Extraction of Si_3N_4 Trap Density Distribution in SONOS Flash Memories based on Optical C-V Method

J. U. Lee, S. W. Kim, K. S. Roh, G. C. Kang, S. H. Seo, K. Y. Kim, C. H. Lee, S. Y. Lee, K. J. Song, C. M. Choi, S. R. Park
*B.-G. Park, *H. Shin, *J. D. Lee, K. S. Min, D. J. Kim, D. H. Kim, and D. M. Kim

School of Electrical Engineering, Kookmin University, Seoul 136-702
* School of Electrical Engineering, Seoul National University, Seoul, 151-742

Abstract

For extracting the nitride trap distribution in SONOS capacitors, a new optical C-V method is proposed. Applying an optical source with λ= 532nm (E_{ph}= 2.33eV) to ONO layer with 50Å/60Å/23Å, the nitride trap density is successfully extracted in the range of 1.16×10^{18} to 1.67×10^{19} $cm^{-3}eV^{-1}$ for the energy level from E_C-E_t=1.36 to 1.64 eV. This method can be used for extracting the deep trap density as well as shallow trap density over the wide bandgap nitride layer in SONOS capacitors by controlling the wavelength of the optical source. This method is relatively simple and fast method because it doesn't require time-dependent measurement or high temperature characterization.

I. Introduction

For improved SONOS flash memories as the next generation nonvolatile memories replacing the conventional floating gate flash memories, technologies for a low programming voltage, high endurance, high scalability, and the compatibility with the conventional CMOS process have been pursued. As the tunnel oxide is scaled down for a low voltage programming, the mechanism of charge loss or long-term retention in SONOS flash memories is recognized as a key concern deciding their industrial usefulness. The charge loss in SONOS systems is dominantly influenced by the distribution of charge trap density in the nitride composing ONO layers. In as much as the shallow trap over the energy bandgap is known to result in reliability challenges such as the degradation of long-term retention, high temperature charge loss, and the threshold voltage (V_T) instability, it is necessary to exactly extract the distribution of charge trap density in the nitride.

Yang and White proposed a high temperature charge decay model, and extracted the nitride trap density in energy level ($D_{nitride}$) from the time- and temperature-dependence of V_T [1]. Recently, Kim *et al.* proposed an advanced charge decay model and extracted the nitride trap density in two SONOS capacitors with different tunnel oxide thickness each other, pointing out that the rate of charge decay is a function of process parameters as well as both time and temperature [2]. Actually, a few weak points appear in previous works on the extraction of the $D_{nitride}$ because they rely on the thermal excitation of trapped charges in nitride at high temperature. One is that the extraction of a shallow trap in energy level induced erroneous results, because the charge loss by the trap-to-band tunneling becomes comparable to that by the thermal excitation as the temperature decreases [1]. They also require a characterization at high temperature for deep trap extraction. It means that previously proposed models is not adequate for the case experiencing a large number of program/erase cycles, because the bake effect at high temperature influences the quality of the interface and oxide traps in the tunnel oxide, eventually the long-term retention. The extraction itself is substantially involved and time-consuming procedure because both the time- and temperature-dependent measurements are required. Furthermore, usage of a flat band voltage (V_{FB}) as function of time in a logarithm scale or temperature in an exponential manner may cause a large error with a small variation in the measurement setup.

On the other hand, an electrical stress-free method using optical excitation has been used to characterize the distribution of traps at Si-SiO_2 interface in conventional MOS systems [3-5].

In this work, an optical capacitance-voltage (C-V) method is proposed, as a new tool for extracting the nitride trap density distribution in energy level. The trapped charges in the nitride of SONOS capacitor in a program state are excited by photons supplied from a laser diode with a specific wavelength. Corresponding energy level of the extracted trap density is controlled by both the wavelength of an optical source and the range of the gate voltage (V_G) swept in a C-V measurement. Proposed method is generally applicable to the extraction of both a shallow trap density and deep trap density by controlling the wavelength of an optical source. Furthermore, it is relatively simple and fast method for extracting $D_{nitride}$, because both the high temperature and the time-dependent measurement are unnecessary.

