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Citation: Applied Physics Letters 91, 053502 (2007); doi: 10.1063/1.2761831

View online: http://dx.doi.org/10.1063/1.2761831

View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/91/5?ver=pdfcov

Published by the AIP Publishing
Mesoscopic approach to progressive breakdown in ultrathin SiO₂ layers

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(Received 21 May 2007; accepted 28 June 2007; published online 31 July 2007)

The opening of a breakdown path across the ultrathin oxide layer in a metal-oxide-semiconductor structure caused by the application of electrical stress can be analyzed within the framework of the physics of mesoscopic conductors. Using the Landauer formula for a quantum point contact, the author is able to show that the saturation of the gate leakage current is linked to the progressive evolution of the constriction’s conductance toward the ballistic transport regime. The possible physical mechanisms responsible for energy dissipation inside the breakdown path as well as the limitations of the proposed approach are discussed. © 2007 American Institute of Physics

[DOI: 10.1063/1.2761831]

It is widely recognized that the application of electrical stress to an ultrathin dielectric in a metal-oxide-semiconductor (MOS) structure can open, following a degradation process in which traps or defects are randomly created across the oxide layer, a localized conducting path running between gate and substrate. This is the signature of dielectric breakdown (BD). In relatively thick oxides, from 3 to 6 nm, this event is characterized by an abrupt change of conduction mechanism that leads to a bimodal post-BD current distribution. These stable conduction modes are often referred to as soft BD (SBD) and hard BD (HBD) and are presumably associated with preferred atomic configurations. On the other hand, if the oxide thickness is less than 2 nm and the voltage applied to the gate is low enough, the current flowing through the broken down device exhibits an evolutionary behavior which reveals the progressive lateral enlargement of the leakage spot size. This transitory, also called progressive breakdown (PBD), ends when the system arrives to a final HBD state. Even though the issue has been extensively investigated, mainly from the oxide reliability viewpoint, there are still many dark points concerning the details of the electron transport process through this nanometer-sized constriction. To deal with this problem, a number of models based on mechanisms such as percolation in nonlinear conductor networks, variable range hopping, tunneling, and quantum-point contact (QPC) conduction among others have been proposed. In particular, the QPC model is able to explain consistently the shape of the I-V characteristics for both the SBD and HBD conduction modes. According to this model, the main distinction between SBD and HBD is the cross-sectional area of the constriction at its narrowest point. In mesoscopic devices, the transversal confinement induces energy subbands which act as potential barriers for the incoming electrons so that the conduction properties of the BD path are determined by the transmission probability coefficient.

Here, we extend these concepts and show that the BD spot cannot be regarded as an isolated entity since factors such as the series resistance and background tunneling current must be taken into account to simulate properly the dynamical behavior of the whole system when subjected to stressing conditions. In this way, by means of a separate analysis of the power dissipated at each part of the proposed equivalent circuit model, we are able to connect the local heating effects at the constriction’s bottleneck with the current saturation.

For the experiments we used standard MOS capacitors with p-type Si substrate (10¹⁵ cm⁻³) and poly-Si gate. The nominal oxide thickness is 2.1 nm and the gate area is 6.4×10⁻³ cm². Figure 1 shows three experimental gate current-time (I-G-t) characteristics measured under accumulation conditions with a constant voltage stress V_G=-3.75 V. Notice that the onset of PBD is sample-to-sample dependent, as expected, and that the sigmoidal behavior is a common feature of all curves. In particular, curves C1 and C2 reach the same current level within the considered time window. Initial differences in the tunneling current, such as that exhibited by curve C3, may be attributed to oxide thickness variations. If we assume that I_G at any moment, consists of the tunneling current contribution flowing through the non-

FIG. 1. Three experimental gate current-time characteristics obtained during a constant voltage stress at V_G=-3.75 V. The inset shows a typical fresh I_G-V_G characteristic (squares). The solid and dashed lines are obtained using the tunneling model considered in Eq. (1) with R_S=1.75 kΩ and R_S=0 kΩ, respectively. In both cases, A=2.16×10⁻⁹ A and B=2.9 V⁻¹.
damaged area of the device $I_T$ and the current flowing in parallel through the BD spot $I_{BD}$ we can find the post-BD conductance $G_{BD}$ as

$$G_{BD} = \frac{I_{BD}}{V_{ox}} = \frac{I_G - I_T}{V_{ox}} = \frac{I_G - A \exp[B(V_G - I_GR_S)]}{V_G - I_GR_S},$$

