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Universal thermal activation process and current induced degradation on dielectric breakdown in HfSiO(N)

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Introduction

HfSiO(N) have been extensively studied for use in future ULSIs. One of the serious concerns for high-k gate dielectrics is the long-term reliability of gate dielectrics [1-3]. However, because various characteristics in the high-k reliability show the strong process dependence [1-3], the all over discussion in high-k reliability is difficult for us. The universal description for reliability is demanded. The thermal activation process is also important for the temperature acceleration test of production devices.

In this paper, we experimentally demonstrated the universality of thermal activation process in breakdown and the current inducing breakdown acceleration.

Experimental

The devices used in this study were n/p-MIS capacitors and MISFETs with HfSiO (Hf/(Hf+Si)=20% $T_{phys.}$~4.2 nm) and HfSiON (Hf/(Hf+Si)=50% N=20% $T_{phys.}$~4.5 nm) dielectrics fabricated by the sputtering method and MOCVD method. As a reference, the MOSFETs with SiO_2 were also prepared. Time dependent dielectrics breakdown (TDDB) were measured under the constant voltage stress (CVS) and the constant current stress (CCS) conditions.

Results and Discussion

Fig. 1 shows the TEM images of MOCVD HfSiON and sputtered HfSiO dielectrics. The amorphous structures and smooth interface of Si substrate are clearly observed. Qbd distributions with Weibull slope (β) are independent of temperatures (Fig.2). This result indicates that the breakdown processes may not change in the measured temperature. Fig. 3 shows the temperature dependence of time to breakdown (Tbd) and charges to breakdown (Qbd) for CVD HfSiON and sputtered HfSiO. The reported results of sputtered HfSiON [4] are also shown in Fig. 4. Note that all samples show almost the same activation energies (Ea) of around 0.5 eV (0.4~0.6eV) for Tbd and Qbd, irrespective of the compositions and the dielectrics fabrication processes, though the absolute life-time (Tbd,Qbd) are different. This Ea is considered to be a universal parameter in Hf-silicate dielectrics breakdown process.

Then the contents of this particular Ea were further investigated. The novel thermal activation processes in TDDB were observed especially under CVS, where Ea strongly decrease in high temperatures with depending on temperature (Fig.5). As shown in Fig.4, the Qbd temperature dependences of HfSiON under CCS are similar to those of SiO_2[5]. On the contrary, TDDB temperature dependences of HfSiON under CVS are quite different from those of SiO_2 and those of HfSiON under CCS. SiO_2 show about the same dependences between under CCS and CVS (Fig.5). These experimental results clearly indicate that the leakage currents (Jg) have significant role for the degradation of breakdown. Jg also shows the strong temperature dependence (Fig.6). The both measurement data of Tbd and Jg are clearly divided into two high and low temperature regions (Fig. 6,7). Then, the temperature dependence of Tbd were fitted to the simple analytical representations described by

$$Tbd^{-1}(T)=(C_1 \exp(Ea_1/\kappa T))^{-1}+(C_2 \exp(Ea_2/\kappa T))^{-1} \quad (1)$$

Ea show the activation energy of breakdowns. Ea_1 of HfSiON in high temperatures are about 0.4~0.6 eV, which is much larger than that of SiO_2. Ea_2 of HfSiON in the low temperature is about 0.11~0.13eV which is also larger than that of SiO_2. On the other hand, the temperature dependence of Jg were described by

$$J(T)= B_1 \exp(Eaj_1/\kappa T)+B_2 \exp(Eaj_2/\kappa T) \quad (2)$$

Eaj shows the activation energy of current changes. Then the activation characteristics of experimental results at whole temperature are summarized in the Fig. 7. As shown in Fig. 7, the Tbd decrease with increasing temperature, while Jg increases with increasing temperature. Tbd is inversely proportional to Jg. Therefore it is considered that the Tbd can be described by

$$Tbd(T)=A\, J^{1}\, Tbd_0(T)=A(\exp(Eaj/\kappa T))^{-1} \exp(E_0/\kappa T) \quad (3)$$

E_0 is considered to be the intrinsic activation energy of breakdown except the current enhancing degradation on breakdown. From these equations, it was found that the E_0 shows the constant value of about 0.1 eV at the whole temperature region (Fig. 8). The intrinsic Tbd can be described by

$$Tbd\text{-}intrinsic(T)=C_0 \exp(-0.1eV/\kappa T) \quad (4)$$

C_0 corresponds to the intrinsic strength in breakdown. Fig. 9 shows the stress voltage dependence of C_0. C_0 were estimated supposing Tbd(100K)=Tbd-*intrinsic*(100K). C_0 show the weak polarity dependence.

