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Extraction of Trap Energy Distribution in Nitride-based MANOS Charge Trap Flash Memory by Combining the Iteration Method with Optical C-V Measurement

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Abstract

For extracting the trap distribution in the charge trapping layer of charge trap flash memory devices, a new iteration method with optical C-V data is proposed. Applying photons with E_{ph}=2.33 [eV] to the Alumina-Nitride-Oxide (ANO) layer with 100/60/30 [Å] in the Metal-Alumina-Nitride-Oxide-Semiconductor (MANOS) charge trap flash devices, the trap density in the charge trapping nitride layer is successfully extracted to be 4.02×10^{19}~9.77×10^{19} [$\mathrm{cm^{-3}eV^{-1}}$] in the energy range E_C-E_t=1.30~1.60 [eV]. Combining sub-bandgap photons in the C-V characterization, the optical C-V method is free from the thermal and electrical stresses which are inherent in the conventional characterization methods even though they are critical error factors for accurate characterization of charge trap flash memory devices.

I. Introduction

Nitride-based charge trap flash (CTF) memories are under active development with low programming voltage, good endurance, long retention, high scalability, and compatibility with conventional CMOS process. With a scaling down of the tunneling bottom oxide in SiO_x/Al_2O_3-Nitride-Oxide (O/A-N-O) layers, both the retention and program/erase (P/E) efficiency in nitride-based CTF memories are dominantly influenced by the trap energy distribution. Therefore, simple, accurate, and fast method for extracting the nitride trap density which is the key parameters are strongly required in perspective of modeling and design of CTF memories. Nevertheless, time- and temperature-dependent characterization or the numerical calculation of the tunneling rate has been reported in D_{NIT} extraction [1-3]. In this work, an optical characterization framework for simple, fast, and electrical stress-free extraction of D_{NIT} is proposed.

II. Extraction of Energy Distribution in Nitride Traps

Fig.1 (a) shows the illustrative band diagram of the proposed optical C-V method under accumulation bias across the MANOS capacitor. When photons with E_{ph}=2.33 eV and P_{opt}=50 mW are illuminated on a fully programmed MANOS CTF capacitor, trapped charges over the energy range (E_C-1.28)<E_t<E_C in the nitride layer ($E_{g,SiN}$~4.7 eV) are excited to the conduction band of the tunnel oxide (ΔE_C=1.05 [eV]). When the V_{GS} is swept from V_{FB} to more negative voltage, trapped charges in the deeper energy levels over E_C-(1.28+E_{tunnel})<E_t<E_C can be excited to the conduction band by photonic excitation. ΔE_{tunnel} and t_{tunnel} are defined as available energy range and the maximum tunneling barrier thickness, respectively, for F-N tunneling at any specific V_{GS}. In the characterization, t_{tunnel} was assumed to be 1 nm [4]. With more negative V_{GS}, ΔE_{tunnel} for F-N tunneling can be larger and consequentially allows extracting D_{NIT} over the energy bandgap in deeper energy levels (from E_{t1} to E_{t2} in Fig. 1(a)). The C-V characteristics for MANOS capacitors (A/N/O=100/60/30[Å]) under optical excitation can be modeled as an equivalent circuit shown in Fig. 1(b) and analytically written by

$$\frac{1}{C_{PR,OPT}}=\frac{1}{C_{TOX}}+\frac{1}{C_{NIT}+\Delta C_{NIT,OPT}}+\frac{1}{C_{BOX}}+\frac{1}{C_{Si}+C_{it}+C_{GEN}} \tag{1}$$

$$\frac{1}{C_{ER,OPT}}=\frac{1}{C_{TOX}}+\frac{1}{C_{NIT}}+\frac{1}{C_{BOX}}+\frac{1}{C_{Si}+C_{it}+C_{GEN}} \tag{2}$$

$$\Delta C_{NIT,OPT}=\frac{\partial Q_{NIT}}{\partial V_{NIT}}=\left[C_{NIT}{}^{-1}+C_{PR,OPT}{}^{-1}-C_{ER,OPT}{}^{-1}\right]^{-1}-C_{NIT}, \tag{3}$$

$$D_{NIT\_02}=\frac{\Delta C_{NIT,OPT}}{q^2}\times\frac{1}{A\times\alpha\times T_{NIT}}\quad. \tag{4}$$

By using Eqs.(1) and (2), $\Delta C_{NIT,OPT}$ and the trap distribution D_{NIT} can be obtained. However, we note that a correction in the flat band voltage (V_{FB}) is necessary due to different V_{GS} in calculating C-V curves due to charges in the nitride storage layer. Then, $\Delta C_{NIT,OPT}$ can be extracted from Eq. (3) after correcting the difference in V_{FB} between C-V curves ($C_{PR,OPT}$ and $C_{ER,OPT}$) by Eq. (5). Because the DC bias of V_{GS} during $C_{PR,OPT}$-V_{GS} measurement causes a change in the total trapped charge (Q_{NIT}) in the nitride layer, the V_{GS}-dependent flat band voltage shift $\Delta V_{FB}(V_{GS})$ can be described by

$$\Delta V_{FB}(V_{GS})=q\times\int_{E_V}^{E_t(V_{GS})}D_{NIT\_01}dE\times\alpha T_{NIT}\times\left(\frac{1}{C_{TOX}}+\frac{X_{C,NIT}}{\varepsilon_{NIT}}\right) \tag{5}$$

where α, $X_{C,NIT}$, and A are an empirical parameter reflecting the spatially non-uniform trap density along the vertical direction, charge centroid, and area of MANOS capacitor, respectively. α and $X_{C,NIT}$ were assumed to be 1/4 and 0.75 nm from Al_2O_3/SiN_x interface [5].

