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# Short-Term and Long-Term Reliability of Nitrided Oxide MISFET's

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This paper describes the short-term and long-term reliability of thin nitrided oxide (oxynitride) films. Empirical results of tests conducted on several oxynitride films fabricated under various nitridation conditions show that (1) the pin hole density of thin (5nm) oxynitride film is very low, (2) oxynitride MISFETs exhibit less transconductance ($G_m$) degradation due to hot carrier injection than oxide MISFETs and (3) these thin films have superior time-dependent dielectric breakdown (TDDB) characteristics. Thus, the prospects that this film can be used in various thin film MIS devices are good.

## 1. Introduction

Due to recent down-scaling of MIS devices, their gate insulators have become thinner, thus increasing pin hole density[1]. Furthermore, due to down-scaling under constant power supply voltage, the electric field in thin insulating films is increasing, which, in turn, increases the surface states. The problem of time-dependent dielectric breakdown (TDDB) is also of increasing interest.

This paper describes a new insulating thin film, oxynitride, that is expected to provide thin, hard film with, from the viewpoint of short-term reliability, (1) decreased pin hole density; and, from the viewpoint of long-term reliability, (2) less hot-carrier degradation and (3) better TDDB characteristics.

## 2. Fabrication Process

Fabrication of the oxynitride film consisted mainly of 1000°C dry oxidation of a (100) 10ohm*cm n- or p-type C-Z silicon substrate and 60minutes of ammonia nitridation at 1050°C. Insulator thickness was controlled by regulating the $O_2/(O_2+N_2)$ ratio during oxidation. MIS capacitors and n-channel MISFETs with phosphorus-doped poly-crystalline silicon gates were then fabricated for evaluations of the films.

## 3. Short-Term Reliability of Oxynitride

### 3.1 Pin Hole Density

Pin hole density, D, is shown in fig.1 as a function of thickness, with D calculated using the equation proposed by J.E.Price[2]:

$$D=(1/A)*(1/Y-1). \quad (3.1)$$

Here, A is gate area and Y is capacitor yield. As shown, D for thin oxynitride film (less than 6nm) is much lower than that for the oxide. However, this changes drastically at a thickness range of about 6nm. Above that point, the thicker the oxynitride film becomes, the higher the value of D.

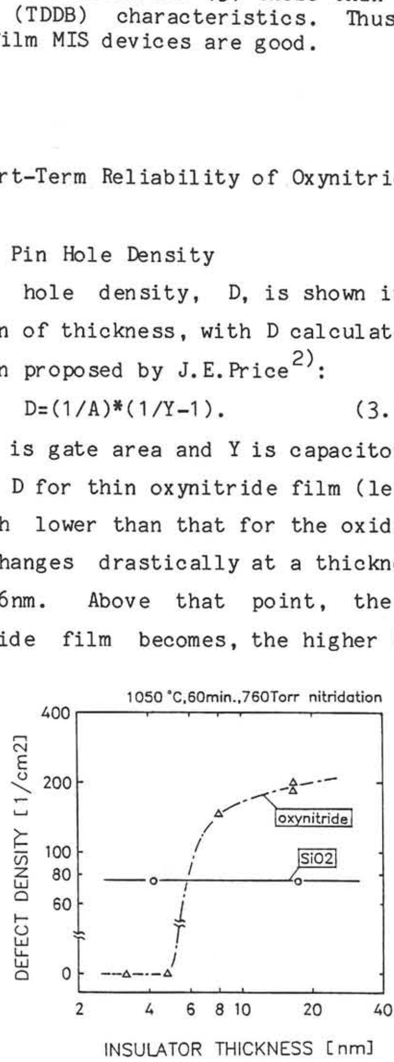



Fig.1 Pin hole density vs. insulator thickness.

### 3.2 Self-Repair Model for Pin Holes in Oxynitride

To explain the lower D in thin oxynitride film, we propose "A self-repair of pin holes by nitridation" model. That is to say, when the oxide thickness is less than 6nm, pin holes disappear after nitridation because insulator thickness rapidly increases due to silicon substrate nitridation in this thickness range (see fig.2). However, when the oxide is more than 6nm thick, the insulator volume decreases during nitridation, so that the number of pin holes increases and the yield becomes lower.

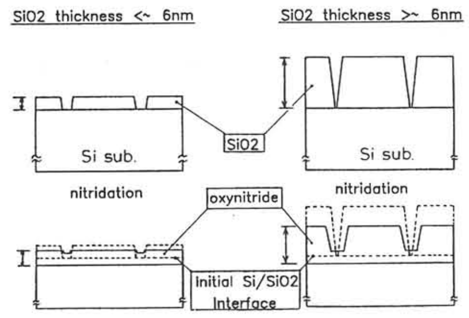



Fig.2 Model for self-repair of pin holes due to the nitridation.

