Lateral Profiling of Interface States in SONOS Flash Memories Using the Optical Charge Pumping Method

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Abstract

The optical charge pumping method (OCPM) for extracting the spatial distribution of the interface state density (N_{it}) is proposed. By combining the concept of local threshold voltage in CPM and the drain current generated by the trapped electrons excited from the interface states to the conduction band by incident photons, the N_{it} is successfully extracted in the SONOS-type flash memory cell transistor undergoing program/erase(P/E) cycles. Extracted lateral profile explains the trend of increase of N_{it} with P/E cycling very well, with respect to corresponding P/E conditions.

I. Introduction

SONOS-type flash memory has received much attention as a promising next generation EEPROM substituting conventional floating gate-type flash memories. It has many advantages of simpler process, smaller bit size, lower voltage operation, suppressed drain-induced turn-on. Concerning the reliability, degradation of both program/erase (P/E) efficiency and long-term retention caused by a large number of P/E cycles is a challenging issue to improve. It is well known that the stress-induced leakage current (SILC) followed by the degraded retention characteristic is induced by increased interface traps and oxide traps. Compared with floating gate-type flash memory, the spatial distribution of traps becomes more and more important in SONOS-type flash memory because of the spatially discrete nature in the nitride layer. Recently, moreover, a multi-bit operation per cell based on localized charge trapping has been extensively investigated using P/E scheme by the channel hot electron injection (CHEI) and the band-to-band tunneling-assisted hot hole injection (HHI) [1, 2]. It means that the injection path of electrons and/or holes during P/E operation is laterally localized. This results in a complex lateral profile of both interface traps and oxide traps increasing with P/E cycles. Therefore, an accurate and simple method extracting the lateral profile of interface traps and oxide traps is strongly required for the development of robust commercial flash memory products.

On the other hand, the charge pumping method (CPM) has been a conventional method to quantitatively extract the energy and spatial distribution of interface traps and oxide traps [3], and has been extensively used to investigate the hot carrier degradation induced by localized trap generation [4]. However, as the spatial variation of the channel dopants density becomes higher, CPM requires larger amplitude for the input signal pulse. This may cause an unnecessary additional electrical stress during characterization. Furthermore, more complicated is the spatial distribution of the channel doping concentration, more erroneous the result of CPM becomes [5]. In addition, the monitoring of the charge pumping current through the substrate contact is strictly limited in the SONOS-type flash memory implemented on SOI structures [6].

We have already proposed the optical method for extracting both the spatial distribution (N_{it}) and the energy distribution (D_{it}) of the interface trap density of conventional MOSFETs [7, 8].

In this work, an optical CPM for extracting N_{it} is proposed and applied to the SONOS-type flash memory. By combining the concept of local threshold voltage ($V_{TH}(x)$) in CPM and the drain current (I_D) induced by the trapped electrons excited from the interface states to the conduction band by the incident photon having the sub-bandgap energy, the N_{it} is successfully extracted in the SONOS-type flash memory cell transistor undergoing P/E cycles.

II. Optical Charge Pumping Method

(A) $I_{D.it}$: Interface trap-assisted current

Fig. 1 shows energy-band diagram of SONOS under optical illumination. The $I_{D.photo}$ and $I_{D.dark}$ are I_D's with and without an optical illumination, respectively. Then, the interface trap-assisted current ($I_{D.it}$) is defined as

$$I_{D.it} = I_{D.photo} - I_{D.dark} \quad (1)$$

As increasing the gate voltage (V_G) from the flat band voltage (V_{FB}) to the threshold voltage (V_{TH}), the number of traps under Fermi-level is increased. When sub-bandgap photons with a wavelength λ=1305nm (E_{ph}=0.95eV<$E_{g,Si}$=1.11eV) are incident to the measured device, the trapped electrons in the interface state below the Fermi-level are excited from interface states to the conduction band by the photons, and eventually contribute to $I_{D.it}$. This electrical stress-free *optical CPM* can substitute the conventional CPM. Proposed optical CPM is very simple and fast method in that all to have to do is to measure only the I_D-V_G characteristic with and without a sub-bandgap optical excitation. In addition, the proposed method is applicable to various emerging SOI-based EEPROMs in that the response of the interface state is monitored through the drain terminal.

