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# PECVD SiN막의 절연파괴특성과 Wearout 현상에 관한 연구

# A Study on the Breakdown Characteristic and Wearout Phenomena of PECVD SiN Film

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## 요 약

본 논문에서는 $SiH_4-N_2$ 혼합가스에 의한 PECVD 방법으로 퇴적시킨 실리콘 질화막의 신뢰성을 평가하기 위해 절연파괴 분포와 TDDB(Time Dependent Dielectric Breakdown) 특성을 고찰하였다. MNS 캐패시터의 절연파괴 분포는 7-8MV/cm의 전계세기에서 그 파괴전계가 집중되었으며, 전계와 온도 stress에 의해 파괴시간이 지수함수적으로 감소함을 알 수 있었다. 아울러 이러한 TDDB 특성과 계면준위 밀도 및 SiN 막내의 공간전하형성과의 관련성을 고찰하였다.

## ABSTRACT

In this paper, to evaluate the reliability of silicon nitride film obtained by plasma enhanced chemical vapor deposition under glow discharge of $SiH_4$-$N_2$ gas mixture without ammonia, we investigate both breakdown distribution and time dependent dielectric breakdown (TDDB) characteristics. It is found that breakdown field distributions of MNS capacitors are concentrically distributed over field range from 7 to 8 MV/cm. And under electrothermal stressing, the breakdown time decreased exponentially with applied field and stress temperature. And also, we investigate the relationship of TDDB characteristic with the interface state density and the formation of space charges in SiN film.

## 1. Introduction

Recently, in the modern semiconductor VLSI technology, many problems are raised as the high integration and more fine patterning are required. Especially, for the MIS (Metal-Insulator-Semiconductor) structure, the most basic element in the semiconductor integrated circuits, the improvement of the reliability and stability of the devices, so in recent times the study on the breakdown mechanism and the TDDB characteristics of this device is progressed very actively.

The dielectric strength has a role of the limiting factor to the device reliability and

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stability as the device integration is increased. So the improvement of this characteristic has become an essential subject to produce a high reliability device. But until present times the probabilistic consideration on the dielectric strength and the TDDB characteristic of this device is investigated very poorly, and also, the identification of the theory of the breakdown mechanism is not yet made owing to the diversity of the analysis on the experimental results and to the disagreements among that various results.

Furthermore, still the most investigation in this field is mainly concentrated on the $SiO_2$ film, so the study on the SiN film deposite by PECVD which is widely used as the passivation layer and the insulating interlayer because of its extra film characteristic and of the advantage corresponding to the low-temperature processing is urgently necessary in this point of view.

Therefore, in this paper, we deposit the SiN film by PECVD method with ammonia-free $SiH_4$-$N_2$ gas mixture, and then for that device structure we evaluate the reliability of the PECVD SiN film in accordance with the application of the Weibull distribution to the breakdown distribution measured with the voltage-temperature stress, and from this results we estimate the device usage lifetime by extracting the parameters of the TDDB characteristic.

And also, from the before and after voltage stress experiment and the high frequency C-V measurement, we get the aspect of the change of the interface state density and the formation of the space charge layer in the SiN film, and by comparing these results to the TDDB characteristic we investigate the relationship of the TDDB characteristic with the interface state density and the formation of the space charge in the SiN film.

## 2. Experimental Procedure

Silicon n- and p-type wafers of (100) orientation with the resistivity of 5-25 Ω-cm were used as the starting material to fabricate the MNS (Metal-Nitride-Silicon) capacitors. As the pretreatment process, the wafers are cleaned by the standard cleaning procedure.

SiN film is deposited with the thickness of 850Å by the use of capacitively coupled PECVD system. The deposition of film is carried out at the temperature of 300°C with the $SiH_4/N_2$ gas flow rate of 0.01, RF power density of 0.35 W/$cm^2$ and pressure of 1 torr.

