Briefs

A Trap Generation Closed-Form Statistical Model for Intrinsic Oxide Breakdown

Huan-Tsung Huang, Ming-Jer Chen, Chi-Wen Su, Jyh-Huei Chen, Chin-Shan Hou, and Mong-Song Liang

***Abstract*—A trap generation statistical model with the trap sphere radius r as parameter has been newly formulated in closed-form for intrinsic breakdown of ultrathin oxides and, by incorporating the trap filling fraction p as the secondary parameter, can be practically useful in a manufacturing process. Experimental reproduction for different oxide thicknesses and areas has been achieved through the model. A certain criterion has readily been drawn from the model, with which the ultimate thickness limit for breakdown can be set.**

I. Introduction

The oxide wearout can essentially be regarded as a process of the neutral electron trap generation during high field stressing, eventually leading to a breakdown event. Thus, the intrinsic oxide breakdown can be defined at the critical density of neutral electron traps via which a conductive path is formed from one interface to the other. To get the critical electron trap density as well as its statistics, Degraeve *et al.* [1] have introduced a Monte Carlo (MC) percolation simulation experiment in which these traps randomly generated are treated sphere-like with a radius r. Percolation simulation, in combination of the trap filling fraction p such as to set up a linkage to another experiment of hot-electron filling the generated traps [1], has created the remarkable ability of consistently reproducing the thickness and area dependencies [1]. The similar MC percolation simulation but treating the traps lattice-like has further been proposed by DiMaria and Stathis [2], from which a phenomenon of the ultimate thickness limit for breakdown has been satisfactorily explained.

The goal of our paper is to present a model in such a way to advance the work of [1] and [2]: the three physically-based controlling factors constitute explicitly model formulation. The potential of the resultant model in experimental reproduction as well as prediction of ultimate thickness limit will be highlighted.

II. Percolation Simulation and New Model

A three-dimensional MC percolation simulation program [3] using the breakdown algorithm described in [1] has been thoroughly performed for different combinations of the oxide thickness $t_{\rm OX}$, the oxide area A, and the electron trap sphere radius r. The practical oxide thickness for simulation is $t_{\rm OX}-2t$ where t (=0.5 nm throughout the work) features the transition layer in both interfaces of oxide, where the chemical composition is not of stoichiometry and the bonds are strained. Such a defect-rich region is thus conductive in nature and its thickness depends significantly on the processes used.

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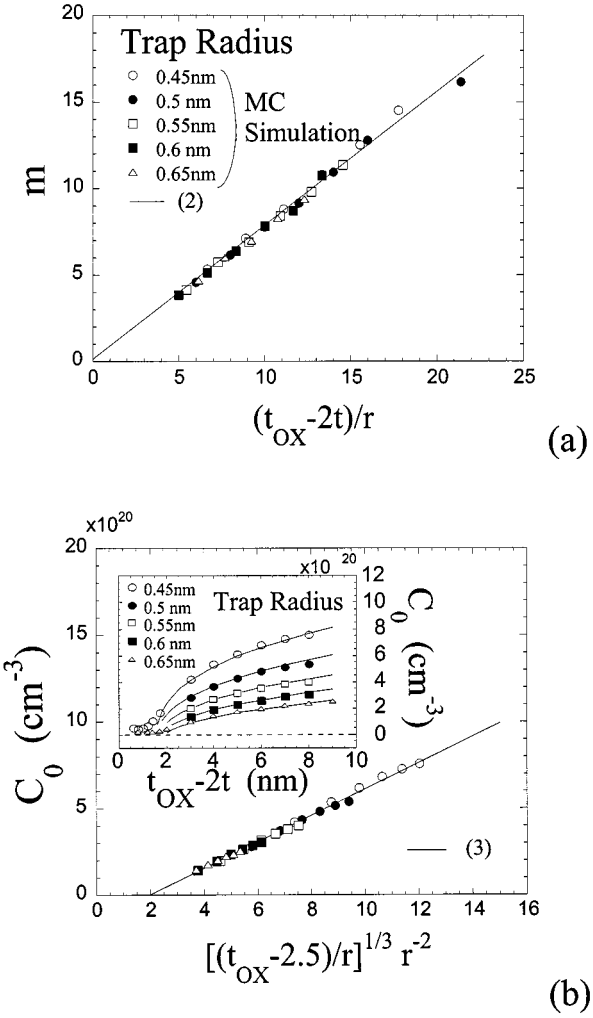

Fig. 1. (a) Extracted m versus $t_{\rm OX}-2t/r$. Also plotted is the line from (2). (b) Extracted C_0 versus $[t_{\rm OX}-2.5/r]^{1/3}\cdot r^{-2}$. Detailed comparison of MC percolation simulation and the deduced model on the modal value C_0 versus $t_{\rm OX}-2t$ for different trap radii is shown in the inset. Also plotted is the line from (3). The ultimate oxide thickness limit can be derived by setting C_0 to zero.

