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A New Method to Extract the Charge Centroid in the Program Operation of MONOS Memories

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Introduction

MONOS type device is a candidate to replace conventional floating gate (FG) non-volatile memory devices because of its low program/erase (P/E) voltage and reduced cell-to-cell interference effect. Instead of poly silicon FG, silicon nitride (SiN), which has discrete traps distributed in the thickness direction, is employed as a charge trap layer of MONOS devices. Then, the information about vertical position of trapped charge is important to understand the trapping properties of SiN layer and to improve the performance and reliability of MONOS devices. Although several techniques for charge centroid evaluation are proposed [1-4], some of these techniques require special device structures such as MONOS with lightly doped poly Si gate [3] or very thick (~50nm) SiN layer [4]. Three-level pulse method [1] is a relatively simple technique among the existing methods in the sense that it uses an ordinary MONOS structure, but this method demands a measurement of P/E characteristics in advance. Here, we present a new simple measurement technique to extract the charge centroid in the nitride layer during the program operation that improves the three-level pulse method.

Extraction Method

The measurement setup and sequence are shown in Fig. 1(a). This configuration is a usual measurement setup for P/E characteristics evaluation, except for a Coulomb meter attached to the substrate of a MONOS cell. The measurement sequence is also a common procedure with only addition of a charge measurement step inserted during P/E operation (Fig. 1(b)). As shown in Fig. 2, the measured charge $Q_{measure}$ before and after a program operation is composed of

$$Q_{measure} = Q_{trap} + Q_{leak} + \Delta Q_{sub} \tag{1}$$

where Q_{trap} is the charge trapped in the nitride, and Q_{leak} is the charge that passes through the MONOS cell. Besides, there is a charge component ΔQ_{sub} that corresponds to displacement current. It should be noted that the charge flow due to displacement current is equivalent to the change in the surface charge density of a Si-substrate. Since a C-V curve shifts along the V_g axis after program operation as shown in Fig. 3, the surface charge density of the Si-substrate at V_g = 0V is different before and after the program operation. This change ΔQ_{sub} is expressed as the shaded area in Fig. 3, and is calculated by the following equation,

$$\Delta Q_{sub} = -\int_{-\Delta V_{fb}}^{0} C(V)dV \tag{2}$$

where $C(V)$ is an initial C-V curve of the MONOS cell before a program operation, and ΔV_{fb} is the flat-band voltage shift due to the program operation. If the leakage charge Q_{leak} is negligibly small, Q_{trap} is approximately given by

$$Q_{trap} = Q_{measure} + \int_{-\Delta V_{fb}}^{0} C(V)dV\ . \tag{3}$$

Therefore, the electrical distance of the charge centroid (z_{eff}) from the gate electrode is

$$z_{eff} = -\frac{\varepsilon_{ox}\Delta V_{fb}}{Q_{trap}} = -\frac{\varepsilon_{ox}\Delta V_{fb}}{Q_{measure} + \int_{-\Delta V_{fb}}^{0} C(V)dV} \tag{4}$$

where ε_{ox} is dielectric constant of SiO_2.

Experimental

The MONOS devices used in this paper are n-substrate capacitors with n^+poly-Si gate. The gate stack consists of 4 nm tunnel oxide, SiN charge trap layer (14 nm or 5 nm), and 15 nm Al_2O_3 block dielectric. Areas of the capacitors are all 100 × 100 μm^2.

Comparison with Three-Level Pulse Method

Previous method [1] requires a three-level pulse where the third pulse level compensates the displacement current. As shown in Fig.4, this method is equivalent to the combination of a programming pulse and an auxiliary pulse [2]. The transition from the state S1 to S3 maintains the same condition at the Si-substrate/tunnel oxide interface (i.e. ΔQ_{sub} = 0) and eliminates the displacement current. Although this method is straightforward, it needs to measure ΔV_{fb} during P/E operation beforehand in order to determine the auxiliary-pulse level. Moreover, the application of the auxiliary-pulse may cause unexpected charge injection which disturbs accurate evaluation of the charge centroid.

