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Impact of Source/Drain Junction and Cell Shape on Random Telegraph Noise in NAND Flash Memory

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A comprehensive numerical study of threshold voltage fluctuation ($\Delta V_T$) in scaled NAND flash memory caused by random telegraph noise (RTN) and discrete dopant fluctuation (RDF) in both the channel and the cell-to-cell space (source/drain (S/D)) region was carried out. Following a three-dimensional (3D) Monte Carlo (MC) procedure, the statistical distribution of $\Delta V_T$ is estimated, considering the effects of both the random placement of discrete doping atoms and a discrete single trap at the tunnel oxide/substrate interface. The result demonstrates the significant influence of the doping in the S/D regions. For the cells with and without an S/D junction, the electron concentration in the S/D region is determined by the pass voltage of the unselected cell ($V_{pass}$) and the neighboring cell $V_T$ ($V_{T(p)}$), owing to the fringing fields of neighboring floating gates (FGs). As a result, $\Delta V_T$ increases in the S/D region as $V_{pass} - V_{T(p)}$ decreases. The fluctuation amplitude strongly depends on the [single-trap RTN] position along the cell length (L) and width (W) directions. For the cell shape with rounding of the active area (AA) at the shallow trench isolation (STI) edge, the results indicate that the high $\Delta V_T$ area moves from the AA edge towards the center area along the W-direction.

1. Introduction

Recent NAND Flash scaling trends have already been extended below 25 nm. The threshold voltage fluctuation ($\Delta V_T$) caused by random telegraph noise (RTN) produces severe reliability problems in the read operation of NAND Flash memory as the cell size is scaled down. Consequently, it is widely considered that RTN affects cell reliability.1–11) Owing to the capture and emission of an electron at the trap state in the tunnel-oxide layer, RTN causes changes in both conducting carrier number and mobility. Previous research has attributed $V_T$ distribution widening by RTN to the percolation effect due to atomicistic doping spread and trapped charge instability (SCE) and program disturbance,18–22) thus warranting a more thorough investigation of RTN for the cell with low $V_T$ fluctuations. Statistics of the $V_T$ instability can be examined by analyzing the cumulative distribution of $\Delta V_T$.17)

Both channel and source/drain (S/D) regions must be considered when examining how RTN affects NAND Flash memory. It is well known that omit to avoid program disturbance, the scaled cell gate length cannot increase the boron channel doping concentration. Correspondingly, the S/D doping must be reduced to suppress short channel effect (SCE) and program disturbance,18–22) thus warranting a more thorough investigation of RTN for the cell with low $V_T$ or eliminated S/D doping levels. Even without S/D doping, fringing fields induced by neighboring floating gates (FGs) can produce an adequate number of surface electrons and achieve a sufficient string ON-current level.23–26)

Several RTN-related studies involving SCE, S/D implantation,8,21) channel doping, cell shape,27–29) and adjacent cell interference have been performed recently.30,31) Analyzing how RTN affects S/D regions is a priority concern owing to the reduction of S/D doping when the cell size is scaled down to sub-25 nm. However, to the best of our knowledge, exactly how the channel-to-cell S/D region affects RTN with various cell geometries and $V_{pass}$ in the NAND Flash string has not yet been explored.

By three-dimensional (3D) technology computer aided design (TCAD) simulations, in this work we simulated a complete discrete-acceptor and discrete-donor dopant profile with the RTN trap for the NAND Flash string. The RTN distribution amplitudes are also investigated with and without the S/D junction, where various $V_{pass}$ values and different cell shapes are considered. The results of this study remain valid, despite the fact that the feature size of cell dimensions approaches 15 nm. Therefore, the results of this study will contribute to the improvement of the $V_T$ distribution widening by RTN for the further scaled down NAND Flash memory.

2. Simulation Method

The statistical distribution of $V_T$ fluctuation amplitude is studied by performing a large number of 3D numerical simulations with a random placement of discrete acceptor (RDA) and donor (RDD) atoms, and a single electron trap at the tunnel oxide/substrate interface (Fig. 1). Cell width and length are set to 22 nm, and the substrate average boron doping concentration of $1 \times 10^{19}$ $\text{cm}^{-3}$ is implemented. Two S/D profiles are prepared: one without S/D doping (S/D junctionless) and the other with a Gaussian profile of an arsenic implant with a low peak concentration of $1 \times 10^{18}$ $\text{cm}^{-3}$. The coupling ratio (FG to control gate capacitance divided by the total capacitance) is set to 0.6 with 8-nm-thick SiO$_2$ as the FG oxide. The statistical distribution of the $V_T$ fluctuation amplitude of a read cell is then obtained using the Monte Carlo (MC) procedure.27,28) Conventionally, with a highly doped S/D, the RTN effect arising only in the channel region has been studied.27–30) However, considering the recent S/D doping level reduction trend, both the channel region and S/D region should be taken into account. Figure 1 shows the RTN trap placement site (RTN region), deliberately extended over the channel and cell-to-cell S/D area. The $V_T$ value of a selected cell is extracted as the world line (WL) bias (voltage) that elicits a bit line (BL) current $I_{BL}$ of 100 nA. The BL and source line (SL) bias as are set to 0.1 and 0 V, respectively. All cells in the NAND string are assumed to be in the neutral state (i.e., no charge placed in FG). Additionally, RTN instabilities are examined, in which the statistical distribution of the single-trap fluctuation amplitude was considered, which was shown in Ref. 13.

