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Electron transport through electrically induced nanoconstrictions in HfSiON gate stacks

E. Miranda,[1,a)] P. Falbo,[2,b)] M. Nafría,[1,c)] and F. Crupi[2,d)]
[1]*Escola Tècnica Superior d'Enginyeria, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*
[2]*Dipartimento di Elettronica Informatica e Sistemistica, University of Calabria, Via P. Bucci 41C, I-87036 Arcavacata di Rende (CS), Italy*

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A microscopic picture for the progressive leakage current growth in electrically stressed $Hf_xSi_{1-x}ON/SiON$ gate stacks in metal-oxide-semiconductor transistors based on the physics of mesoscopic conductors is proposed. The breakdown spot is modeled as a nanoconstriction connecting two electron reservoirs. We show that after eliminating the tunneling current component that flows through the nondamaged device area, the postbreakdown conductance exhibits levels of the order of the quantum unit $2e^2/h$, where e is the electron charge and h the Planck's constant, as is expected for atomic-sized contacts. Similarities and differences with previous studied systems are discussed. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2949748]

In the relentless race toward the miniaturization of metal-oxide-semiconductor devices, the gate oxide material properties and the quality of its interface with the channel region play an ever increasing technological role. In this connection, the use of high permittivity (high-κ) dielectrics addresses the problem of the large tunneling current by increasing the oxide thickness while at the same time allows preserving the oxide capacitance to the values required for standard operating conditions.[1] However, not all high-κ's are useful to this purpose and the search for the most appropriate materials is still in progress. In particular, we have investigated the degradation dynamics of hafnium silicate nitride ($Hf_xSi_{1-x}ON$) films, one of the best positioned candidates to replace SiO_2 as gate insulator. A number of experimental works have pointed out that HfSiON exhibits not only good electrical properties in terms of leakage current[2,3] and reliability[4] but also presents a high protection barrier against boron penetration.[5] In addition, the inclusion of a thin interfacial layer of SiON between the high-κ and the Si substrate further improves the system's properties by providing better thermal stability and a lower density of interface states.[6] While the conduction characteristic in the fresh stack has been ascribed to tunneling,[7] there is no clear picture about the electron transport mechanism after the occurrence of a breakdown (BD) event. It has been reported that, for low applied biases, these structures exhibit the so called progressive BD (PBD) mode,[8] i.e., a gradual increase in localized leakage current over time. In this letter, we explore this behavior in detail and show that the evolution of the current can be interpreted within the framework of the physics of mesoscopic conductors. Because of the particular conductance levels reached at the earliest stages of degradation, we propose that the current mainly flows across the oxide layer through nanoconstrictions only a few atoms wide. In order to find key features governing the PBD phenomenon in thin gate dielectrics, we compare the BD trajectory in HfSiON with previously reported results for SiO_2.

The devices used in this study are transistors (channel length=0.8 μm × channel width=10 μm) with HfSiON/SiON gate dielectric and poly-Si gate. The substrate is p-type Si with acceptor doping $N_A=5\times10^{17}$ cm^{-3}. The Hf content was 23% and the dielectric was deposited by metal-organic chemical vapor deposition. The high-κ deposition was followed by a 1 min postdeposition annealing in NH at 800 °C and the poly-Si was activated at a 10 s 1000 °C spike. From capacitance-voltage measurements, an interfacial SiON thickness of 0.9 nm and a Hf silicate of 2 nm were extracted, with a nominal total equivalent oxide thickness of 1.6 nm. In all cases, the stress voltage was $V_G=3.5$ V. Figure 1(a) illustrates the evolution of the post-BD current for three cases of particular interest. These curves were selected from a set of 50 I-t characteristics whose stationary levels are shown in the histogram of Fig. 1(b). The values were taken at the end of the BD transients and before the detection of any sign of additional degradation caused by

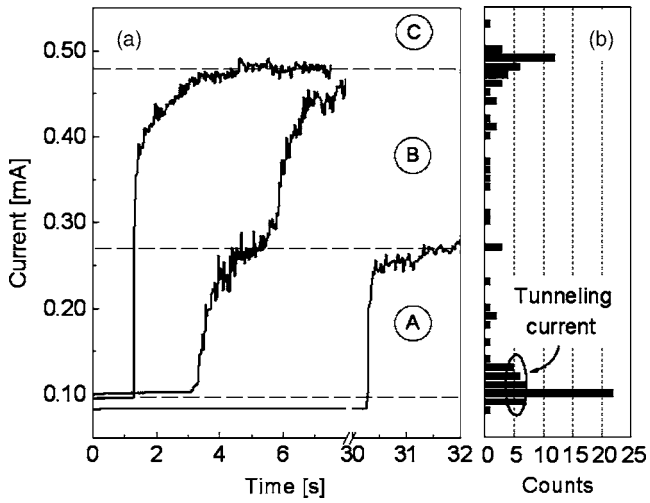

FIG. 1. (a) Evolution of the leakage current under a constant voltage stress of 3.5 V in three different samples. A, B, and C identify the regions of interest discussed in the text. (b) Histogram for the stationary current levels of 50 samples.