The film thickness is determined by nanoscope and is confirmed by the capacitance measurement. Al electrode is evaporated on the film by the high vacuum evaporator with the diameter of 1mm under the pressure of $2 \times 10^{-5}$ torr. The breakdown voltage of MNS capacitor is measured using the measuring circuit schematically shown as in Fig. 1, when ramp voltage is applied to the sample. When the applied voltage to the sample gives rise to the sample breakdown, the voltage across the sample dropped abruptly, so holding the applied voltage by peak dector, and then we have measured the breakdown voltage using the DVM.

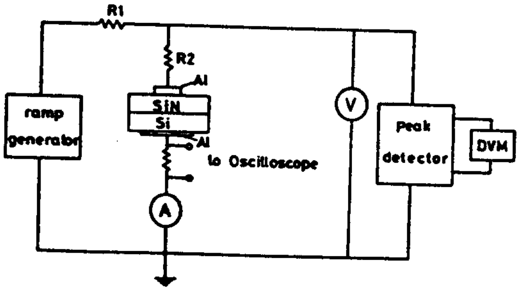

Fig. 1. Breakdown measurement circuit diagram.

On the other hand, in order to investigate the TDDB characteristic of the SiN film, we have measured the $t_{BD}$ which is the time to reach the breakdown under the condition of the applying the constant voltage to the sample, and also investigated the temperature dependency of the aspects of the breakdown phenomena by varying the measuring temperature.

Meanwhile, we also investigate the aspects of the change of the interface state density and the formation of the space charge layer in the SiN film by measurement of the high frequency C-V characteristic before and after voltage stress using the measuring circuit schematically shown as in Fig. 2.

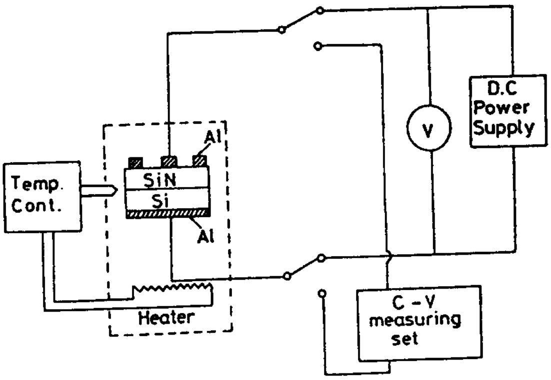

Fig. 2. Schematic diagram of D.C. stress and C-V measuring system.

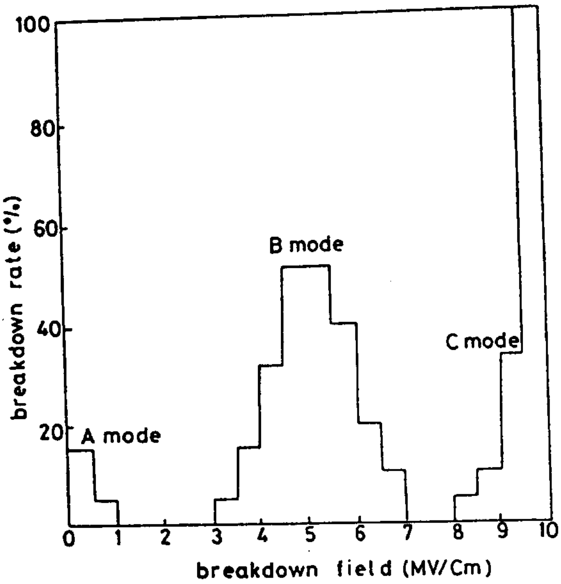

Fig. 3. A typical breakdown histogram.

## 3. Results and Discussion

### 3.1. Breakdown voltage distribution of PECVD SiN film.

Fig. 3 shows a typical dielectric breakdown histogram$^{1)}$. The breakdowned capacitors are categorized into three modes: A, B, and C modes. The A mode can be attributed to the pinhole of the gate insulator because of the nearly zero breakdown field (<1 MV/cm). The B mode reveals the breakdown by the weak spot with the breakdown field range of 1-8 MV/cm, and C mode is considered as the intrinsic breakdown of the defect-free capacitor at which the breakdown field is above 8 MV/cm.

