Random Telegraph Noise-Induced Sensitivity of Data Retention to Cell Position in the Programmed Distribution of NAND Flash Memory Arrays

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I. INTRODUCTION

COMING from the uncontrollable capture and emission of single electrons in tunnel-oxide traps, random telegraph noise (RTN) is today one of the most relevant reliability issues for Flash memories [1]–[5]. RTN limits, in fact, the possibility of achieving and keeping narrow threshold-voltage (V_T) distributions in Flash arrays [6], [7], constraining the number of bits per cell that can be safely stored in multi-level devices. In particular, RTN broadens the V_T distribution resulting from a program-and-verify operation [8] both in its upper and in its lower part [7], [9], with the broadening growing as time elapses during data retention.

In this letter, we show that RTN introduces a non-negligible contribution to the sensitivity of the V_T transients during post-cycling data retention of nanoscale NAND Flash cells to cell position in the programmed array distribution. This RTN-induced sensitivity contributes to reducing the V_T loss of cells in the lower part of the programmed distribution and to increasing the V_T loss of cells in the upper part of the distribution. Results, which are not related to any fundamental data retention issue of cells in different parts of the array distribution, are explained as an artifact of the program-and-verify operation trying to compact the array V_T distribution in the presence of RTN.

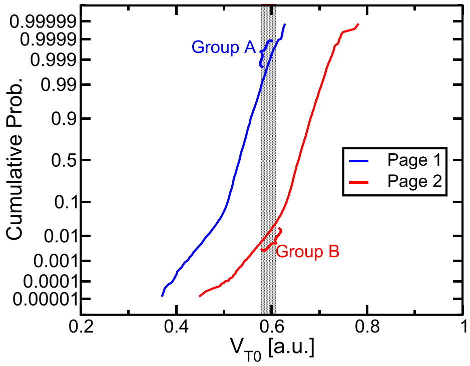

Fig. 1. Cumulative distribution of the V_T of two pages of a NAND array which were moved by program-and-verify operations to slightly different programming levels (the as-programmed cell V_T will be referred to as V_{T0} in this work). All of the voltages shown in this letter have been normalized to the same arbitrary constant.

II. EXPERIMENTAL RESULTS

In order to investigate the sensitivity of the data retention V_T transient of Flash cells to their position in the programmed array distribution, we moved two pages of a heavily cycled NAND array made with our 16 nm planar technology [10] to slightly different programming levels, as shown in Fig. 1. A program-and-verify algorithm [8] was used to fit all the cells of the two pages into two narrow and partially overlapped V_T intervals, allowing to investigate the behavior of cells with the same initial V_T (V_{T0} from here on) but with different positions in the programmed distribution. For instance, cells in group *A* of page 1 and in group *B* of page 2 in Fig. 1 have the same V_{T0} (shadowed region in the figure), but are, respectively, in the top and in the bottom part of their page distribution.

Manuscript received April 10, 2015; accepted April 28, 2015. Date of publication April 30, 2015; date of current version June 24, 2015. The review of this letter was arranged by Editor M. Jurczak.

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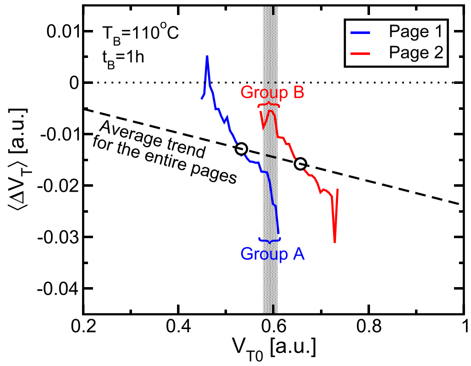

Fig. 2. $\langle \Delta V_T \rangle$ after a bake period $t_B = 1$ h at $T_B = 110$ °C for cells with the same initial V_{T0} in each of the two pages considered in Fig. 1, as a function of V_{T0}.

