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Increase of Leakage Current and Trap Density Caused by Bias Stress in Silicon Nitride Prepared by Photo-Chemical Vapor Deposition

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Leakage current at low electric fields in silicon nitride (SiN_x) prepared by photo-chemical vapor deposition is increased by bias stress. Discharging current transient spectroscopy (DCTS) for determining the density and energy distribution of traps in insulators is applied to the study of the change of traps by bias stress. After holes of 2.6×10^{-2} C/cm^2 are injected into SiN_x, the densities of single-level traps ($\sim$0.80 eV) and energetically distributed traps located between 0.83 eV and 0.90 eV above the top of the valence band in SiN_x increase, which could result in the increase of leakage current.

KEYWORDS: discharging current transient spectroscopy (DCTS), electrical traps, silicon nitride, leakage current, dielectric breakdown

1. Introduction

Dielectric breakdown of insulators has been a great problem affecting device reliability. It could result from thermal runaway,[1] avalanche generation of hole-electron pairs,[2] or generation of traps.[3] An increase of leakage current at low electric fields is induced by bias stress in silicon dioxide (SiO_2), and is argued to be related to the generation of traps.[4] Since silicon nitride (SiN_x) has many traps, the leakage current and the dielectric breakdown are considered to correlate strongly with traps.

Since an increase in specific traps would result in these phenomena, information not only on single-level traps but also on energetically distributed traps is required. Although thermally stimulated current (TSC)[5,6] and photocurrent spectroscopic techniques[7] can be applied to the evaluation of single-level traps in insulators, it is difficult to evaluate energetically distributed traps in the band gap. These techniques require temperature scanning or light illumination which stresses insulators. However, the density and energy distribution of traps should be measured without any stress after the bias stress is removed.

A novel method for evaluating traps in insulators has been developed by us,[8] which is referred to as discharging current transient spectroscopy (DCTS). By DCTS, one can easily evaluate not only single-level traps but also energetically distributed traps without any stress to insulators after bias stress has been removed.

We describe the correlation between the leakage current at low electric fields and the density and energy distribution of traps in SiN_x prepared by photo-chemical vapor deposition (photo-CVD). These traps are evaluated by DCTS, and the effect of bias stress on the leakage current and the trap density is discussed.

2. Experimental

Capacitors have an Al/SiN_x/heavily doped p-type crystalline silicon (p^+ c-Si) metal-insulator-semiconductor (MIS) structure, where Al and p^+ c-Si act as electrodes of the capacitor. After p^+ c-Si was soaked in a solution of HF and rinsed in deionised water, SiN_x was deposited on p^+ c-Si at a substrate temperature of 500°C by direct photo-CVD with a low-pressure mercury lamp using N_2-diluted mixtures of SiH_4 and NH_3.[9] The flow rates of NH_3 and SiH_4 were kept at 45 and 1.5 sccm, respectively, and the total pressure was maintained at 7.6 Torr. The SiN_x thickness was 76 nm. After depositing SiN_x, an ohmic contact to p^+ c-Si was formed using Au–Ga alloy, and then Al was evaporated on SiN_x in a vacuum. The area of circular Al electrodes was 3.14 mm^2.

The deposition rate of SiN_x was 1.7 nm/min. The refractive index determined by ellipsometry was 1.94, and the dielectric constant estimated from capacitance at 1 MHz was around 7.0. The resistivity was about 5×10^{16} Ω·cm below an electric field of 3 MV/cm, and the breakdown field was around 8 MV/cm. The minimum interface-trap density at SiN_x/Si was around 3×10^{10} cm^{-2}·eV^{-1} in Al/SiN_x/n-type c-Si MIS diodes.[9] These electrical properties are better than those of SiN_x prepared by plasma CVD.[10]

