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A Percolation Approach to Dielectric Breakdown Statistics

Tetsufumi TANAMOTO and Akira TORIUMI

Research and Development Center, TOSHIBA Corporation
1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 210, Japan

The stochastic breakdown model proposed by Niemeyer et al. has been improved by taking the time evolution into account in the two dimensional lattice system. The Markov process has been assumed in the breakdown process and ' time' has been defined reflecting the distribution of broken bonds in the cluster. The change of breakdown patterns with time evolution predicts various aspects of breakdown phenomena. We have shown that the final breakdown path does not always form a straight line. The polarity problem is understood by the relative position of the damaged layer to the starting point of breakdown.

1 Introduction

Although dielectric breakdown is a critical issue in the reliability of thin SiO_2 films, the mechanism has not been clarified, because of the many steps influencing the dielectric breakdown in the MOS device production process. The aim of this paper is to propose a dynamical stochastic model of thin SiO_2 film breakdown by the percolation theory and to investigate the essence of the breakdown phenomena. The time evolution of the breakdown is introduced and discussed in relation to the breakdown pattern.

2 Percolation Model of Breakdown

The lattice model bounded by two parallel biased plates to form a dielectric constant network is employed for the insulating SiO_2 thin film. The breakdown proceeds under the external electric field by assigning the larger dielectric constant $\epsilon_{\rm bd} = 300$ to the bond to express the conducting bond instead of the initial insulating value, $\epsilon_0 = 3$. The potential distribution is determined by a finite difference method of Laplace's equation. The bond to be broken next is selected among bonds in the local region around the cluster of bonds, by introducing a bond breaking probability, P_{ij}, between the site, i which belongs to the cluster and the nearest site j which does not belong to the cluster, defined as,

$$P_{ij} \propto |E_{ij}|^{\alpha}, \tag{1}$$

where E_{ij} is a local electric field applied to the bond and α shows the strength of directivity of the electric field which we set 1. The actual broken bond in the next step is determined corresponding to the magnitude of the probability P_{ij} by generating a random number[1]-[3]. In this paper the definition of breakdown is that the cluster of broken bonds reaches the opposite side of the electrode.

3 Definition of Time Evolution

The time evolution of breakdown of each bond is assumed to be a Markov process. The next breakdown process will be determined by the form of the cluster and its electromagnetic environment at that time, and will not be related to the past growth of the cluster of broken bonds. Thus the number of bonds on the surface of the cluster, N_S, will be closely related to the time interval, Δt and this relationship will be such that Δt is roughly inversely related to N_S. We set $\Delta t^{-1} = N_S$ as the simplest case.

4 Results and Discussion

4.1 Dynamical Aspect of Time Evolution

Figure 1 shows the correlation between the time to breakdown, $t_{\rm bd}$ and the number of sites in that cluster, $N_{\rm bd}$ in 8x16 and 16x32 lattices after a hundred of calculations. The larger cluster tends to have the larger $t_{\rm bd}$. Figures 2 (a) and (b) show the two breakdown patterns for a 8x16 lattice corresponding to (A) and (B) results in Fig. 1, while Fig. 2 (c) and (d) show other patterns for a 16x32 lattice corresponding to (C) and (D) results in Fig.1. These breakdown patterns show that the larger cluster does not always have a shorter time to breakdown. The breakdown path with the shortest time becomes the resultant leakage path. This shows that the path through the thin film is not always a straight line perpendicular to the biased plates. This results from the stochastic behavior of our model.

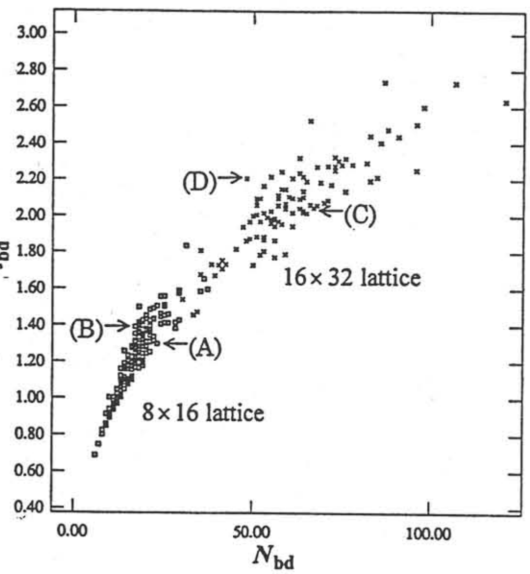

Fig. 1 Correlation between the time to breakdown, t_{bd} and the number of sites in the cluster at that time, N_{bd}. 100 calculations are made in a 8x16 lattice and 200 calculations are made in a 16x32 lattice.

