Extended Abstracts of the 1991 International Conference on Solid State Devices and Materials, Yokohama, 1991, pp. 32-34

Modified Impact-Ionization Recombination Model under Dynamic Stress of Thin Oxide

Seiji Yamada, Kiyomi Naruke, Masashi Wada

Semiconductor Device Engineering Laboratry
TOSHIBA Corporation
1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 210, Japan

A modified Impact-Ionization Recombination(IR) model is proposed to explain oxide damage under dynamic stress. The stress applied to the tunnel oxide of an EEPROM is not D.C. but A.C. equivalent current. According to coventional theory, the oxide lifetime depends on electric field[1][2]. However, experiments on EEPROMs do not indicate any such clear dependence.

In the modified IR model, trapped holes and free holes in the oxide are dealt with separately, and the drift of holes in the oxide valence band is considered. This model allows the experimental results to be explained.

INTRODUCTION

There are two widely known theories of oxide degradation. The first is expressed by equation below[1]. Qh represents the critical value of trapped holes in the oxide at which breakdown occurs.

$$Qh \propto \alpha Qbd = \text{constant} \tag{1}$$

where α is the hole generation rate and Qbd is total injected charge to breakdown. This relationship assumes D.C.condition, and does not apply directly to dynamic stress. The second is expressed by the simple rate equation below(IR model)[3].

$$\frac{\partial P}{\partial t}=\frac{J}{q}(\alpha-\sigma P) \tag{2}$$

where P is hole density, J is electron current, q is the electron charge, and σ is the hole capture-cross section. This equation does not lead to a prediction of oxide lifetime.

The Modified IR model presented in this paper can be used to predict oxide lifetime under dynamic stress.

EXPERIMENTS

The devices used in this study are FLOTOX EEPROM cells with 9.4nm tunnel oxide. The tunnel oxide lifetime can be precisely described in terms of W/E(Write/Erase) cycles. Furthermore, FLOTOX cells are useful in discussions of the damage to the oxide by F-N tunneling current, because the tunnel oxide is affected by F-N tunneling current alone. We investigate the dependence of tunnel oxide damage on programming pulse waveform by measuring endurance characteristics. Typical experimental data is shown in Fig.1.

DISCUSSION AND RESULTS

1. Modified IR Model

Figure 2 shows the schematic energy diagram. Electrons pass through the SiO_2 film by F-N tunneling(I), obtaining sufficiently energy to cause impact ionization from the applied high field(II), the generated holes drift in the valence band of the oxide(III), where some recombine with injected electrons(IV), and others are trapped in the oxide(V), some trapped hole recombine with injected electrons(VI). Element A is unit volume in the valence band. Each vector indicates a hole flow rate into A and out of A. Element B is a unit volume in the oxide.

At element A, the rate equation is:

$$\frac{\partial P}{\partial t}=\frac{Je}{q}\left[\alpha-\left(\sigma_1+\frac{\kappa}{Je}\right)P\right]-\frac{1}{q}(Jp_1-Jp_2) \tag{3}$$

(Jp1-Jp2)/q replaces $v_p \partial P/\partial X$. vp is hole velocity in the valence band. At steady state, $\partial P/\partial t=0$, We have the differential equation.

$$\frac{\partial P}{\partial t}=\frac{Je}{v_p p}\left[\alpha-\left(\sigma_1+\frac{\kappa}{Je}\right)P\right] \tag{4}$$

Hence initial condition is P(x=0)=0. The final expression for hole distribution in the oxide is then

$$P(x)=\frac{Je\alpha}{Je\sigma_1+\kappa}\left[1-\exp\left(-\frac{X}{\lambda}\right)\right] : \lambda=\left(\frac{Je\sigma_1+\kappa}{v_p q}\right)^{-1} \tag{5}$$

The hole density transient at element A (to simplify calculations, $\partial p/\partial x$ is assumed 0) is:

$$\frac{\partial P}{\partial t}=\frac{Je}{q}\left[\alpha-\left(\sigma_1+\frac{\kappa}{Je}\right)P\right] \tag{6}$$

