# Dynamics of the Charge Centroid in MONOS Memory Cells during Avalanche Injection and FN Injection Based on Incremental-Step-Pulse-Programming

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# Introduction

Although MONOS type memory cells are intensively studied thanks to their applicability to 3-dimensionally integrated structure such as BiCS flash memory [1], the future memory generations are facing performance and reliability issues. To solve these issues, it is important to clarify the transient carrier capture dynamics and evaluate key parameters such as the charge centroid [2].

Further multibit requirement imposes wider programming window on memory cells, and the window enhancement has been studied in terms of trap density and distribution by means of avalanche injection method [3]. However, the applied electric fields across the memory cell during avalanche injection and FN injection (normally used in NAND flash memory) are substantially different. So we have to know whether the extracted traps in avalanche injection are available on NAND application at a high field. In this paper we clarify the dynamics and electric field dependence of the charge centroid for the first time.

As a prerequisite to extract the charge centroid, capture efficiency of 100% should be verified [2]. For this purpose, we make use of an indicator derived from the incremental step pulse programming (ISPP), and found that the extracted charge centroid moves toward the charge layer / block layer interface during avalanche injection. In addition, the location of available traps shifts as a function of electric field, continuously from avalanche injection to FN injection.

# Evaluation of Capture Efficiency from the Incremental-Step-Pulse-Programming (ISPP) Slope

MONOS memory cell is equivalently expressed as a series capacitance circuit having a floating node corresponding to the charge centroid (Fig. 1). If the gate voltage varies as  $V_g=V_{g,0}+\alpha(t-t_0)$  (where  $V_{g,0}$  is the initial voltage at the time  $t_0$ , and  $\alpha$  (= $dV_g/dt$ ) is the ramp rate of the gate voltage), the differential equation for the tunnel oxide electric field  $E_{ox}$  is given by:

$$dE_{\alpha x}/dt = (\alpha + \eta J/C_2)/EOT$$
(1)

where *EOT* is the total equivalent oxide thickness of the MONOS stack; *J* is the tunneling current as a function of  $E_{ox}$ ;  $C_2$  is the capacitance between the gate and the charge centroid; and  $\eta$  is capture efficiency. As the gate voltage increases, the steady state (a):  $\alpha = -\eta J/C_2(=dV_{fb}/dt)$  will be satisfied. The condition (a) keeps the tunnel electric field  $E_{ox}$  constant, and ISPP slope remains  $dV_{fb}/dV_g=1$  until the traps are saturated. The capture efficiency is estimated from the ISPP slope, because  $\langle slope \rangle = dV_{fb}/dV_g = \langle \eta \rangle (dV_{fb}/dV_g)_{100\%} = \langle \eta \rangle$ . Then, when we find the ISPP slope is unity, it indicates 100% capture efficiency for that period. Note that at the initial stage of ISPP before the condition (a) is fulfilled (ISPP slope<1), we can believe  $\eta=1$  because the electric field is so weak and traps are all empty.

We may extend this methodology to step-up pulses with an approximation:  $\alpha = \Delta V_{g.step}/T_{pulse}$  where  $\Delta V_{g.step}$  is a voltage increment in each time step  $T_{pulse}$ . It is also applicable to avalanche injection where sinusoidal high-frequency pulse stream is contained in each pulse step (Fig. 2) [4].

#### Experimental

The MONOS devices used in this paper are capacitors depicted in Fig. 3. The gate stack consists of 5 nm tunnel oxide, 7 nm SiN charge trap layer, and 12 nm Al<sub>2</sub>O<sub>3</sub> block

layer. TaN is used as a gate metal.

High frequency sinusoidal pulse stream consisting of positive voltage generated by an arbitrary waveform generator (AWG) is applied to the gate, while monitoring the charge injection through the substrate.

#### **Confirmation of Avalanche Injection based on ISPP**

As the gate voltage consists of high-frequency positive pulse streams where a depletion layer is formed, the injection current can be evaluated as a function of maximum tunnel electric field ( $E_{ox.max}$ ). As the injection current shows linear frequency dependence (Fig. 4), we confirm that *avalanche current* ( $J_{ava}$ ) is injected during avalanche-ISPP. We also checked the ISPP slope as in Fig. 5 and see that neither  $V_{jb}$ -shift nor ISPP slope depends on the frequency used in avalanche injection. Instead, it is confirmed that the charges injected by avalanche-breakdown depend only on the pulse count  $N_{ava}$  (= $f_{ava}T_{ava}$ ) during each pulse stream.

