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# New Charge Pumping Method for Extraction of Nitride Trap Energy Distribution in SONOS Flash Memory

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## 1. Introduction

According to IRTS [1], for long time retention in SONOS (Silicon-Oxide-Nitride-Oxide-Silicon) devices, the thick tunnel oxide (>3nm) is imperative. But, previously reported methods on trap extraction in charge trapping layer of nitride [2-4] are complex and limited to devices with thin tunnel-oxide. Therefore, it is needed to develop new evaluation method, which is applicable to the device having the thick tunnel oxide (>3nm). In this study, we propose a new charge pumping method, which enables one to extract energy distribution of nitride traps.

## 2. Modeling for Charge Pumping Measurement

In this section, the proposed charge pumping model is presented, which can be used to extract the energy distribution of nitride traps in SONOS device having thick tunnel-oxide (>3nm).

Figure 1 shows the conduction mechanism in tunneling oxide and nitride in SONOS device. The conduction mechanism through the tunnel oxide is tunneling while nitride layer is controlled by Frenkel-Poole transport [5]. Therefore, the trapped electrons at a large positive bias will be emitted during a large negative bias with following emission rate

$$e = e_{FP} T_t \tag{1}$$

where, $e_{FP}$ is the Frenkel-Poole emission rate in the nitride, and $T_t$ is the tunneling probability. The Frenkel-Poole emission rate is defined as

$$e_{FP} = \nu \exp\left( -\frac{q(\phi_t - \sqrt{qE_{\sin}/\pi\varepsilon_{\sin}}}{kT} \right) \tag{2}$$

where $\nu$ is the escape factor, $q$ is the electron charge, $\phi_t$ is the trap energy depth, $E_{\sin}$ is the electric field across the nitride layer, $\varepsilon_{\sin}$ is the permittivity in nitride, $k$ is the Boltzmann constant, and $T$ is the absolute temperature. And the tunneling probability is given by the Wentzel-Kramers-Brillouin (WKB) approximation [5] with a triangular barrier as eq. (3)

$$T_t \approx \exp\left( -\frac{4\sqrt{2m^*}}{3q\hbar E_{ox}} \phi_b^{3/2} \right) \tag{3}$$

where $m^*$ is the effective mass in the tunnel oxide, $\hbar$ is the reduced Planck constant, $E_{ox}$ is the electric field across the tunnel oxide, and $\phi_b$ is the barrier height. During negative bias, hole tunneling through the tunnel oxide can be neglected due to its higher barrier height compared to electron, which give the significantly lower tunneling probability for the holes compared to electrons. Figure 2 shows that the detectable energy range extracted using eq. (1) agrees fairly well with previously reported values [5-7]. The measured $I_{cp}$ can be converted to charge recombination per cycle ($Q_{cp}$) defined by $I_{cp}/f$, $Q_{cp}$ can be expressed as

$$Q_{cp} = qA_G \int_{\phi_t} \int_{X_n} \rho_{\sin}(x,\phi)\,dx\,d\phi \tag{4}$$

where $A_G$ is the gate area, $X_n$ is the thickness of the nitride layer, $\rho_{\sin}$ is nitride trap density (eV$^{-1}$cm$^{-3}$). By differentiating with respect to $ln(f)$ and assuming spatially uniform nitride trap density throughout the nitride film, then eq. (4) can be written as

$$\rho_{\sin}(\phi_t) \approx \frac{1}{qkTX_n A_G} \frac{\partial Q_{cp}}{\partial \ln(f)} \tag{5}$$

Therefore, we can extract the energy distribution of nitride traps by using eq. (1) and (5).

## 3. Results and discussion

Figure 3 shows the well-behaved C-V curve with 13.8nm EOT. The device structure for experiments is summarized at inset of Figure 3. The tunnel-oxide thickness of our device is 4 nm. Figure 4 shows the measurement system setup of the charge pumping method. Figure 5 shows $Q_{cp}$ as function of frequency at each pulse amplitude condition. For confirmation of variation of charge pumping measurement technique in our experiment, we measured three same devices. In our experiment, we had setup pulse swing with +12 V and -12 V due to sufficient carrier emission and low gate leakage. At this condition, electric field across the tunnel oxide and nitride layer is 8.7 MV/cm and 4.5 MV/cm, respectively. This high electric field is enough for tunneling and Frenkel Poole emission mechanism at the tunnel oxide and nitride layer [5]. For retention measurement, hot chuck system is used to increase the wafer temperature. During retention experiment, the temperature of hot chuck was maintained as 150 $^{o}$C.

By using eq. (1) and (5), we extracted the energy distribution of nitride traps as shown in Figure 6. Figure 6 is comparatively plotted with data extracted using retention model [2]. The detection range of trap energy depth in our experiment conditions is 1.06 ~ 1.24 eV. The extracted trap density distribution in energy levels of the nitride layer of prepared sample shows the peak trap density of $1.21 \times 10^{20}$ $eV^{-1}cm^{-3}$ at 1.17 eV while the peak trap density extracted using retention model is $6.24 \times 10^{19}$ $eV^{-1}cm^{-3}$ at 1.32 eV. The retention model uses charge decay of trapped charge caused by electron tunneling through the thin tunnel oxide followed by thermal excitation of trapped charges during retention mode at high temperature. In case of thick tunnel oxide, however, the tunneling probability is significantly decreased. As a result, the trap energy depth is exhibited with deeper energy depth than its original energy depth. In other hand, because our proposed model uses high electric field, the tunneling probability of emitted electrons in nitride layer is significantly increased. Therefore, the trap energy depth extracted using our proposed model will be relatively shallow.