The simulated critical neutral electron trap density N_T distributions [3] for the cumulative percentage of intrinsic breakdown denoted F_i can be adequately expressed by

$$F_i = 1 - \exp\left[-\left(\frac{N_T}{C_0}\right)^m \cdot \left(\frac{A}{A_0}\right)\right]. \tag{1}$$

Here, the slope m is a measure of the spread of the distribution and the C_0 is the modal value for $A = A_0$ The extracted m and C_0 were found to be independent of the area [4], as expected by Poisson area scaling [5] for random distribution of the breakdown sites. For an arbitrarily chosen area of 900 nm^2, we extracted m and C_0, as plotted in Fig. 1. Parameterizing data points in Fig. 1 yields

$$m = 0.7821 \times \frac{t_{\rm OX}-2t}{r} \tag{2}$$

$$C_0 = -1.5\times 10^{20} + 7.611\times 10^{19}\cdot\left[\frac{t_{\rm OX}-2.5}{r}\right]^{1/3}\cdot r^{-2}. \tag{3}$$

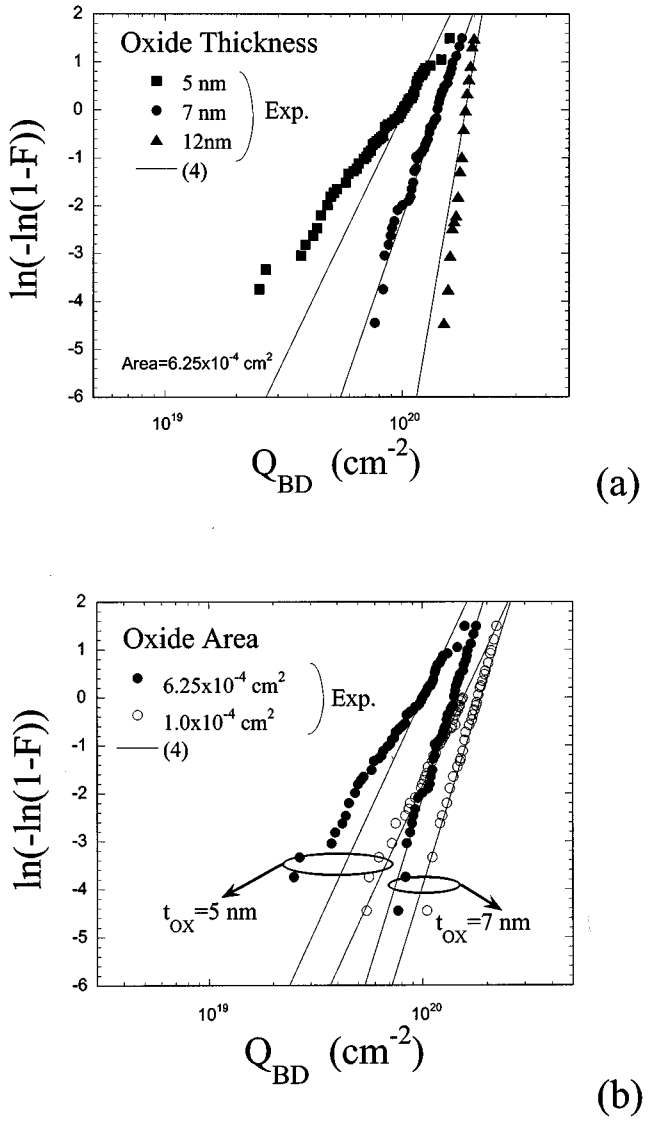

Fig. 2. Reproduction of the experimental $Q_{\rm BD}$ in Weibull scale for (a) three different oxide thicknesses with $A = 6.25 \times 10^{-4}$ cm^2 and (b) two distinct thicknesses each with different areas. The trap radius r and the trap filling fraction p were 0.42 nm and 6%, 0.45 nm and 5.5%, and 0.42 nm and 5.9% for oxide thicknesses of 5, 7, and 12 nm, respectively.