# **Charge-Centroid Monitoring during Avalanche-ISPP**

In Fig. 6, we can trace the capture dynamics as a function of injection charge in each step ( $\Delta Q_{inj}$ ). First, flatband voltage shift in each step ( $\Delta V_{fb}$ ) increases to the peak of  $\Delta V_{g,step}$ =0.9V, following the guide indicating the bottom of the charge layer ( $\eta$ =1 can be assumed during the initial capture although ISPP slope<1). After that,  $\Delta V_{fb}$  stays constant (ISPP slope=1 and  $\eta$ =1, condition (a)) until the charge centroid reaches the guide corresponding to the top of the charge layer. After passing the "top" guide line,  $\Delta V_{fb}$ decreases towards zero. It means that the carrier capture saturates after the  $\Delta V_{fb}$  peak. Thus, Fig. 6 indicates that the charge centroid shifts from the bottom interface to the top interface of the charge layer while the ISPP slope keeps constant (~1). Fig. 7 clearly shows the charge-centroid trajectory as a function of flatband voltage shift.

#### **Electric Field Dependence of Charge Centroid**

We evaluated the charge centroid as a function of electric field. The carrier capture starts near the bottom of the charge layer when the avalanche-ISPP is performed at a low electric field ( $E_{ox.max}$ ~4MV/cm). Then, trap filling develops toward the charge layer / block layer interface even at a constant tunnel-oxide electric field during ISPP.

The constant voltage programming (CVP) measurement [2] was also performed to extract the *initial position* of the charge centroid for each programming voltage. The electric field dependence of the charge centroid is shown in both the FN- and avalanche-CVP, implying that available trap sites becomes limited to those near the charge layer / block layer interface as the electric field increases.

#### Conclusions

In this work, we have extracted charge-centroid dynamics during avalanche injection, on the basis of ISPP analysis. We have confirmed the charge-centroid movement by assuring 100% carrier capture from the ISPP formalism. From this measurement, carriers are trapped near the bottom of the charge layer at first and then reach the top interface of the charge layer. In contrast, when higher electric field is used during programming (e.g. FN injection) carriers are captured near the top interface of the charge layer due to the high field acceleration.

Finally, it is revealed that the trap sites accessed by carrier injection through the tunnel oxide increases for low electric

field. So, it is prospected that the enlargement of program window is possible with appropriate tunnel-oxide engineering for low-field programming.

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Fig.1 MONOS memory is described as a series capacitance having a floating node corresponding to the charge centroid.



Fig.4 Injection current  $(J_{inj})$  as a function of  $E_{ox,max}$ . It depends linearly on the frequency of the sinusoidal pulse stream, so positive high-frequency pulse stream is effective to generate avalanche current.



Fig.7 Charge centroid extracted during ISPP slope  $\sim 1$  as a function of flatband voltage  $(V_{fb})$ . Traps are filled from the bulk region of the charge layer toward the charge layer / block layer interface.

Fig.2 ISPP is based on linear voltage increment. It is applicable to avalanche injection if the current is a function of maximum tunnel electric field  $E_{axmax}$ .



Fig.5 Flatband voltage shift as a function of step-up gate voltage. ISPP slope  $\sim 1$  is achieved showing capture efficiency is 100% during that period.



Fig.8 Electric field dependence of charge centroid. The data from constant voltage programming (CVP) using avalanche injection and FN injection are also attached. Carrier capture occurs nearer to the charge layer / block layer interface when a higher electric field is applied.

#### References

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Fig.3 Experimental setup in avalanche -ISPP. High frequency sinusoidal waveform is used to inject the avalanche current for the MONOS capacitor without diffusion layer.



Fig.6 Flatband voltage shift in each step  $(\Delta V_{fb})$  as a function of injected charge  $(\Delta Q_{inj})$ . If the charge centroid is constant, it has linear dependence  $(\Delta V_{fb} \quad \Delta Q_{inj})$ . In contrast, charge centroid shifts during ISPP slope ~1 in avalanche-ISPP.



Fig.9 A picture for carrier capture derived from avalanche and FN injection. With low electric field traps are filled from bulk region of the charge layer toward the block layer interface. Accessible trap sites through tunnel injection depend on  $E_{ax}$ .