In this model, we assume that increase or decrease of pin holes is connected with the change in insulator thickness. It should be theoretically explained that thin oxide becomes thicker and thick oxide becomes thinner due to nitridation (see table1). This table shows the theoretical 1mol-volume of silicon, oxide and nitride. As shown by this table, when substrate nitridation is dominant, the insulator thickness increases, but when oxide nitridation is dominant, the thickness decreases.

TABLE 1 1 mol Volume of Si,SiO2,Si3N4

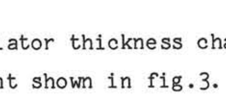
| Molecule | Si | SiO2 | Si3N4 |
|---|---|---|---|
| Molecular weight | 28 | 60 | 140 |
| Density (g/cm3) | 2.3 | 2.2 | 3.1 |
| 1 mol Volume (cm3) | 12.0 | 27.3 | 45.2 |

Si-Substrate Nitridation

Si + 2/3 N2 ----> 1/3 Si3N4
1 mol (12.0cm3) 1/3 mol (45.2/3=15.1cm3)

$SiO_2$ Nitridation

SiO2 + 2/3 N2 ----> 1/3 Si3N4 + O2
1 mol (27.3cm3) 1/3 mol (15.1cm3)



Actual insulator thickness change was observed in the experiment shown in fig.3. In that figure, oxynitride thickness is shown as a function of pre-nitridation (oxide) thickness. Thickness was measured using ellipsometry. Thin oxynitride film (less than 6nm) is thicker than the oxide and thick oxynitride (more than 6nm) is thinner than oxide.

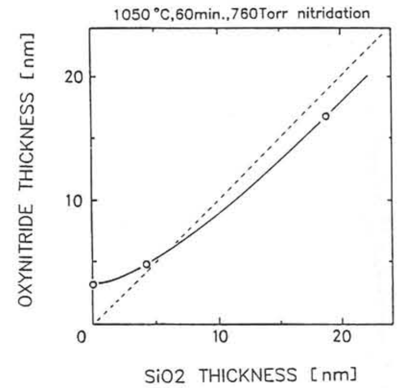



Fig.3 Oxynitride thickness vs. pre-nitridation (oxide) thickness.

From the above discussion, it should be clear that a self-repair model can fully explain the phenomena in fig.1.

## 4. Long-Term Reliability of Oxynitride

### 4.1 Hot Carrier Degradation in MISFETs

Fig.4 shows transconductance ($G_m$) degradation and shift in the threshold voltage ($V_{th}$) observed in oxynitride and oxide MISFETs as a function of time. Effective channel length ($L_{eff}$) in these devices was 0.8um. Insulator thickness was about 20nm. Bias conditions for hot carrier injection

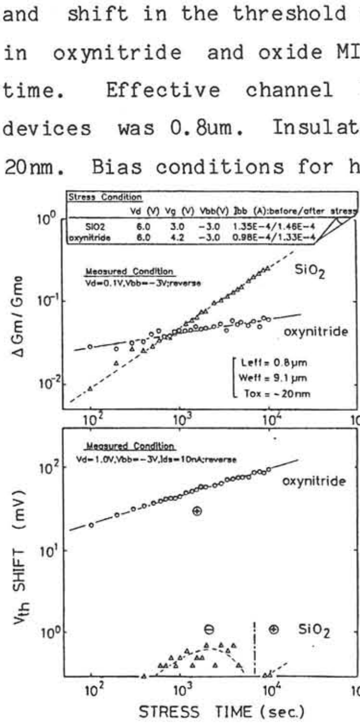



Fig.4 Transconductance and threshold voltage degradation in oxide and oxynitride MISFETs due to hot-carrier injection.

were: drain voltage $V_d$=6.0V, and substrate voltage $V_{bb}$=-3.0V for both devices. Gate voltages ($V_g$) for the oxide and oxynitride were 3.0V and 4.2V, respectively. Under these bias conditions, substrate current $I_{bb}$-$V_g$ characteristics indicated that peak $I_{bb}$ was about 0.1mA for both devices.

In this figure, $G_m$ degradation rate for oxynitride, d log(delta$G_m/G_{m0}$)/d log(t), is almost 25% lower than that for oxide. However initial channel electron mobility in the oxynitride is almost half that in the oxide.

