

Conductive Channel in ONO Formed by Controlled Dielectric Breakdown

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Abstract – For the first time, cross section TEM photos capture the conductive channel of Oxide-Nitride-Oxide (ONO) films after electric breakdown. It reveals a single crystal or polycrystal channel with a dome-shaped cap depending on the breakdown current. The implication of this structure on electric characteristics is analyzed with a spherical thermal-electric model. The use of ONO as antifuses in FPGA's is also discussed.

INTRODUCTION

ONO as well as NO or ON has been well developed for DRAM capacitor and FPGA antifuse applications[1][2]. Its low defect density, scalability, and reliability make it very attractive[3]. One main difference between DRAM capacitor and FPGA antifuse application is that besides good dielectric integrity for both applications, understanding how the conductive channel is formed during breakdown is of considerable importance in controlling the resistance of the conductive channel in antifuse applications. Since the breakdown spot is very small and randomly located, capturing this spot in cross section TEM with high degree of repeatability has not been reported before.

STRUCTURE OF THE CONDUCTIVE PATH

Fig.1 Shows the TEM cross section of an ONO dielectric with an equivalent of 9nm oxide thickness. ONO is sandwiched between N+ poly and N+ diffusion. Programming, or breakdown of the ONO film, was achieved with controlled high voltage pulses. External resistor is used to limit the current going through the breakdown spot.

Fig.2 shows the SEM top view of the breakdown spot after the polysilicon gate is removed by wet etching. Etching stops on ONO film. Fig.2 revealed a dome-shaped loose network of the dielectric over the breakdown spot. The many channels through the loose network are apparently the conductive paths of the breakdown dielectric. The diameter of the dome is roughly 3000Å for 16mA programming current and the link resistance is 100Ω.

This dome-shaped structure is confirmed by cross sectional TEM as shown in Fig.3. Fig.3(a) shows a 200nm diameter dome produced by programming current of 12mA. In addition, the material inside the breakdown spot is single crystal. Fig.3(b) shows a small dome produced by a programming current of 3.5mA. Close examination of the photo shows that there are defects inside the N+ silicon near the breakdown channel and the material inside the conductive channel now is polycrystalline.

Apparently, during breakdown (programming), programming current produces sufficiently high temperature to melt the silicon and ONO film over a small volume centered around the point of breakdown. ONO film breaks up into a loose network and protrudes toward anode, probably due to the drift momentum of the electrons in the molten silicon. Upon cooling at the end of programming, nitride (melting point 1900°C) and oxide (melting point 1700°C) solidify into the dome first, then followed by silicon (melting point

1400°C) solidification. High quality epitaxial growth of silicon takes place when the melt volume is large, eg. at 16mA current. When the melt volume is small, such as at 3.5mA current, the temperature gradient and cooling rate are large – resulting in defects in the breakdown spot below ONO film. This prevents formation of epitaxial single crystal inside the channel. In addition, a small-grain polysilicon crest is formed over the dome. It shows that molten silicon region has a large diameter than the molten ONO because of silicon's lower melting point.

RESISTANCE CHARACTERISTICS AND MODEL

It was mentioned above that when the programming current is 3.5mA, the conductive channel is constituted with polysilicon. Temperature dependence of the resistance of a 5mA programmed antifuse, shown in Fig.4 is indeed similar to that of polysilicon resistor. Fig.5 shows that the conductive channel resistance decreased with increasing programming current.

Without the dome-cap (ONO part) in Fig.3(a), the resistance through the opening of 100nm radius, r , in the ONO film would have been $R = \rho/2r$, where ρ is the resistivity (2mΩ-cm) of the surrounding N+ silicon, i.e. $R=100\Omega$. The measured resistance is about 200Ω, from which the resistivity of the dome material can be estimated to be 15mΩ-cm. Empirically, the dome cap contributes about half of the resistance over the range of programming current studied, i.e. it raised the effective ρ by 2X. To understand what determines r and R , assume that the temperature is spherically symmetrical and equal to 1900°C, ONO melting point, at radius r during programming and that most of the heat I^2R is dissipated within r . The result is

$$r = I \cdot \left(\frac{\rho}{8\pi \cdot 1900 \kappa} \right)^{1/2} \quad (1)$$

$$R = \frac{\rho}{2r} = \frac{(1900 \cdot 2\pi \kappa \rho)^{1/2}}{I} = \frac{2.5(V)}{I} \quad (2)$$

where ρ is resistivity of the surrounding N+ silicon (2mΩ-cm), κ is the silicon thermal conductivity (0.25W/cm°C), and I is the programming current.