The breakdown characteristics of Tbd-*intrinsic* are similar to those of SiO_2. Consequently, the novel characteristics measured in high-k dielectrics breakdown are considered to be mainly due to the leakage current behavior under some stress and thermal conditions.

Conclusion

By the temperature dependence measurements, we experimentally proved the universality of activation energies of breakdown in HfSiO(N) dielectrics with various compositions and fabrication processes. Furthermore, the significant degradations on breakdown induced by leakage currents are also proved experimentally. The intrinsic strength of HfSiON without current influence is similar to that of SiO_2. The control of leakage current is the key concern for maintaining the enough long-term reliability of the further scaled ULSIs with high-k dielectrics.

Acknowledgement
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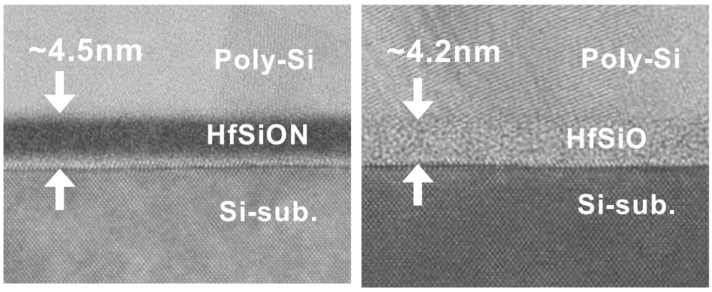

Fig. 1 TEM images of MOCVD HfSION(Hf~50%) (a) and Sputtered HfSiO(Hf~20%) (b), which show the amorphous structures and flat Si interfaces. MOCVD HfSiON dielectrics include the thin interface layer.

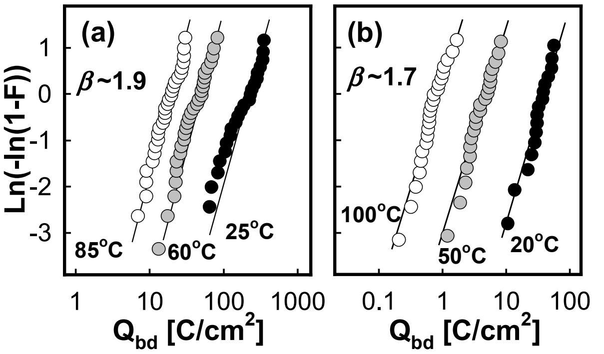

Fig. 2 Temperature dependence of Qbd distribution of (a) MOCVD-HfSiON and (b) Sputtered HfSiO under constant voltage stress (CVS). Webull β are independent of temperature.

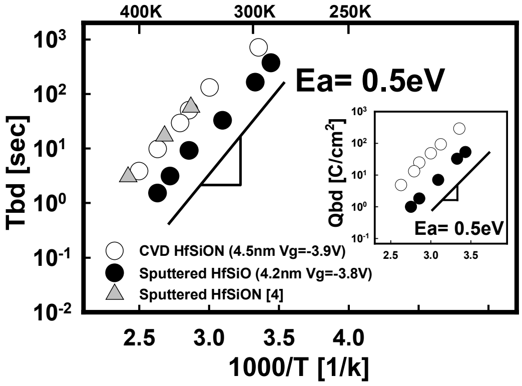

Fig. 3 Temperature dependence of Tbd and Qbd of various Hf-silicate dielectrics under CVS. All samples show almost the same activation energy of breakdown with independent of compositions and processes.

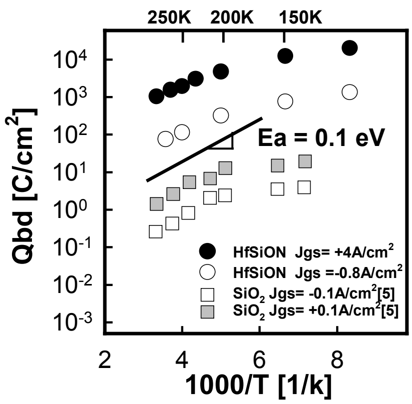

Fig. 4 Temperature dependence of Qbd of MOCVD HfSiON and SiO_2[5] under constant current stress (CCS) with both stressing polarities . All data shows the almost same Ea.