Breakdwon voltage is measured by the ramp voltage stress with ramp rate of 4 V/sec at the temperature of 22°C and 85°C. The result of this experiment is shown in Fig. 4 as the breakdown histogram. From this figure, it is considered that the distribution of breakdown voltage is due to the partial difference of local electric field by the defects of SiN film, such as the rugged surface, pin hole and weak spots.

The breakdown distribution concentrated on the B, C mode implies that the SiN film used as

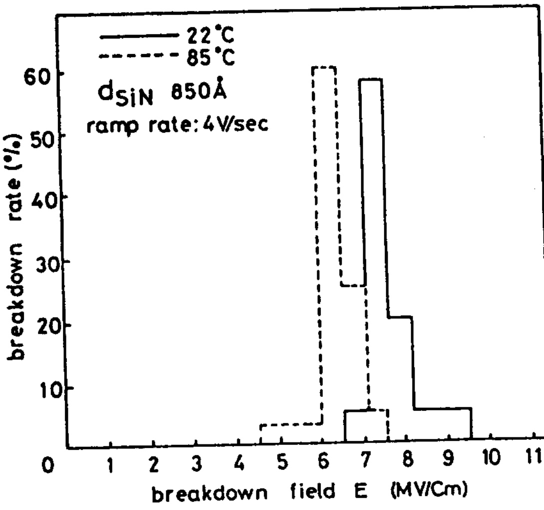

Fig. 4. Breakdown field strength distribution of PECVD SiN film.

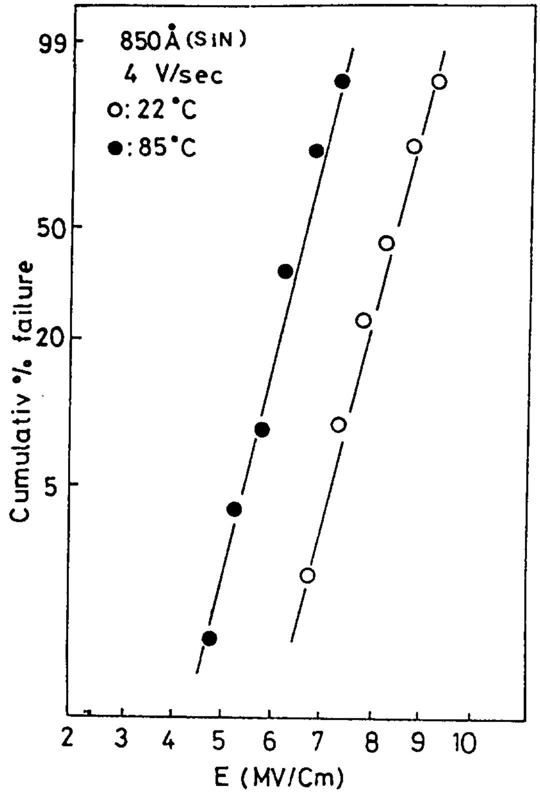

Fig. 5. Weibull distribution of breakdown strength.

samples in this experiment has a low defect density and the defects density calculated from the breakdown distribution is about 25 defects/cm$^2$.

Breakdown fields of 60% of the samples are concentrated around 7-8 MV/cm and from this fact the SiN film used in this experiment can be said to have relatively uniform breakdown distribution and to be high reliable.

Fig. 5 shows Weibull distribution of the breakdown voltage distribution of Fig. 4. As can be shown from this, the breakdown characteristic reveals that the breakdown field is lowered by the increase of temperature.

The temperature acceleration factor $\alpha$ can be expressed by the following Arrhenius equation and this can be applicable to the following section of TDDB characteristics.

