


Ultra-thin oxide breakdown for OTP development in power technologies

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OTP (One Time Programmable) memory in power technology enables electrical performance optimization together with area occupation reduction. In this paper, the aspects relative to the oxide breakdown (which is the key mechanism for memory programmability) are studied and applied to the development of an antifuse OTP cell in a 350 nm-CMOS power technology. The physical analysis of the degradation phases of an oxide layer is presented together with the physical models, exploited to foresee the device time-to-breakdown depending on applied voltage, oxide thickness etc. The achieved results are used in the development and reliable implementation of OTP cells in the target 350 nm-CMOS node.

Keywords: 1/E model; E model; oxide breakdown; OTP; power law; tunneling; time-to-breakdown

Ultradünner Oxidabbau für die OTP-Entwicklung in der Energietechnik.

OTP-Speicher (One Time Programmable) in der Energietechnik ermöglicht die Optimierung der elektrischen Leistung bei gleichzeitiger Reduzierung der Flächenbelegung. In diesem Beitrag werden die Aspekte in Bezug auf den Oxiddurchbruch (welcher der Schlüsselmechanismus für die Programmierbarkeit des Speichers ist) untersucht und auf die Entwicklung einer OTP-Zelle mit Antifuse-Funktion in einer 350nm-CMOS-Leistungstechnologie angewandt. Die physikalische Analyse der Degradationsphasen einer Oxidschicht wird zusammen mit den physikalischen Modellen vorgestellt, die ausgenutzt werden, um die Zeit bis zum Durchbruch des Bauelements in Abhängigkeit von der angelegten Spannung, Oxiddicke usw. vorherzusehen. Die erzielten Ergebnisse werden bei der Entwicklung und zuverlässigen Implementierung von OTP-Zellen im 350nm-CMOS-Zielknoten verwendet.

Schlüsselwörter: Oxidabbau; Tunnelbau; E-Modell; 1/E-Modell; Energierecht; Time-to-Breakdown; OTP

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1. Introduction

Recently aggressive optimization of power devices is exploiting digital programmability, which is possible for the availability of on-chip low-cost memory as OTP (One Time Programmable) cells. Digital programmability is exploited in power devices to configure the circuit and optimize it for any operation condition. On the other hand, in the design of analog blocks, where the power devices are not specifically developed for, digital programmability is exploited to adjust and tune performance to achieve accuracy otherwise critical in such technology. This key need of on-chip memory in power technology is satisfied by the development of low-cost OTP cells, which have to guarantee efficient and reliable programmability mechanism.

In an OTP cell, the oxide is the antifuse element to be programmed by inducing its Breakdown reliability and within a certain time, defined Time-To-Breakdown (T_{BD}).

In this paper, the mechanisms producing the Breakdown events are presented and their effects are studied for the development of an OTP cell in 350 nm technology with 7.7 nm oxide thickness (t_{ox}).

2. Oxide degradation processes

The main classes of processes producing oxide degradation, resulting in damages and, then, in Breakdown are the Wearout currents and the Defect Generation Mechanisms, as described in the following.

2.1 Wearout currents

If a voltage is applied to an oxide layer, a leakage current flows, called *tunneling* or *wearout* current. There are two main mechanisms causing such current:

- *Fowler-Nordheim tunneling (FN)*: the band diagram deforms such that the electron crosses a triangular potential barrier. Such FN current is due to electrons reaching the anode passing through the oxide conduction band, as in Fig. 1(left), and is:

$$J_{FN} = A \cdot E_{ox}^2 \cdot \exp\left(-\frac{B}{E_{ox}}\right) \quad (1)$$

where q is the elementary charge, and A, B parameters are:

$$A = \frac{q^3}{8\pi\hbar\phi_e} \cdot \frac{m_{Si}^*}{m_{ox}^*} \quad \text{and} \quad B = \frac{8\pi\sqrt{2m_{ox}^*}\phi_e^{3/2}}{3\hbar q} \quad (2)$$

with m_{Si}^* the electron rest mass, m_{ox}^* the electron effective mass within the dielectric and ϕ_e the injecting electrode barrier height. FN mechanism dominates for high electric fields;

- *Direct Tunneling (DT)*: the current is due to cathode injected electrons crossing a trapezoidal potential barrier (between metal/oxide/Si in CMOS) reaching the anode without flowing into

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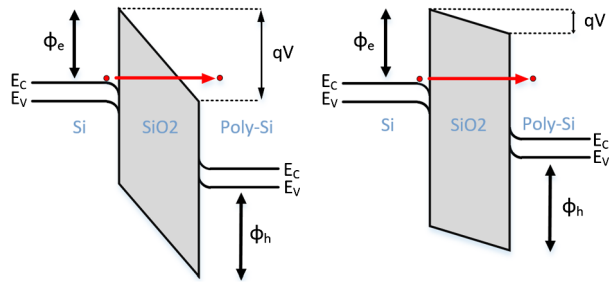