II. Modeling and Experiment Results of Optical C-V Method

The C-V characteristics were measured using HP4284A *LCR* meter with a laser diode (wavelength λ= 532 nm, photon energy E_{ph}= 2.33 eV, optical power P_{opt}= 14 mW) for the optical source. The SONOS system under characterization has 50Å/60Å/23Å for the O/N/O layers, respectively. Under a flat band condition, trapped charges over the energy range E_C-1.28eV<E_t<E_C in the nitride are excited to the conduction band of tunnel oxide due to the energy band discontinuity (ΔE_C=1.05eV) between the nitride and tunnel oxide. When the gate voltage V_G is swept from V_{FB} to more negative value, band bending followed by F-N tunneling of electrons from the nitride layer to the conduction band of the tunnel oxide occurs. In this way, the amount of more deeply trapped charges (in ΔE= 1.28 eV+E_d, E_d is the function of V_G) can be extracted. Combining the surface potential (ϕ_S: band bending at the bottom tunnel oxide/nitride interface) as a function of V_G, therefore, the $D_{nitride}$ can be extracted from the difference ($\Delta C_{nitride}$) of the capacitance in the measured C-V curves between under optical illumination and under dark.

It should be also noted that the secondary effects, such as the oxide trap-assisted tunneling and the band-to-band electron hole pair (EHP) generation in Si-substrate followed by a back tunneling into the nitride, may appear because the E_{ph} is larger than the energy band-gap of Si ($E_{g,Si}$= 1.12 eV) in the optical C-V method.

Fig. 1 shows the equivalent capacitive circuit model for the optical C-V characterization. Equivalent total capacitances in the four experimental cases can be summarized as followings.

$$\frac{1}{C_{ER,dark}}=\frac{1}{C_{top,ox}}+\frac{1}{C_{nitride,ER}}+\frac{1}{C_{bottom,ox}}+\frac{1}{C_m+C_d+C_{it}} \quad (1)$$

$$\frac{1}{C_{ER,opt}}=\frac{1}{C_{top,ox}}+\frac{1}{C_{nitride,ER}}+\frac{1}{C_{bottom,ox}}+\frac{1}{C_m+C_d+C_{it}+C_{ot}} \quad (2)$$

$$\frac{1}{C_{PR,dark}}=\frac{1}{C_{top,ox}}+\frac{1}{C_{nitride,PR}}+\frac{1}{C_{bottom,ox}}+\frac{1}{C_m+C_d+C_{it}} \tag{3}$$

$$\frac{1}{C_{PR,opt}}=\frac{1}{C_{top,ox}}+\frac{1}{C_{nitride,PRopt}}+\frac{1}{C_{bottom,ox}}+\frac{1}{C_m+C_d+C_{it}+C_{ot}} \tag{4}$$

$$\Delta C_{nitride}=C_{nitride,PRopt}-C_{nitride,PR} \tag{5}$$

Where $C_{ER,dark}$ and $C_{ER,opt}$ ($C_{PR,dark}$ and $C_{PR,opt}$) are measured capacitances of the erased (programmed) SONOS capacitor without and with the optical illumination, respectively. As a result of tuning ϕ_s by V_{FB} and normalizing in an equivalent energy level relative to E_C of the nitride in four experimental cases, we can eliminate those secondary effects mentioned above, which is the key idea of the proposed method. In other words, the $C_{nitride}$ is extracted by the subtraction of Eq. (1) from Eq. (3), and the subtraction of Eq. (2) from Eq. (4), respectively. The surface potential ϕ_s should be tuned for obtaining $\Delta C_{nitride}$ in Eq. (5) because V_T in the the program is different from that in the erase state.

$$\Delta C_{nitride}=\frac{\partial Q_{nitride}}{\partial V_G}=\left(\frac{\partial Q_{nitride}}{\partial \phi_s}\right)\left(\frac{\partial \phi_s}{\partial V_G}\right)=C_{nitride}\cdot\left(\frac{\partial \phi_s}{\partial V_G}\right) \tag{6}$$

$$D_{nitride}=\frac{\Delta C_{nitride}}{q}\frac{\partial V_G}{\partial \phi_s} \tag{7}$$

$\Delta C_{nitride}$ can be related to $D_{nitride}$ as shown in Eq. (6) and (7). In order to calculate the exact ϕ_s of bottom oxide as a function of V_G, the charge amount is calculated by the Poisson equation, and the used ϕ_s is verified by Silvaco TCAD simulation as shown in Fig. 3. Fig. 4 shows extracted $D_{nitride}$ from proposed optical C-V method. Both the value range of 1.16×10^{18} to 1.67×10^{19} ($cm^{-3}eV^{-1}$) and overall shape agree well with previous works [1, 2]. Moreover, the energy distribution from E_C-E_t=1.36 eV to 1.64 eV covers a relatively deep range in comparison with previous works because the measurement at high temperature is unnecessary in this optical C-V method.

