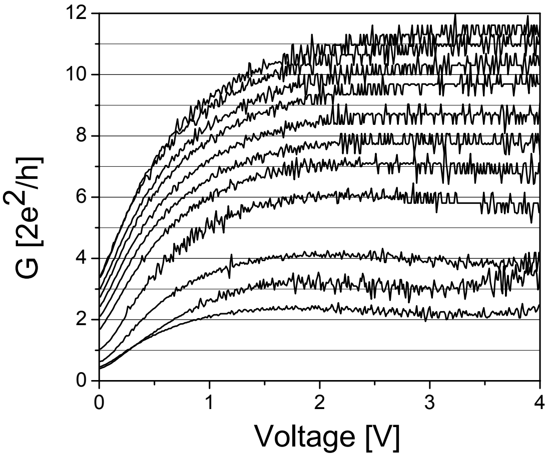

Fig. 5. Conductance-voltage characteristics associated with the I-Vs shown in Figs. 3 and 4.

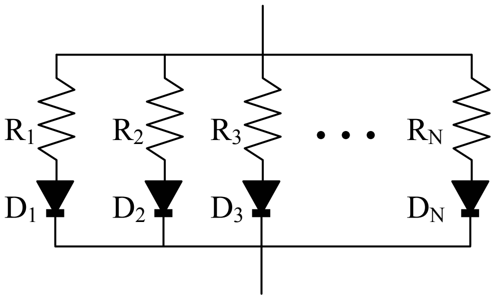

Fig. 6. Equivalent circuit model for the leakage current flowing through the broken down structure.