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ONO Thickness Dependency of Complementary Bit Disturb in SONOS-type Nonvolatile Memory

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I. INTRODUCTION

The discrete trap nonvolatile memories such as 2-bit SONOS-type nonvolatile memory [1] and nanocrystal memory have been actively researched recently. 2bit / cell of the SONOS-type memory means charge localization in the silicon nitride above the drain and the source junction. 2-bit data in a cell can be programmed by forward program (FP) and reverse program (RP), and they can be read by reverse read (RR) and forward read (FR), respectively [1]. The stored charge by FP/RP has a certain amount of influence on FR/RR current, which is called the 2nd bit effect or complementary bit disturb (CBD). It degrades the read margin. That means the CBD is a one of the key parameters of the memory.

In this paper, ONO thickness dependency of the CBD is studied experimentally and theoretically by modifying the past one-dimensional works by Reddi [2] and Leblebici [3].

In this paper, the following notations and definitions are used; V_{th} is threshold voltage. V_{th0} is V_{th} in case of no stored charge in ONO. V_{thF} and ΔV_{thF} are V_{th} at FR and $V_{thF} - V_{th0}$, respectively. V_{thR} and ΔV_{thR} are V_{th} at RR and $V_{thR} - V_{th0}$, respectively. $V_T Window$ is $V_{thR} - V_{thF}$. V_{gs}, V_{ds} and V_{ss} are gate, drain and source potentials.

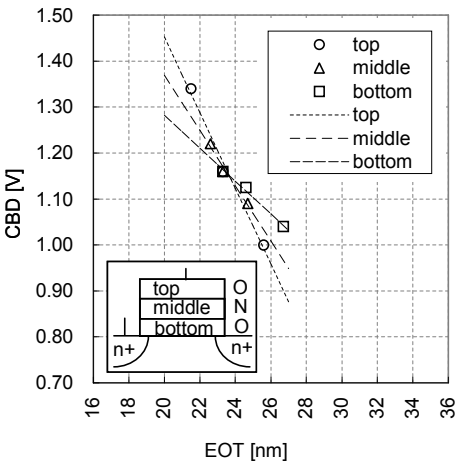

Fig. 1. Experimental results of ONO thickness dependency of the CBD. The samples are planer-type with 230nm technology, and lower left illustration is the cross section of a memory cell. The thickness of each ONO layer is independently controlled from the standard ONO thickness, which are $t_{top} = 12.0$, $t_{middle} = 7.00$, $t_{bottom} = 7.00$ [nm]. The cell has stored charge at either side of the drain /source junction. FP is executed with $V_{gs} \approx 10.0[V]$, $V_{ds} \approx 5.00[V]$ until $\Delta V_{thR} \geq 3.00[V]$. $V_{ds} = 1.20$ [V] at read and V_{th} is defined as V_{gs} at $I_{ds} = 1.00\,[uA]$.

II. EXPERIMENTAL RESULTS

Experimental results of ONO thickness dependency of the CBD are shown in Fig.1 where the CBD is ΔV_{thF} when $\Delta V_{thR} = 3.00$ [V]. In Fig.1, these results can be seen; 1. Thicker equivalent oxide thickness (EOT) of ONO makes the CBD smaller. 2. The EOT dependency is strong in order of top, middle, and bottom film thickness. They are discussed in the section IV.

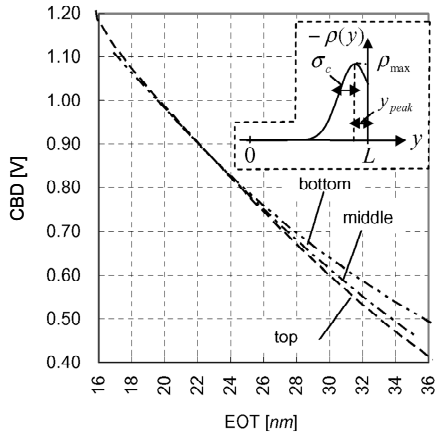

Fig.2. The theoretical result of the CBD. The thickness of each ONO layer is independently controlled from the standard ONO thickness. Inset explains the Gaussian distribution adopted as the charge distribution in this study. These are the similar distribution to that used in fig.4.