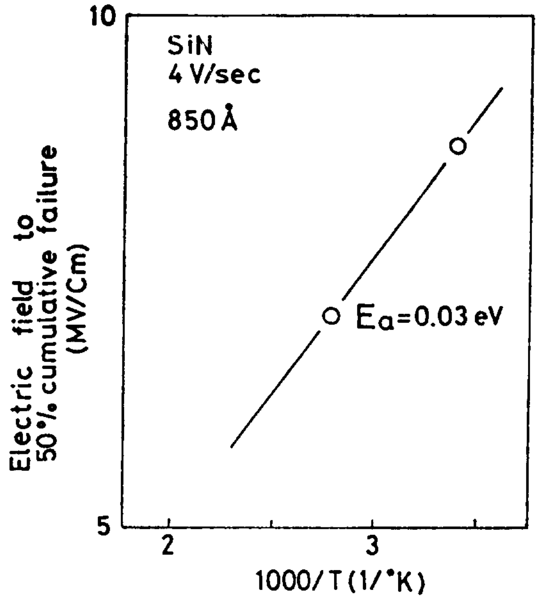

Fig. 6. Activation energy of breakdown strength.

$$\alpha = \exp[\frac{E_a}{K}(\frac{1}{T_s} - \frac{1}{T_o})] \qquad (1)$$

Where, $T_s$ is the stress temperature, $T_o$ is a device operating temperature, k is a Boltzmann's constant and the $E_a$ is an activation energy.

In this experiment, the electric field of 50% cumulative failure vs. 1/T is plotted in Fig. 6, and the activation energy $E_a$ is obtained as 0.03 eV from the slope of Fig. 6.

### 3.2. TDDB of PECVD SiN film.

To evaluate the TDDB characteristics[3)-5)] of SiN film, a constant voltage stress is applied until the breakdown is occured, which is the result from the time dependent degradation mechanism of SiN film.

Generally, the following empirical equation[2)] is used for the evaluation of the TDDB characteristic.

If the t (F%) is the time at which the F% of capacitors breakdowned, time t is decreased by $\Delta t$ when the constant stress field is increased by $\Delta E$, and they are related as follows.

$$\Delta t = A \cdot 10^{-\gamma \cdot \Delta E} . \exp\left[\frac{E_a}{K} . \Delta\left(\frac{1}{T}\right)\right] \qquad (2)$$

Where, A is constant, $\gamma$ (cm/MV) is electric field acceleration factor, $\Delta E$ is the difference between stress field and operating electric field and $\Delta$ (1/T) is the difference between the inverse of stress temperature and the inverse of operating temperature.

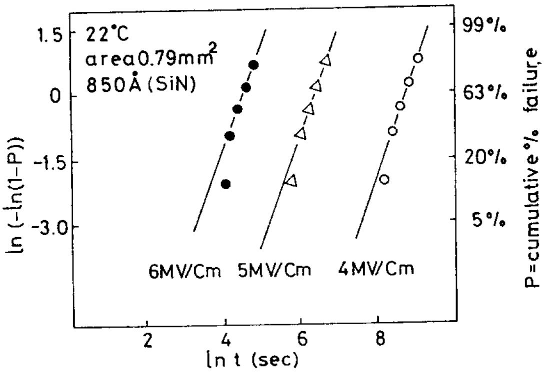

Fig. 7. Wearout curve of MNS capacitor as a parameter of stress field.