In contrast, our method uses a usual rectangular pulse, i.e. the transition from S1 to S2 in Fig. 4. Thus, displacement current is not compensated by applying the auxiliary pulse. Instead, we calculate ΔQ_{sub} from the C-V integration to make correction. Hence, the actual charge flow due to displacement current between the states S2 and S3 ($\Delta Q_{S2\rightarrow S3}$) should be equal to the calculated ΔQ_{sub}. We measured the charge $\Delta Q_{S2\rightarrow S3}$ by a Coulomb meter and compared it with the calculated ΔQ_{sub} from the C-V curve (Fig. 5), and found reasonable agreement. As a result, it is also found that the injected charges (Q_{trap}+Q_{leak}) extracted by our method and the three-level pulse technique [1] are in good agreement, as shown in Fig. 6. Thus, using our method, z_{eff} can be extracted without applying the three-level pulse.

Advantages of this method relative to the previous three-level pulse technique are summarized in Table 1. Since this method uses a simple measurement sequence, it is compatible with other test sequences without causing disturbance due to additional ΔV_{fb} measurement and the application of the third-pulses.

Dependence of Charge Centroid on SiN Thickness

Fig. 7 shows the extracted charge centroid z_{eff} for the MONOS with 14 nm thick SiN layer. The position of the charge centroid is initially located around the middle of the nitride layer, irrespective of the programming voltage. However, as the MONOS is programmed and ΔV_{fb} increases, the charge centroid moves toward the SiN/Al_2O_3 interface. This shift of charge centroid may be an artifact due to the leakage charge Q_{leak} through the Al_2O_3 layer.

The charge centroid of the MONOS device with 5 nm thick SiN layer is shown in Fig. 8. Although the Q_{leak} disturbance is observed in ΔV_{fb} > 0.5V, it is found that the charge centroid is located close to the SiN/Al_2O_3 interface as indicated by the dotted circle. This result is different from that of the 14 nm thick SiN MONOS (Fig. 7), indicating that available charge trap sites can be dependent on the thickness of the SiN layer.

Conclusions

In this work, we proposed and demonstrated a new method to extract the charge centroid of MONOS devices. This method has the advantage of simplicity and the compatibility with other test sequences. Using this method, it was found that the charge centroid of the thick SiN MONOS is located around the middle of the SiN layer, while the thin SiN MONOS has the centroid at the SiN/Al_2O_3 interface. These results indicate that the available trap site may depend on the thickness of the SiN layer.

Acknowledgement

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References

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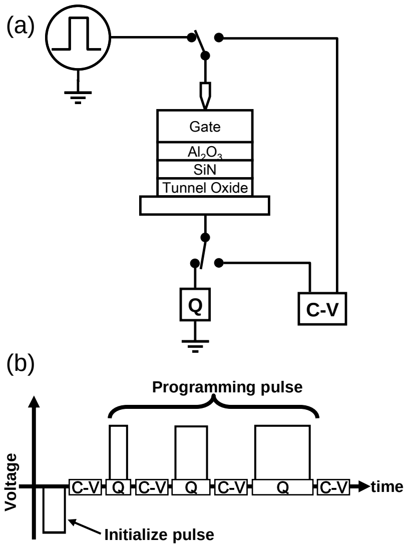

Fig.1 (a) Measurement setup and (b) measurement sequence used to obtain the charge centroid.

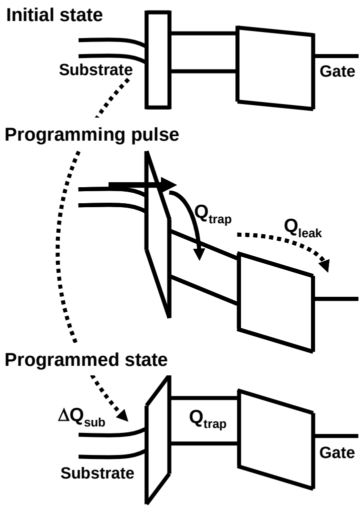

Fig.2 Band diagrams during the program operation. The measured charge is composed of $Q_{trap}+Q_{leak}+\Delta Q_{sub}$.