Measured C-V curves for a MANOS capacitor (Program/Erase: V_P/V_E=10/-12 V, T_P/T_E=10/10 ms) are shown in Fig. 2. In order to obtain $\Delta V_{FB}(V_{GS})$ from Eq.(5), however, the initial distribution D_{NIT} is needed to know. $D_{NIT,01}$ and $D_{NIT,02}$ for the iteration can be calculated by ΔV_{FB} combining experimental data from Eq.(4) and Eq. (5). Once ΔV_{FB} is determined, C-V curve is shifted by the amount of ΔV_{FB} and then Eq.(4) can be re-calculated through Eqs. (1) to (3) by iteration until calculated D_{NIT_01} and D_{NIT_02} coincide with experimental C-V data shown in Fig.3. Distribution of the trap energy level D_{NIT} was extracted by modulating V_{GS}, which modulates ΔE_{tunnel} and thus the surface potential ϕ_s, & trap level E_t, under assumption of the thickness of FN tunneling=10 [Å]. In the accumulation region, the corrected C-V curve is again drawn by ΔV_{FB} in Fig.5.

The extracted distribution of D_{NIT} by combining the iteration method with optical C-V data is shown in Fig.6. In the iteration, the initial D_{NIT}=10^{16}~10^{19} [$\mathrm{cm^{-3}eV^{-1}}$] resulted reliable distribution after iteration for the ΔV_{FB}. The trap density in the charge trapping nitride layer of MANOS under characterization was successfully extracted to be D_{NIT}= 4.02×10^{19}~9.77×10^{19} [$\mathrm{cm^{-3}eV^{-1}}$] over the energy range E_C-E_t=1.30~1.60 [eV]. Employing with different photon energies, we expect that both shallow and deep energy distribution of charge traps in the trapping nitride layer can be fully characterized.

III. Conclusions

Combining an iteration method with optical C-V characteristics, a new method for extracting D_{NIT} in MANOS CTF memories was proposed. High thermal effect and electrical stress under characterization in the conventional method can be effectively removed by combining C-V data from four different measurements (program/erase and with/without optical illumination) and the converted surface potential ϕ_s. Applying optical source with E_{ph}=2.33 [eV] to ANO layer (100/60/30 [Å]) in MANOS systems, the trap density was extracted to be D_{NIT}=4.02×10^{19}~9.77×10^{19} [$\mathrm{cm^{-3}eV^{-1}}$] over the energy range E_C-E_t=1.30~1.60 [eV]. We expect that this method can be used for extracting the deep trap density as well as shallow trap density over the wide bandgap nitride layer by controlling the wavelength of the optical source.

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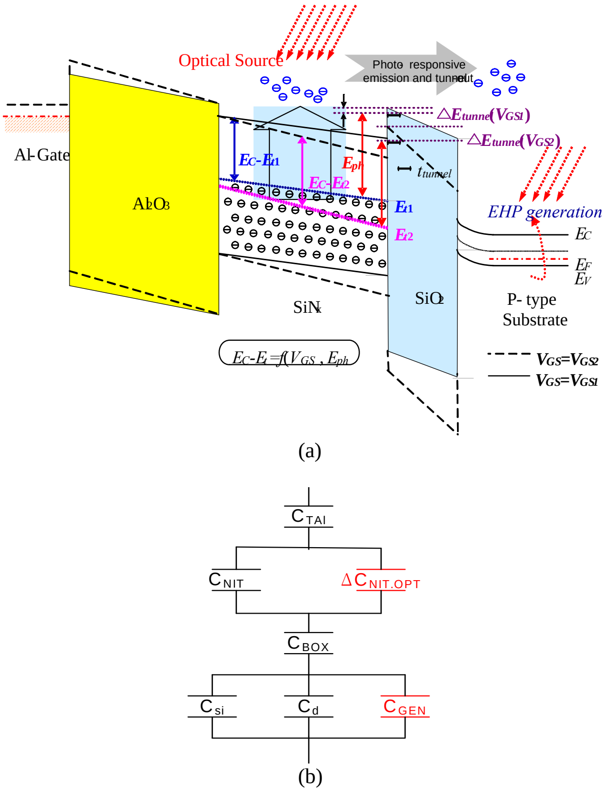

Fig.1. (a) The illustrative band diagram of the proposed optical C-V method under accumulation region (b) equivalent capacitance model for the charge trapped flash memory capacitor with illumination. C_{GEN} = capacitance by electron-hole-pair (EHP) generation from Si substrate ($E_{ph}>E_{g,Si}$), and $\Delta C_{NIT,OPT}$ = capacitance by photo-responsive program states charge excited from $E_t(V_{GS})$ to E_C.