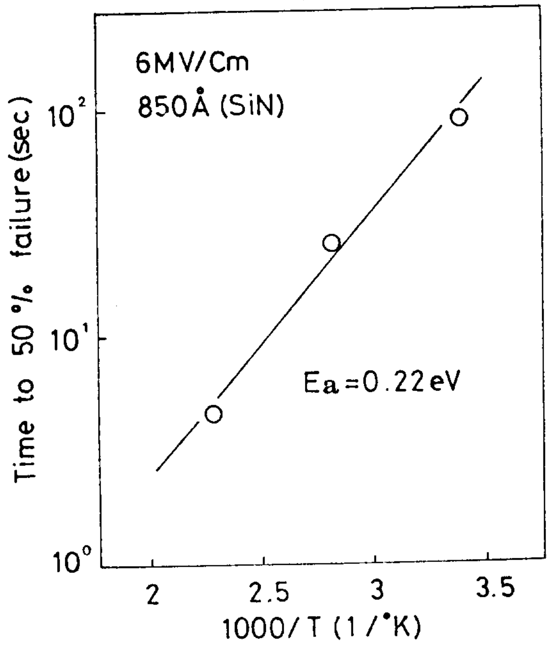

Fig. 8. Time to reach the 50% cumulative failure as a function of stress field.

TDDB characteristics can be accelerated by electric field and temperature. We examine the TDDB with the constant electric fields of 4, 5, 6 (MV/cm) to evaluate the electric field acceleration factor[6), 7)] which also depends on the thickness of SiN film.

Fig. 7 shows the data of this result replotted on the Weibull probability paper. From this figure it is appeared that $t_{BD}$ (time to reach breakdown) decreases exponentially with the increase of the stress field. The time to reach for the 50% cumulative failures is plotted as a function of stress field in order to calculate the electric field acceleration factor in Fig. 8.

$\gamma$ is calculated from the slope of this curve and the value of 0.9 cm/MV is obtained. This means that as the stress field is increased by 1 MV/cm, $t_{BD}$ will be shortened by $10^{-0.9}$ times.

Fig. 9 shows the $t_{BD}$ by the Weibull distribution of breakdown of the sample undergoing a constant stress field of 6 MV/cm at three different temperatures (22, 85, 160°C). The TDDB activation energy is obtained as 0.22 eV from the slope of Fig. 10.

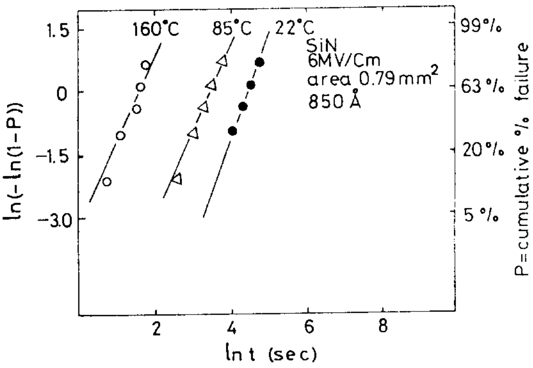

Fig. 9. Werarout curve of MNS capacitor as a parameter of stress temperature.

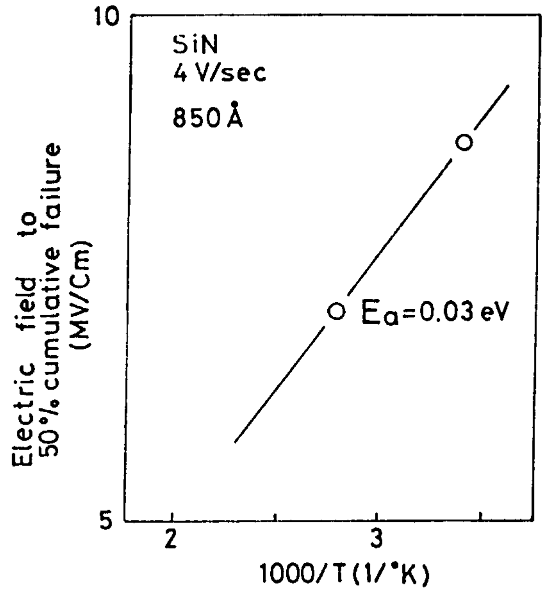

Fig. 10. Activation energy of temperature acceleration factor.