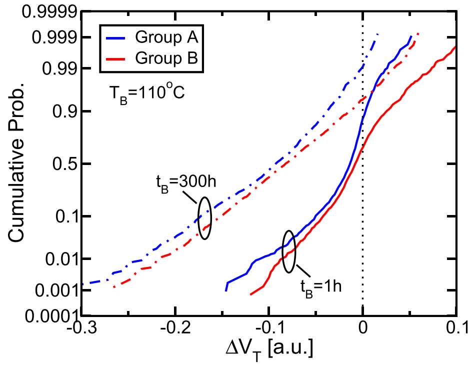

Fig. 4. Cumulative distribution of ΔV_T at $t_B = 1$ h and 300 h ($T_B = 110$ °C) for cells in group A and in group B of Fig. 1.

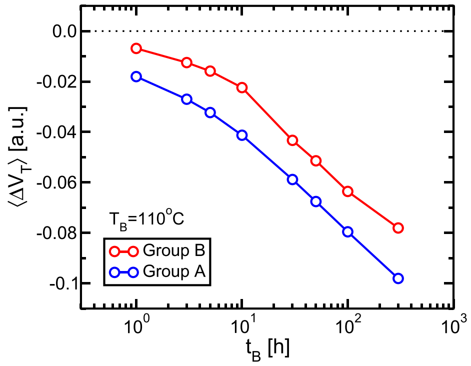

Fig. 3. $\langle \Delta V_T \rangle$ dependence on t_B ($T_B = 110$ °C) for cells in group A and in group B of Fig. 1.

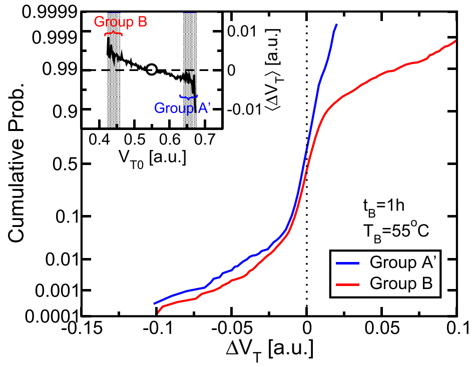

Fig. 5. Cumulative distribution of ΔV_T at $t_B = 1$ h when $T_B = 55$ °C, for cells in the bottom part of the V_{T0} distribution (group B) and those in its top part (group A'). The inset shows $\langle \Delta V_T \rangle$ vs. V_{T0} in this test.

After page programming, the memory array underwent a bake experiment at $T_B = 110$ °C, which was periodically stopped to gather the V_T of all the cells to monitor their high-temperature data retention (all the read operations were done at room temperature). Fig. 2 shows the average V_T shift ($\langle \Delta V_T \rangle$) after a bake time $t_B = 1$ h of cells with the same V_{T0} in page 1 and in page 2. Results reveal, first of all, that cells display an average V_T loss during bake (negative $\langle \Delta V_T \rangle$), coming from electron detrapping from their tunnel oxide [11]–[14]. Owing to the sensitivity of this process to the electric field in the tunnel oxide during the bake period [13], [15], an increase of the average V_T loss of the entire page (see the open circles in the figure) appears when moving from page 1 to page 2. This average V_T loss gives, however, a $\langle \Delta V_T \rangle$ dependence on V_{T0} which is weaker than that followed by the cells inside each of the two pages, as clearly appearing from the comparison of the blue and of the red curve in Fig. 2 with the black dashed line (this represents a perfectly repeatable phenomenon observed in all of our data retention results, for whatever page programming level). As a consequence of this, cells in group B of page 2 display a lower $\langle \Delta V_T \rangle$ than cells in group A of page 1, despite the fact that they were initially at the same V_{T0}. Fig. 3 shows that this is true even for increasing t_B and, therefore, in the presence of higher V_T losses during the data retention transient.

In order to investigate the origin of the different data retention transient of cells in group A and in group B, Fig. 4 shows the cumulative distribution of ΔV_T for these cells at $t_B = 1$ h and 300 h. Results reveal that, besides the displacement of their $\langle \Delta V_T \rangle$, the two groups of cells display far more relevant differences in the tail regions of their ΔV_T distribution. In particular, the upper tails of the two distributions reveal, first of all, the possibility that some cells display positive ΔV_T and, moreover, that this is more likely to occur for cells in group B. The comparison of the lower tails of the distributions reveals, instead, that cells in group A are more prone to reducing their V_T in the experiment than those in group B.