Hence, the initial condition is P(t=0)=0. The final expression for the hole density transient in the oxide is:

$$P(t)=\frac{Je\alpha}{Je\sigma_1+\kappa}\left[1-\exp\left(-\frac{Je\sigma_1+\kappa}{q}\right)t\right] \tag{7}$$

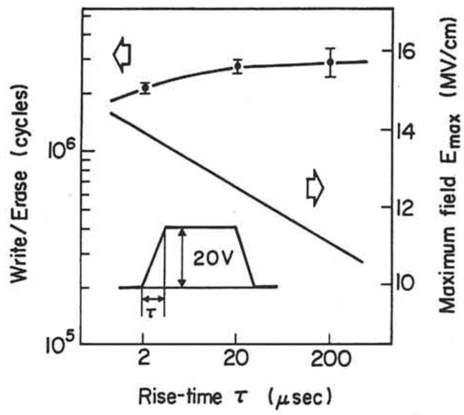

Fig. 5. Maximum number of W/E cycles for different rise times.

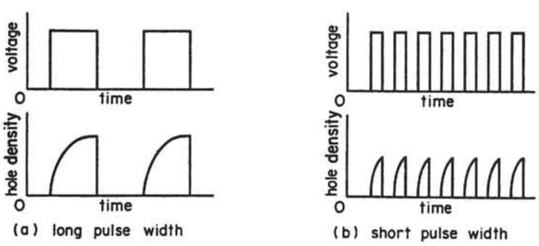

Fig. 6. Comparison between long pulse and short pulse.

Thus the hole current with short pulses is less than with long pulses.

When the leading edge is steep, the high field accelerates hole generation as a result of impact ionization, but a narrow pulse prevents the hole density in the oxide from increasing. That is, a narrow pulse compensates for the effect of the high field. Accordingly, maximum number of W/E cycles for several rise times are almost the same value as shown in Fig.5.

3. Narrow Burst Pulses

Figure 7 shows the programming pulse waveform used in the following measurements of endurance characteristics. The rise time is fixed at 1usec. With this fairly steep leading edge, the resulting transients of tunnel oxide field, tunnel current, and hole density are shown in Fig.7. Figure 7-(2) shows results for a burst of narrow pulses. In this case, the tunnel oxide field and tunnel current of Fig.7-(1) is simply divided to give that of Fig.7-(2). The hole density resulting from the burst of narrow pulses, as predicted by the modified IR model, is less than that of single long pulse. That is, a burst of narrow pulses causes less damage to the tunnel oxide.

Figure 8 shows the pulse width dependence of the maximum number of W/E cycles. The original pulse is 50usec in width. This pulse is divided into varying number of pulses; for instance, two burst pulses of 25usec width, five burst pulses of 10usec width, and so on. The number of W/E cycles increases as the pulse width is narrowed. Clearly, this result sustains the modified IR model.

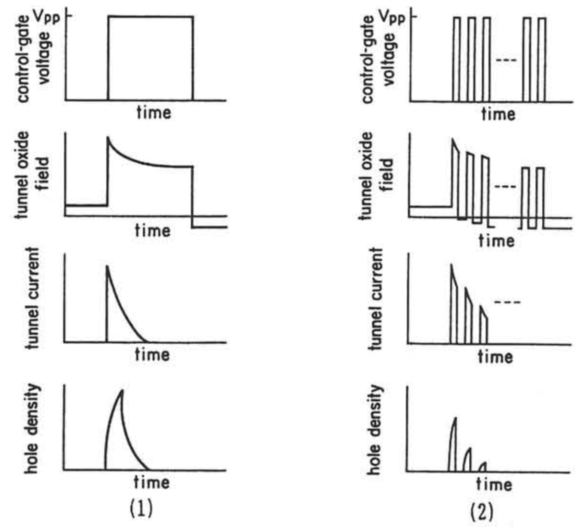

Fig. 7. Effect of programming pulse waveforms on tunnel oxide field, tunnel current, and hole density. Rise time is 1 μsec. (1) a single pulse of large width ; (2) burst pulses of narrow width.

