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Low-Frequency Current Fluctuations in Post-Hard Breakdown Thin Silicon Oxide Films

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Abstract

This paper focuses on the current fluctuation of post-hard breakdown thin silicon oxide films with thicknesses ranging from 3 nm to 5 nm. The post-degraded structure of silicon oxide films by analyzing current fluctuation spectra after hard breakdown is characterized.

1. Introduction

It is well-known that constant voltage stress generates many kinds of defects inside SiO₂ films. The first stage of degradation is characterized by the emergence of a stress-induced leakage current (SILC), followed by soft breakdown (SBD). Finally, hard breakdown (HBD) occurs. In some cases, the percolation algorithm can provide a qualitative understanding of the degradation mechanism, but the need for a full analysis and interpretation remains. Other analyses have recently been carried out to model defect properties of sub-5-nm-thick SiO₂ films, because such films are needed to realize many contemporary devices. However, because defect nature has such a complex dependency on process technology and thickness, no unified interpretation of degradation evolution has yet been made.

In this paper, we focus on the tunneling current characteristics of thin SiO₂ films whose thickness ranges from 3 nm to 5 nm. The post-degraded structure of SiO₂ films by analyzing current fluctuation spectra after HBD is characterized.

2. Device structure and experimental method

Metal-oxide-semiconductor capacitors are used¹⁾. The devices were fabricated on n-type (001) Si substrates with resistivity of 4 Ωcm. Thin SiO₂ films with a thickness of 3.3 nm or 5.2 nm were formed by means of rapid thermal oxidation at 950 °C. N-type poly-Si film for the gate electrode was formed by using an LPCVD technique. The gate electrode was patterned by wet-etching to avoid process-induced damage. Positive gate bias (V_g) was applied to all devices when evaluating device degradation; both polarities were used in current fluctuation measurements. All measurements were carried out at room temperature²⁾. Gate electrode area was 150 μm x 200 μm.

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3. Experimental results and discussion

In the previous paper²⁾, it was stated that a barrier for electrons is present inside post-HBD SiO₂ films, as shown in Fig. 1(a). While this assumption has been verified by analyzing dc characteristics, the model is based on a macroscopic rather a microscopic view of the phenomenon (Fig. 1(b)). This paper investigated post-HBD conduction in detail in terms of fluctuation of leakage current under a constant V_g .

Fig. 1 Simplified conduction mechanisms of post-hard breakdown oxide films.

The fluctuation characteristics of the leakage current are shown in Fig. 2 for various positive V_g . In these measurements, a constant V_g was applied to the device for a short time (20 sec.). The most significant characteristics seen in Fig. 2 are that typical random telegraph noise (RTN) is observed when $V_g = 50$ mV and 0.2 V, and that semi-analog random noise (SARN) is seen when $V_g = 1.5$ V. On the other hand, semi-digital random noise (SDRN) is always observed when $V_g < 0$ V (not shown here). The fluctuation amplitude for $V_g < 0$ V is one order smaller than that for $V_g > 0$ V, regardless of V_g . This strongly suggests that the current fluctuation reflects the microscopic aspect of the post-HBD SiO₂ film.

Similar fluctuation characteristics of the leakage current were also evaluated for various V_g over a long time period (600 sec.). SDRN is observed when $V_g = 50$ mV; RTN is observed when $V_g = 0.2$ V; and SARN is seen when $V_g = 1.5$ V (not shown here). On the other hand, SDRN is observed when $V_g = -50$ mV and -0.2 V; while RTN occurs when $V_g = -1.5$ V (not shown here). The fluctuation amplitude for $V_g > 0$ V is almost identical to that for $V_g < 0$ V regardless of V_g . Polarity dependence and bias dependence of these noise features suggest that the post-HBD SiO₂ film has an inherently asymmetrical band structure and different microscopic conduction mechanisms.

The numerical calculation results yielded by Fourier transforming the experimental results of Fig. 2 are shown in Fig. 3. It should be noted that Lorentzian spectra are observed when $V_g = 50$ mV and 0.2 V, and that simple $1/f$ spectra are observed when $V_g = 1.5$ V. Since most electrons go through the narrow-pass region in region B for $V_g = 50$ mV and 0.2 V ($< U/e$), this strongly suggests that, as suggested, defects (labeled D_{bp1}) with specific energy level exist inside the narrow-pass region as expected (see Fig. 1). The estimated time constant (τ_{bp1}) ranges from 0.5 sec (Fig. 3(b)) to 2.5 sec (Fig. 3(a)).

