Field-dependent charge trapping analysis of ONO inter-poly dielectrics for NAND flash memory applications

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ABSTRACT

The effect of the operation voltage on the leakage current of SiO2/Si3N4/SiO2 (ONO) stack is investigated which is used for the inter-poly dielectric (IPD) of the floating gate (FG) type NAND flash memory. In this work, the field dependent charge trapping mechanism of ONO stack and the effect of the trapped charges on the electrical characteristics are examined. The leakage current density–electric field (J–E) and the capacitance–voltage (C–V) characteristics are measured for various test samples of ONO stack by varying the voltage sweep ranges. The charge trapping/detrapping mechanisms of ONO stack are observed as the range of the applied sweep voltage is increased and then decreased to a given voltage, which is corresponding to the given electric field. The numbers of trapped and detrapped charges are extracted from the difference of J–E curves using the same recursive voltage sweeps and the effects on the electrical characteristics of ONO stack are demonstrated. Moreover, the dominant trapping layer is also investigated by varying the thickness of ONO stack.

1. Introduction

The inter-poly dielectric (IPD) is crucial for nonvolatile NAND flash memory applications with scaling down because IPD is related to the coupling ratio and the performance of flash memory such as the programming speed and the read current. A multi-stack dielectric, silicon oxide–silicon nitride–silicon oxide (ONO), has been used for the scaled IPD, since ONO stack has high breakdown voltage and low trap density compared with an equivalent thickness of oxide [1,2]. The quality of ONO stack is related to the electrical characteristics and the reliability of flash memory since the trapped charges in ONO stack are impacted on the coupling ratio and the leakage current during the data retention [3]. For this reason, many researches have been investigated about charge trapping as follows.

For the enhancement of the reliability of memory cell, the studies of both the leakage current mechanism and trap states were necessary to investigate [4–6]. In addition, deep trap profiling in ONO stack was analyzed using thermally simulated exoelectron emission, and the trap state related to the low electric field conduction mechanism was investigated and confirmed by the theoretical energy level of trap state [4,7]. The reduction method of the trap density in bottom oxide was examined using additional plasma oxidation and the trap location was also inspected using photocurrent characteristics [6].

However, the studies about the effect of a short and recursive applied bias on ONO stack have not been investigated. The studies of the relationship between the charge trapping and the applied electric field are necessary since the operation voltage of the cell is able to cause the charge trapping repeatedly, resulting in the variation of the electrical characteristics of ONO stack. Thus, in this paper, the number of the charge trapping and effective trap center with varying the applied electric field are analyzed using the current–voltage (I–V) and capacitance–voltage (C–V) characteristics.

2. Experiments and measurements

The ONO test structure was fabricated on 12-inch wafers using the 2× NAND flash process by SK Hynix Semiconductor Inc. The test structures of IPD were constructed with ONO stack sandwiched with two heavily doped poly-Si layers, which are floating gate (FG) and control gate (CG), as shown schematically in Fig. 1 [8]. The silicon oxide (bottom oxide, BO), silicon nitride and silicon oxide (top oxide, TO) of ONO stack were sequentially blanket deposited using low pressure chemical vapor deposition (LPCVD) and the area of test structures was 2.78 × 10^-4 cm².
The oxide and nitride layer thickness of ONO stack were varied to demonstrate the effect of each layer thickness on the number of trap charges. The test samples were divided into two groups: group 1 was consisted of S1 and S2 varying with nitride layer thickness. The equivalent of oxide thickness (EOT) of S2 was 0.15 nm less than S1 (S1 is a reference sample), Group 2 was composed of S1, S3 and S4 varying with both TO and BO coincidently. The EOTs of S3 and S4 were 0.45 nm less and 0.45 nm more than S1, respectively. Although the variation of the ONO layer thickness was small, the effect of thickness variation was significant since the scale of ONO stack was small enough to be impacted by the ONO layer thickness variation.

To analyze the leakage current and charge trapping characteristics, the current–voltage (I–V) and capacitance–voltage (C–V) characteristics were measured using an Agilent 4156C parameter analyzer and Agilent E4980A LCR meter at 10 kHz, respectively. The leakage current density–electric field (J–E) characteristics were measured twice using an Agilent 4156C parameter analyzer and Agilent E4980A LCR meter at 10 kHz, respectively.

The measured curves of J–E and C–V with varying the sweep range for S1 were shown in Figs. 3 and 4, respectively. The tendencies of J–E and C–V curves for S2, S3, and S4 were similar to that of S1, thus the measured data of S1 was shown as a representative.

