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# A Novel Explanation of Power-Law Model with Quantitative Hydrogen Mechanism for Ultra-Thin Oxide Breakdown

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**Abstract**

A novel experimental method of time dependent dielectric breakdown(TDDB) lifetime on ultra-thin oxide PMOS with a quantitative hydrogen-based model is studied. Raise an asymmetric energy barrier for proton($H^+$) to escape to far distances into the oxide bulk will lower the exponents in paw-law fit and shorten the lifetime prediction in PMOSFET based on the quantum mechanism and chemical reactions at the Si-$SiO_2$ interface (suboxide bonds) and in the oxide bulk.

**Introduction**

The electron current is passed through the gate dielectric of a MOS capacitor or transistor, defects such as electron traps, interface states, positively charged donor-like states, etc., gradually build up at silicon/oxide interface or in the oxide until a point where the oxide suddenly and destructively breaks down. The most widely accepted theories of defect generation are the AHI model[1] and AHR model[2]. According to the recent results suggest that AHI may be not suited for oxide breakdown mechanism[3]. So far the degradation mechanism of PMOS is still not well understood. In this paper, we investigate the quantitative hydrogen-based model with adjust different DPN pressure for the first time, relating the defect generation and ultra-thin oxide breakdown to $H^+$ physics in $SiO_2$. And allow us to extend the proper reliability projections more accuracy and confidence.

**Experiment**

The ultra-thin PMOSFET for this experiment was fabricated as follows: a shallow trench isolation process was form on Si-substrate. The 1.4nm gate oxide dielectric, $P^+$ poly-crystalline silicon gate electrode. After thin oxide growth, DPN was implemented with different pressure conditions followed by a post anneal. We modulated DPN pressure to balance the device performance and gate leakage as well as plasma power and time. We found that pressure change was an efficient way to achieve the goal of balancing gate leakage and device performance. Gate dielectric and FET characteristics were measured every periodical testing time at constant voltage stress between 2.7~2.9 V applied (valence band electron dominate range in PMOS) as shown in **Fig.1.** with a dimension of L/W = 0.09/10 um, where L and W is gate length and gate width, respectively. Oxide breakdown defined in this work is taken to be the first sudden change in stress current and also verified by subsequent sudden change in SILC[4.,5]

**Results and discussions**

The collision probability and recombination rate of active nitrogen are much higher for a DPN process at a high pressure than at a low pressure. Therefore high-pressure DPN process generates a lower active nitrogen plasma density, which results in a lower nitrogen penetration and concentration in the gate dielectric. Accordingly, the nitrogen induced fixed charge for high pressure DPN is reduced as shown in **Fig.2.** It demonstrates that the sub threshold slope shift is induced by positive oxide charge in gate oxide bulk For the same reasons, the peak Gm for DPN devices can be improved by optimizing the pressure conditions. Compares PMOS peaks Gm between different DPN pressure processes as shown in **Fig.3.** Lower DPN pressure will degrade Gm maximum which is caused by interface state density increasing. The positive fixed charges and interface states generated more by low-pressure DPN process at a higher active nitrogen plasma density, which will relate defect generation in ultra-thin oxide breakdown.

As mentioned above, different DPN pressure will influence the quantity of Si-$SiO_2$ interface state and fixed charges in oxide bulk. A new quantitative hydrogen-based model is based on the quantum mechanical description of chemical reactions which involve protons and oxygen vacancies both at the Si-$SiO_2$ interface (suboxide bonds) and in the oxide bulk[6]. The model react with two processes related to chemical reactions involving protons. First, electrons dissipate energy at the anode interface and release protons($H^+$) from interface suboxide bonds as shown in **Fig.4(a).** Second, the released protons react with oxygen vacancies(Si-Si) as shown in **Fig.4(b).**

The description of chemical reactions in terms of potential barriers is a common practice in the field of quantum chemistry and also considered in[7,8].

$$x_1(V,T) = \frac{K_1}{1+\exp((E_{th1} + q\Phi_b - qV)/E_0)} \quad \text{.....(1)}$$

$$x_2(V,T) = K_2 V^2 \exp(-\frac{B}{V}); B = \frac{4(2m_H)^{1/2} toxE_{th2}^{3/2}}{3q\hbar} \quad \text{.....(2)}$$