Fig. 1. Energy band diagrams: Fowler-Nordheim (left) and Direct (right) Tunneling

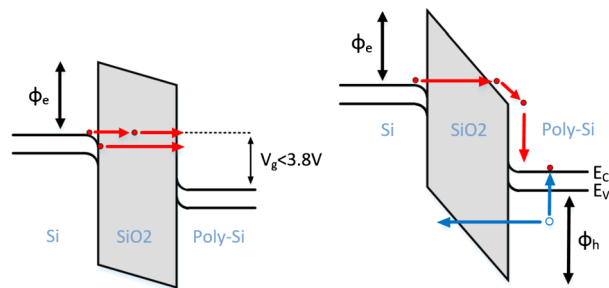


Fig. 2. Trap assisted tunneling (left), AHI mechanism (right)

the oxide conduction band as shown in Fig. 1(right). The approximated DT current is:

$$J_{DT} = A \cdot E_{ox}^2 \cdot \exp\left(-\frac{B}{E_{ox}} \cdot \left[1 - \left(1 - \frac{V_{ox}}{\phi_e}\right)^{3/2}\right]\right) \quad (3)$$

This mechanism dominates for low electric fields;

For a given E_{ox} , the DT current density is higher than the FN one. Based on the tunneling regime, differences in the Breakdown event, such as its rapidity, are to be expected.

The Electric field (E_{ox}) threshold between the DT and FN is between 5–20 MV/cm, e.g. for a $t_{ox} = 7.7$ nm corresponds to $\approx 3.8V$. For thick oxide ($t_{ox} > 5$ nm) and electric fields above 5–8 MV/cm FN current dominates [1]. While for thin oxide ($t_{ox} < 5$ nm) and voltage below 3.1–3.2 V (corresponding to the barrier height between n-doped silicon and SiO₂) the DT dominates. Since $E_{ox} = V_G/t_{ox}$, where V_G is the voltage applied across the gate oxide, any t_{ox} change would affect the MV/cm ratio. In the implementation of an OTP cell using 350 nm technology ($t_{ox} = 7.7$ nm) in high voltage (>10 V) domain, the $E_{ox} \approx 13$ MV/cm, therefore the FN current is expected to dominate.

2.2 Defect generation mechanisms

Defects in an oxide layer are due to fabrication imperfections and/or generation mechanisms. These defects would introduce traps or recombination centers into the forbidden SiO₂ band-gap, which enable carriers to tunnel the oxide and, depending on their energies, to trigger other defect creation mechanisms. In a trap-assisted tunneling, considering a single trap, electrons tunnel from the cathode to the trap and then from the trap to the anode, as shown in Fig. 2 (left) for a deep (top) and an interface (bottom) trap.

For electrons with energy > 5 eV [1], [2] (as it is the case for the higher voltages required in the OTP Breakdown) the Anode Hole Injection (AHI) mechanism and bonds rupture, shown in Fig. 2 (right), are activated. Hot electrons tunnel the triangular barrier reaching the anode conduction band. Then, they transfer their energy to deep

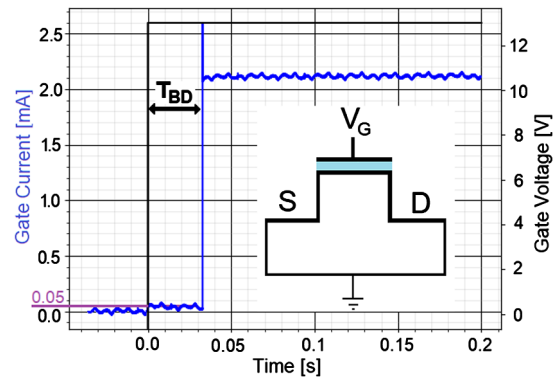


Fig. 3. Gate Current waveform for T_{BD} detection with a 13V- V_G

valence-band electrons, which are promoted to the conduction band leaving holes behind. Due to E_{ox} , hot holes tunnel into oxide valence band. This could lead to interface traps generation and recombination centers for incoming electrons [8]. Trap assisted tunneling in localized spots follows, leading to irreversible oxide damages.

3. Breakdown physical models

The OTP programmability efficiency and reliability depends on the accuracy of the evaluation of T_{BD} , whose value depends on the dominating defect creation mechanisms. There are three main mechanisms producing Breakdown, each of which leading to a different T_{BD} .

