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Post-radiation-induced soft breakdown conduction properties as a function of temperature

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When a thin oxide is subjected to heavy ion irradiation, a large leakage current similar to the soft breakdown can be produced. In this work, we have studied the radiation soft breakdown (RSB) after 257 MeV Ag and I irradiation by using a quantum point contact (QPC) model, which also applies to hard and soft breakdown produced by electrical stresses. We have also studied the temperature dependence of RSB current from 98 K up to room temperature, and found that the gate current after irradiation is strongly reduced by decreasing temperature. It is shown that this behavior can be attributed to a temperature dependence of the carriers supplied from the cathode rather than to a temperature-induced modification of the size and/or shape of the oxide RSB paths. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1398329]

Deep submicron complementary metal–oxide–semiconductor (CMOS) devices can be successfully used in radiation-harsh environments by adopting some simple layout rules [such as guard rings and metal–oxide–semiconductor field effect transistor (MOSFET) with enclosed structures].[1] At present, high-speed CMOS integrated circuits are fabricated in 0.18 μm technologies, with gate oxide thickness of 3 nm. In these thin oxides, the total trapped charge after exposure to ionizing radiation is quite modest, due to fast recombination or escape of an oxide trapped charge, leading to a negligible threshold voltage shift.[1] Also, the MOSFET transconductance is only marginally affected by irradiation. On the contrary, the main reliability problem of thin oxides is the increase of the gate leakage current after irradiation (Radiation Induced Leakage Current),[2,3] which hampers the device lifetime. Recently, it has been shown that radiation induced soft breakdown (SB) can be produced in 4 nm oxides after exposure to irradiation with high linear energy transfer (LET) ions.[4] Such leakage current appears similar to the SB produced by electrical stresses.

Recently, both electrically induced oxide hard breakdown and SB were successfully modeled using a quantum point contact (QPC) picture.[5,6] The basic idea of the QPC model is that the conduction is strongly localized and flows through one or more breakdown paths. In the case of radiation, it is likely that we are dealing with several conductive paths generated by the ions passing across the oxide.[4] Each of these conductive paths should behave similarly to a single path generated after an electrical stress, but with a smaller area. Based on the QPC model, the lateral dimension of the breakdown paths is so small that the momentum in the direction perpendicular to propagation is quantized. If the path is narrow enough (as in the case of electrical SB), the ground subband E_0 is above the Fermi level at the cathode, and the conduction can only take place by tunneling across an effective one-dimensional (1D) potential barrier. This barrier is not material related, but its height cannot be larger than that of the Si/SiO_2 system because electrons would be otherwise no longer laterally confined. This model leads to the exponential relation for the gate current:[6]

$$I_g = A \times \exp[B(V_g - V_0)]. \quad (1)$$

The parameter A and B have been related to the height and thickness of the local barrier in the breakdown path. The offset voltage V_0 is due to some potential drop in the substrate. Our present goal is to extend the validity of such a model also to the case of the radiation soft breakdown (RSB), and to investigate which is the effect of temperature on the spot parameters.

We have used square MOS capacitors on p-Si substrate with gate area $A = 10^{-2}\,\mathrm{cm}^2$. The oxide thickness was $t_{ox} = 4$ nm. All capacitors were surrounded by a n^+ ring in order to supply electrons when a positive gate voltage was applied. The gate is a N^+ polysilicon layer and the gate oxide has been thermally grown in a steam ambient and subjected to a high temperature N_2 anneal.

Heavy ions were supplied by the Tandem Van der Graaff accelerator of the Laboratori Nazionali di Legnaro, Instituto Nazionale de Fisica Nucleare (INFN), and Università di Padova, Italy. The ion species were 257 MeV ^{121}I and 257 MeV ^{107}Ag. with LET of 52.2 and 61.6 MeV cm^2/mg, respectively. The gate current–voltage (I_g–V_g) characteristics were measured before and after irradiation at temperatures ranging from 98 to 300 K.

