Discharging Current Transient Spectroscopy for Evaluating Traps in Insulators

Hideharu MATSUURA, Masahiro YOSHIMOTO and Hiroyuki MATSUNAMI

Department of Electrical Engineering, Kyoto University, Sakyo, Kyoto 606-01, Japan

A novel method [discharging current transient spectroscopy (DCTS)] is developed for evaluating traps in insulators, and is then applied to silicon nitride (SiN_x) films prepared by direct photo-chemical vapor deposition. A single-level trap on the order of 10^{16} cm^{-3} with an emission rate (e_p) of around 0.3 s^{-1} and energetically distributed traps on the order of 10^{17} cm$^{-3} \cdot$eV^{-1} with $e_p < 0.1$ s^{-1} are obtained at room temperature.

KEYWORDS: discharging current, discharging current transient spectroscopy (DCTS), electrical traps, insulator, silicon nitride

1. Introduction

The dielectric breakdown of thin gate insulators in metal-insulator-semiconductor field-effect transistors (MISFETs) is one of the most important problems affecting reliability. The dielectric breakdown could result from thermal runaway,[1] avalanche generation of hole-electron pairs,[2] or generation of traps.[3] Moreover, an increase of leakage current at low electric fields, which could result in the breakdown, is induced by high-field stress, and may be related to the generation of traps.[4] In order to understand the relationship between the number of traps and the excess leakage current (or the dielectric breakdown), it is necessary to evaluate traps in insulator films.

Since an increase in specific traps would result in these phenomena, information on the density and energy distribution of traps in the film is required. There are transient capacitance methods for determining the density and energy distribution of traps, for example, deep level transient spectroscopy (DLTS)[5] and isothermal capacitance transient spectroscopy (ICTS)[6] for low-resistivity semiconductors, and heterojunction-monitored capacitance (HMC)[7] for high-resistivity semiconductors such as undoped hydrogenated amorphous silicon. In the case of applying the transient capacitance methods to metal-insulator-semiconductor (MIS) diodes, the distribution of traps at the insulator/semiconductor interface is mainly studied.[8,9]

For insulators, the following methods can be applied to evaluation of traps. Photocurrent spectroscopic techniques[10] and charge-centroid methods[11,12] are suitable for evaluating deep traps such as memory traps in silicon nitride (SiN_x). Although thermally stimulated current (TSC)[13] is suitable for evaluating single-level traps which could be related to current in insulators, the heating rate of samples should be kept rigidly constant during the measurement. In order to avoid the difficulty of keeping the heating rate constant, charge DLTS (QDLTS), where transient charges at specified times are analyzed as in ordinal DLTS, has been proposed.[14,15] QDLTS enables direct determination of trap density and depth from a single temperature scan regardless of the heating rate.

In order to evaluate not only single-level traps but also energetically distributed traps in insulators, in this letter we describe a method for analyzing transient current measured isothermally. This method is referred to as discharging current transient spectroscopy (DCTS). Then, DCTS is applied to evaluation of traps in SiN_x.

