# Observing of charges stored in metal-oxide-nitride-oxide semiconductor flash memory by using higher order nonlinear dielectric microscopy

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Recently, Scanning Nonlinear Dielectric Microscopy (SNDM) has attracted much attention for use in semiconductor device analysis owing to its high sensitivity for the capacitance variation. Previously, we revealed the detailed distribution of accumulated charges in the $SiO_2$-SiN-$SiO_2$ (ONO) layer of a cell transistor in a metal-ONO-semiconductor (MONOS) memory by SNDM. [1- 3]

In the SNDM measurement, alternating electric field $Vcos\omega_p t$ ($V$ - the applied voltage, and $\omega_p$ - angular frequency) is biased between the electrode and sample. The capacitance variation of the surface region of the sample ($\Delta C_s (t) = C_s (t) - C_{s0}$) was monitored.

$$C_s(t) = C_{s0} + \left(\frac{dC_s}{dV}\right)V + \frac{1}{2}\left(\frac{d^2C_s}{dV^2}\right)V^2 + higher\ order \qquad (1).$$

$$\frac{\Delta C_s(t)}{C_{s0}} = \left(\frac{\varepsilon_{333}}{\varepsilon_{33}}\right)E\cos\omega_p t + \frac{1}{4}\left(\frac{\varepsilon_{3333}}{\varepsilon_{33}}\right)E^2\cos 2\omega_p t + higher\ order \qquad (2).$$

In this equation, $\varepsilon_{33}$ - linear permittivity, $\varepsilon_{333}$ - lowest-order nonlinear permittivity and $\varepsilon_{3333}$ – 1st order higher nonlinear permittivity. $E$ is the induced electric field by $V$. Here, $C_{s0}$ (the static capacitance) is proportional to the $\varepsilon_{33}$. The $\varepsilon_{333}/\varepsilon_{33}$ and $\varepsilon_{3333}/\varepsilon_{33}$ can be obtained by detecting the $cos\omega_p t$ (ω-component) and $cos2\omega_p t$ (2ω-component) of the SNDM signals, respectively. The nth-order nonlinear permittivity can be obtained from the nω–component. From the higher order signal, we can obtain higher resolution SNDM image. Higher-order signals from capacitance variations are quite weak and it is very difficult to detect these weak signals by any method besides SNDM.

In MONOS memory devices, as shown in Fig. 1, at the two points adjacent to the source and drain in the ONO layer under the gate electrodes; the charges can be stored separately. In downscaled MONOS memory devices, charges are confined in a further narrow area of the cell transistor. Therefore, a high-resolution evaluation method is necessary to detect such localized charges. In this study, we succeeded in visualizing the charge distribution in the ONO gate film to measure a higher-order nonlinear permittivity. In this study, we detect the capacitance ($C$) deviation underneath the ONO film of the n-type MONOS system. From equations (1) and (2), the higher-order differentials by V at V = 0 are $dC/dV \sim \varepsilon_{333}/\varepsilon_{33}$, $d^2C/dV^2 \sim \varepsilon_{3333}/\varepsilon_{33}$, and so on.

The sample was prepared by charge injection into the ONO film before the SNDM measurements. The Vth of the cell transistors before and after the electron injection were about 1 V and 5 V, respectively. To expose the ONO films for SNDM measurement, the upper layers of the word line were removed by mechanical grinding, which would prevent losing of injected charges.

Figure 2 shows a comparison between ω, 2ω, 3ω and 4ω components of the SNDM images of 0.23-μm–channel–length memory. Electrons were injected from one side of the channel and were stored in the gate ONO film. As can be seen from the ω image, a bright area appeared in the electrons stored region. In contrast, in the 2ω image, a high-contrast dark area is observed in the same region where electrons were stored. The contrast of this area changes to dark in the 3ω image, and changes to bright (but blurry) in the 4ω image. In the no-injected areas, bright contrast observed in the 1ω image. In the 2ω image, a high-contrast bright area is observed. The contrast of this area changes to dark (3ω and 4ω). These images can be interpreted as the capacitance variation ($d^nC/dV^n$) of the n-MONOS system. When there are electrons in the ONO layer, quasi-static $C$-$V$ curve of the n-MONOS transistor is shifted in the negative $V$ direction relative to that for an empty region. [3] If we fix the $C$-$V$ curves and define the (+) direction of the applied electric field as from the

Si substrate, the V = 0 axis shifts in the (+) direction with electron accumulation. Figure 3 shows schematic *C-V* and $dC^n/dV^n$ (n = 1- 4) curves and V = 0 axes (“not injected” and “electron”). In this figure, the *V*-axis of the *C-V* curve is drawn in the opposite direction to the usual convention.

In the channel region, p-type ions are shallowly implanted, keeping $V_{th}$ positive (n-MONOS).