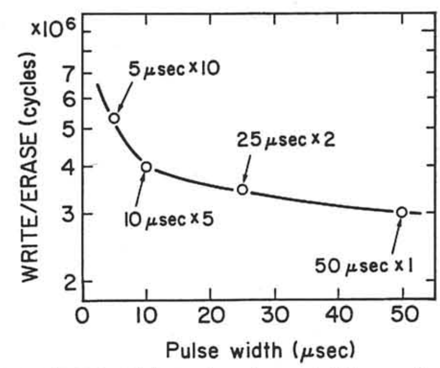

Fig. 8. Dependence of burst pulse width on the maximum number of W/E cycles.

CONCLUSION

Compared with the oxide lifetime under D.C conditions, oxide survives a long time under A.C. conditions. To explain this, a modified IR model is proposed. In this model, trapped holes and free holes in the oxide are dealt with separately, and the drift of holes in the valence band of the oxide is considered. As a result, it is confirmed that the hole density in the valence band has time-constant. This time-constant result in the difference in oxide lifetime under A.C conditions and D.C. conditions.

ACKNOWLEDGMENT

The authors would like to thank Drs. K.Kanzaki, S.Shinozaki, K.Maeguchi for their continuous encouragement during the work. They also thank S.Taguchi, D.Thoyama and H.Taneda for their useful discussion.

REFEERENCES

[1] C.Hu,IEDM Tech.Dig.(1985)368.
[2] I.C.Chen, et al,IEEE Electron Device Lett.7(1986)164.
[3] N.Klein,J.Appl.Phys.53(1982)5828.
[4] Y.Nissan-Cohen, et al,J.Appl.Phys.54 (1983)5793.
[5] Z.A.Weinberg and T.N.Nyugen,J.Appl.Phys. 5(1987)1956.

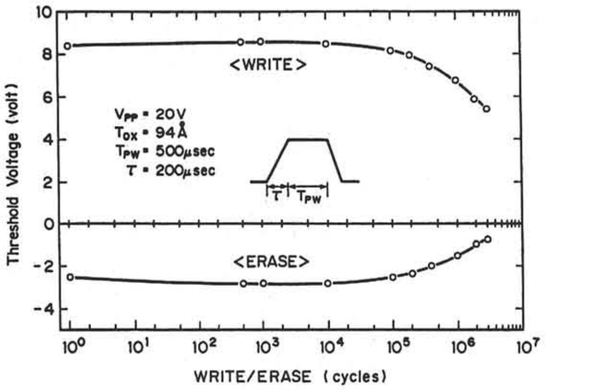

Fig. 1. Typical Endurance characteristics. In this figure the threshold voltage changes at about 3million cycles. We identified this as tunnel oxide breakdown.

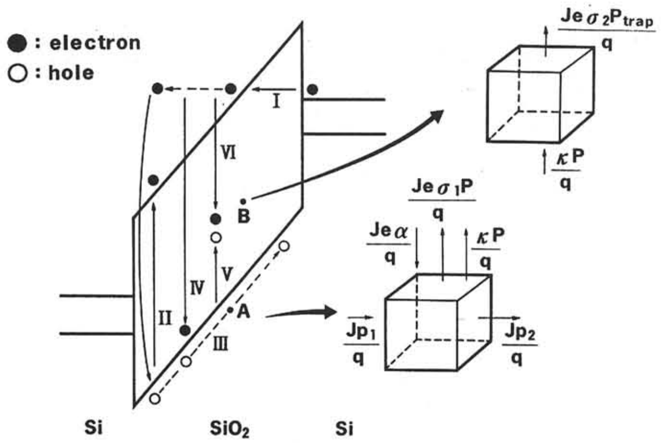

Fig. 2. Schematic energy band diagram. Je: electron current density, Jpi: hole current density, $\sigma 1$:capture cross-section of holes in the valence band, $\sigma 2$: trapping cross-section of trapped holes. P :density of holes in the valence band, Ptrap: density of trapped holes in the oxide, κ is possibility of hole trapping to the oxide.