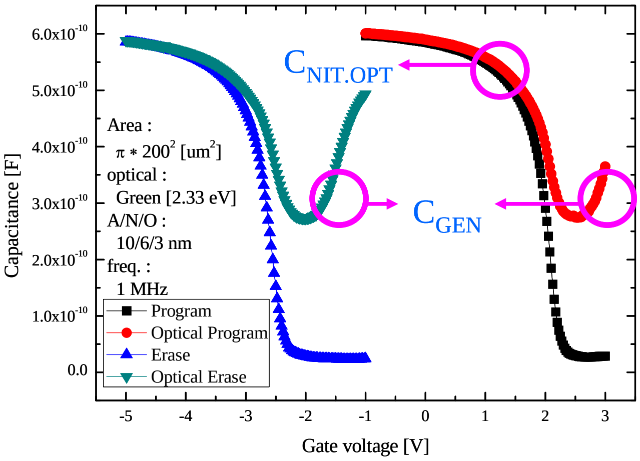

Fig.2. Program and erase C-V curves for the charge trapping MANOS flash memory capacitor.

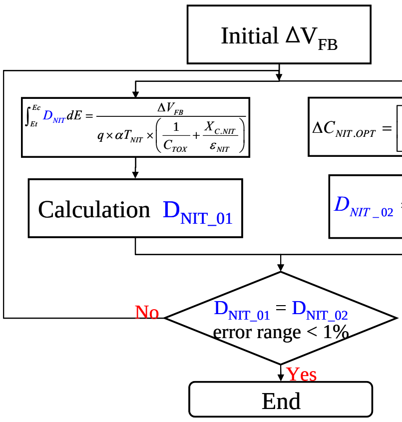

Fig.3. Flow chart of the new iteration method combining optical C-V data for extraction of the trap distribution in the charge trapping layer in MANOS

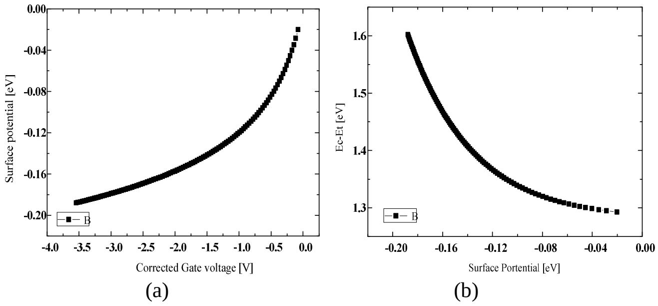

Fig.4. (a) Gate voltage (V_{GS}) versus surface potential (ϕ_s), (b) surface potential versus trap level (E_C-E_t) under accumulation mode of bias.

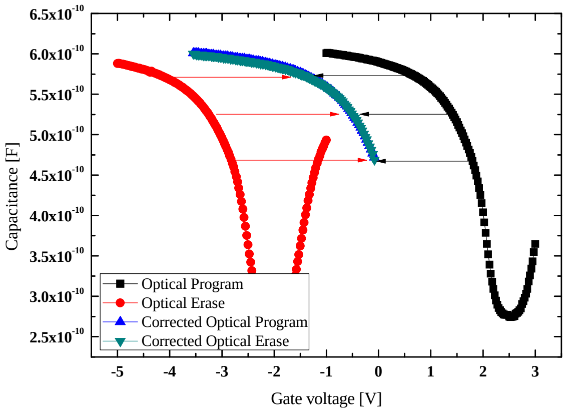

Fig.5. Shifted by ΔV_{FB} (due to charges in the nitride layer) of C-V curves under optical Illumination in the accumulation region.

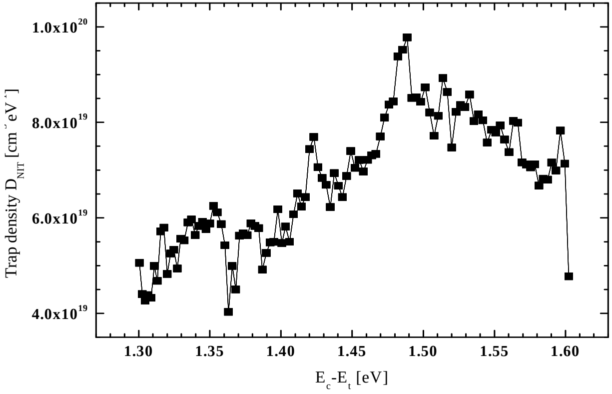

Fig.6. Extracted trap distribution D_{NIT} in MANOS by the new iteration method combining the optical C-V measurement data.