$x_1(V,T)$ is modeled as electron-energy-assisted proton tunneling through an energy barrier(eq.(1)). According to recent first-principles calculations, $H^+$ in a suboxide bond sees an asymmetric barrier. On the $SiO_2$ side, the barrier is relatively small(~1eV) for $H^+$ to exit than on the Si side(~1.5eV) followed by another barrier of about ~0.8eV to escape to far distances into oxide[6]. The height of the $E_{th1}$ total barrier for proton release is ~1.8eV. The $x_2(V,T)$ is the reaction of a proton with an oxygen vacancy, produces the positively charged hydrogen bridge which has been recently proposed to be responsible for SILK and oxide breakdown[9]. The activation barrier $E_{th2}$ for the reaction of a proton with an oxygen vacancy from first-principle calculations is of about 0.2~0.3eV. The total defect generation rate is given by $1/x = 1/x_1 + 1/x_2$ and bottleneck for the whole process is the slowest reaction. The links to breakdown data are $Q_{BD} = N_{BD}/x$ and $T_{BD} = N_{BD}/J(V)\,x$, where $N_{BD}$ is the average density of defects at breakdown.

Lower DPN pressure will increase positive fixed charges and generated more interface states which will relate to defect generation in ultra-thin oxide breakdown. Based on quantitative hydrogen-based model[3], lower DPN pressure results in a higher nitrogen concentration in the gate oxide dielectric. The phenomenon will raise the energy barrier for $H^+$ to escape to far distances into the oxide. On the other hand, The height of the $E_{th1}$ total barrier for proton release will increase. The composition of the defect generation rate $x$ with adjust different height of the barrier for proton release energy $E_{th1}$(1.8, 2.2 and 2.6eV) which are corresponded to the power-law model n=39, 33 and 26 simulations as shown in **Fig.5.** And our experimental results compare nicely to the quantitative hydrogen-based model with adjust DPN process to modify the $E_{th1}$ energy barrier. The fitting of the breakdown results is excellent with power-law empirical model[10] as shown in **Fig.6.** Higher DPN pressure will cause more steeper paw-law n value with longer lifetime

prediction in PMOSFET TDDB as shown in **Fig.7.**

## Conclusions

We investigated the ultra-thin oxide PMOS degradation mechanism of a new quantitative hydrogen-based model with adjust different DPN pressure for the first time. A complete set agreement between the model parameters fitting and the DPN experimental data favorably. Raise the energy barrier for proton($H^+$) to escape to far distances into the oxide will increase the $E_{th1}$ energy barrier hence lower the exponents in paw-law fit and shorten the lifetime prediction in PMOSFET.

## Refefe nces


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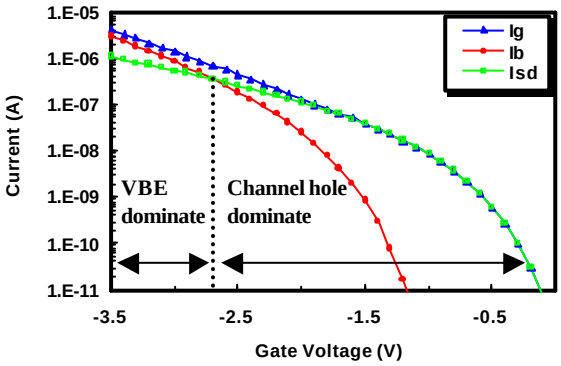


Fig.1. The PMOSFET carrier separation result. Triangle line(Ig), circle line(Ib) and square line(Isd) are fitted line of gate current, valence band electron(VBE) current and source-drain current, respectively.

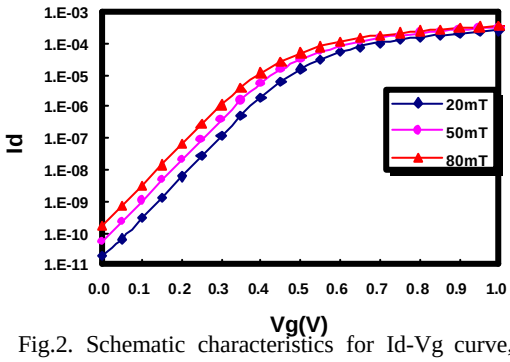


Fig.2. Schematic characteristics for Id-Vg curve, the subthreshold slope shift is induced by positive oxide charge in gate oxide bulk.