III. CALCULATION METHOD

Considering the stored charge above a certain region of the channel, the channel under the charge is difficult to become inversion. In addition, the channel near the electrical drain junction is also difficult to become inversion. When the channel far from the charge and the electrical drain junction begins being inverted, the channel near the drain junction and under the charge is still in depletion. As a result, there are two discrete depletion regions along the channel. In general, in case there are some partial charge regions along the channel in silicon nitride film in Fig.3, the length of the *l*th partial depletion region from the electrical source can be described using the same method as Reddi [2] by the following equation;

$$\Delta L_l = \sqrt{\frac{2\varepsilon_{si}}{qN_A}\sum_{m=1}^{l}\left(V_m - V_{pm}\right)} - \sum_{m=1}^{l-1}\Delta L_m \qquad (1)$$

where V_{pm} and V_m are the channel potentials of the *m*th partial depletion region at the electrical source-side and the electrical drain-side, respectively. q, ε_{si} and N_A are electronic charge, dielectric constant of Si and acceptor concentration in silicon, respectively.

Modifying the method of [3], the transistor is modeled by infinitesimal partial transistors in series. The charge in inversion layer is described by the following equation;

$$Q_I(y) = -C_{ONO}\left(V_{gs} - V_{th}(y)\right) \qquad (2)$$

where C_{ONO} is the electrical capacitance of ONO film. $V_{th}(y)$ is described by the following equation,

$$\begin{aligned} V_{th}(y) &= 2\phi_f + \frac{1}{C_{ONO}}\sqrt{2\varepsilon_{si}qN_A\left(2\phi_f + V(y)\right)} \\ &\quad + V(y) - \rho(y)t_{middle}\left(\frac{t_{top}}{\varepsilon_{ox}} + \frac{t_{middle}}{2\varepsilon_{nit}}\right) \qquad (3) \\ &\equiv V_{th0} + V(y) + \Delta V_{FB} \end{aligned}$$

where $\rho(y)$ is the stored charge density and t_{top}, t_{middle} and

t_{bottom} represent the ONO physical thickness. ε_{ox} and ε_{nit} are the dielectric constants of SiO_2 and Si_3N_4, respectively. ϕ_f is the Fermi potential of the substrate.

To obtain the relation between V_{th} and V_{ds}, $V_{th}+0$ (as V_{gs}) and V_{ss} are given at first, then, V_{ds} is obtained by calculating $V(y)$ from the electrical source to the electrical drain while keeping potential continues rule . That is, when $-Q_I(y)<0$ (depletion), $V(y)$ is calculated using (1). When $-Q_I(y)\geq 0$ (inversion), $V(y)=const$ because $|I_{ds}|\rightarrow +0$ when $V_{gs}-V_{th}\rightarrow +0$, $V_{ds}>0$ according to the past one-dimensional model [2][3][4].

V_{ds} should be calculated from V_{th0} to $V_{th0}+\Delta V_{FB\max}$; When $V_{ds}\rightarrow 0$, the punch-through current explained in [2] is suppressed and the current flows through inversion layer only. That means the region under ONO film with the maximum stored charge density ($\rho_{\max}$), where it is most difficult to be inverted, decides V_{th} ($=V_{th0}+\Delta V_{FB\max}$). In addition, V_{ds} should be less than $(qN_AL^2)/(2\varepsilon_{si})$ due to presupposition of the model of [2], where L is the channel length.