[a)]Author to whom correspondence should be addressed. Electronic mail: enrique.miranda@uab.es.
[b)]Electronic mail: subguitar2002@yahoo.it.
[c)]Electronic mail: montse.nafria@uab.es.
[d)]Electronic mail: crupi@unical.it.

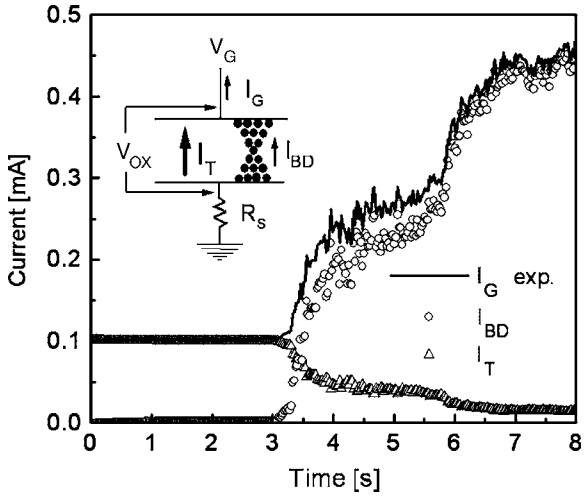

FIG. 2. Evaluation of the current components that flow through the gate oxide stack using the equivalent circuit shown in the inset. I_G is the measured gate current, I_{BD} the current through the BD spot, and I_T the tunneling current through the nondamaged area. V_{OX} is the potential drop across the oxide layer and R_S is a series resistance.

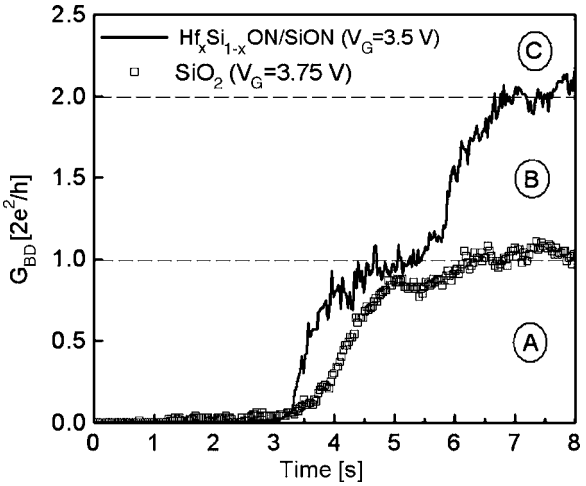

FIG. 3. Post-BD conductance as a function of time for the gate stack under investigation and for a 2-nm-thick SiO_2 film in units of $2e^2/h$.

the application of a long-term stress. In all cases, the time-to-BD is less than 35 s and the transient time not longer than 5 s. The distribution of the tunneling currents in the fresh samples [see Fig. 1(b)] arises as a consequence of oxide thickness variations. While the leftmost and rightmost curves in Fig. 1(a)exhibit a current jump followed by a gradual evolution toward steady-state current levels, the central curve reaches similar levels by means of a progressive trajectory. The fact that regardless of the type of evolution the plateaus coincide may be indicative of preferred atomic configurations within the BD path. Moreover, since the two transients in the central curve are almost identical, they may arise from similar microscopic arrangements. The peak corresponding to the uppermost final current level in Fig. 1(b)is a remarkably feature that supports this conjecture. We have defined three regions, A, B, and C, which will help us discuss the different stages that, in our view, take place during the formation of the BD path. In order to assess whether the aforementioned current saturation levels can be linked to the atomic scale of the constriction, we need first to isolate the current component that flows through the BD path, I_{BD}. To this aim, we assume that our system can be represented by the equivalent electrical circuit depicted in Fig. 2, so that the post-BD conductance G_{BD} reads

$$G_{BD} = \frac{I_{BD}}{V_{OX}} = \frac{I_G - A\exp[B(V_G - I_G R_S)]}{V_G - I_G R_S}, \quad (1)$$