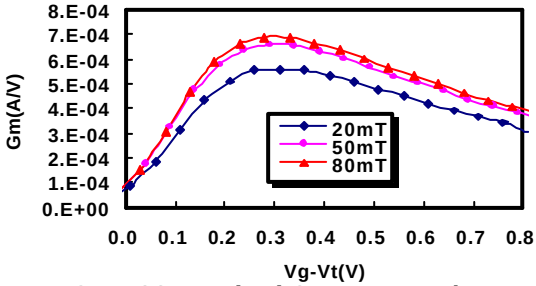


Fig.3. PMOS normalized Gm comparison between different DPN process with 20mT, 50mT and 80mT pressure.

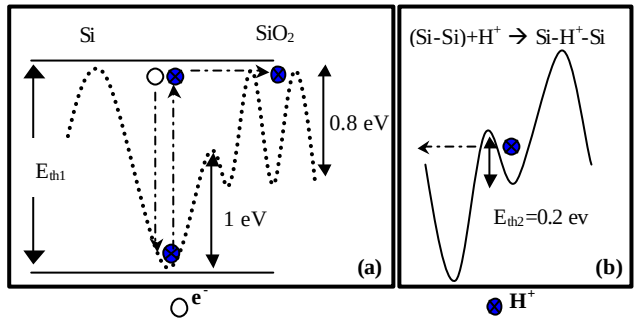


Fig.4. Illustration of the asymmetric potential energy across the interface involved two processes in hydrogen-based breakdown reactions **(a)**Electron-assisted proton release from suboxide bonds at the interface[11]. **(b)**Reaction of hydrogen bridge formation modeled by proton tunneling.

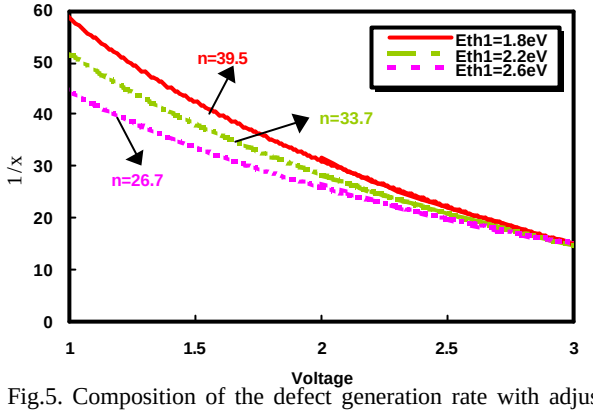


Fig.5. Composition of the defect generation rate with adjust different height of the barrier for proton release energy $E_{th1}$ which are corresponded to the power-law model simulations.

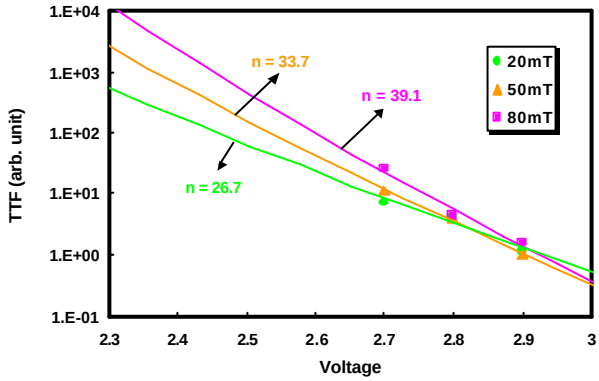


Fig.6. Different DPN pressure experiment from 80, 50, and 20mT correspond to various exponents power-law n values 39.1, 33.7 and 26.7.

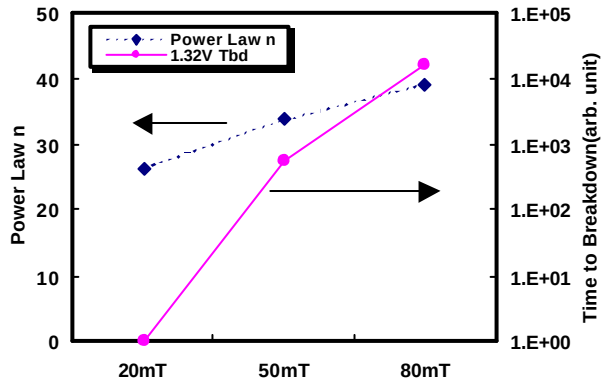


Fig.7. Higher DPN pressure will cause more steeper paw-law n value with longer lifetime prediction in ultra-thin oxide PMOS in 1.32V operation.