where $V_{ox}$ is the voltage drop across the oxide layer. Within this approach, the direct tunneling current is represented by a simple exponential function of $V_{ox}$ whose parameters $A$ and $B$ are determined from the fresh $I_G$-$V_G$ characteristic (see inset of Fig. 1). Of course, more elaborated models for $I_T$ can be used but this is unnecessary for our aims. $R_S$ is the series resistance extracted from the high-bias region of the fresh $I_G$-$V_G$ curve. Eq. (1) is valid as long as the area of the PBD spot remains negligible compared with the total device area and the post-BD conductance is in the linear regime.\(^\dagger\) Using the definitions of $I_{BD}$ and $I_T$ in Eq. (1), we can calculate separately both gate current components. These results are illustrated in Fig. 2 using the experimental data of curve C1. As a first consequence of this approach, notice that we have isolated the actual leakage current associated with the BD path. This is different from an earlier analysis in which the tunneling current preceding the detection of PBD was included as part of the logistic trajectory.\(^\dagger\) Second, because of the potential drop across $R_S$, $I_T$ decreases until reaching a lower steady state conduction level. Alternatively, we can analyze the behavior of the system in terms of power dissipation. At the outset, the dissipated power in the structure is lower steady state conduction level. Alternatively, we can analyze the behavior of the system in terms of power dissipation. At the outset, the dissipated power in the structure is

Using the Landauer formula for the conductance of a single-mode QPC, we calculate an average transmission probability $\bar{T}$ as

$$\bar{T} = G_0^{-1}G_{BD} = (G_0V_{ox})^{-1}I_{BD}, \quad (2)$$

where $G_0 = 2e^2/h = (12.9 \text{ kΩ})^{-1}$ is the quantum conductance unit, $e$ and $h$ being the electron charge and Planck’s constant, respectively. Even though Eq. (2) is strictly valid for very low biases in the zero-temperature limit, this oversimplification allows us to overlook the details of the confinement potential profile.\(^\dagger\) The central point of our approach is that the power dissipated at the narrowest section of the constriction $P_C$ is given by

$$P_C = I_{BD}V_{C} = (1-\bar{T})I_{BD}V_{ox} = [1-(G_0V_{ox})^{-1}I_{BD}]I_{BD}V_{ox}, \quad (3)$$

where $V_{C}$ is the voltage drop across the potential barrier associated with the first subband, as shown in Fig. 3(a). Notice...
that \( V_C \) differs from \( V_{ox} \) because of the mismatch in the number of electron states at the two ends of the constriction.\(^6\) The evolution of \( P_C \) is shown in Fig. 4. Initially, Joule heating increases because of the growth of the spot area, which in turn lowers the tunneling barrier height. This corresponds to the SBD-HBD transition, as depicted in Fig. 3(b). However, notice that as \( \bar{T} \) approaches unity, the dissipated power inside the constriction starts to decrease and eventually become negligible. Under this circumstance, the BD path behaves as a ballistic conductor and the power is totally dissipated at the capacitor electrodes. From a classical viewpoint, this situation closely resembles to what happens in a vacuum diode where power is dissipated at the metal plates and not in the vacuum. This power transfer can explain why a so small conducting channel is able to sustain a large stable current far from thermodynamic equilibrium conditions. Moreover, this localized heating might explain the formation of hillocks at the Si substrate during PBD.\(^8\) Electromigration effects within the BD path are also likely.\(^9\) The incorporation of these phenomena into the proposed model could lead to more complex dynamics such as the asymmetric logistic growth\(^10\) and the nonsaturating behavior of the current for prolonged injection.\(^11\) These effects were not included in the present analysis.

To conclude, let us mention that the problem of power dissipation in a QPC has raised some interesting questions. As stated by Eq. (2), even in the case of ballistic conduction, the BD path has associated a finite conductance as a consequence of the contact resistances at the two ends of the constriction.\(^6\) During the transient, the BD spot must dissipate electrical energy at a rate \( P = I_{BD} \, V_{ox} \) by means of some mechanism in which the energy gained by the injected electrons is passed incoherently in part to the contacts and in part to the surroundings of the PBD path.\(^12\) However, dissipation in a QPC is not only due to the presence of phonons but dissipation can be locally enhanced by the confinement effect. In this regard, a recent study based on the boosted Fermi function indicates that a localized elastic scattering barrier may induce dissipation by modifying the electron-phonon coupling.\(^13\) Nevertheless, this is at variance with earlier proposals in which dissipation is assumed to be strictly restricted to the electrodes, where strong scattering events are supposed to occur.\(^14\) Additionally, it is worth pointing out that conductance deviations from the ideally ballistic Landauer limit, as that exhibited by curve C3 in Fig. 1, are not unusual in the field of mesoscopic conductors.\(^15\) Deviations are often represented in terms of histograms and have been attributed to enhanced role of inelastic scattering within the constriction.\(^16\) This effect cannot be ruled out in our system.

In summary, we have presented a possible scenario for the PBD dynamics in ultrathin SiO\(_2\) layers. This new approach is different from our own previous phenomenological model for the gate current based on the Verhulst equation.\(^5\) Here, we were able to isolate the electrical behavior of the breakdown site and relate its degradation dynamics to power dissipation. Of course, because of the many oversimplifications involved, the model has its limitations and does not attempt to cover all cases. It only suggests a new framework for the understanding and discussion of the physics associated with progressive breakdown.

This work was supported by Ministerio de Ciencia y Tecnología (Spain) under Project No. TEC2006-13731-C02-01.

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