### 4.2 Stability of $N_{ss}$ and $V_{fb}$ in MIS Capacitors

As is well known[3], oxynitride fabricated under ideal nitridation conditions is strongly resistant to voltage and current stress and its surface state density hardly increases during such stress. These phenomena were also observed in our experiment. In fig.5 the capacitances (C) of oxide and oxynitride MIS capacitors are shown as a function of the gate voltage ($V_g$). The gate area of these capacitors was $1*1 mm^2$. After current stress ($1uA/mm^2$, 80s), the C-V characteristics of the oxide show a frequency distribution induced by $N_{ss}$ increase and the characteristics shift slightly toward the negative bias, whereas the oxynitride show hardly any frequency distribution, but shifts toward the positive bias.

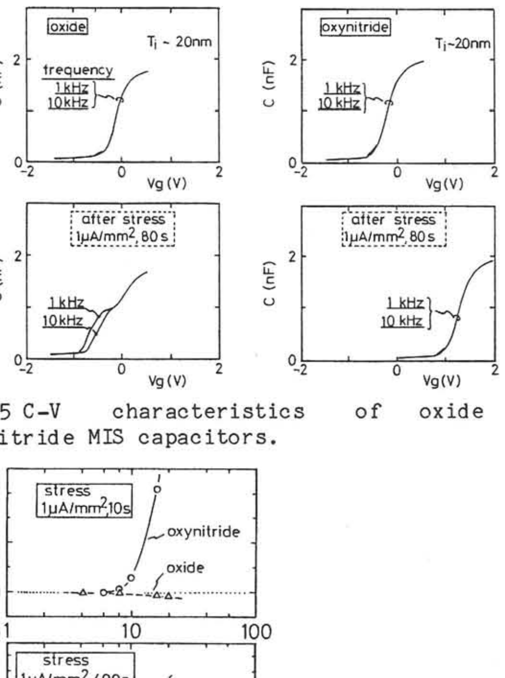



Fig.5 C-V characteristics of oxide and oxynitride MIS capacitors.

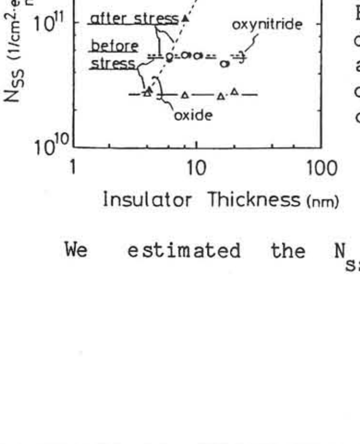



Fig.6 $V_{fb}$ and $N_{ss}$ degradation in oxide and oxynitride MIS capacitors due to the current stress.

We estimated the $N_{ss}$ and $V_{fb}$-shifts for various oxides and oxynitrides using the conductance[4] and C-V methods, respectively, as shown in fig.6. The frequency for C-V measurement was 1kHz. In that figure, $V_{fb}$-shift and $N_{ss}$ near the mid-gap are shown as a function of insulator thickness. As shown, $N_{ss}$ for the oxynitride hardly increases due to stress, whereas that for oxide increases remarkably. Thus, oxynitride film has exceptionally good interface stability: however, this film has many electron traps in its bulk, so $V_{fb}$ shifts after current stress.

It is assumed that this interface stability is due to the chemical characteristics of oxynitride film at the insulator-silicon interface, as shown in fig.7. In this figure, the auger electron intensities of Si, O and N are shown as a function of sputtering time. Sputtering was done using Ar atoms. As shown, there are two N peaks, one at the surface and the other at the interface. The interface of this film is stable to stress due to the latter.

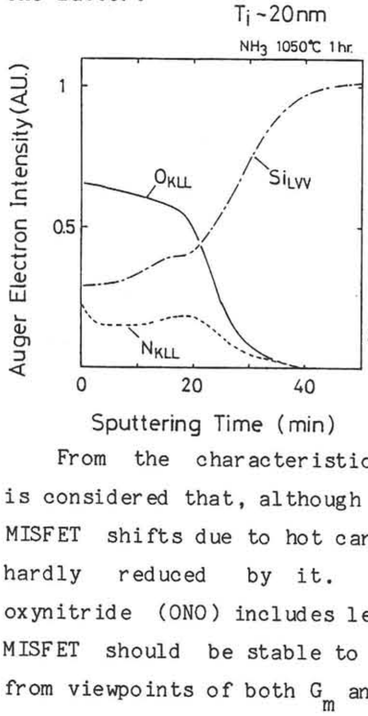



Fig.7 Distribution of N, O and Si atoms in 20nm oxynitride film.