(B) Local threshold voltage $V_{TH}(x)$

Proposed OPCM method is built with the idea introduced in [3]. Fig. 2 shows the local threshold voltage $V_{TH}(x)$ of n-MOSFETs. At a specific V_G, the channel region is classified into two regions; the electron captured region and not-electron captured region. As V_G increases from V_{FB} to over-threshold voltage, the electron captured region widens and captured electrons at traps are increased resulting increased $I_{D.it}$. When V_G is larger than $V_{TH.max}$, it is expected that the $I_{D.it}$ is saturated because all trapped charges are emitted. It implies that we can make one-to-one mapping between the $I_{D.it}(V_G)$ and the lateral channel location x (same as electron captured region) as described in Eq. (1). In this way, the characteristic of $I_{D.it}$ versus V_G is converted into that of x versus V_G (same as local V_{TH}).

$$x = \frac{I_{D.it}(V_G)}{I_{D.it,\max}} \times L_{ch} \quad (2)$$

Now, we make a few assumptions. First, the virgin N_{it} is uniform over the whole channel region. Second, $I_{D.it}$ has a linear dependence on the channel length L_{ch}. From the difference of $V_{TH}(x)$ between before and after stress, the increase of N_{it}, the $\Delta N_{it}(x)$ is extracted by

$$\Delta V_{TH} = \frac{q \cdot \Delta N_{it}}{C_{ox}} \quad \Rightarrow \quad \Delta N_{it} = \frac{C_{ox} \cdot \Delta V_{TH}}{q} \quad (3)$$

III. Result and Discussion

The optoelectronic current-voltage characteristic of n-channel SONOS flash memory cell transistor (W×L=10μm×0.24μm, O/N/O layers:40/40/40Å) was measured with an optical source (E_{ph}=0.95eV, ILX Lightwave Co., Model 7200), a cascade probe station, and an HP4156C precision semiconductor parameter analyzer. In P/E conditions, Fowler-Nordheim (F-N) tunneling (V_G=10V, program time T_P=1 ms) and the band-to-band assisted hot hole injection (HHI) (V_S/V_D=7/3 V, erase time T_E=2 ms) are used, respectively. In the read operation, the V_G is swept from –2V to 3V with a fixed V_D=0.1V. Not mentioned electrodes were grounded.

Fig. 3 shows both the I_D-V_G curves with and without an optical illumination, and the $I_{D.it}$-V_G curve as a function of P/E cycles (after 50/500/5000 cycles). Of course, the $I_{D.it}$-V_G curve is tuned by the shift of V_{FB} with P/E cycling. As mentioned in II-(B), when V_G is larger than $V_{TH.max}$, $I_{D.it}$ is expected to be saturated because all trapped charges are emitted. However, the measured $I_{D.it}$ is decreasing rather than saturated. This decrease of $I_{D.it}$ is due to the increase of the thermionic emission of charges trapped in the interface states. As V_G increases to be over V_{TH}, the electrons trapped in the interface state in energy level slightly higher than the edge of the conduction band (E_C) should be emitted to the conduction band, followed by the increase of $I_{D.dark}$. Therefore, $I_{D.dark}$ starts to increase from the specific V_G value larger than the V_{TH}. Eventually, $I_{D.it}$ decreases from that point. Nevertheless, it is still valid that the peak value of $I_{D.it}$ is considered to be the maximum value of $I_{D.it}$ where all interface states are excited and contribute to the current because V_G point where the thermionic emission dominantly appears is larger than V_{TH}.

Fig. 4 shows the local V_{TH} obtained from both Fig. 3 and Eq. (2). The difference of the local $V_{TH}(x)$ from the virgin $V_{TH}(x)$ can be converted into locally increased $\Delta N_{it}(x)$ as in Eq. (3). Fig. 5 shows the finally extracted spatial distribution of $\Delta N_{it}(x)$ after P/E cycles which is normalized to the erase state after 50 cycles. Due to the F-N program/HHI erase(source & drain sides), $N_{it}(x)$ increases all over the channel region, and the rate of increase is larger in the source/drain junction edge than in the center of the channel.