**Table 1**
The measurement procedure for I–V and C–V characteristics.

<table>
<thead>
<tr>
<th>Measurement scheme and symbol</th>
<th>I–V measurement</th>
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**Fig. 2** shows the repetitive J–E curves swept from 0 to $V_e$. Here, $\Delta E$ is the difference in the electric fields between two sequential J–E sweep curves at arbitrary current density of 0.1 $\mu$A/cm². Based on the measurements, it can be said that the variation of $\Delta E$ was caused by charge trapping/detrapping in trap sites of ONO stack when the electric field was applied. The number of trapped charges is proportional to $\Delta E$ and the reduced capacitance compared to an initial capacitance [6,9,10]. C–V curves as shown in the inset of Fig. 2 were measured before and after the 1st J–E sweep. The capacitance of ONO stack exhibits parabolic shape like as metal–insulator–metal (MIM) capacitor because two poly-Si were heavily doped and the depletion of polysilicon was induced as the applied voltage was increased [11]. Thus, C–V curve can be fitted with a quadratic polynomial:

$$C = aV^2 + bV + c$$  \hspace{1cm} (1)

where C is the normalized capacitance, V is the applied voltage, and a, b, and c are the coefficients of capacitance. Using the Eq. (1), the variations of the voltage shift and the maximum capacitance of C–V curves were extracted.

The measured curves of J–E and C–V with varying the sweep range for S1 were shown in Figs. 3 and 4, respectively. The tendencies of J–E and C–V curves for S2, S3, and S4 were similar to that of S1, thus the measured data of S1 was shown as a representative.
Fig. 3(a) shows J–E curves with increasing the sweep range and Fig. 4 illustrates the variations of the voltage shift and the maximum capacitance of C–V curves with varying the sweep range. The maximum capacitance was normalized by initial maximum capacitance to verify the charge trapping during I–V sweep. The variations of C–V curves shift as shown in inset of Fig. 4 were calculated using the difference of voltages at the maximum capacitance of C–V curves.

As shown in Fig. 3(a), when the voltage sweep range was increased, the leakage current of ONO stack was increased and J–E curves were shifted toward positive direction. In addition, the maximum capacitance after the 1st J–E sweep for each voltage sweep range was reduced and C–V curves were positive shifted continuously with the increase of the voltage sweep range as shown in Fig. 4. It was due to the trapped charges affected by the electric field of ONO stack and the charge trapping was reduced as the same voltage sweep range was repeated.

Moreover, the shift of J–E curves was remarkable after the 1st J–E sweep for each voltage sweep range compared with those of the repetition of the same voltage sweep range. In the inset of Fig. 3(a), the same voltage sweep range was repeated three times. Here, as an example, it is found that ΔE between the 1st and 2nd sweeps for E3 was 0.276 MV/cm² and ΔE between the 2nd and 3rd sweeps was 0.071 MV/cm² at a current density of 0.1 μA/cm². It was due to the trapped charges affected by the electric field of ONO stack and the charge trapping was reduced as the same voltage sweep range was repeated.

Fig. 3(b) illustrates J–E curves as the voltage sweep range was decreased. When the sweep range was decreased, J–E curves were shifted slightly to the opposite direction and the leakage current of a moderate electric field was reduced. The capacitance of ONO stack was increased and C–V curves were negative shifted as the sweep range decreased as shown in Fig. 4. These results were related to the charge detrapping [1,12,16]. In ONO stack, the various trap sites exist and their energy levels were different as shown in Fig. 5. The trap states below the Fermi level of charge injection

Fig. 4. The normalized maximum capacitance as a function of varying the voltage sweep range and the shifting of C–V curve for ONO stack with varying the sweep range (inset) for sample S1.

Fig. 5. The charge trapping/detrapping of shallow trap states for ONO stack with varying the sweep range of (a) Em and (b) Em+1 (where Em > Em+1).
layer were filled [16]. The trapped charges in ONO stack were emitted from the traps when the sweep range was decreased compared with the previous sweep range since the band bending of ONO stack was reduced and the trap sites occupied by the trap charges were raised above Fermi level of FG as shown in Fig. 5(b) [16,17]. In other words, the trapped charges located at relatively shallow and near FG were escaped from the traps easily than those of the deep trap sites when the sweep range was decreased compared with the previous sweep range. Thus, the charges trapping/detrapping were impacted on the reduction of the leakage current in a moderate electric field region. The changes of $J-E$ and $C-V$ curves were decreased in the region of decreasing sweep range. However, they are smaller than those in the region of the increasing sweep range. In Fig. 4, the difference of capacitance occurred although the applied sweep range of $E_{m+2}$ was equal to that of $E_{m-2}$. It can be concluded that the detrapped charges of $E_{m+2}$ were much smaller than those of the trapped charges of $E_{m-2}$.