From the characteristics described above, it is considered that, although $V_{th}$ in the oxynitride MISFET shifts due to hot carrier injection, $G_m$ is hardly reduced by it. However, re-oxidized oxynitride (ONO) includes less traps[3], so an ONO MISFET should be stable to hot carrier injection from viewpoints of both $G_m$ and $V_{th}$ degradation.

### 4.3 TDDB Characteristics

In fig.8 the time for 50% failure ($\tau$) at room temperature is shown as a function of electric field (E). E can be expressed as

$$E = (V_{stress} - V_{fb}) / T_i, \qquad (4.1)$$

where $V_{stress}$ is the stress voltage, $V_{fb}$ is the initial flat-band voltage and $T_i$ is the oxide conversion thickness, as calculated from capacitance using relative permitivity=3.82. The gate area was $300*300 um^2$, and $V_{stress}$ was applied as pulses. The figure shows that

(1) the thinner an oxynitride film becomes, the longer $\tau$ becomes for the same E. In particular, $\tau$ for 5nm oxynitride is almost 1decade longer than for oxide, and the electric field acceleration factor[5] was estimated to be 4.5~95cm/MV from the slope of the curves,

(2) both 4nm and 17nm oxides indicate the same $\tau$-E characteristics and their electric field acceleration factor for oxide was estimated to be approximately 95cm/MV.

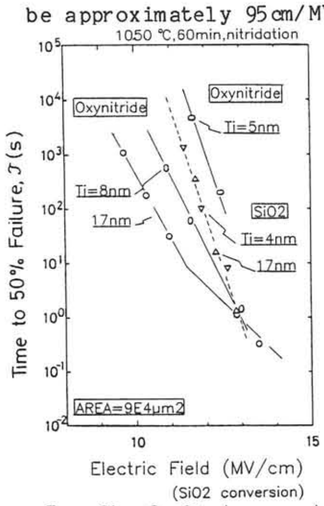



Fig.8 $\tau$ vs. electric field.

In fig.9, $\tau$ at room temperature is shown as a function of stress current density (J). J was estimated from the initial I-V characteristics before stress and from the stress voltage. This figure shows that

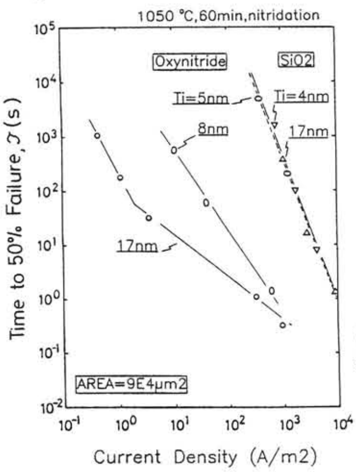



Fig.9 $\tau$ vs. current density.

(a) the thinner an oxynitride film becomes, the longer $\tau$ becomes for the same current density. In particular, $\tau$ for 5nm oxynitride is almost equal to that for oxide, and the current acceleration factor was estimated to be 6.5~550(log ampere)$^{-1}$,

(b) 4nm and 17nm oxides indicate almost the same $\tau$-J characteristics and the current acceleration factor was estimated to be approximately 550(log ampere)$^{-1}$.

The electric field acceleration factor ($A_{EF}$) for oxynitride indicates both thickness dependence and electric field dependence. The thinner an oxynitride becomes, the longer $\tau$ becomes. This means that this thin film is superior to oxide for capacitor use. However it is difficult to use thicker oxynitride films in MIS devices because of their shorter $\tau$.

The $A_{EF}$ of oxide, 95cm/MV, is little larger than the previously reported value of 55cm/MV[5]. It is also different from the previous report[5] that $\tau$ of 17nm oxide is almost equal to that of 4nm oxide. Thus, it should be assumed that intrinsic dielectric breakdown behavior is dependent not upon thickness but upon the fabrication conditions, that is, upon oxidation temperature, time and oxidizer.

The current acceleration factor ($A_I$) of oxynitride also indicates thickness dependence and current dependence. Thin oxynitride film indicates the same $\tau$ as oxide for the same J, but the $\tau$ of thick oxynitride is inferior to that of oxide.

## 5. Conclusion

Although oxynitride thin film can still be greatly improved, since it has low channel-electron mobility and there are electron traps in its insulating layer, it also has very strong merits including lower defect density, longer breakdown life-time and exceptionally good stability of the interface between the insulator and silicon substrate. Thus the prospects that this film can be used in various thin film MIS devices are good.

## References

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