Currents of these capacitors were measured at room temperature using a Keithley 237 source-measure unit. A set of measurements of DCTS and current-voltage (I–V) characteristics was repeated, as shown in Fig. 1. During the charging time (i.e., in $-600\ \text{s}<t<0\ \text{s}$), a bias voltage ($V_g$) of 50 V was applied to the Al electrode of a capacitor, and charging current $[I_{cha}(t)]$ was measured. In this study, charging corresponds to bias stress. Discharging current $[I_{dis}(t)]$ was measured at $V_g=0$ V in $t>0$ s. After measuring $I_{dis}(t)$, the I–V characteristics were measured in a short time interval of 1 s, in order to reduce the number of injected holes during the I–V measurements. All measurements were controlled by a personal computer.

Applying a positive voltage to the Al electrode implies that holes injected from the Al electrode flow through SiN_x, since electrons cannot be injected into the film from p^+ c-Si. The number of holes (q_h^n) injected into the film during the n-th charging time was estimated to be the integrated value of $I_{cha}(t)$ from -600 s to 0 s. After the n-th charging, the total number of injected holes (Q_h^n) was calculated as the sum of q_h^i from $i=1$ to n.

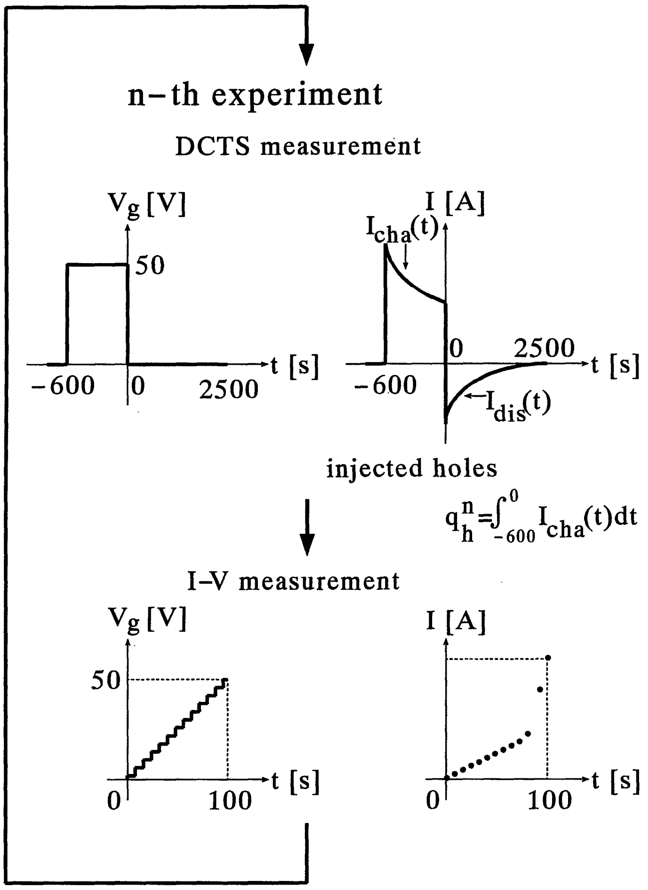

Fig. 1. A set of measurements for DCTS and I–V.