- *E Model (also Thermo-Chemical model)*: the Breakdown results from the covalent SiO₂ bonds rupture due to the electric field [7]. In this case:

$$T_{BD,E} = (C \cdot e^{\frac{E_a}{k_b T}}) \cdot e^{-G \cdot E_{ox}} \quad (4)$$

where G is the electric field acceleration factor and E_a is the activation energy for the oxide Breakdown;

- *1/E Model (also AHI model)*: the Breakdown is due to the hot holes injected from the anode. The hole tunneling current can be expressed as the product between the electron FN tunneling current and a term expressing the probability of the hole generation and tunneling through the anode barrier [3], [4]. The amount of injected holes determines the T_{BD} , expressed as:

$$T_{BD,1/E} = (D \cdot e^{\frac{E_a}{k_b T}}) \cdot e^{\frac{F}{E_{ox}}} \quad (5)$$

- *Power Law*: linked to the hydrogen release phenomena. Hot tunneling electrons may break the Si-H bonds, leading to releasing of hydrogen atoms at the cathode interface. These can subsequently diffuse through the oxide and combine with oxygen vacancies [5]. In such a way, defects are generated till the Breakdown happens and T_{BD} is given by:

$$T_{BD,Power} = K \cdot V_G^{-\beta} \quad (6)$$

where β is the voltage acceleration factor [6], related to the disruption energy of Si-H bonds.

Depending on the implementation aspects (oxide quality, technology processes, electric field etc.) the relative importance of the three mechanisms changes and one of these could become dominating. The case with a 350 nm technology is discussed in the following section.

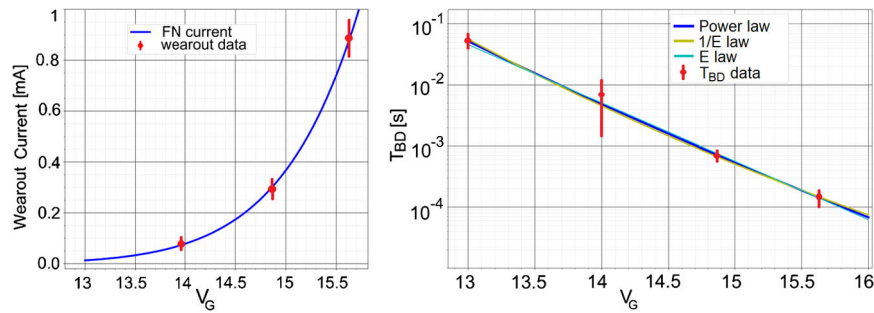


Fig. 4. Wearout current fit with FN equation (left), T_{BD} fit (right)

4. Models validation

Based on the above described physical mechanisms, the case of an OTP cell in the 350 nm technology with oxide surface of $9.2 \mu\text{m}^2$ and thickness of 7.7 nm is studied. The goal is to relate electric field, oxide properties and T_{BD} . For this purpose, high voltage (>13 V) pulses are applied to the gate (while source and drain were shorted) to induce Breakdown. From Fig. 3, for 13 V programming voltage, the Wearout current is about 50 μA and the T_{BD} is 30 ms. Since the electric field is >15 MV/cm, the FN current dominates, as proven in Fig. 4 (left) where the Eq. (1) correctly fits the data. The extrapolated A and B parameters of Eq. (1) are:

$$A = 3.5 \cdot 10^{-3} \text{ A/V}^2 \quad \text{and} \quad B = 3.8 \cdot 10^{10} \text{ V/m} \quad (7)$$

The T_{BD} behaviour as a function of the applied voltage is shown in Fig. 4 (right). The fitting equations are (4), (5) and (6) where $V_g/t_{ox} = E_{ox}$. The extrapolated parameters are:

$$E \text{ model: } (C \cdot e^{\frac{E_a}{k_b T}}) = 1.2e^{11}, \quad G/t_{ox} = 2.22$$

$$1/E \text{ model: } (D \cdot e^{\frac{E_a}{k_b T}}) = 2.4e^{-17}, \quad F \cdot t_{ox} = 460 \quad (8)$$

$$\text{PowerLaw model: } K = 2.3e^{34}, \quad \beta = 32$$

These results are validated also by the good agreement with literature. In fact, B is consistent with [6] and E model parameters are comparable with those obtained in [7].

The fitting to the experimental data proves the pertinence of the three models. However, the experiment is yet not enough to determine which of those defect generation mechanisms have more impact. Indeed, breakdown is generally a consequence of more mechanisms superimposed. Anyway, guesses of T_{BD} can still be obtained by extrapolation. Must be pointed out that it is important to guarantee a maximum failure rate: the programmed oxide must be hardly broken, to avoid misunderstanding while reading the memory. The higher the electric field, the higher is the probability of having hard breakdowns in the programming time window. Nevertheless, producing a higher voltage would require more power and area consumption, affecting the overall chip cost. On the basis of these considerations, the specifications concerning the oxide properties, the target T_{BD} and the applied field are drawn and the OTP circuit design follows.

5. Conclusion

The paper explains the oxide Breakdown process in a high-voltage technology required for the development of an OTP cell. The main models and formulas, useful to relate the oxide lifetime with the oxide dimension and the applied field are presented. From the conducted experiments in the adopted 350 nm technology and in the range 13 to 16 V, the three mechanism results in similar T_{BD} and

then T_{BD} optimization requires to manage all three phenomena. This validates the presented research activity. The same methodology can also be adopted for predicting the devices lifetime for the surrounding 350 nm CMOS circuit.

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