IV. Summary

The optical CPM for extracting N_{it} was proposed and applied to the SONOS-type flash memory. By combining the concept of local threshold voltage ($V_{TH}(x)$) in CPM and I_D generated by the trapped electrons excited from interface states to the conduction band by incident sub-bandgap photons, lateral distribution of traps N_{it} was successfully extracted in the SONOS-type flash memory cell transistor undergoing P/E cycles. Extracted lateral profile explains the trend of increase of N_{it} with P/E cycling very well with respect to corresponding P/E conditions. Proposed optical CPM have advantageous over the conventional CPM as a simple, fast, and electrical stress-free method. Furthermore, it is applicable to various emerging SOI-based EEPROMs without electrical stress during characterization

Acknowledgements

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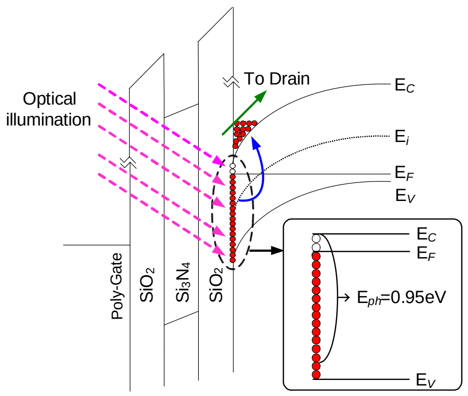

Fig. 1. Energy band diagram of the SONOS-type flash memory cell transistor under an optical illumination.

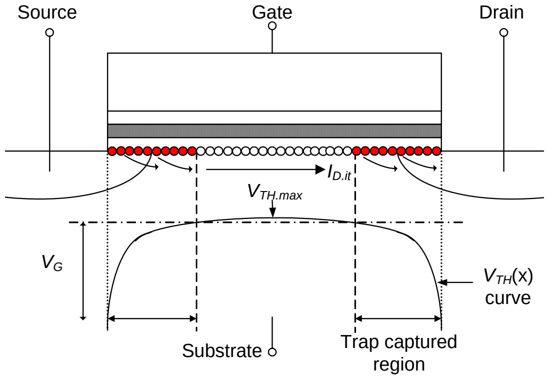

Fig. 2. The schematic diagram of the electrical CPM using the concept of a local threshold voltage $V_{TH}(x)$.

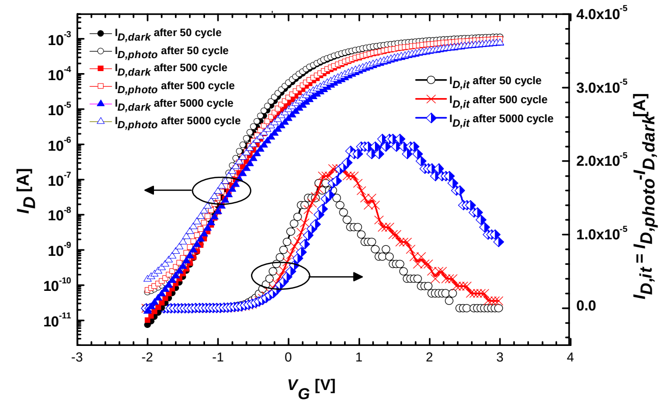

Fig. 3. The V_G -dependence of both I_D and $I_{D.it}$ after P/E cycling.

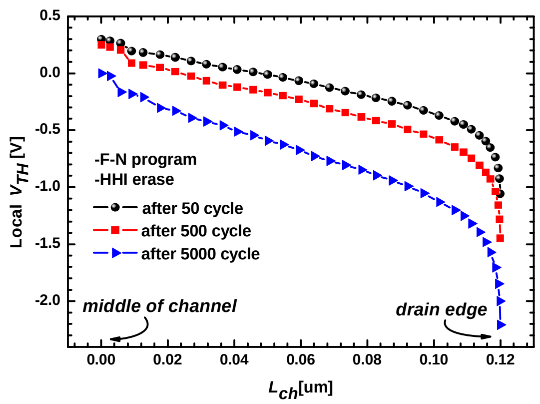

Fig. 4. The spatial distribution of a local threshold voltage $V_{TH}(x)$ after P/E cycling.

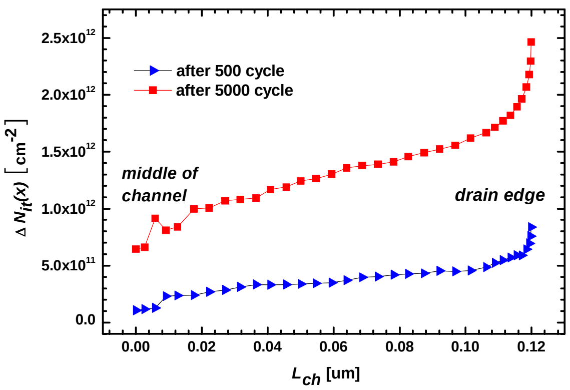

Fig. 5. The spatial distribution of the N_{it} increased from P/E 50 cycle after P/E cycling (ΔN_{it}). It is extracted by the proposed optical CPM.