Equations (2) and (3) hold for any area A with $A_0 = 900$ nm^2 as explained above. Although empirically derived, factors like $(t_{\rm OX}-2t)/r$, 2.5 nm, and r^{-2}, in formulating (2) and (3) do have physical meanings. For example, the first factor is directly related to the possible minimum trap number $(=(t_{\rm OX}-2t)/2r)$ [6]; the second factor is close to the ultimate thickness limit of 2.7 nm [2]; and the third factor is directly related to the possible minimum area of the conductive path (or equivalently cell area in Sune's model [7]) such as to match the trap with sphere radius r. In other words, the smaller the trap radius, the more traps required to form the conducting path and thus more chances for the traps to be overlapped (in the vertical direction, relative to $t_{\rm OX}-2t$) and spreading (in the horizontal direction, relative to πr^2). The created model has successfully reproduced all the simulated N_T distributions for different combinations of $t_{\rm OX}$, A, and r [4]. It is interesting to notice the presence of the ultimate thickness limit in the inset of Fig. 1(b); that is, for thickness below this limit, the critical neutral trap density for breakdown tends to saturate, a phenomenon discovered earlier [2]. Thus, the criterion $C_0 = 0$ can set the limit of 2.53 nm for $r = 0.45$ nm, quite close to 2.7 nm in citation [2].

For a series of oxides subjected to high-field stress and then followed by hot-electron filling scheme, a systematic analysis [1] produced a power law relation between the occupied trap density ΔN_{ot} and the hole fluence Q_p: $\Delta N_{ot} = \beta \cdot Q_p^{0.6}$ with $\beta = 3.3 \times 10^8$ cm$^{-1.8}$. N_T, the generated trap density, can be related to ΔN_{ot} by $\Delta N_{ot} = p \cdot N_T$. By further incorporating the anode hole injection model [8] and letting the charge-to-breakdown $Q_{\rm BD} = Q_p'/\alpha$, where Q_p' is the hole fluence at the onset of breakdown and α is quantum yield, we get an explicit statistical model with r and p as fitting parameters

$$\ln\left[-\ln\left(1-F_i\right)\right] = m\left\{0.6\cdot\ln\left(\alpha\cdot Q_{\rm BD}\right) + \ln\left(\frac{\beta}{p\cdot C_0}\right)\right\} + \ln\left(\frac{A}{A_0}\right). \quad (4)$$

Both r and p are essentially dependent on the manufacturing processes, and can be extracted based on $Q_{\rm BD}$ statistical data. Evidently, the intrinsic Weibull slope depends upon only r for a fixed $t_{\rm OX}$ according to (2) and (4); and the role of p is to adjust the shift of the distribution lines.

III. Experiment and Comparisons

In our work, a variety of capacitors having different oxide thicknesses and areas were fabricated in a 0.25-μm CMOS process. Also fabricated on chip were the nMOSFETs for measuring the hole generation coefficient by means of a carrier separation technique. Our test samples were dry oxygen grown as in [1]. The stress current was 0.4 A/cm^2. Fig. 2 plots the corresponding measured TDDB data in terms of the charge-to-breakdown $Q_{\rm BD}$ distributions, showing that the Weibull slope decreases with decreasing oxide thickness. With the known A and $t_{\rm OX}$ and the measured α into (4), a fitting to experimental data was performed to extract r and p. The measured α were 4.8×10^{-4}, 9.6×10^{-4}, and 8×10^{-3}, leading to p of 6%, 5.5%, and 5.9%, and r of 0.42, 0.45, and 0.42 nm for oxide thicknesses of 5, 7, and 12 nm, respectively. This indicates that, relative to a large change in measured α for different $t_{\rm OX}$, the extracted r and p values are only slightly different. They are also quite reasonable when comparing $r = 0.45$ nm and $p = 3\%$ in [1] as well as the capture cross section $(\approx \pi r^2)$ of $10^{-15} \sim 10^{-16}$ cm^2 in [9]. Thus, the intrinsic breakdown portion can be located as fitted in Fig. 2(a). Note that as oxide thickness decreases, α decreases or equivalently the amount of generated traps decreases for a given electron fluence; however, the critical trap density for percolation path decreases more dramatically, and, as a result, $Q_{\rm BD}$ decreases. Another evidence is presented in terms of the area effect as illustrated in Fig. 2(b) for two distinct thicknesses, where the proposed model again reproduces experiment well using the same parameters in Fig. 2(a). A significant deviation at low $Q_{\rm BD}$ is found with larger area for $t_{\rm OX} = 5$ nm. Since statistically the Weibull slopes of the intrinsic distributions have to be unchanged for different areas (i.e., Poisson area scaling [5]), this deviation can be reasonably attributed to "local oxide thinning" induced extrinsic breakdown [10].