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to be sufficient for an adequate description of NAND Flash memory. A single negative charge, which represents a trapped electron, is randomly placed in the channel or cell-to-cell S/D region (refer to Fig. 1 RTN region) at the tunnel-oxide/substrate interface, where its electrostatic property impacts the magnitude of the corresponding bit-line current reduction. 3D drift-diffusion simulation is carried out to estimate the $I_{\text{BL}}-V_{\text{SCG}}$ ($V_{\text{SCG}}$: selected cell CG bias) trans-characteristic with the trap empty (neutral) or filled (negatively charged) by one electron. Consequently, $I_{\text{BL}}$ or $V_T$ is extracted as the $V_T$ difference between the case of a negatively charged state and a neutral trap state, which is randomly placed in the channel or cell-to-cell S/D region. More than 1000 MC runs are performed for each computation. The string current that is forced through a few narrow channels connecting SL to BL is greatly influenced by the positioning of discrete dopant atoms. The Coulomb potential associated with each impurity atom acts as a barrier for the current flow. Such current channels can be completely blocked by an electron trapped near one of them, causing a large $I_{\text{BL}}$ or $V_T$ variation.

3. Results and Discussion

Figure 2 shows the simulated Gaussian behavior of neutral $V_T$ distribution due to the random dopant fluctuation (RDF), where simulation is performed with and without an S/D junction. Discrete acceptors are randomly distributed in both cases, and discrete donors are added to the case of the S/D junction. Figure 3 shows a comparison between cells with and without an S/D junction in terms of the cumulative distribution of $\Delta V_T$. Under the condition of $V_{\text{pass}} = 3 \text{ V}$, $\Delta V_T$ of the S/D junctionless cell is larger than that of a cell with S/D doping. In the S/D junctionless cell, the fringing fields of the neighboring FG heavily influence the electron density in the S/D region. Consequently, a single electron trap more significantly impacts the S/D junctionless cell under a low $V_{\text{pass}}$. Figures 4(a) and 4(b) demonstrate the statistical contour plots of the $\Delta V_T$ distribution, as a function of the electron trap position along the L- and W-directions. Figure 4 provides insight into the origin of the tail bits shown in Fig. 3. For the S/D junctionless cell shown in Fig. 4(b), $\Delta V_T$ is significantly larger in the S/D region than in the channel region, owing to the reduced electron density in the cell-to-cell S/D area. The data pattern of the neighboring cell must be considered as well. Figure 5 shows a
Fig. 4. (Color online) Statistical contour plots of $\Delta V_T$ distribution as a function of single-trap position along the $L$- and $W$-directions for cells (a) with and (b) without S/D junction.

Fig. 5. (Color online) Simulated $\Delta V_T$ statistical distribution for cells with and without S/D junction. Adjacent cells are in a neutral or PGM state. $V_T$ of programmed adjacent cells is 3 V.