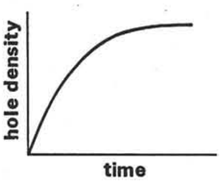

Fig. 3. Schematic hole density transient in the valence band.

The schematic hole density transient in the valence band is shown in Fig.3. There is a clear time constant in the characteristic.

At element B, the rate equation is:

$$\frac{\partial Ptrap}{\partial t} = \frac{1}{q}(\kappa P(x,t) - Je\sigma_2 Ptrap) \qquad (8)$$

where P is function of distance and time. Hence, in the steady state $\partial Ptrap/\partial t=0$. The trapped hole density is:

$$Ptrap = \frac{\kappa}{Je\sigma_2} P(x,t) \qquad (9)$$

Equation 8 is similar to Eq.2. The relationship expressed by Eq.2 is measured by C-V method. So P in Eq.2 represents the trapped holes expressed by Ptrap in Eq.8. Equation 8 is also consistent with other experimental data collected by the authors[4][5].

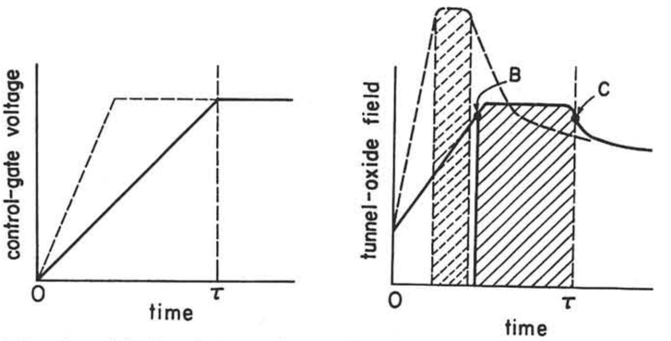

Fig. 4. (a) Leading-edge of the programming pulse; (b) tunnel oxide field calculated by a capacitive circuit simulator. Shaded area indicate the stress due to F-N tunneling current. Dotted line shows the case of a steep leading edge.

τ (μsec)	200	20	2
Emax (MV/cm)	11.3	12.5	14.0
ratio of tunnel oxide lifetime	~4	~2	1

Table 1. Prediction of tunnel oxide lifetime for different rise times.

2.Leading-edge Dependence

To change the tunnel oxide field, the leading-edge of programming pulse is used. When the applied control gate voltage rises linearly, the tunnel oxide field transient is described by Fig.4. At point B, F-N tunneling current start to flow and charge accumulates in the floating gate. This stored charge prevents the tunnel oxide field from increasing. As a result, from point B to C, the tunnel oxide field is almost constant. The stress on the tunnel oxide due to F-N current is the characteristic pulse-shaped shaded area. If the leading-edge of the program pulse rises more steeply, the width of shaded pulse is reduced, and the hight of the pulse increases(dotted line). Table 1 shows predictions of tunnel oxide lifetime as made by Eq.1 for several rise times. In esch programming operation, an equal amount of charge passes through the tunnel oxide. Thus, this estimated lifetime corresponds to the maximum number of W/E cycles, and means the number of W/E cycles to programming failure due to tunnel oxide breakdown.

According to calculations, maximum number of W/E cycles with a 200usec rise-time is expected to be about four times greater than that with a 2usec rise-time. The experimental results in Fig.5, however, indicate almost equal values.

Figure 6 is a schematic comparison of long and short pulse cases. The hole density transient in the valence band has a time-constant. Hence, a long pulse width allows enough time for the hole density to reach the steady state, while short pulses do not.