IV. Conclusion

The presented model comprising physically-based controlling factors has adequately reproduced percolation simulation results and thus can find promising applications of offering flexibility in real manufacturing processes. Experimental intrinsic breakdown statistics regarding thickness and area effects has been properly reproduced. The ultimate thickness limit for breakdown has also been set based on the model.

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Impact of N_2O Activation Treatment on Junction Characteristics of p^+/n Junctions Formed by a Solid Diffusion Source

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***Abstract*—P^+/N junctions formed by a solid-boron-source under different activation ambient gases have been investigated. It was found that the junction depth strongly depends on the activation ambient gas and the corresponding flow rate. Especially in the N_2O ambient, the diffusion of boron is enormously enhanced. Futhermore, the thermal stability of $CoSi_2$ is profoundly improved by the N_2O treatment during activation.**

***Index Terms*—Activation, junction, solid-diffusion-source.**

I. INTRODUCTION

Shallow junction is needed to suppress short-channel effects for CMOS technologies. Meanwhile, CMOS circuits are susceptible to latch-up because of the presence of a four-layer p-n-p-n structure.

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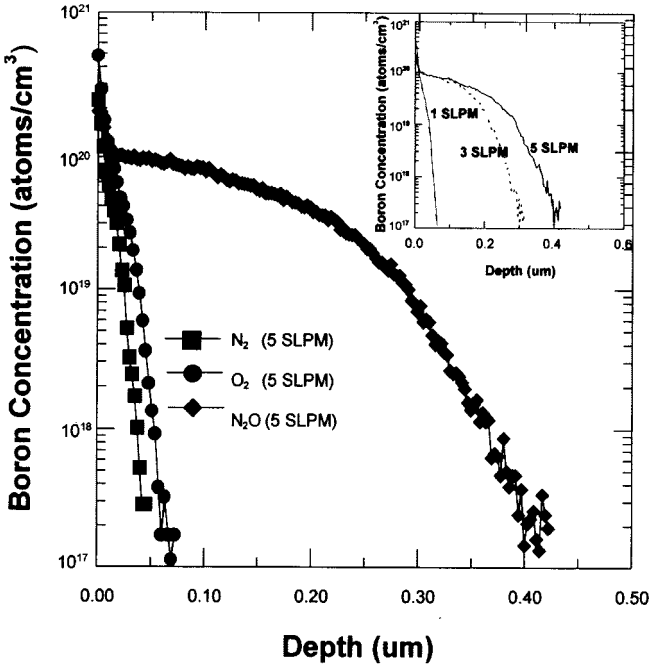

Fig. 1. SIMS profile of boron in p^+/n junctions formed by the polysilicon-diffusion-source. The inset shows the boron profile under N_2O with different flow rates.

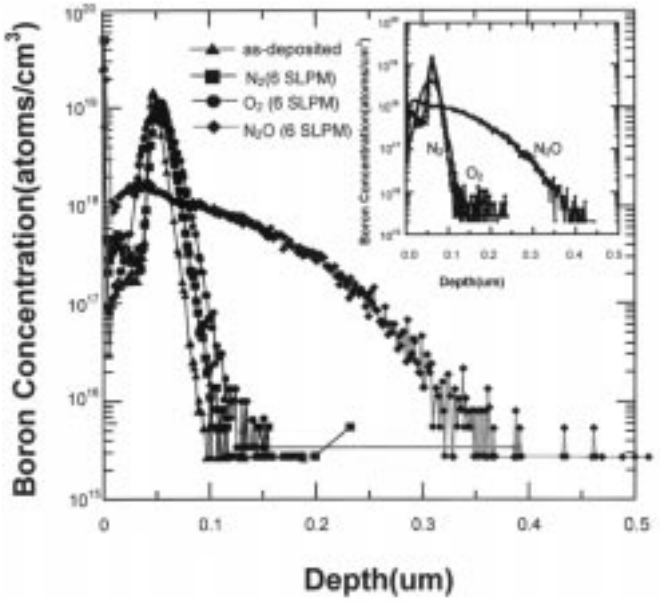

Fig. 2. SIMS profile of boron in 500 Å *in-situ*-doped SiGe-epilayer. The inset shows the boron profiles in 500 Å Si-epilayer.

Several methods have been proposed to minimize the risks of latch-up [1]. For example, immunity to latch-up can be achieved by increasing the well junction depth to decrease the current gain. Therefore, forming shallow junctions and deep wells are both important issues for CMOS technologies.

Recently, much effort has been devoted on forming junctions by the technique of solid-diffusion-source. However, in contrast to the popular study on forming shallow junctions, few studies have been reported about forming deep wells. In this paper, the effects of N_2O on the char-