Laterally-Trapped-Charge Profiling Based on the Extraction of the Flat-Band Voltage by Using the Optical Substrate Current in Charge Trapping Flash Memory Cells

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A novel extraction method for the locally-trapped-charge profiling combined with a new local flat-band voltage ($V_{FB}$) extraction under optical excitation is proposed. Under optical illumination in metal-oxide-semiconductor field effect transistors (MOSFETs), the substrate current ($I_{sub,photo}$) is abruptly increased at $V_{FB}$ due to a sudden increase in the excess carrier diffusion current. In nitride read-only memory (NROM)-type charge trapping flash (CTF) memory cells, there are multi-step responses in optical substrate current ($I_{sub,photo}$)-gate voltage ($V_G$) curves because $V_{FB}$ is varied along the channel by the laterally non-uniform profile of electrons trapped in the nitride storage layer. We analyzed the mechanism of $I_{sub,photo}$ and verified it by using integrated systems engineering technology computer aided design (ISE TCAD) simulations. The height of the step is shown to be related to the programmed region and the width is shown to be related to the density of trapped charges. Using this novel method, we investigated laterally-trapped-charge profiling in CTF memory cells.

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I. INTRODUCTION

As one of the promising next generation electrically erasable programmable read-only memories (EEPROMs), nitride-based charge trapping flash (CTF) memories are under active study. Compared with floating gate-type flash memories, the spatial distribution of traps becomes more important in nitride read-only memory (NROM)-type CTF memories due to the spatially discrete nature of the nitride storage layer. Especially, multi-bit operation per cell based on the localized charge trapping has been extensively investigated using a program/erase (P/E) scheme with channel hot electron injection (CHEI) and band-to-band tunneling-assisted hot hole injection (HHI) [1, 2]. This means that the injection path of electrons and/or holes during P/E operation is laterally localized. Moreover, both the evolution of the lateral charge profile and a mismatch between programmed electrons and erased holes were recently reported to have a critical influence on the retention characteristic with P/E cycling [3]. Therefore, an accurate and simple method for extracting the lateral profile of charges trapped in the nitride storage layer is required for the robust design of flash memory products.

Various lateral profiling techniques have been demonstrated to extract the lateral profile of charges trapped in the nitride storage layer. While Gu et al. [4] and Arreghini et al. [5] have proposed modified charge pumping (CP) methods, Kumar et al. [6] and Lusky et al. [7] have combined the experimental CP/DC current-voltage ($I-V$) characteristics and the gate induced drain leakage (GIDL)/subthreshold DC $I-V$ characteristics with the device simulation. Because the electrical stress is inevitably induced during characterization and its accuracy decreases as the channel doping concentration becomes laterally more nonuniform, the conventional CP method is not applicable to extremely scaled nonvolatile flash memories. Also, the separation of the interface trap density and the local flat-band voltage shift is so difficult that many efforts and much time are needed.

In this work, for the first time, a new lateral-charge-profiling technique based on local flat-band voltage ($V_{FB}$) monitoring by using the optical substrate current ($I_{sub}$) is proposed and is applied to the extraction of the local charge density in charge-trapping flash memory cells. This method monitors the change in the local $V_{FB}$ to the exclusion of interface state density. Thus, it is suitable for extracting the trapped charge distribution of CTF memory cells. Firstly, we explain the mechanism of photo-generated substrate current $I_{sub}$ in metal-oxide-semiconductor field effect transistors (MOSFETs).
A step-wise change in the substrate current is shown under optical illumination of the MOSFETs. Secondly, we apply this mechanism to extracting the lateral distribution of the charges trapped in CTF memory devices.

II. NOVEL EXTRACTION METHOD FOR THE LOCAL FLAT-BAND VOLTAGE BY USING AN OPTICAL SOURCE

A schematic diagram illustrating the concept of the proposed technique for extracting of the local flat-band voltage in n-type MOSFETs is shown in Figure 1(a). Under optical excitation at \( \lambda = 850 \) nm and \( P_{opt} = 1 \) mW, a photo-induced substrate current density is generated in two regions of the MOSFET substrate. One is at the source/drain space charge region \((J_{L,s}, J_{L,d})\) and the other is the channel region \((J_{L,c}, J_{n,diff}, J_{diff})\).