2. Theory of Discharging Current Transient Spectroscopy

When a voltage (V_g) is applied in the interval of $-t_a < t < 0$ to a capacitor which has a thin insulator film between two electrodes, charging current [$I_{cha}(t)$] flows through the capacitor as shown in Fig. 1, where $I_{cha}(t)$ is the sum of current [$I_c(t)$] for charging the capacitor, absorption current [$I_a(t)$], and leakage current [$I_l(t)$]. $I_c(t)$ gives the charge of $Q_e = CV_g$ at the electrodes, where C is the capacitance of the insulator film. After V_g is made zero (i.e., in $t > 0$), discharging current [$I_{dis}(t)$] flows in the opposite direction to $I_{cha}(t)$, and is given by $-[I_c(t) + I_a(t)]$. Q_e disappears in a short time $t_{RC} = R_s C$, suggesting that $-I_c(t)$ becomes zero in a short time, where R_s is the series resistance in the circuit except for the capacitor and is very low. Therefore, $I_{dis}(t)$, which can be experimentally measured, is given by $-I_a(t)$, as shown in Fig. 1. This phenomenon
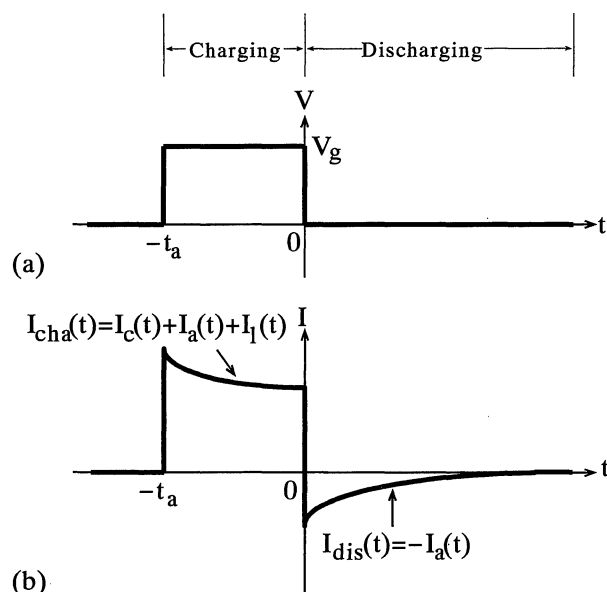

Fig. 1. Schematic representation of (a): voltage and (b): current profiles in discharging current transient spectroscopy.

is well known in dielectric materials.

The discharging current through a thin gate insulator in MIS diodes is considered to determine the density and distribution of traps in the band gap of the insulator. For the sake of simplicity, hole conduction and a single trap level for holes in the insulator are assumed at first. In this case, $I_a(t)$ is given by accumulation of the positive charge $Q_t(t)$ at traps in the film. At $t=0$, the positive charge $Q_t(0)$ is given by qn_tSd, where n_t is the density of trapped holes in the insulator, q the magnitude of electrons, S the electrode area, and d the thickness of the insulator.

Since trapped holes are emitted in $t>0$, $Q_t(t)$ decreases with t according to the following equation:

$$dQ_t(t)/dt = -e_pQ_t(t), \tag{1}$$

where e_p is the rate of hole emission from traps. Therefore, $Q_t(t)$ is derived from eq. (1):

$$Q_t(t)=qn_tSd \exp(-e_pt). \tag{2}$$

When the trapped holes are thermally emitted from the trap level to the valence band, e_p is given by

$$e_p=\nu_p \exp[-(E_t-E_V)/kT], \tag{3}$$

where E_t is 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.

Since holes, which are emitted from traps in the film, are attributed to $I_{dis}(t)$,

$$\begin{aligned} I_{dis}(t)&=dQ_t(t)/dt \\ &= -qSdn_te_p \exp(-e_pt). \end{aligned} \tag{4}$$

Let us consider the determination of n_t and e_p independently from the measured $I_{dis}(t)$. If we can obtain an expression of the form $n_tx \exp(-x)$ where $x=e_pt$, this gives a maximum value of $n_t \exp(-1)$ at $x=1$, which indicates that n_t and e_p are independently determined. When we define a function

$$D(t) \equiv -tI_{dis}(t)/qSd, \tag{5}$$

the desirable function can be obtained:

$$D(t)=n_te_pt \exp(-e_pt). \tag{6}$$

Since this function has a maximum at $e_pt_m=1$, n_t and e_p can be independently determined by

$$n_t=D(t_m)/\exp(-1), \tag{7}$$

and

$$e_p=1/t_m. \tag{8}$$

From eq. (8), the energy level of hole traps is derived using eq. (3):

$$E_t-E_V=kT \ln(\nu_pt_m). \tag{9}$$

In the case that the film has many discrete trap levels, the function becomes

$$D(t)=\sum_i n_t^ie_p^it \exp(-e_p^it), \tag{10}$$

suggesting that $D(t)$ shows many peaks corresponding

to each condition of $e_p^it=1$, where e_p^i is the hole emission rate from the i-th trap level and n_t^i is the number of holes captured at the i-th trap level.