comparison of the RTN results when adjacent cells are in neutral ($V_{T(n)} = 0.3$ V) and program (PGM) ($V_{T(n)} = 3$ V) states. Comparison between Figs. 3 and 5 reveals that the $\Delta V_T$ distribution under high $V_{T(n)}$ and $V_{pass}$ ($V_{T(n)} = 3$ V, $V_{pass} = 6$ V) is nearly the same as that under low $V_{T(n)}$ and $V_{pass}$ ($V_{T(n)} = 0.3$ V, $V_{pass} = 3$ V). This observation is attributed to the electron density in the S/D region being almost determined by $V_{pass} - V_{T(n)}$. Therefore, exactly how $V_{T(n)}$ and $V_{pass}$ affect can be written simply as $V_{pass} - V_{T(n)}$, allowing us to resolve the adjacent cell interference effect by varying $V_{pass}$ with all neighboring cells in neutral states. Figures 6(a) and 6(b) show the cumulative distribution of $\Delta V_T$ as a function of $V_{pass}$ for cells with and without an S/D junction. These figures reveal that the cumulative distribution of $\Delta V_T$ under low $V_{pass}$ ($V_{pass} = 3$ V) is the broadest. In particular, in the case of an S/D junctionless cell, the RTN effect significantly worsens at the tail. Thus, the $V_T$ fluctuation amplitude is larger in the S/D region as $V_{pass} - V_{T(n)}$ becomes smaller. To estimate the contribution of the channel region and S/D region to $\Delta V_T$, the origin of the detected severe RTN effect under various $V_{pass}$ conditions is determined by separately simulating a single-trap in the channel region and S/D region (Fig. 7). Figures 7(a) and 7(b) show a cell with an S/D junction, while Figs. 7(c) and 7(d) show the S/D junctionless cell in the channel region and S/D region, respectively, under various $V_{pass}$ conditions. $\Delta V_T$ slightly increases with increasing $V_{pass}$ in the channel region [Figs. 7(a) and 7(c)]. Nevertheless, Figs. 7(b) and 7(d) demonstrate that $\Delta V_T$ significantly decreases with increasing $V_{pass}$ in the S/D region. This reduction is attributed to the fact that a higher electron can be induced by the fringing field of the neighboring FG, resulting in less impact on $\Delta V_T$ in the S/D region. Figures 8(a) and 8(b) demonstrate the statistical contour plots of the $\Delta V_T$ distribution along the $L$- and $W$-directions with and without the S/D junction, at various $V_{pass}$ values. These figures reveal that $V_{pass}$ heavily influences the extent to which the S/D region affects RTN. Figure 9 shows the average values of $\Delta V_T$ from the cumulative distribution of $\Delta V_T$ in Figs. 6 and 7. The average $\Delta V_T$ is extracted from the contribution of 1) the channel region, 2) the S/D region, and 3) both the channel and S/D regions. The simulation is executed by distributing a single trap randomly in each region. The RTN effect along the $W$-direction must also be considered. A high $\Delta V_T$ is crowded at the active-area edges (AA) along the $W$-direction (Fig. 8). In other words, the RTN effect without an S/D junction strongly depends on $V_{T(n)}$ under constant $V_{pass}$.

Next, the dependence of cell geometry on the $\Delta V_T$ distribution is considered. The RTN effect with different cell shapes (i.e., rounding of the FG and AA) is estimated by simulating three cell shapes. Figures 10(a)–10(c) show the cross-sectional views along the $L$- and $W$-directions with
three cell shapes. The fluctuation amplitude $\Delta V_T$ of a single-trap RTN source is obtained by estimating cell $V_T$ with and without a single electron randomly placed over the channel or cell-to-cell S/D region at its interface with the tunnel oxide (refer to Fig. 1, RTN region) for each cell shape. $\Delta V_T$ caused by RTN is observed following the MC procedure, considering ensembles of more than 1000 atomistically different devices for each cell shape. Case A represents a
sharp-edge device with the fully planar AA. In the case of B, corner rounding occurs at FG edges along the L-direction. In the case of C, corner rounding occurs at both FG and AA edges along the W-direction. Case A has a uniform tunnel-oxide thickness over the entire AA, resulting in a strong electric field and current crowding at the AA edges. Case C exhibits a strong electric field and current crowding in the middle of the channel due to the AA edges rounding along the W-direction. Figures 11(a) and 11(b) show the cumulative distribution of $\Delta V_T$ with and without an S/D junction at the channel region and S/D region under a low $V_{\text{pass}}$ ($V_{\text{pass}} = 3 \text{ V}$). Simulation results indicate that the cell geometry does not significantly impact RTN. Notably, $\Delta V_T$ in the S/D region plays a dominant role in the S/D junctionless cell, even though the cell geometry changes. To give insight into the origin of the tail bits shown in Fig. 11, Figs. 12(a) and 12(b) demonstrate the statistical contour plots of the $\Delta V_T$ as a function of single-trap position along the L- and W-directions, where a single-trap RTN is randomly placed in the channel and cell-to-cell S/D region. For the S/D junctionless cell, these figures clearly indicate that $\Delta V_T$ in the S/D region is significantly larger than that in the channel region. Moreover, for both cases A and B with and without an S/D junction, $\Delta V_T$ in the AA edge region is larger than that in the center of AA. This phenomenon can be explained by the electric field intensification and current crowding at the AA edges. For case C with and without an S/D junction, a high $\Delta V_T$ area moves from the AA edge towards the center area along the W-direction. Therefore, the magnitude of the RTN fluctuation amplitude heavily depends on the trap position along the L- and W-directions.

4. Conclusions

In this paper, we show that $\Delta V_T$ strongly depends on the lateral position of a trap over the active area. The obtained result allows us to highlight the importance of S/D region characteristics against RTN instabilities. We have presented, for the first time, the great influence of the S/D region on the RTN amplitude in NAND Flash. Considering the results of
RTN, the reduction in the number of surface states in the S/D region is crucial. The knowledge collected in this study will be useful to fix the $V_T$ distribution widening by RTN for the further down scaled NAND Flash.

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