## 4. Conclusions

A new charge pumping method was proposed to extract the energy distribution of nitride traps in SONOS flash memory. Based on the Frenkel-Poole emission model and the tunneling model, we established an advanced model for charge pumping measurement of SONOS device applicable to the thick tunnel oxide. The proposed model is more precise by considering the tunnel oxide thickness, otherwise trap density could be underestimated and the trap energy level calculated to be deeper.

## 5. References

[1] ITRS 2005 version; [2] Yang Y, *et al.*, Solid State Electron 2000, vol. 44, pp. 949-58; [3] Gu S.H., *et al.*, Appl Phys Lett 2006, vol. 89, pp. 163514-1-3; [4] Liao Y.Y., *et al.*, IEEE Electron Dev Lett 2007, vol. 28, pp. 828-30; [5] Sze SM. Physics of Semiconductor Devices. Hoboken, NJ: Willey 1981.

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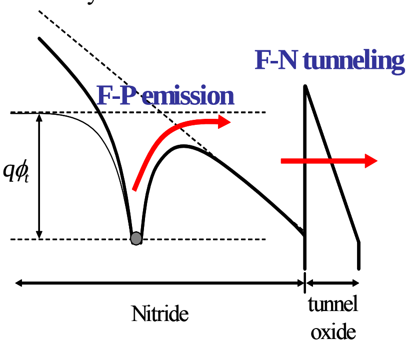


**Fig. 1.** A band diagram with conduction mechanisms (FP emission in nitride and FN tunneling in tunnel-oxide) in SONOS device under a large negative bias.

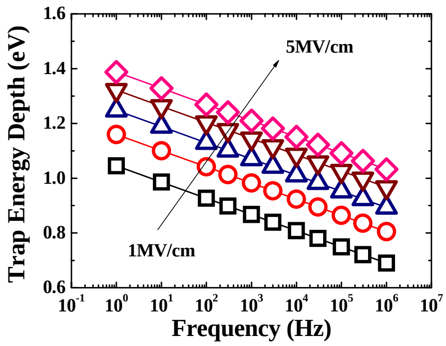


**Fig. 2.** Detectable trap energy level (0.6 ~ 1.4eV) as a function of frequency at each electric field across the nitride layer. The energy level extracted using our proposed model agrees fairly well with previously reported values.

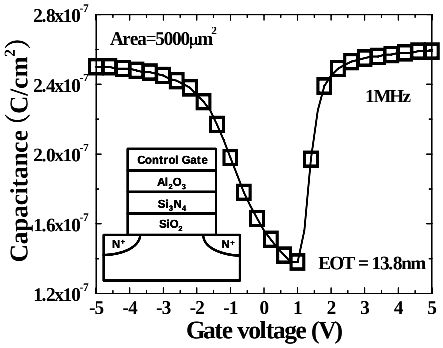


**Fig. 3.** Well-behaved C-V curve. Gate area of the device for experiment is 5000 $\mu m^2$, and EOT of our device is 13.8nm. The inset of graph shows device structure with 4nm tunnel-oxide.

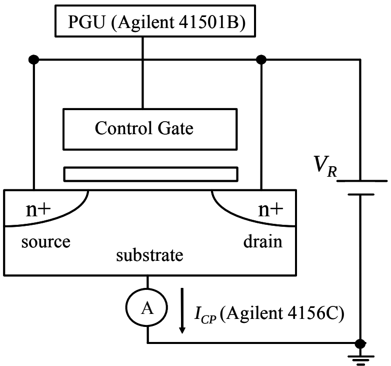


**Fig. 4.** Measurement configuration for charge pumping method. The control gate of SONOS device is connected to a pulse generator, reverse bias ($V_R$) is applied to source and drain, and corresponding $I_{cp}$ is measured at substrate.

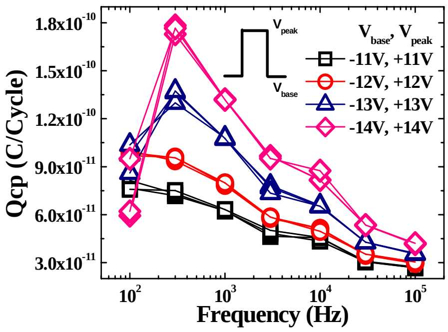


**Fig. 5.** Charge recombination as a function of frequency. The measured $I_{CP}$ during charge pumping measurement is the recombination current, which is originated from tunneling electrons followed by FP emission in nitride recombined with substrate holes.

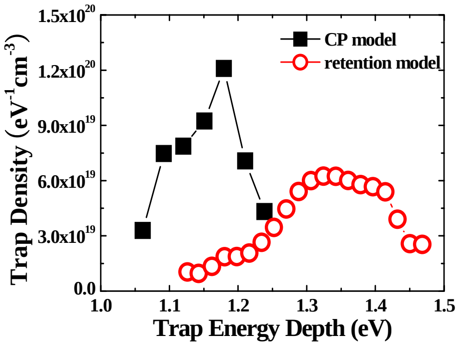


**Fig. 6.** The energy distribution of nitride traps plotted with data extracted using retention model. The relative shallow trap energy extracted using our cp model is due to different tunneling probability through the tunnel oxide.