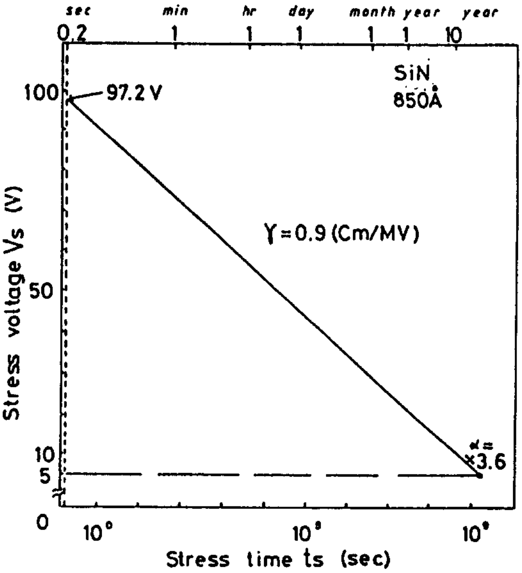

Fig. 11. Stress voltage vs. time of stress test.

If $T_s$ is 20°C and $T_o$ is 70°C, then $\alpha$ is obtained as 3.6. This means that the stress test for 10 years at 70°C is comparable to the test for 36 years at 20°C.

Voltage $V_s$ (V) in the T (sec) stress test at 20°C, necessary to guarantee 10 years of device operatior at voltage $V_g$ at 70°C is given by[4] the following equation[1].

$$V_s\,(V) = V_g + \frac{t_{SiN}}{100\times\gamma}\left[\log(\alpha\times3.2\times10^8) - \log(T)\right] \tag{3}$$

So we can obtain the relationship between stress time and stress voltage at 20°C which guarantees for 10 years stress test at 70°C of $V_g$ = 5V when the thickness of SiN film 850Å As shown in Fig. 11, for example, stress voltage $V_s$ (V) for 0.2 sec at 20°C, comparable to 10 years of stable device operation at voltage $V_g$ (5V) at 70°C, is about 97.2V from the value of $\gamma$ (0.9 cm/MV) and $\alpha$ (3.6).

From the above result, SiN film used in this study has a sufficient reliability. Of course, in practical device fabrication, the breakdown strength would be degraded by the damage from the decrease of film thickness. Thus, these problems are to be solved in the development of each process technology for the pursuit of high quality device fabrication.

### 3.3. High Frequency C-V characteristic of PECVD SiN film.

In order to estimate the relationship of TDDB characteristic with the formation of space charge layer in SiN film and interface state density, the results of high frequency C-V characteristic before and after D.C. stress (+5 MV/cm, 90 sec, 210 sec) are investigated and the characteristic curves are shown in Fig. 12. As can be shown in this figure, with the increase of stress time, the C-V curve shifts to the right and from the formation of negative charge by the trapping of electron in SiN film can be shown.

Fig. 13 shows the change of interface state density before and after stress calculated from the C-V characteristic curve.

As can be shown in Fig. 14, the increase of interface state density with the increase of D.C. stress time can be attributed to the increase of dangling bonds in the vicinity of the Si surface which is arisen from the high energy electrons when they are injected into the SiN film from Si substrate being destructed the Si-H bond existing in the Si-SiN interface or weak bond owing to the nonstoichiometric composition such as $Si_xN_y$. Differently from the low field D.C. stress, the phenomena of the saturation of the electron trapping in the SiN film does not appear in this experiment, and from this results it is concluded that this is originated from the formation of the new trap site in the SiN film in the same way as the increase of the interface state density at the Si-SiN interface.

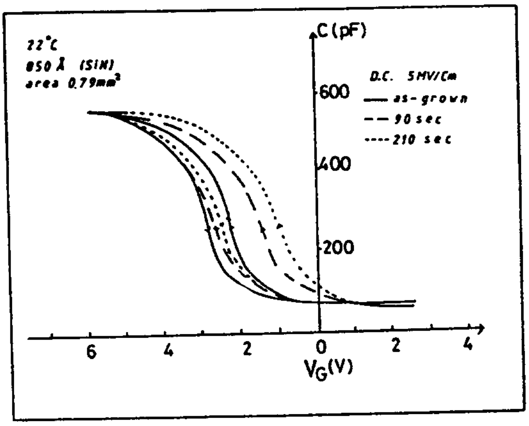

Fig. 12. The change of C-V curve after D.C. stress.