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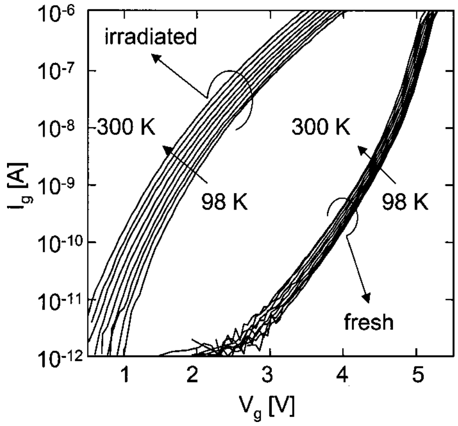

FIG. 1. $I_g - V_g$ curves before and after irradiation measured at temperatures ranging between 98 and 300 K in a MOS capacitor with $t_{ox} = 4$ nm are shown.

Figure 1 shows $I_g - V_g$ characteristics of a MOS capacitor before and after irradiation with 32×10^9 Ag ions/cm^2. A similar behavior has been observed for 12×10^9 I ions/cm^2 irradiation. The RSB appears as a large increase in the leakage current after irradiation with respect to the fresh device, as previously reported.[4] In addition, we show here that the RSB is largely affected by the measuring temperature. The RSB current significantly decreases when the temperature is reduced while the fresh $I_g - V_g$ shows a weaker temperature dependence. Moreover, the main temperature effect on the RSB characteristics can be modeled as a rigid shift of the $I_g - V_g$ curves parallel to the voltage axis. In Fig. 2, the RSB current measured in the same device at nine different temperatures has been plotted as a function of $V_g - \Delta V(T)$ for both positive and negative polarity, $\Delta V(T)$ being the voltage shift needed to overlap the curves measured at temperature T and at 300 K. All nine curves nicely overlap each other for the $\Delta V(T)$ values shown in the inset of Fig. 2. Noticeably, $\Delta V(T)$ varies almost linearly with T.

A comparison between experimental data and theoretical curves is shown in Fig. 3. An excellent fit is obtained when $V_g > 2V$, by using the A and B values shown in the inset. The value of $V_0 = 0.6$ V at room temperature is the same as reported in Ref. 6 for electrical SB. A and B do not depend on

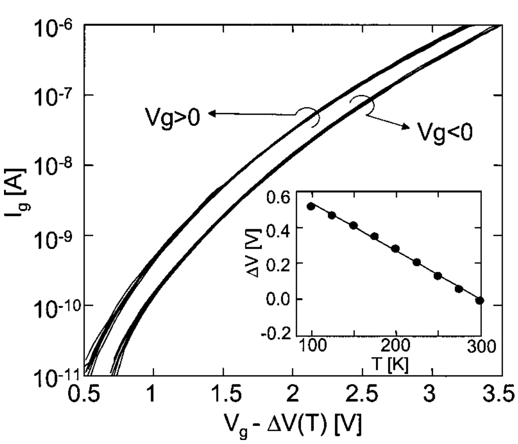

FIG. 2. $I_g - V_g$ curves of Fig. 1 plotted as a function of $V_g - \Delta V(T)$ are shown. $\Delta V(T)$, shown in the inset, is the temperature-dependent gate voltage shift required to overlap the curves measured at temperature T and at 300 K.

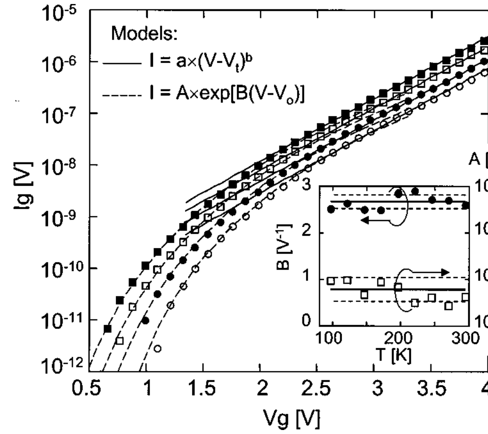

FIG. 3. Comparison between experimental results (symbols) and data derived from the QPC model [see Eq. (1) in the text] (solid lines) is shown. The different curves refer to the measurement temperatures $T = 98$ (○) 173 (●), 248 (□), and 300 K (■). Curves derived form the empirical model ($I = a \times (V - V_t)^b$) are shown as dashed lines.

temperature, indicating that temperature has a negligible effect on the height, thickness, and shape of the 1D effective barrier associated to the weak spots generated by radiation. Since this is a barrier related to the quantum confinement, this also means that the geometry of the RSB paths does not depend on the temperature. This is consistent with the results of Fig. 2, since only V_0 depends on temperature. In our opinion, the temperature-dependent shift, $\Delta V(T)$, only reflects the thermal occupancy of the electron states in the electrode regions adjacent to the RSB path. The state occupancy affects the electron supply to the RSB path and the voltage drops in the access region to the QPC.