III. Conclusions

An optical C-V method is proposed as a new method for extracting the $D_{nitride}$ in SONOS systems. Secondary effects under characterization are efficiently eliminated by combining C-V data from four different measurement setups (program/erase and with/without optical illumination) and tuning ϕ_s. Using an optical source with λ= 532nm to ONO layer with 50Å/60Å/23Å, the nitride trap density was extracted to be $D_{nitride}$=1.16×10^{18} ~ 1.67×10^{19} $cm^{-3}eV^{-1}$ for E_C-E_t=1.36 to 1.64 eV. 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 free from the time-dependent or high temperature characterization.

Acknowledgement

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References

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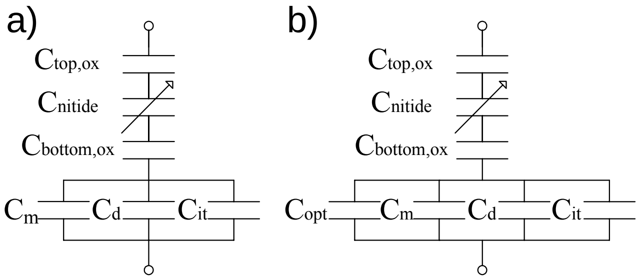

Fig. 1. Equivalent capacitive circuit model for SONOS capacitor in optical C-V method. (a) without and (b) with optical illumination, respectively. The $C_{nitride}$ has different value in each P/E state.

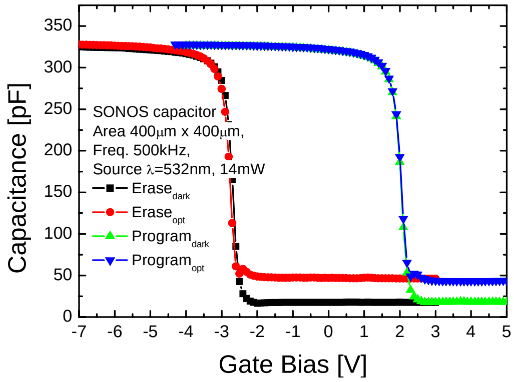

Fig. 2. Fully programmed and erased C-V curves of SONOS capacitor (ONO=50 Å/60 Å/23 Å) with and without optical illumination.

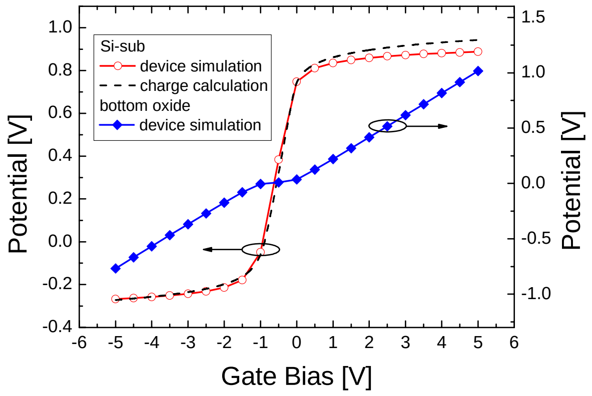

Fig. 3. The surface potential of bottom oxide for calculating the energy level of nitride trap density.

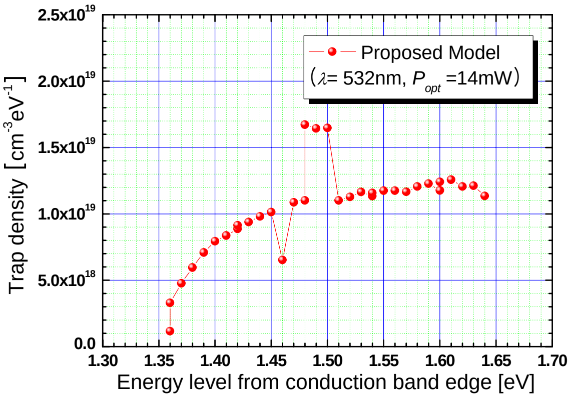

Fig. 4. Extracted nitride trap density in energy level using proposed model.