On the other hand, if trap levels in the film are continuously distributed in the band gap, the function is given as

$$D(t)=\int g(E)e_p(E)t \exp[-e_p(E)t] dE, \tag{11}$$

where $g(E)$ in $cm^{-3} \cdot eV^{-1}$ is the number of holes which are trapped in the film during the charging time. Assuming that the function of $e_p(E)t \exp[-e_p(E)t]$ behaves as a delta function $kT\delta(E-E_m)$ since the integrated value of $e_p(E)t \exp[-e_p(E)t]$ from $E=0$ to infinity using eq. (3) is kT, we can easily derive the following relationship from eq. (11):

$$g(E_m) \doteqdot D(t_m)/kT, \tag{12}$$

which is similar to the relationship obtained from ICTS[16] and HMC[7] analyses. In a more general form, E_m and E_t are replaced by energy E, and t_m is replaced by time t in eqs. (9) and (12).

3. Experimental

SiN$_x$ films were deposited on heavily doped p-type crystalline silicon (p^+ c-Si) at a substrate temperature of 500°C by direct photo-chemical vapor deposition (photo-CVD) with a low-pressure mercury lamp using N$_2$-diluted mixtures of SiH$_4$ and NH$_3$. The flow rates of NH$_3$ and SiH$_4$ were maintained at 45 and 1.5 sccm, respectively, and the total pressure was maintained at 7.6 Torr. The SiN$_x$ thickness was 76 nm. The physical and electrical properties of SiN$_x$ films were excellent, and were reported elsewhere.[17] After depositing SiN$_x$, an ohmic contact was formed to p^+ c-Si with Au-Ga alloy, and then Al was evaporated on SiN$_x$ in a vacuum. The area of circular Al electrode dots was 3.14 mm^2. Here, p^+ c-Si and Al act as electrodes of a capacitor. A silicon wafer was used instead of a metal substrate, in order to investigate SiN$_x$ films similar to gate layers in MISFETs. The reason for the use of a heavily doped wafer was to avoid the effect of interface states at SiN$_x$/c-Si on DCTS signals, because little band bending occurs in p^+ c-Si under bias voltage. In the case of using lightly doped c-Si, the interface-state distribution can be estimated by DCTS, although this will not be discussed in this letter.

Currents of these capacitors were measured at room temperature using a Keithley 237 source-measure unit. During the charging time (i.e., in -600 s $<t<0$ s), V_g of 50 V was applied to the Al electrode of an Al/SiN$_x$/ p^+ c-Si capacitor. Applying a positive voltage to the Al electrode implies that holes injected from the Al electrode should flow through SiN$_x$, since electrons cannot be injected into the film from p^+ c-Si. $I_{dis}(t)$ was measured at $V_g=0$ V in $t>0$ s. All measurements were controlled by a personal computer.

4. Results and Discussion

Figure 2 presents the data of $D(t)/\exp(-1)$ for Capacitors A and B. $D(t)$ was calculated from the meas-
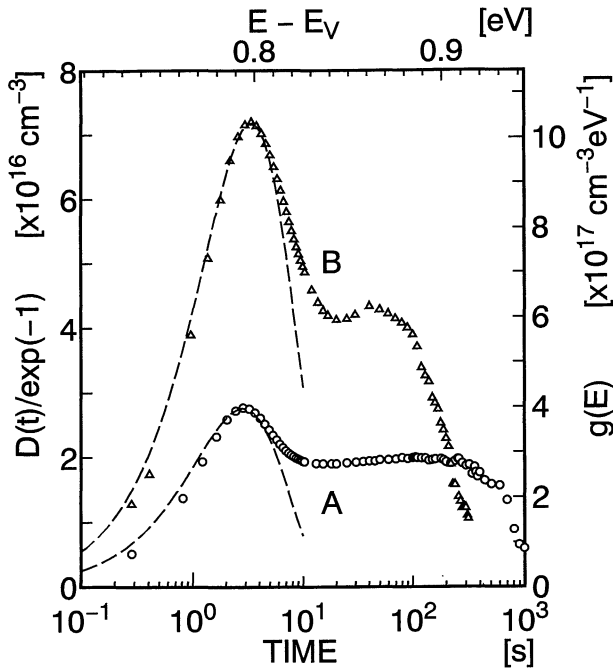
Fig. 2. DCTS signals of an Al/SiN$_x$/p$^+$ c-Si MIS capacitor with an SiN$_x$ thickness of 76 nm for Capacitors A and B. Dashed lines are calculated ones for a single-level trap with $e_p=0.35$ s^{-1} and $n_t=2.8\times10^{16}$ cm^{-3} for Capacitor A, and $e_p=0.29$ s^{-1} and $n_t=7.2\times10^{16}$ cm^{-3} for Capacitor B. The right ordinate is calculated from eq. (12) and the upper abscissa is calculated from eq. (9) using $\nu_p=10^{13}$ s^{-1}, for interpretation of the data in $t>10$ s as energetically distributed traps.