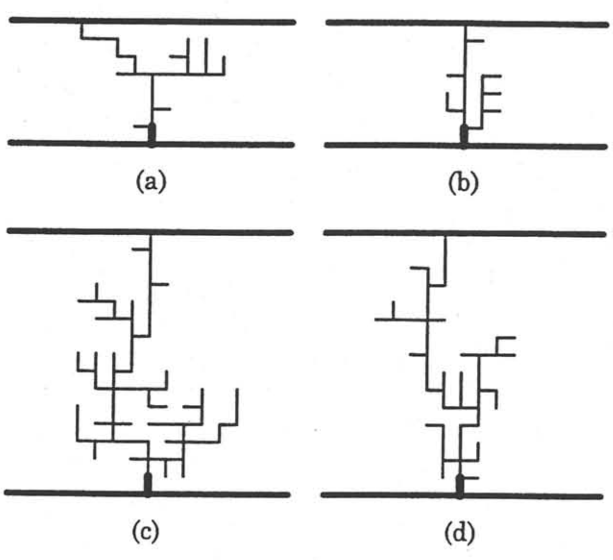

Fig. 2 Example of a case in which the larger cluster size with larger surface has shorter time to breakdown than the smaller cluster with smaller surface. (a) Cluster size, 25, time, 1.29687. (b) Cluster size, 19, time, 1.38881. (c) Cluster size, 69, time, 2.04604. (d) Cluster size, 50, time, 2.20484. (a) and (b) are the cases of two dimensional 8x16 lattice and (c) and (d) are those of two dimensional 16x32 lattice.

4.2 The Polarity Problem - The Effect of Damaged Layer on Breakdown

It is assumed that there exists damaged layer induced by the stress at Si/SiO_2 interface[4] and hot electrons have their highest energy at the exit interface. Figure 3 shows a typical application of our breakdown model to the polarity problem. The damaged layer is defined as bonds whose dielectric constant, ϵ_{dg} is randomly distributed as $\epsilon_0 < \epsilon_{dg} < \epsilon_{bd}$. The starting point of bond breaking is considered to be the bond which the hot electrons attack with their highest energy. In other words, the starting point of breakdown is determined by the injection polarity.

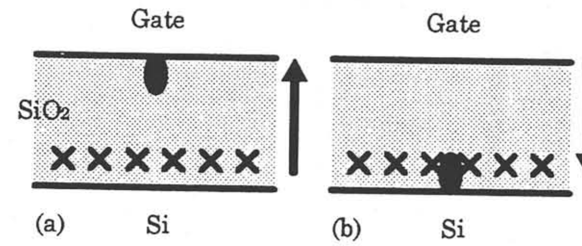

Fig. 3 A schematic of polarity problem. The solid arrows show the direction of injected hot electrons. The cross marks show the damaged layers. The bond breaking is assumed to begin from the opposite side of the injections(thick bond). (a) Substrate injection mode. (b) Gate injection mode.

Figure 4 shows the Weibull plot of a hundred of calculations of one damaged layer[d1] and two damaged layers[d2] at the interface of a 16x32 lattice. The average t_{bd} of Fig.3 (a) which corresponds to the substrate injection case is larger than that of Fig. 3 (b), which corresponds to the gate injected case. More damaged layers[d2] make the t_{bd} of the latter case longer and we can see the polarity dependence more clearly. Figure 5 shows breakdown patterns of the 50 % of cumulative failure rate. Compared with the breakdown path of gate injection case, that of substrate injection case is larger because of the damaged layer.

Figure 6 shows the relationship between t_{bd} and the conductance of its breakdown path over 100 calculations. In the case of gate injection, there is no correlation between them, and both concentrate on a small area, reflecting the short and small path. On the other hand, in the case of substrate injection, there can be seen a clear correlation that the breakdown path of the larger conductance has the larger t_{bd}. These are expected to be compared with experiments.