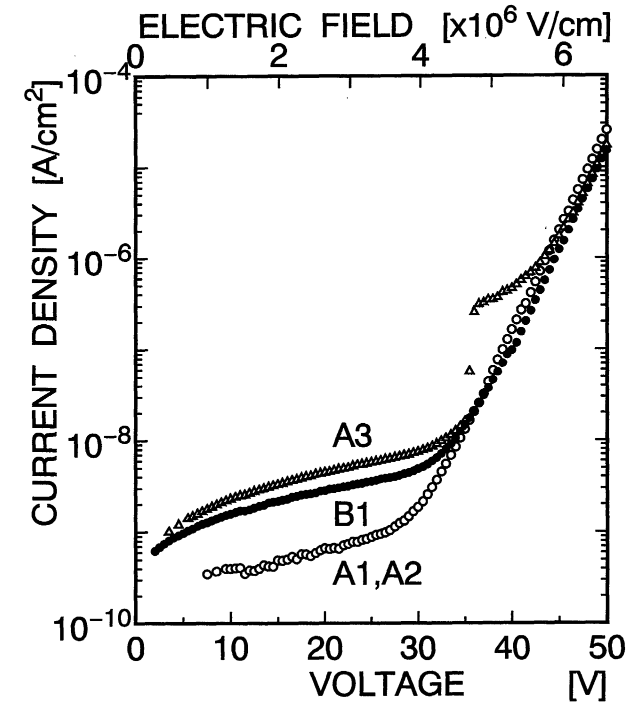

Fig. 2. I–V characteristics of Al/SiN_x/p^+ c-Si MIS capacitors (A and B) with an SiN_x thickness of 76 nm (A1: the first experiment, A2: the second experiment, and A3: the third experiment for Capacitor A, and B1: the first experiment for Capacitor B]. I–V characteristics were measured at a short time interval of 1 s after applying each voltage.

3. Results and Discussion

The effect of bias stress on capacitors was studied. Figure 2 shows the I–V characteristics for Capacitor A [A1: the first experiment ($q_h^1=1.2\times10^{-2}$ C/cm^2), A2: the second experiment ($q_h^2=7.3\times10^{-3}$ C/cm^2), and A3: the third experiment ($q_h^3=7.2\times10^{-3}$ C/cm^2)]. The upper abscissa in the figure shows an electric field (E). Although the leakage current at low electric fields did not change for the first and second bias stresses, it increased for the third bias stress. In order to study the relationship between the leakage current and the trap density in detail, the I–V characteristics of Capacitor B were also shown in the figure. Capacitor B exhibited greater leakage current at low electric fields in the first experiment than the others.

As is clear from the figure, currents in $V_g>40$ V are similar. These currents in high electric fields are reported to be Poole-Frenkel current caused by traps located at 1.3 ± 0.2 eV.[11-13] On the assumption of Poole-Frenkel conduction, the dielectric constants were calculated to be around 3.6 from the slope of $I/E-E^{1/2}$ curves replotted from Fig. 2. Although these dielectric constants are slightly smaller than that of about 4 obtained from the refractive index in the visible light region,[11,12] these currents can be assumed to be Poole-Frenkel current. The densities of these traps should not be different in these capacitors, since Poole-Frenkel current is proportional to the trap density.

On the other hand, currents in $V_g<30$ V are quite different. There are only a few reports on currents in low electric fields. These currents may result from hopping conduction[11] or trap-assisted injection,[14-16] and they increase with an increase of trap densities. These traps should be located in energy levels shallower than 1.1 eV, because these currents flow with lower electric fields than does Poole-Frenkel current. In order to fit experimental results with theoretical curves (I–V characteristics or time-dependent flat-band voltage) as trap-assisted injection of holes into SiN_x, the energy level and density of single-level traps were assumed to be 0.95 ± 0.2 eV and on the order of 10^{17} cm^{-3} by Svensson and Lundstrom,[14] and 0.87 eV and between 10^{16} and 10^{18} cm^{-3} by Maes and Van Overstraeten,[15] respectively. As is clear from the discussion above, Capacitors A1 and A2 have lower density of shallow traps, while Capacitor A3 has higher density. In Capacitor A3, an increase of traps may result in excess current in $35\text{ V}<V_g<40$ V, which could lead to the dielectric breakdown.