Since the tails of the data retention ΔV_T distribution may be significantly affected by RTN [14], [15], we explored the possibility that this noise source represents also the origin of the increased sensitivity of data retention to cell position in the page V_{T0} distribution. To this aim, we repeated the data retention experiment with a lower T_B. Note, in fact, that the reduction of T_B largely decreases charge detrapping from the tunnel oxide [12], [13], [15], while having only a minor impact on the statistics of RTN instabilities in the array [16]. Fig. 5 shows the statistical results for ΔV_T gathered on cells in the bottom part (group B) and in the top part (group A') of the V_{T0} distribution of a programmed page when $T_B = 55$ °C and $t_B = 1$ h. The inset shows that the $\langle \Delta V_T \rangle$ of the entire page is $\simeq 0$, confirming that charge detrapping is almost negligible in this experiment and that RTN is the only mechanism impacting cell V_T. Despite this, however, cells display the same $\langle \Delta V_T \rangle$ trend inside the V_{T0} distribution shown in Fig. 2, with those in the bottom part of the distribution having now positive $\langle \Delta V_T \rangle$ and those in the top part

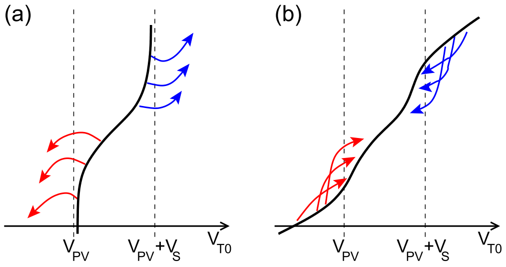

Fig. 6. Schematic picture for the V_T distribution of a page of the NAND array at the end of the program-and-verify operation (a) and at the first read operation used as reference for the data retention experiments (b).

negative $\langle \Delta V_T \rangle$ (see inset). Moreover, the same differences between the tails of the ΔV_T distribution of the two groups of cells previously observed in Fig. 4 also appear in Fig. 5. These results reveal that RTN introduces a contribution to the sensitivity of ΔV_T to cell position in the V_{T0} distribution, explaining the results of Figs. 2-3-4.

III. DISCUSSION

Data in Fig. 5 revealed that the RTN behaviors of cells in the bottom part and in the top part of a programmed page distribution display non negligible differences. This result can be explained with the help of Fig. 6, showing a schematic view of a page distribution considering the V_T determining the end of the program-and-verify operation (a) and those resulting from the first read operation on the array (b). The program-and-verify algorithm stops programming each cell when it overcomes a selected level V_{PV} and this should result, neglecting program noise contributions [17], in a V_T distribution included between V_{PV} and $V_{PV} + V_S$, where V_S is the programming step amplitude [8]. However, immediately after the end of the program operation, RTN starts affecting cell V_T, with the possibility for some cells to move below V_{PV} (see red arrows in Fig. 6a) and for others to move above $V_{PV} + V_S$ (blue arrows). This introduces a tail in the lower and in the upper part of the V_{T0} distribution resulting from the first read operation on the page (Fig. 6b), with the former and the latter made of cells that, respectively, reduced and increased their V_T due to RTN. As a consequence, when cells are monitored during data retention using this distribution as a reference, those in its bottom and in its upper part will, respectively, most likely increase and decrease their V_T due to RTN, owing to fluctuations towards their initial V_T level. Although the average ΔV_T of the entire page is $\simeq 0$, this introduces a non zero $\langle \Delta V_T \rangle$ for cells far from the average V_{T0}, as shown in Fig. 5 and explaining the results of Fig. 2. Note, however, that this does not give rise to a narrowing of the V_T distribution as data retention proceeds, since cells moving from the sides towards the center of the distribution are replaced by more cells moving in the opposite direction.

IV. CONCLUSION

In this letter, we have highlighted a contribution given by RTN on the data retention ΔV_T sensitivity to cell position in the programmed array distribution. Results have been explained with a simple physical picture for cell movements in the V_T distribution in the time stretch in-between the program-and-verify operation and the first read operation used as reference for data retention assessment.

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