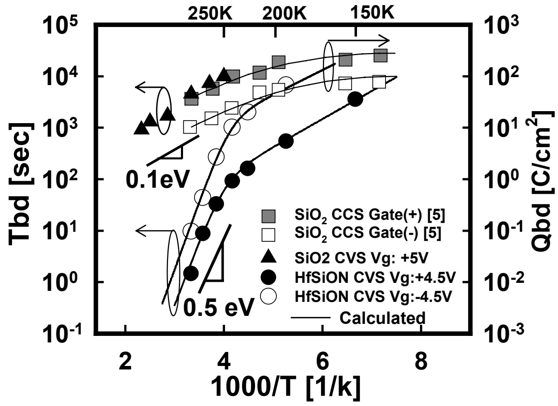

Fig. 5 Temperature dependence of Tbd and Qbd for HfSiON and SiO_2, under CVS and for SiO_2 under CCS[5]. Ea in HfSiON is much larger than that in SiO_2 especially above room temperature.

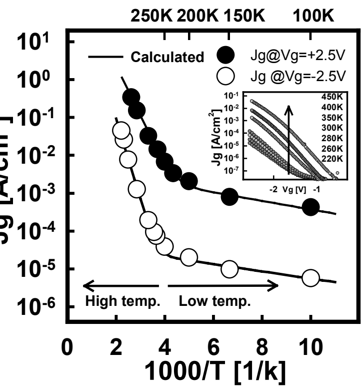

Fig. 6 Temperature dependence of Jg of HfSiON with both polarities, which shows clear temperature dependence. Two (high and low) temperature regions are observed.

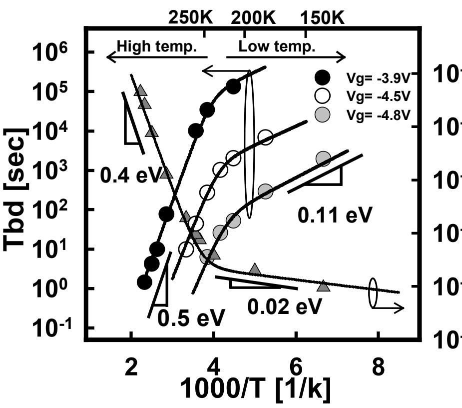

Fig. 7 Comparison of temperature dependence of Jg and Tbd in HfSiON. Each activation energy for Jg and Tbd were evaluated at two temperature regions respectively.

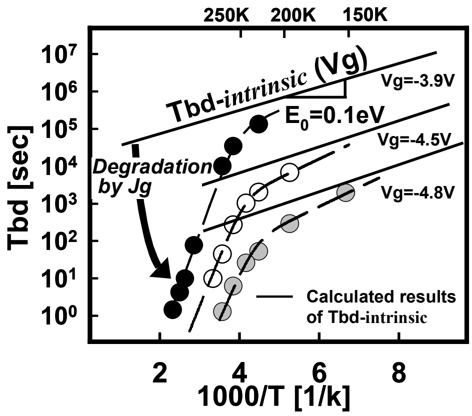

Fig. 8 Experimental Tbd and intrinsic Tbd for HfSiON, estimated by the exception of the degradation induced by Jg-increases. Ea of Tbd-*intrinsic*(=E_0) shows 0.1eV at the whole temperature and stress. Tbd show the clear stress voltage dependence.

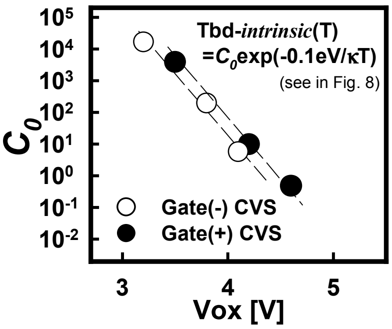

Fig. 9 Stress voltage dependence of C_0 for both stress polarities. C_0 corresponds to the intrinsic strength in breakdown. C_0 shows the almost same stress voltage dependence irrespective of the polarities. The values of C_0 slightly depend on the polarities.