\( J_{L,s} \) and \( J_{L,d} \) are photo-induced current densities in the S/D junction, respectively and \( J_{L,c} \) is the generation current density in the channel depletion region. \( J_{n,diff} \) and \( J_{diff} \) are minority carrier diffusion current densities under the channel depletion region. \( J_{L,s} \) and \( J_{L,d} \) are constant and independent of the applied gate voltage while \( J_{L,c}, J_{n,diff} \) and \( J_{diff} \) depend on the applied gate voltage. In the case of a n-type MOSFET, \( J_{L,s}, J_{L,d} \) and \( J_{L,c} \) (hole current density) and \( J_{n,diff} \) (electron current density) contribute to the total substrate current, as shown in Figure 1(a).

We define this as the total photo-induced substrate current \( J_{sub,photo} \).

Because the excess carrier generation is exponentially reduced along the substrate, there is a diffusion current to the substrate contact due to nonuniform electrons and holes. Majority carrier hole diffusion is negligible, so there is only a minority carrier electron diffusion current density \( J_{diff} \). In Figure 1(b), the position of the generated electron density’s peak concentration is not at the channel surface \((x = 0)\) like the generation rate, but is in the middle of the substrate region. In the accumulation region \((V_G \leq V_{FB})\), the recombination rate at the channel surface is higher than it is in the bulk region under the influence of the interface trap density. There, the excess minority carrier concentration at the channel surface becomes lower than that in the bulk region. In the case of \( V_G > V_{FB} \), a channel depletion region starts to appear. The minority carrier concentration at the depletion-region edge \((x = W_d)\) becomes almost zero. Eventually in both cases, there should be a peak concentration position in the middle of the substrate region, as shown in Figure 1(b).

Hence, the excess minority carrier diffusion current flows in directions (a) to the channel surface \((J_{n,diff})\) and (b) to the substrate contact \((J_{diff})\). In the Figure 1(b), \( J_{diff} \) is the electron current density contributing to the total substrate current density \( J_{sub,photo} \) by a positive number, while \( J_{n,diff} \) contributes by a negative number. \( J_{L,c}, J_{L,s}, J_{L,d} \) are the hole current density contributed by a negative number.

For \( V_G < V_{FB} \), the minority carrier concentration at the channel surface, \( n(0) \), depends on the surface recombination velocity, \( S_{front} \) and it determines \( J_{n,diff} = -qD_ndn(0)/dx \). Figure 1(b) shows \( n(0) \) for \( V_G < V_{FB} \). When \( V_G = V_{FB} \), a channel depletion region starts to appear and the excess minority carrier concentration at the depletion edge abruptly decreases, as shown in Figure 1(b). This means that \( J_{n,diff} \) starts to abruptly increase at \( V_G = V_{FB} \). Because the positive increased value of \( J_{n,diff} \) is the same as the negative decreased value of \( J_{diff} \), the total substrate current \((J_{sub,photo} = J_{L,s} + J_{L,d} + J_{n,diff} + J_{diff})\) is increased, as shown in Figure 2. In the simulation, \( V_G \) is swept from \(-3 \) V to \(3 \) V with the drain bias fixed at \( V_D = 0.05 \) V. All the other electrodes are grounded. The parameters needed to implement the photo-generation simulation are summarized in Table 1.

The flat-band voltage for the simulated n-type MOSFET \((N_{pdy} = 10^{20}\mbox{ cm}^{-3}, N_{sub} = 10^{17}\mbox{ cm}^{-3})\) is found to be \( V_{FB} = -0.933 \) V. In Figure 3(a), \( J_{sub,photo} \) is decreased near the flat-band voltage \( V_{FB} \) and the mechanism is explained in Figure 3(b). As shown in Figure 3(b), the minority carrier concentration at the left-end \((x = 0)\) is abruptly reduced when \( V_G \) become larger than...
Table 1. Parameters for the simulation of photo generation in a MOSFET.