Let us evaluate traps shallower than 1.1 eV in these SiN_x films by DCTS. In Fig. 1, $I_{cha}(t)$ is the sum of current [$I_c(t)$] for charging the capacitor, absorption current [$I_a(t)$], and conduction current [$I_l(t)$]. The integrated value of $I_c(t)$ corresponds to the charge $q_e=CV_g$ at the electrodes (C: capacitance of the insulator), while the integrated value of $I_a(t)$ corresponds to the total charge of trapped holes in the insulator. $I_l(t)$ is the current which flows through the insulator, but $I_l(t)$ does not flow during discharging because $V_g=0$ V. $I_{dis}(t)$ flows in the opposite direction to $I_{cha}(t)$. Since

q_e disappears in a short time after $t=0$, charges emitted thermally from traps contribute to $I_{dis}(t)$ which can be experimentally measured. Therefore, $I_{dis}(t)$ includes information on traps.

In order to evaluate traps from $I_{dis}(t)$, the function $D(t)$ is defined as[8)]

$$D(t) \equiv -tI_{dis}(t)/qSd, \tag{1}$$

where q is the charge of an electron, S the electrode area, and d the film thickness. The single-level trap density (n_t) and the trap level ($E_t - E_V$) for holes are obtained from the figure as follows:

$$n_t = D(t_m)/\exp(-1), \tag{2}$$

and

$$E_t - E_V = kT \ln(\nu_p t_m), \tag{3}$$

where t_m is the time at which $D(t)/\exp(-1)$ becomes a maximum, E_t the energy level of hole traps, E_V the top of the valence band, ν_p the attempt-to-escape frequency, k the Boltzmann constant, and T the absolute temperature.

Figure 3 presents $D(t)/\exp(-1)$ calculated from the measured $I_{dis}(t)$. The narrow peaks appearing at around 3 s in the figure represent single-level traps.[8)] The obtained values of n_t and $E_t - E_V$ were 2.8×10^{16} cm^{-3} and 0.79 eV for A1 and A2 using $\nu_p = 10^{13}$ s^{-1},[8)] 7.2×10^{16} cm^{-3} and 0.80 eV for A3, and 4.3×10^{16} cm^{-3} and 0.80 eV for B1, respectively. The energy level and density of traps estimated here coincide with those in the trap-assisted injection of holes.[14,15)]

Since the data for $t>10$ s do not have a narrow peak, the traps corresponding to these data should be energetically distributed. In this case, the following relations can be derived:[8)]

$$g(E) = D(t)/kT, \tag{4}$$

and

$$E - E_V = kT \ln(\nu_p t), \tag{5}$$

where $g(E)$ in cm$^{-3}\cdot$eV^{-1} is the trap density for holes. Therefore, the right ordinate and the upper abscissa in Fig. 3 are useful for assigning the results for $t>10$ s to energetically distributed traps. From the figure, energetically distributed traps on the order of 10^{17} cm$^{-3}\cdot$eV^{-1} were located at 0.83 eV$<E-E_V<$0.94 eV.

The value of q_h^1 corresponds to the sum of the integrated value (q_l) of $I_l(t)$, and charges (q_{sh} and q_{de}) trapped at shallow and deep traps. As is clear from Fig. 3, traps deeper than 1 eV cannot release holes during discharging. Therefore, q_h^i ($i\geq2$) corresponds to the sum of q_l and q_{sh}. This agrees with the finding that in Capacitor A q_h^1 was larger than $q_h^2 (\doteqdot q_h^3)$. Since q_{sh}, which is given by the product of q, d, and shallow trap densities obtained in this measurement, is on the order of 10^{-8} C/cm^2, q_h^i ($i\geq2$) is nearly equal to q_l.

In a comparison of Figs. 2 and 3, it is found that the current at low electric fields increases with an increase in the densities of the single-level traps as well as of the traps distributed at 0.83 eV$<E-E_V<$0.90 eV, indicating that the leakage current could be caused by these traps. The density of the single-level trap is larger than the integrated value of $g(E)$ for the distributed traps, and the former energy level is shallower than those of the latter (distributed traps). Therefore, the single-level trap is considered to correlate strongly with the leakage current. The current at 20 V is approximately proportional to $n_t^{1.9}$. This relationship is now under consideration.