In the low voltage region ($V_g < 2$ V), the QPC model does not satisfactorily fit the experimental results. Nevertheless, they are nicely described by the empirical power law proper of SB conduction at low oxide fields:[7]

$$I_g = a \times (V_g - V_t)^b. \tag{2}$$

V_t is temperature dependent, and we observed $V_t(T) \approx \Delta V(T)$ (data are not shown for brevity). At room temperature, we found $V_t \approx 0V$ in agreement with previous results.[4,7] We have verified even in this case that parameters a and b of Eq. (2) are not affected by temperature, as in case of A and B in Eq. (1), confirming that the RSB path properties do not change with temperature. According to the QPC model predictions,[8] the parameters a and b must be correlated through:[7]

$$b = k_1 \times \log(a) + k_2. \tag{3}$$

Even for RSB, this correlation is satisfied with $k_1 = -0.81$, and $k_2 = -1.64$ as illustrated in Fig. 4 (filled symbols), together with the solid lines found for the SB, correlation.[7] While the slope k_1 has practically the same value for RSB and SB, $k_2(\mathrm{RSB}) > k_2(\mathrm{SB}) = -3.27$. In our opinion, this apparent disagreement is derived from the fact that many RSB spots are active after irradiation while only one SB spot appears after electrical stresses. Eqs. (1) or (2) should be modified accordingly as:

$$I_g = N \times A \times \exp[B \cdot (V_g - V_0)], \tag{4a}$$

$$I_g = N \times a \times (V_g - V_t)^b, \tag{4b}$$

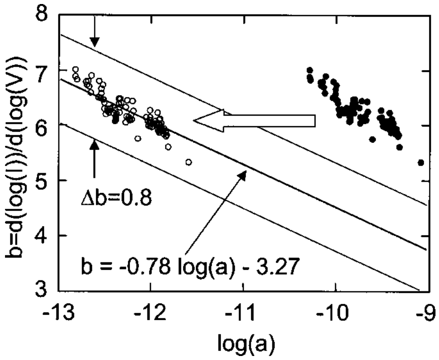

FIG. 4. Correlation between parameters *a* and *b* measured for RSB [see Eq. (3) in the text] (filled symbols) are shown. Results are compared to those previously reported for SB induced by electrical stress represented by the dotted line (average value) and solid line (data dispersion). Overlap is achieved by shifting the RSB data along the *X* axis by a constant (open symbols).

N being the number of radiation-induced spots. Hence, for $N>1$, the RSB experimental data should horizontally shift by $\log(N)$ in Fig. 4 (open symbols), then nicely overlapping the previous SB results. In this way, we may evaluate the spot number N as 446 for 32×10^9 Ag ions/cm^2 and $N=255$ spots for 12×10^9 I ions/cm^2, respectively, corresponding to a generation efficiency around 1.7×10^{-6} spot/ion. From the values of A, B, and N, we evaluated the average barrier height $\phi=3.20$ and 2.82 eV, and the average spot area 10^{-18} and 10^{-17} cm^2, for the Ag and I irradiation, respectively. The barrier thickness has been estimated around 2.5 nm independently on the ion source.

In summary, we have analyzed the radiation induced SB measured at different temperatures. We have applied the QPC model to explain the RSB conduction mechanism. Following this model, we have estimated the number of radiation-generated spots, which are some hundreds after the total irradiation doses used in our experiments. This corresponds to a generation efficiency around 1.7×10^{-6} spot/ion. Moreover, by measuring the gate current at different temperatures, we have found that the parameters of the spots, i.e., the barrier height and thickness, do not depend on temperature. The large decrease of the RSB leakage current with decreasing temperature is only related to some change in the electron distribution in the regions of the electrodes adjacent to the RSB path. The presented results confirm that the nature of the RSB paths is essentially the same as that of the electrically induced SB paths.

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