The origin of the polarity is that in the substrate injection case the cluster is inclined to grow toward the transverse direction, because of the relatively stronger electric field at the boundary of the damaged layer. This delays the percolation of path in the substrate injection. This is a new aspect of our model which has not been understood by the ordinary one dimensional model in which the path cannot progress toward the transverse direction.

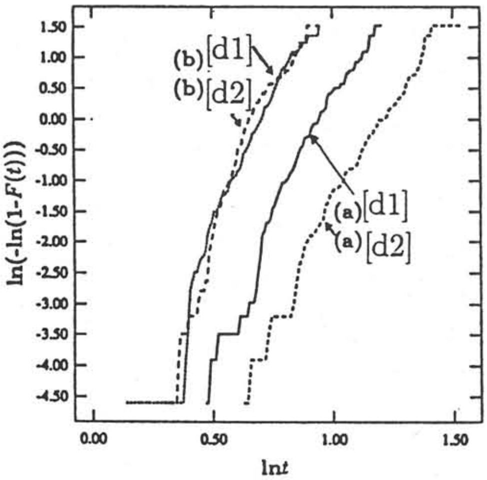

Fig. 4 Weibull plot ln(-ln(1-$F(t)$))-ln$t$ of the results of hundred of calculations. In both breakdowns of one damaged layer[d1] and two damaged layer[d2], the breakdown times of the gate injection case is smaller than those of substrate injection case.

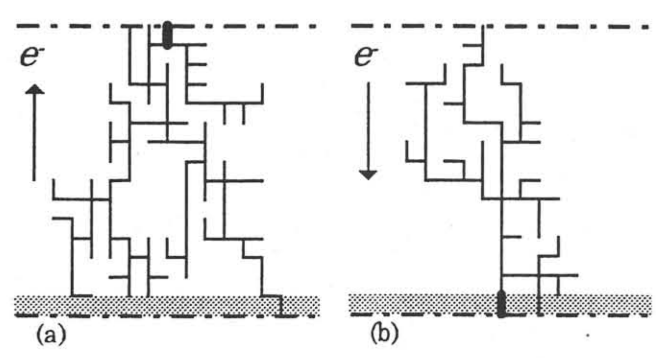

Fig. 5 The breakdown paths of 50 % of cumulative failure rate. The hatched area shows the damaged layer whose dielectric constants are randomly distributed. (a)substrate injection mode. (b) gate injection mode.

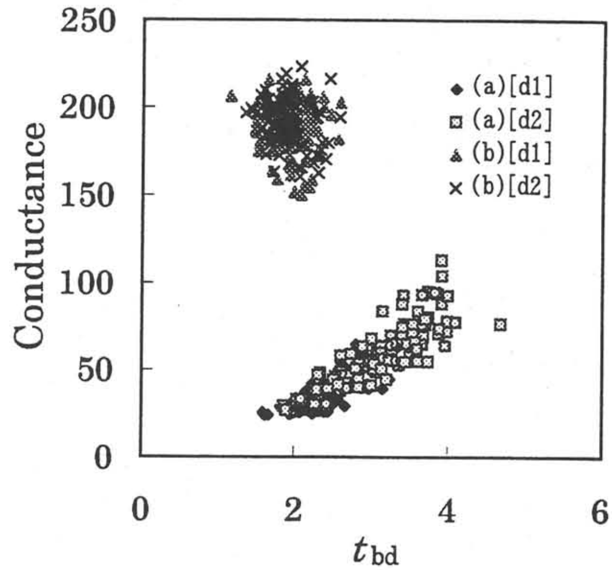

Fig. 6 The correlation between t_{bd} and the conductance of the results of hundred of calculations in the substrate injection case and the gate injection case.

5 Conclusion

It has been found that the time to breakdown is not always proportional to the number of sites in the breakdown cluster, and that the current leakage path has a possibility to expand toward the directions perpendicular to the external electric field. The polarity problem is understood by a simple arrangement of damaged layers. It is found that the stochastic breakdown model is a powerful tool to investigate the breakdown phenomena.

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References

[1] L. Niemeyer, L. Pietronero and H. J. Wiesmann: Phys. Rev. Lett. **52**, 1033 (1985).

[2] H. J. Wiesmann and H. R. Zeller: J. Appl. Phys. **60**, 1770 (1986).

[3] D. A. Willming and C. H. Wu: J. Appl. Phys. **63**, 456 (1988).

[4] H. Satake, N. Yasuda and A. Toriumi: Ext. Abst. SSDM'95., 264.