<table>
<thead>
<tr>
<th>Device Parameters</th>
<th>Parameters</th>
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</thead>
<tbody>
<tr>
<td>$L_g$</td>
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</tr>
<tr>
<td>$H_{sub}$</td>
<td>5 μm</td>
</tr>
<tr>
<td>$t_{ox}$</td>
<td>4 nm</td>
</tr>
<tr>
<td>$N_{poly}$</td>
<td>10$^{20}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$N_{sub}$</td>
<td>10$^{17}$ cm$^{-3}$</td>
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Optical Source Parameters

<table>
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<th>Optical Source</th>
<th>Parameters</th>
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</thead>
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<td>$λ(E)$</td>
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<tr>
<td>$α$</td>
<td>830 cm$^{-1}$</td>
</tr>
<tr>
<td>$P_{opt}$</td>
<td>1 mW (J/s)</td>
</tr>
<tr>
<td>$P_{opt}$</td>
<td>1 mW (J/s)</td>
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</table>

$V_{FB}$. This means that the gradient of the minority carrier concentration at the depletion edge is abruptly increased, followed by a sudden increase of $I_{sub,photo}$. The $V_{FB}$ point defined by this mechanism is the gate voltage at which $I_{sub,photo}$ start, to have a large increasing gradient. Consequently, $I_{sub} - V_G$ has a sudden increase in the substrate current $I_{sub}$ at $V_G = V_{FB}$ when measuring in an optical illuminated state.

III. LATERAL PROFILING OF TRAPPED CHARGES IN CTF MEMORY CELLS

If $V_{FB}$ is nonuniform along the channel length, caused by a laterally nonuniform profile of electrons trapped in the nitride storage layer as shown in Figure 4(a), multi-steps in the $I_{sub} - V_G$ curve are expected to be observed, as shown in Figure 4(b). The reason for these multi-steps is that $I_{sub,photo1}$ under the non-program region is abruptly increased at $V_{FB1}$ and $I_{sub,photo2}$ under the program region is increased at $V_{FB2}$. This means that the multi-step-like substrate current has information on the local flat-band voltage $V_{FB}(x)$. As the density of the trapped electron charges increases, the width of the second step, which is induced by trapped charges, shifts to the right. As the distribution length of trapped charges at fixed channel length, $L_{ch}$, becomes longer, the height of the second step becomes more pronounced. The trapped charge density, $Q_{nit}(x)$ and the distribution length, $x$, are described by

$$Q_{nit}(x) = ΔV_G(x) \cdot C_{ONO}, \quad (1)$$

$$x = \frac{ΔJ_{sub,photo2}}{ΔJ_{sub,photo1} + ΔJ_{sub,photo2}} \cdot L_{ch}, \quad (2)$$

where $ΔJ_{sub,photo1}$ is the total variation of $J_{sub,photo}$ and $ΔJ_{sub,photo2}$ is the variation of $I_{sub,photo}$ under the program region, as shown in Figure 4(b).
### Table 2. Parameters for the simulation of photo generation in a CTF memory cell.

<table>
<thead>
<tr>
<th>Device Parameters</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>( L_g )</td>
<td>1.75 ( \mu )m</td>
</tr>
<tr>
<td>( H_{sub} )</td>
<td>5 ( \mu )m</td>
</tr>
<tr>
<td>( O/N/O )</td>
<td>4 nm / 4 nm / 4 nm</td>
</tr>
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<td>( N_{poly} )</td>
<td>( 10^{20} ) cm(^{-3} )</td>
</tr>
<tr>
<td>( N_a )</td>
<td>( 10^{17} ) cm(^{-3} )</td>
</tr>
<tr>
<td>( L_{prog} )</td>
<td>0/5 ( L_g ) ~ 5/5 ( L_g )</td>
</tr>
<tr>
<td>( N_{nit} )</td>
<td>( 10^{10} ) cm(^{-3} )</td>
</tr>
</tbody>
</table>

### Optical Source Parameters

| \( \lambda(E) \) | 850 nm (1.459 eV) |
| \( \alpha \) | 850 cm\(^{-1} \) |
| \( P_{opt} \) | 1 mW (J/s) |

**Fig. 4.** (a) Schematic diagram of a locally-programmed CTF memory cell in photonic illumination. (b) Schematic diagram of the multi-step-like feature \( J_{sub, photo} \).