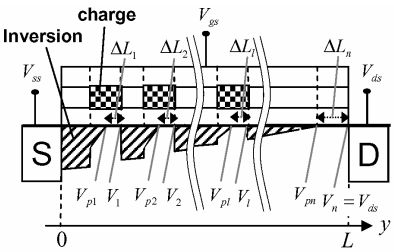

Fig. 3. Schematic cross section in case discrete charge regions exist along the channel in silicon nitride film. Inversion height in the illustration represents the quantity of inversion charge from the point of view of the one-dimensional method.

IV. Calculation Results

A. Deriving charge distribution along channel from experimental data of the relation between V_{th} and V_{ds}

To derive charge distribution programmed by FP, it is assumed that it is Gaussian distribution described with $\rho_{\max}$, y_{peak} and σ_c as 1st step (see the inset of Fig.2.). Then, according to the section III, $\rho_{\max}$ can be obtained from $V_{ds}\rightarrow 0$ data. y_{peak} and σ_c are derived from the relation data between V_{thF} and V_{ds} with minimizing the difference between experimental data and the calculation.

B. ONO thickness dependency of CBD

The theoretical results of the CBD in case of various ONO thicknesses are calculated in Fig.2 where the similar charge distribution derived from the experimental results of the relation data between V_{thF} and V_{ds} for ONO thickness $t_{top}=12.0$, $t_{middle}=7.00$, $t_{bottom}=7.00$ [nm] is adopted to get $\Delta V_{thR}=3.00$ [V]. These results are obtained;

1. Thicker ONO EOT makes the CBD smaller.
2. The EOT dependency is strong in order of top, middle, and bottom film thickness.

According to the theoretical study, V_{thR} is decided by two phenomena; one is the body effect. That is, the potential of the channel at the electrical source-side increases due to the stored charge when the punch-through current flows thorough the depletion layer near the electrical source junction. As a result, ΔV_{thR} increases as the EOT of ONO is thicker as the body effect. The other phenomenon is the flat-band voltage difference from the stored charge. The flat-band voltage depends on the top and middle thickness in order of top and middle thickness in spite of the same charge quantity. Therefore, when $\Delta V_{thR}=const$, as the ONO thickness is thicker, the charge distribution should be smaller. As a result, the CBD should be also smaller in order of top, middle and bottom film thickness.

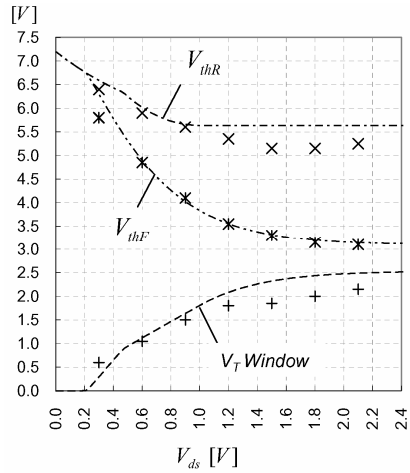

Fig.4. Experimental and theoretical relations between V_{ds} in read and V_{th} for the standard ONO thickness. Lines are the theoretical results, while points are the experimental results where Gaussian distribution parameters are $y_{peak}=14.8[nm]$, $\sigma_c=31.1[nm]$, $\rho_{\max}=9.05\times q\times 10^{18}$. The y_{peak} and the σ_c are decided by minimizing V_{thF} difference between the experimental results and the calculation results, where $N_A=2.32\times 10^{17}$ [cm^{-3}].

V. Conclusion

The ONO thickness dependency of the CBD has been experimentally and theoretically studied by modifying the past one-dimensional works by Reddi [2] and Leblebici [3]. In this study, the theoretical result can explain the experimental result of the relation between CBD and the ONO thickness. The CBD depends on the EOT of ONO and the dependency is strong in order of top, middle and bottom thickness. These phenomena are explained by the body effect and the flat-band voltage difference. The results are a guide to decide the thickness and the ratio of gate dielectric films and charge-trapped films in order to reduce the CBD in the discrete trap nonvolatile memory.

References

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