where V_{OX} is the potential drop across the insulator. The parameters $A = 3.75 \times 10^{-8}$ A and $B = 3.34$ V^{-1} for the tunneling current flowing through the nondamaged device area I_T and the series resistance $R_S = 1.66$ KΩ were extracted from the fresh I-V characteristic following the procedure described in Ref. 9. From Eq. (1)we can separately evaluate I_{BD} and I_T, as shown in Fig. 2, for the two-level curve in Fig. 1(a). It is worth pointing out that at the outset of the BD event, I_{BD} does not coincide with I_G but that the difference becomes less significant as the degradation proceeds. This means that the final current level in stage B is practically independent of the tunneling model considered. To get further insight into the degradation dynamics, we have plotted in Fig. 3 the evolution of G_{BD} in units of $2e^2/h = (12.9\ \text{k}\Omega)^{-1}$, i.e., the quantum conductance unit. Remarkably, the two transients level off at integer values of this quantity. This behavior closely resembles the formation of a quantum point contact (QPC) and can be explained as follows (see Fig. 4). First, phase A corresponds to the formation of a single atom constriction. In this case, the atoms located at the apices of the defects clusters determine the bottleneck of the leakage path. Notice that a symmetric arrangement is represented for the sake of simplicity. As the defect density increases or reaccommodates as a consequence of the electron wind force, the lateral confining potential widens and the first energy subband level in the propagation direction (solid line) drops below the energy window of the passing electrons. This is the transition from soft-BD to hard-BD (Ref. 10) or, in terms of electron transport in QPCs, from tunneling to contact regime.[11,12] Under this condition, there is no electron backscattering and the conductance reaches one quantum unit.[13] In phase B, the creation of new defects leads to the progressive opening of a second bridge (dashed line) until it reaches phase C. To get an idea about the size of the defects in HfSiON, recall that the radius of conduction considered in percolation models is 0.45 nm.[4]

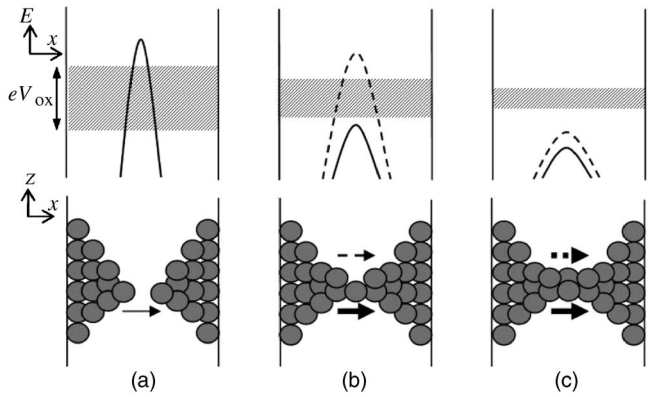

FIG. 4. Formation of the BD path across the oxide layer. (a) Phase A: single tunneling barrier induced by the lateral confinement effect of electron flow. (b) Phase B: first contact is formed and there is a growing tunneling component arising from a close defect's path. (c) Phase C: the second path is completed and both potential barriers are below the energy window of the injected electrons. Notice that the shaded region (eV_{OX}) becomes narrower as the degradation proceeds because of the potential drop in R_S.

Even though the systems investigated are different, Ohnioshi *et al.* reported clear evidences that there is a link between structure and conductance level.[14] They found that a double strand of atoms attached to two electrodes has twice the quantum conductance unit if the interaction between the two individual rows is not strong. A similar correlation between atomic structure and conductance behavior has been established for nanowires[15] and the appearance of conductance steps has been ascribed to the overlap of molecular[16] or atomic[17] orbitals even in a one-atom contact geometry. It is not unlikely that analogous phenomena can occur in a system like the one investigated here if we regard that the conduction properties of the BD path are dominantly determined by the nature of a few atoms only. Intermediate conductance levels such as those observed in Fig. 1(b) can be attributed to the formation of interacting BD paths or to stationary dissipative structures.[18] It is worth emphasizing that conductance data spread is a common feature to a wide variety of mesoscopic systems with nonadiabatic constrictions[13] and that the proposed picture still holds even in the case of having uncorrelated BD spots. Finally, in Fig. 3, we have included for comparison a PBD curve measured for a 2-nm-thick SiO_2 film. The fact that the curve levels off at $2e^2/h$ too, seems to indicate that the conduction properties of the BD paths are more related to their atomic scales rather than to the specific features of the surrounding material. Notice that in spite of the SiO_2 layer has been stressed at a higher bias, $V_G(SiO_2)=3.75$ V, the PBD curve exhibits a lower degradation rate dG_{BD}/dt than that of the HfSiON sample. Perhaps the difference has to be looked for in the strength of the atomic bondings rather than on the series resistance effect, which are very similar $R_S(SiO_2)=1.75$ KΩ and $R_S(HfSiON)=1.66$ KΩ, but this point needs to be further investigated.

The search for a reliable gate oxide material requires a deep understanding of the physics associated with the degradation mechanisms that leads to the loosening of its insulating capabilities. In this work, we have proposed a simple picture for the formation and evolution of nanoconstrictions in HfSiON layers subject to electrical stress following an analogy with the conduction problem in mesoscopic structures. This connection suggests that the progressive degradation of gate oxides could be analyzed invoking the theoretical tools developed for low-dimensionality systems.

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