A schematic diagram of an n-type CTF memory device and the bias conditions are shown in Figure 4(a) and parameters needed to implement the photo-generation simulation are summarized in Table 2. The simulation is im-
As the programmed charge density increases, the second transition point shifts to the right due to the increased applied voltage. After both-sided HHI erase, the first transition point shifts left as much as 0.29 V because $V_{FB}$ is decreased by the injected holes. From there data, the injected volume charge density is $1.38 \times 10^{18} \text{ cm}^{-3}$.

Figure 6(a) shows the photo-generated substrate current, $I_{sub,photo}$, was measured for a n-channel MOSFET ($W \times L = 175 \mu m \times 1.75 \mu m$) with the drain bias dependence and the $I_{D} - V_G$ curve in dark state. (b) $V_{FB}$ extracted from the C-V curve of the MOS by structure using Hillard’s method ($W \times L = 200 \mu m \times 200 \mu m$).

Figure 5(a) shows the photo generation simulation results for a laterally nonuniform profile of electrons trapped in the nitride storage layer in a CTF memory. As shown in Figure 5(a), a multi-step response is clearly observed in the $I_{sub,photo} - V_G$ curve. The first transition points are the same in all cases because the intrinsic flat-band voltage, $V_{FB1}$, is unique for all cases while the $I_{sub,photo}$ varies with the programmed region at the second transition points. As the programmed region is increased, the $I_{sub,photo}$ is increased because the portion of $I_{sub,photo}$ is increased. The programmed charge density dependence of $I_{sub,photo}$ is shown in Figure 5(b). As the programmed charge density increases, the second transition point shifts to the right due to the increased $V_{FB2}$. From Figure 6, we confirm that the second step’s height is related to the programmed region and that the second step’s width is related to the injected charge density.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The photo-generated substrate current, $I_{sub,photo}$ was measured for a n-channel MOSFET ($W \times L = 175 \mu m \times 1.75 \mu m$) with the drain bias dependence and the $I_{D} - V_G$ curve in dark state. (b) $V_{FB}$ extracted from the C-V curve of the MOS by structure using Hillard’s method ($W \times L = 200 \mu m \times 200 \mu m$).

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Laterally-Trapped-Charge Profiling Based on the Extraction

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Fig. 7. (a) Measurement data for the n-channel CTF flash memory cell transistor (W × L = 10 μm × 0.22 μm, O/N/O layers: 40/40/40 Å). In the program conditions, CHEI (V_G = 5.5 V, V_D = 5.5 V and program time T_P = 1 ms) is used. (b) Measurement data for the n-channel CTF flash memory cell transistor (W × L = 10 μm × 0.5 μm, O/N/O layers: 40/40/40 Å). In the Erase conditions, both-sided HHI (V_G = 0 V, V_D = 13 V, V_S = 13 V, erase time T_E = 1 ms) is used.

= 3.45 × 10^{-7} \text{F/cm}^2, t_{nitride} = 4 \text{nm} \) and the lateral distribution range of both-sided injected holes is near 140 nm. Although we could not extract the accurate lateral distribution of trapped charges because of insufficient modeling of the lateral profiling, we confirmed that this method is able to detect the variation in the charge density and the lateral distribution. Further study is going on to extract a more accurate distribution of trapped charges.

V. CONCLUSIONS

In this work, we proposed a new extraction method for the local distribution of the flat-band voltage, V_FB, along the channel by using an optical source having a large energy compared to the silicon band-gap energy (1.12 eV). We clearly verified that the gate voltage starting to have a large increasing gradient of I_{sub,photo} gives an accurate V_FB when using a TCAD simulation and analytic model. We applied this method to a CTF memory cell to extract the lateral profile of trapped charges along the channel in the nitride storage layer. Locally increased V_FB cause of by trapped charges induces a multi-step-like feature in I_{sub}–V_G curve. The second step’s height is related to the programmed region and the second step’s width is related to the injected charge density. Although we could not extract an accurate lateral distribution of trapped charges because of insufficient modeling of the lateral profiling, from the experimental results, we confirmed that this method is able to detect the variation in the charge density and the lateral distribution. Further study is going on to extract a more accurate distribution of trapped charges.

ACKNOWLEDGMENTS

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