1) When electrons accumulate in the ONO layer, the shift in the V = 0 axis is very large (Vth~5V). Then $dC/dV$ at $V = 0$ is positive, making the contrast bright. On the other hand, $d^2C/dV^2$ is negative because the *C-V* curve (at $V = 0$) is convex up. Therefore, the SNDM contrast of the 2ω component is dark. The sign of $d^3C/dV^3$ is negative and that of $d^4C/dV^4$ is positive (see Fig.3), therefore the contrast of the 3ω component is dark and that of the 4ω component is bright.

2) When electrons are not stored in the ONO layer, $dC/dV > 0$ at $V = 0$. Then the SNDM contrast becomes bright. The sign of $d^2C/dV^2$ is also positive, which will make the contrast of the 2ω component bright. $d^3C/dV^3 <0$ and $d^4C/dV^4 < 0$ (see Fig.3), therefore the contrast of 3ω component is dark and that of the 4ω is also dark.

From this comparison, it can be said that there are three merits to use the higher order SNDM for visualizing the charges stored in ONO films: 1) the resolution becomes high; 2) possible to obtain the SNDM signal of electrons in high contrast, since the signal becomes inverted from the channel area (2ω); 3) possible to obtain the charge concentration distribution.

Through the present study on stored electrons in the MONOS flash memory, we found that SNDM is a powerful method for visualizing the charge distribution in dielectric thin films

*References*

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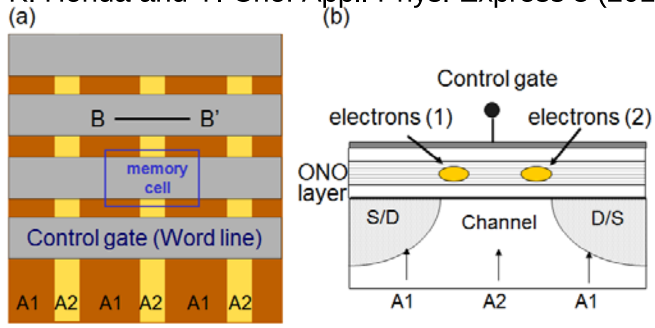
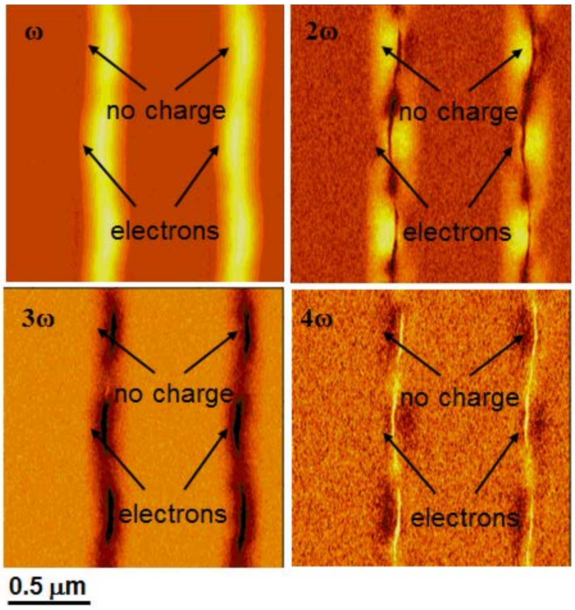


***Figure 1.*** *Schematic of an MONOS-type flash memory cell. (a) Plan view, (b) Cross section along B-B’. A1 is diffusion area (Bit line), A2 is a channel area*



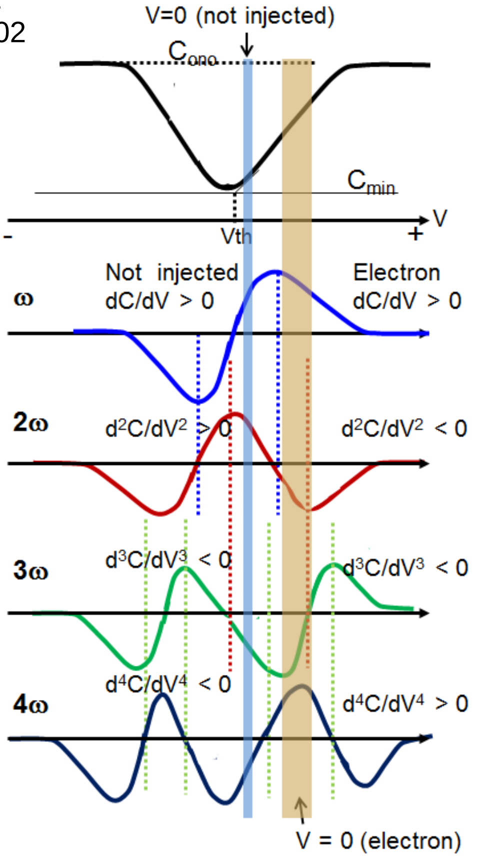


***Figure 3.*** *Interpretation of SNDM contrast from C-V curves of the ONO system. C-V and $d^nC/dV^n$ (n = 1- 4) curves. Signatures of $d^nC/dV^n$, at V = 0*

***Figure 2.*** *Comparison between higher orders (nω, n = 1- 4) SNDM images*