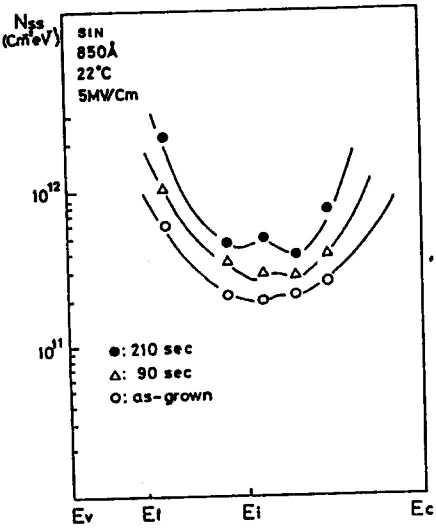

Fig. 13. The change of distribution of interface state density after D.C. stress.

From these experimental results and TDDB characteristics[8], it is considered that since the space charge layer is formed in SiN film and this

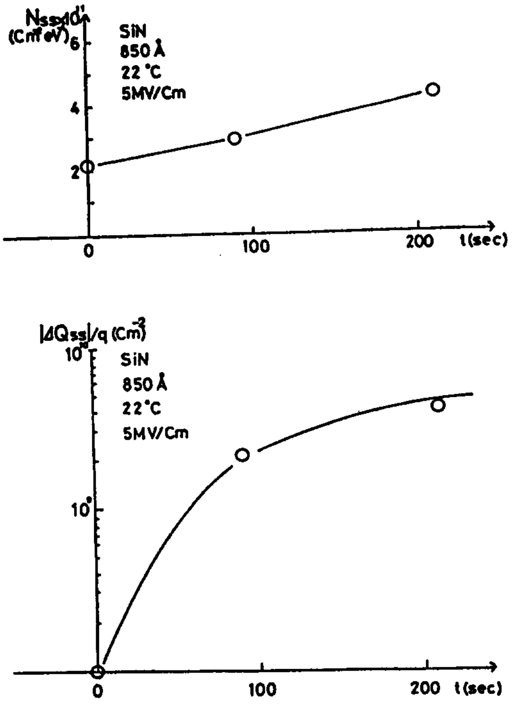

Fig. 14. The change of characteristics of SiN film as a function of stress time.

a) Interface state density ($N_{ss}$)

b) Charge density in SiN film ($Q_{ss}$)

results in the increase of the internal electric field, and consequently the degradation of dielectric strength is to be resulted.

## 4. Conclusion

Silicon nitride films are fabricated by the ammonia free PECVD with $SiH_4$-$N_2$ gas mixture under optimal deposition condition and the following conclusions are obtained from the experimental results of dielectric breakdown and TDDB characteristics of SiN film.

1) Breakdown characteristics of SiN films show the breakdown field of nearly 80% of the samples is concentrated on 7-8 MV/cm and thus consequently it can be concluded that the characteristics of SiN film used in this study is very reliable.
2) In the experiment of the breakdown voltage measurement at the temperature of 22°C, 85°C with ramp voltage (ramp rate of 4 V/sec), the activation energy obtained from the Weibull distribution of the breakdown Voltage histogram is $E_a = 0.03$ eV.
3) In this experiment the important parameters of TDDB characteristics, such as the electric field acceleration factor $\gamma$, activation energy $E_a$, and the temperature acceleration factor $\alpha$, are obtained such as 0.9 (cm/MV), 0.22 eV and 3.6 respectively.
4) From the experimental results of the TDDB characteristics of SiN films for the evaluation of the reliability and stability of MNS capacitors, the stress voltage and stress time at room temperature have following relation.

$$V_s = V_g + \frac{t_{SiN}}{100 \times \gamma}[\log(\alpha \times 3.2 \times 10^8) - \log(T)]$$

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