ured $I_{dis}(t)$ using eq. (5). In order to estimate n_t from the figure directly, $D(t)$ was divided by a factor of exp (-1), as is clear from eq. (7). The narrow peaks around 3 s in the figure appear to represent single-level traps. From the figure, n_t and e_p were graphically determined to be the peak value of $D(t)/\exp(-1)$ and the inverse of the time at which $D(t)/\exp(-1)$ became a maximum, respectively. The obtained values of e_p and n_t were 0.35 s^{-1} and 2.8×10^{16} cm^{-3} for Capacitor A, and 0.29 s^{-1} and 7.2×10^{16} cm^{-3} for Capacitor B. The data fit in well with the dashed lines calculated from eq. (6), assuming a single trap level with the obtained values. These trap levels calculated from eq. (9) were around 0.8 eV above the valence band of SiN$_x$ using $\nu_p=10^{13}$ s^{-1}, since ν_p is related to an optical phonon frequency in the film and is equal to or lower than the order of 10^{13} s^{-1}.

The discharging current was proportional to the area of the Al electrodes (0.79, 1.79 and 3.14 mm^2), supporting the assumption that these discharging currents came from the capacitors. In cases where a discharge of $Q_e=CV_g$ would affect DCTS signals, the peak value of $D(t_m)/\exp(-1)$ should be estimated to be Q_e/qSd of 3.4×10^{18} cm^{-3} from eq. (7), where $V_g=50$ V, $C=2.6$ nF, $d=76$ nm and $S=3.14$ mm^2, since the discharge of Q_e behaves like an emission from a single trap level. This indicates that our results were not affected by the discharge of Q_e, as is clear from Fig. 2.

Since the data in $t>10$ s did not have a narrow peak, the traps corresponding to these data should be ener-

getically distributed. Therefore, the right ordinate and the upper abscissa in Fig. 2 are useful for interpreting the data in $t>10$ s as energetically distributed traps, where $E-E_V$ and $g(E)$ are derived from eq. (9) using $\nu_p=10^{13}$ s^{-1} and eq. (12). 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.

As is clear from the results mentioned above, DCTS is a convenient method for evaluating energetically distributed traps in addition to single-level traps. The sensitivity of DCTS varies with minimum measurable current (I_{min}) which depends on the ammeter. Since I_{min} is around 10^{-13} A, the minimum reliable values of $D(t)/\exp(-1)$ in Fig. 2 are 7×10^{11} cm^{-3} at $t=0.1$ s and 7×10^{15} cm^{-3} at $t=10^3$ s from eq. (5) in the sample structure $(S=3.14$ mm^2 and $d=76$ nm) studied here. Since the range of measuring time is between 10^{-1} s and 10^3 s in the DCTS system studied here, traps with 10^{-3} s$^{-1}<e_p<10$ s^{-1} can be observed at any measuring temperature. The energy levels of traps corresponding to these emission rates change with the measuring temperature according to eq. (3), though at room temperature these traps were located at 0.71 eV $<E-E_V<$ 0.94 eV. By elevating the measuring temperature, therefore, deeper traps corresponding to memory traps[10] can be evaluated, and more reliable values of $E-E_V$ and ν_p can be obtained from temperature dependence of DCTS signals.

5. Conclusions

This is the first report on discharging current transient spectroscopy (DCTS) for evaluation of traps in insulators. SiN$_x$ films prepared by photo-CVD have been evaluated by DCTS at room temperature. A single-level trap on the order of 10^{16} cm^{-3} at E_t-E_V of about 0.8 eV and energetically distributed traps on the order of 10^{17} cm$^{-3}\cdot$eV^{-1} at 0.83 eV $<E-E_V<$ 0.94 eV have been observed.

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