Table 1 Advantages of this method compared to three-level pulse method

Method	Accuracy	Extraction sequence	Compatibility with DR or cycling test
Three-level pulse	The same accuracy	Measure ΔV_{fb} in advance	Disturbance may occur
This method		Preliminary measurement is not required	No disturbance

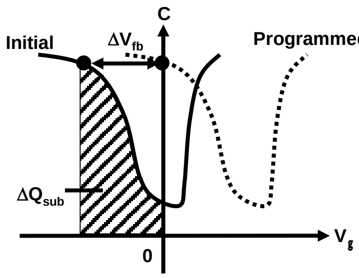

Fig.3 C-V curves before (solid line) and after (dashed line) a program operation. ΔQ_{sub} corresponds to the shaded area.

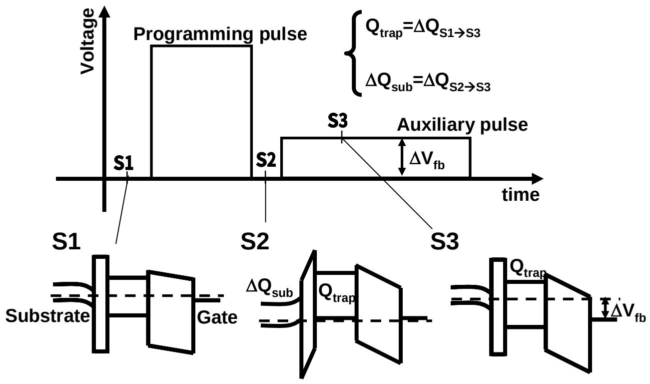

Fig.4 Band diagrams of each state when applying the three-level pulse. The auxiliary pulse is applied in order to cancel out the change in displacement current.

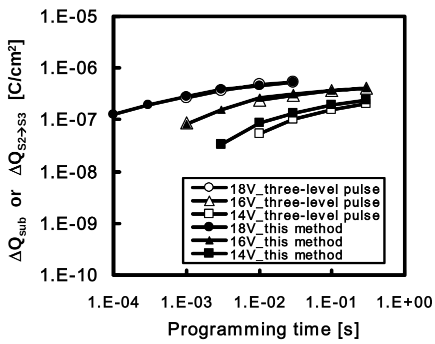

Fig.5 Calculated ΔQ_{sub} (filled symbols) and measured $\Delta Q_{S2\rightarrow S3}$ (open) as a function of programming time. These values are in good agreement.

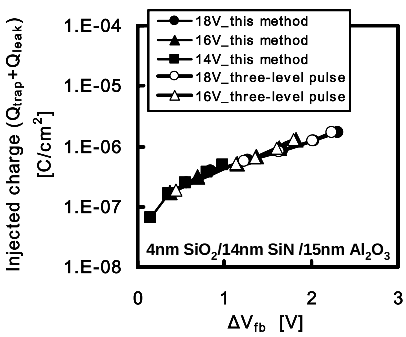

Fig.6 Injected charge ($Q_{trap}+Q_{leak}$) in the program operation of MONOS cells. Injected charge is extracted by our method (filled symbols) or the three-level pulse technique (open).

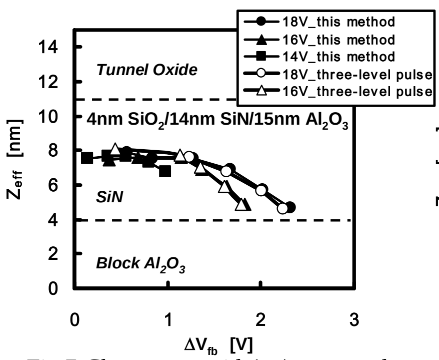

Fig.7 Charge centroid (z_{eff}) extracted by our method (filled symbols) and the previous technique (open). The centroid is initially positioned close to the middle of the nitride layer.

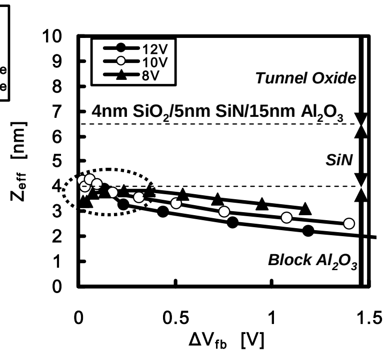

Fig.8 Charge centroid (z_{eff}) of the MONOS with 5nm SiN layer. The centroid is located around the SiN/Al_2O_3 interface.