When $V_g = 1.5$ V, most electrons can jump over region B without tunneling, and the electron current mainly reflects the aspect of region A. Since it is anticipated that region A is composed of many silicon-rich clusters, it can be accepted that the $1/f$ spectra, not the Lorentzian spectra, are typically observed³⁾. On the other hand, when $V_g < 0$ V, it should be noted that clear Lorentzian spectra were observed only when $V_g = -0.2$ V, and that $1/f^2$ spectra are observed when $V_g = -50$ mV and -1.5 V (not shown here). When $V_g = -50$ mV, it is thought that the defects with specific energy level are those aforementioned (D_{bp1}), because most electrons go through the narrow-pass region. The estimated time constant (τ_{bp1}) is 0.3 sec for $V_g = -0.2$ V, whereas the estimated time constant is larger than 10 sec for $V_g = -50$ mV and -1.5 V. The sub-linear current characteristic of the gate current ($V_g < -0.2$ V)²⁾ suggests a specific generation-recombination process inside the narrow-pass region and region A; this should yield Lorentzian spectra. It is thought that the major part of gate current flows through the narrow-pass region at $V_g = -0.2$ V or -1.5 V. This suggests that the $1/f^2$ spectra for $V_g < 0$ V correspond to deep level defects inside regions A and B.

The numerical calculation results created by Fourier transforming the experimental results

Fig. 2 Gate current as a function of measurement time (20 sec). A positive gate bias was applied to the device.

Fig. 3 Fluctuation power of the gate current as a function of frequency. A positive gate bias was applied to the device for 20 sec.

Fig. 4 Fluctuation power of the gate current as a function of frequency. A positive gate bias ranging from 50 mV to 1.5 V was applied to the device for 600 sec.

for 600-sec measurement are shown in Fig. 4. These analyses are demonstrated for the first time in this paper. In this analysis, it should be noted that $1/f^2$ spectra, and not Lorentzian, are observed for all bias conditions. This indicates that high-density defects with a specific time constant exist inside the post-HBD SiO_2 films. Though the time constant (τ_{bp2}) remains unspecified, it is much larger than 100 sec. Most of the defects contributing to current fluctuation lie inside the narrow-pass region for small V_g and inside region A for large V_g . This aspect shows no relation with the measurement period. Thus, the present experiments indicate that there are two different time constants in the current fluctuation phenomenon; the constants appear to be related to defects with different physical origins.

The present experimental results show phenomena that are different from those in past results⁴⁾. Generally speaking, $1/f^2$ spectra mean that the fluctuation source is a group of defects with a specific energy level. Since it is usual to think that there are various defects with different energy levels before HBD which should show $1/f$ spectra, we have to consider that the density of defects with a specific energy level becomes dominant after HBD. We can thus conclude that a significant and profound relation exists between the SBD event and the HBD event⁵⁾.

4. Precursory signal in SILC

Defect-induced leakage current fluctuation is also observed in SILC⁶⁾. In Fig. 5, normalized SILC is shown as a function of gate voltage for $t_{ox} = 3.3$ nm. In the stress experiment, the applied stress current density (J_{stress}) was 330 mA/cm^2 and the average stress voltage was 4.3 V, with an injected charge density (Q_{inj}) of 120 C/cm^2 . In Fig. 5, the simulation result of SILC is also shown assuming a certain in-depth defect distribution⁶⁾.

In SILC, typical $1/f^2$ spectra are observed before and after stressing. Since the level of fluctuation power increases after stressing, this suggests that inherent defects are activated, and that aspects of activated defects are identical with those of un-stressed film. As noted in section 3, it is anticipated that defects yielding SILC have few long time constants and

Fig. 5 Normalized SILC as a function of gate voltage.

Fig. 6 Fluctuation power spectrum of SILC as a function of frequency ($V_g = 2.7V$).

degradation evolves during and after the stress⁷.

5. Theoretical base and modeling

The experimental result reveals that the fluctuation spectra of a post-HBD gate current depend on length of the observation period. The simple theoretical base for this can be

briefly given in the following:

(i) Short-time observation

$$i(z, t) = A_g q n(z, t) v_{th}, \quad (1a)$$

$$n(z, t) = n_m \exp[-t/\tau_m], \quad (2a)$$

$$\langle I(\omega)^2 \rangle = \sum_m A_g^2 q^2 v_{th}^2 \langle N_t \rangle \{ T / [1 + (\tau_m \omega / 2)^2] \}, \quad (3a)$$

where $i(z, t)$ is the post-HBD gate current, $n_m(z, t)$ is the decay process of trapped electrons, and $\langle I(\omega)^2 \rangle$ is the power spectra of current fluctuation. τ_m is the time constant characterizing the defect labeled 'm'. Eq. (3a) suggests that defects with a short-time constant make the predominant contribution to current fluctuation.

(ii) Long-time observation

$$i(z, t) = A_g q n(z, t) v_{th}, \quad (1b)$$

$$n(z, t) = n_m \exp[-t/\tau_m], \quad (2b)$$

$$\langle I(\omega)^2 \rangle = \sum_m A_g^2 q^2 v_{th}^2 \langle N_t \rangle \{ (\tau_m / 2) / [1 + (\tau_m \omega / 2)^2] \}. \quad (3b)$$

Eq. (3b) suggests that defects with a long-time constant make the predominant contribution to current fluctuation. This means that defects near the electron injector must primarily contribute to current fluctuation.

6. Summary

This paper has demonstrated important aspects of post-HBD gate current of MOS devices and characterized defect property with the aid of a theoretical model.

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