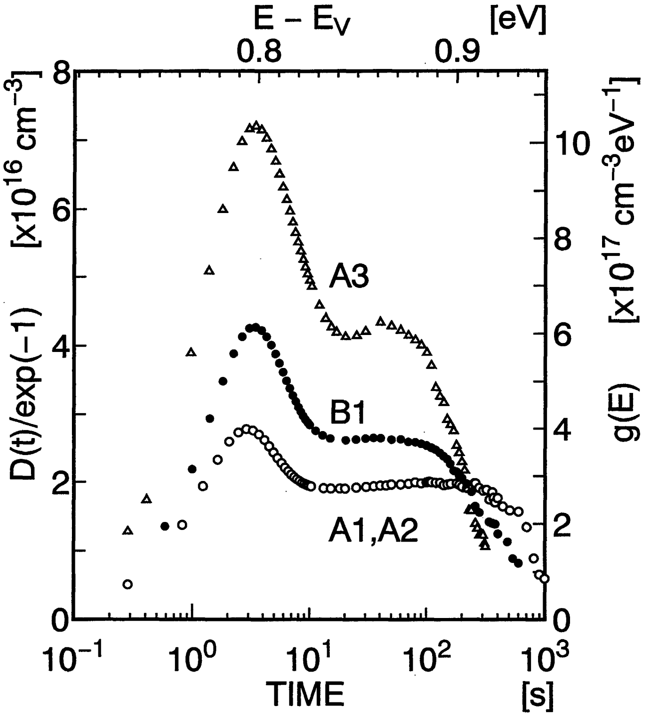

Fig. 3. DCTS signals of Al/SiN$_x$/p$^+$ c-Si MIS capacitors (A and B) with an SiN$_x$ thickness of 76 nm. The right ordinate is calculated from eq. (4) and the upper abscissa is calculated from eq. (5) using $\nu_p = 10^{13}$ s^{-1}, for assigning the results for $t>10$ s to energetically distributed traps.

The degradation of gate insulators is discussed relative to the number of injected charges: a convenient parameter to characterize breakdown due to charge injection is "charge-to-breakdown" Q_{BD}. In thermally oxidized SiO$_2$, Q_{BD} is reported to be larger than 10 C/cm^2 and the hole component in Q_{BD} is around 0.1 C/cm^2,[17)] while for SiN$_x$ there are no reports of Q_{BD}, as far as we know. In this study, the charges of holes emitted during discharging and holes injected during I–V measurements are negligible compared with q_h^n during the bias stress. The similarity between data for A1 ($Q_h^1 = 1.2\times10^{-2}$ C/cm^2) and A2 ($Q_h^2 = 1.9\times10^{-2}$ C/cm^2) indicates that the capacitor was not degraded up to the second experiment. After the third bias stress, the density of the single-level traps increased from 2.8×10^{16} cm^{-3} to 7.2×10^{16} cm^{-3}, and the integrated value of $g(E)$ for the traps distributed from 0.83 eV to 0.90 eV increased from 2.0×10^{16} cm^{-3} to 4.0×10^{16} cm^{-3}. Simultaneously, the leakage current in $V_g<30$ V increased. Therefore, bias stress, which injected 2.6×10^{-2} C/cm^2 holes into SiN$_x$, results in increases of single-level and energetically distributed traps. This probably leads to the increase of leakage current in low electric fields.

If the sample is heated by current, Poole-Frenkel current should increase with charging time. In this study, since the current decreased with time, the increase of traps by hole injection could occur electronically, not thermally.

4. Conclusions

As the first step in understanding the dielectric breakdown of gate insulators in MISFETs, DCTS proposed by us has been applied to the study of the change of traps in SiN_x films due to bias stress. The single-level trap at $E_t - E_V$ of around 0.80 eV and traps energetically distributed at 0.83 eV $< E - E_V <$ 0.90 eV increased with hole injection. The relationship between the densities of these traps and the origin of leakage current at low electric fields has been discussed.

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