Fig.6 shows the antifuse resistance versus measurement current after programming at 5mA. Resistance read at 100uA is very similar to that read at 5mA. As the read current increases, the resistance also increases due to heating and increase in resistivity. The trend reverses when silicon begins to melt. The melting occurs before the read current reaches 5mA since the melting of silicon can take place at lower current than melting of the initial dielectric. Beyond 5mA measurement current, the radius of the opening, r , in ONO increases and resistance, R , continues to decrease. On the second scan, R would start at the new lower value corresponding to the larger r .

When ONO films are used as antifuse in FPGA product, the resistance of the antifuse can be controlled by choosing a sufficiently large programming current level and the resistance remains stable during 1000 hours of burn-in at 125°C and 5.75V. Negligible change in delay time along many different data paths were observed as shown in Fig.7.

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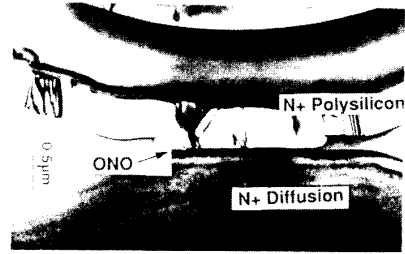


Fig. 1. TEM cross-section of ONO antifuse.

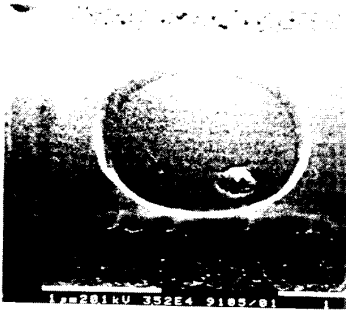
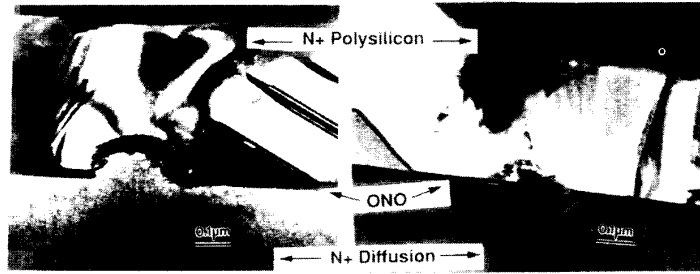


Fig. 2. SEM shows that 16mA breakdown pulse produced a 3000Å opening in the ONO film with a dome cap of a loose network of dielectrics.



(a) (b)

Fig. 3. TEM photos of (a) 2000Å diameter opening in the ONO produced by 12mA breakdown and (b) 700Å diameter opening after 3.5mA breakdown.

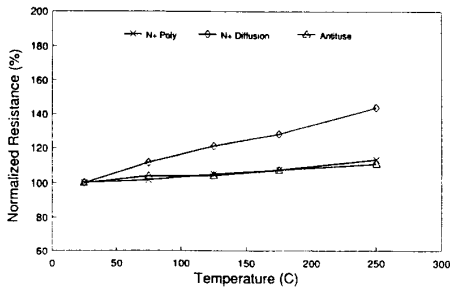


Fig. 4. Temperature dependence of antifuse, N+ diffusion, and polysilicon resistance.

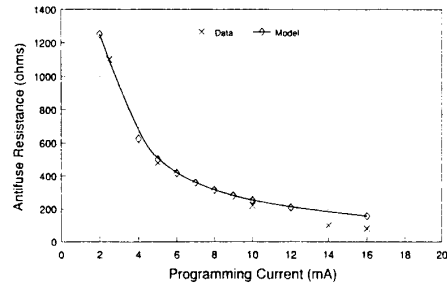


Fig. 5. Antifuse resistance decreases with programming current.

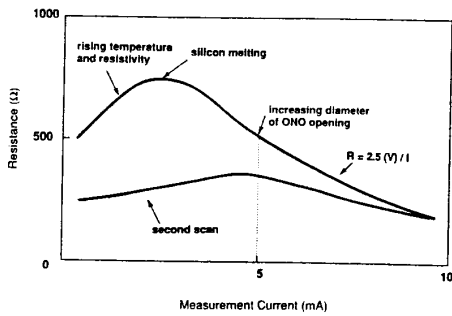


Fig. 6. Resistance versus measurement current after programming with 5mA of breakdown current.

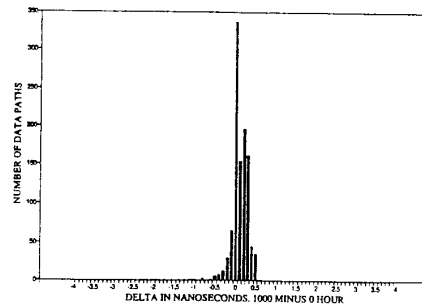


Fig. 7. Change in delay time from a 1000 gate programmable gate array after 1000 hours dynamic burn-in at 125°C and 5.75V.