To verify the charge trapping and/or detrapping of ONO stack with varying the sweep range, the following equation was used [10,18–20]:

$$
\Delta V_{g} = -q N_{T} \left[ \frac{1}{\epsilon_{ox}} \left( d_{TO} - X_{TO} \right) + \frac{1}{\epsilon_{nit}} \left( d_{nit} - X_{nit} \right) + \frac{1}{\epsilon_{BO}} \left( d_{BO} - X_{BO} \right) \right]
$$

(2)

where $q$ is the electron charge (C), $N_{T}$ is the number of trapped charge (cm$^{-2}$), $\epsilon_{ox}$ and $\epsilon_{nit}$ are dielectric constant of oxide and nitride, $d_{TO}$, $d_{nit}$ and $d_{BO}$ are the thicknesses of each layer (cm), $X_{TO}$, $X_{nit}$ and $X_{BO}$ are the trap centers which are the distances of the trapped charges from the CG/TO interface, TO/nitride interface and nitride/BO interface (cm), respectively. The three assumptions were necessary to extract the trapped charges density: (1) the dominant trapping layer was assumed; (2) the trap center was half of the dominant trapping layer thickness; and (3) the trapped charges in the other layers were ignored.

The trap center was assumed to be located in the bulk of the nitride layer and $X_{nit}$ was the half of nitride thickness. Fig. 6 shows the result of group 1 which is the amount of trapped charges for the nitride thickness variation of ONO stack. As the nitride thickness was decreased, the number of cumulative trapped charges was reduced. The trapped charges were about $10^{12} - 10^{13}$ cm$^{-2}$ and the number of trapped charges was consistent with the previ-
ous results for silicon nitride [7,21]. This indicates that the dominant trap sites of ONO stack were in the bulk of the silicon nitride and it is consistent with the previous researches [15,17].

The number of cumulative trapped charges for the oxide thickness variation is shown in Fig. 7. Since the top and bottom oxide thicknesses were varied simultaneously, the trap center used for Eq. (2) was separated from the bulk of top oxide and bottom oxide. The number of trapped charges of the trap center in TO and BO was found to be $2 \times 10^{13}$ cm$^{-2}$ and $6 \times 10^{12}$ cm$^{-2}$ at around 10 MV/cm, respectively. Unlike varying the nitride thickness, however, there was no significant change in the trapped charges when the oxide thicknesses were varied for both assumptions of trap center. The dominant trapping sites, therefore, are in nitride layer and the variations of oxide thickness have less effect on the number of trapped charges comparing with that of nitride thickness. Based on the results of Figs. 6 and 7, the number of trapped charges for applied electric field was extracted using trap center was in the nitride layer.

Fig. 8 shows the number of trapped charges for S1 with varying the applied electric field. As the sweep range was increased, the number of charges in the range of $10^{11}$–$10^{12}$ cm$^{-2}$ was continuously trapped. The trapped charges were then detrapped with decreasing the sweep range and the number of detrapped charges was approximately $10^{10}$ cm$^{-2}$. Since the number of detrapping charges was smaller than that of trapping charges, there was no significant change of J–E curve in Fig. 3(b) except the leakage current at a moderate field region. The results of the trapped charge densities for S2, S3, and S4 were similarly to that of S1. The tendencies of charges trapping/detrapping with varying the electric field, thus, were in agreement with the variations of the measured J–E and C–V curves.

4. Conclusion

The charge trapping and its effect on the electrical characteristics were examined with applying the external electric field to investigate the effect of the operation voltage of the cell on ONO stack. When the voltage sweep range was increased compared with the previous sweep range, the charges were continuously trapped and J–E and C–V curves were shift toward positive direction and reduced, respectively. The number of trapped charges was varied as a function of nitride thickness because the trap sites were in nitride layer. When the voltage sweep range was decreased, the trapped charges of shallow trap states were detrapped. However, the number of detrapping charges was much smaller than that of the trapped charges. From the electrical characteristics of ONO stack, the number of trapped charges can be extracted and the total number of trapped charges can be impacted on the effective electric field on ONO stack. In addition, the charge trapping/detrapping of shallow trap states affected the leakage current density of ONO stack at a moderate electric field region.

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