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Threshold voltage instability of nanoscale charge trapping non-volatile memory at steady phase

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ABSTRACT

Post program/erase (P/E) cycled threshold voltage (Vt) instability is one of the major reliability concerns for nanoscale charge trapping (CT) non-volatile memory (NVM) devices. In this study, anomalous program state Vt instability of fully annealed nanoscale nitride based CT NVM device at steady phase is carefully examined. To the best knowledge of the authors, for the first time, the relationship between the derived apparent activation energy (Eaa) of this anomalous program state Vt instability at steady phase and the P/E cycle count is established. They are found to adhere to the power law decay relationship. Anomalous program state Vt instability at steady phase was found to favor lateral redistribution of trapped charge model instead of vertical charge transport model. Physical interpretations of its underlying physical mechanisms and reliability implications to reliability performance of nanoscale nitride based CT NVM were presented. Plausible technical solutions to mitigate the reliability degradation induced by this anomalous program state Vt instability on nanoscale nitride based CT NVM were proposed.

1. Introduction

Floating Gate (FG) based charge storage NVM devices has suffered severe reliability challenges exacerbated through incessant technology scaling, e.g. point defects induced leakage percolation paths [1–3], cell-to-cell coupling interference issues [1–3], and variability effect to Vt distribution [4–7]. Nanoscale nitride based CT NVM has shown promising characteristics among the alternative emerging NVM technologies that includes inherent immunity towards point defects, improved cell-to-cell coupling interference and compatible CMOS fabrication process that leverages existing Si based technology [1–9]. P/E operations of nanoscale nitride based CT NVM typically performed through high electric field based charge injection mechanisms, e.g. FN Tunneling, channel hot electron injection (CHEI) and band-to-band tunneling assisted hot hole injection (BTBHHI). By applying these charge injection mechanisms in high electric field, charges are able to surmount the tunnel oxide barrier and landed into nitride storage layer. P/E operations will only cease when cell's Vt reaches the predetermined verify level. Thus, extensive P/E cycling degrades data retention performance of nanoscale nitride based CT NVM which manifests in Vt distribution decay over storage time. Two main physical models proposed to elucidate Charge Loss (CL) mechanisms of nanoscale nitride based CT NVM, i.e. (1) vertical charge transport model that attributes CL induced Vt decay to annihilation of P/E cycling induced interface states [8,9] and de-trapping of charges from bulk oxide traps [10–13]; (2) lateral migration of trapped holes toward the channel that quenches electric field over channel and hence effectively determines the Vt decay [14–17]. Many researchers have dedicated their research effort to determine the dominant physical model that dictates CL induced Vt decay, but this intense debate is still on-going. Zambelli et al. has reported possible anomalous erase state Vt instability during P/E cycling arise due to random transitions between normal and fast erase dynamics exhibited by small fraction of erased cells of CT NAND array [5]. On the other hand, Lee et al. has reported that anomalous Vt fluctuation occurs in post cycled nanoscale nitride based CT NVM programmed cells through lateral charge redistribution model and the technology scaling trend was found to exacerbate anomalous program state Vt instability at steady phase [6]. However, the effect of P/E cycle count onto anomalous program state Vt instability of programmed cells of nanoscale nitride based CT NVM was not further elucidated. This paper presents a study of anomalous program state Vt instability. Furthermore for the first time, the physical interpretation of the relationship between P/E cycle count and anomalous program state Vt instability exhibited by programmed cells of nanoscale nitride based CT NVM device is elucidated in this paper. Comprehension on the reliability implication of anomalous program state Vt instability is immensely critical with respect to the need for tight control of cells Vt especially for internal Vt reference cells and multi-level cell architectures [14–16].

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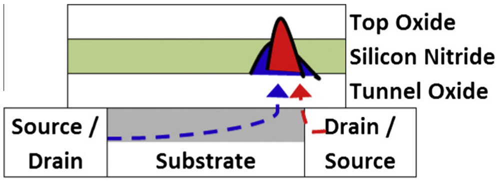

Fig. 1. Typical cell structure of nitride based CT NVM functional samples.

2. Experimental

The experiment conducted in this study was performed on functional samples of 1 million cells of nanoscale nitride based CT NVM. Fig. 1 shows the typical cell structure of the functional samples used in this study which consists of Oxide–Nitride–Oxide (ONO) stack. Silicon nitride layer of the ONO stack is implemented as the charge storage layer since the injected charges localized in the inherent traps of that layer. P/E cycling was performed using CHEI and BTBHHI mechanisms that inject electrons and holes respectively into nitride storage layer. For program operation, CHEI mechanism was performed to inject electrons into nitride storage layer with the gate voltage set at 10 V, drain voltage set at 5 V and the source is grounded. The program pulse time used in this study is 300 ns per pulse. On the other hand, for erase operation, BTBHHI mechanism was performed to inject holes into nitride storage layer with the gate voltage set at −7 V, drain voltage set at 6 V and the source is grounded. The erase pulse time used in this study is 100 µs per pulse. Different P/E cycle count was performed onto functional samples, namely, 10, 100, 1000 and 8000 cycles. Every P/E cycle builds up internal dipole in nitride storage layer due to mismatch in spatial distribution of injected holes and electrons [14–16]. These samples were programmed to checkerboard pattern where half of the total cells were programmed while the other half of total cells were left at blank state. Then, these samples were fully annealed for 100 h at 175 °C bake to ensure post baked Vt level of these functional samples have reached steady phase [6,25]. Moreover, post baked Vt distributions measured on these functional samples showed that there is no significant shift in the Vt cumulative distributions to lower level for subsequent high temperature bake. Therefore, this result indicates the fully annealed functional samples have reached steady phase. Vt measurement of program cells was performed on all cells after each subsequent high temperature bake of 25, 90, 150, 175 °C for different read point durations at 0, 0.1, 1, 24, 100 h to carefully monitor the development of the variability effect exhibited by program cells. All Vt measurements were performed in protective ambient of 25 °C. For each subsequent bake, sigma of Vt variability of each subgroup of program cells with initial identical Vt level were computed based on Eq. (1). In Eq. (1), $\Delta\sigma_{\mathrm{Vt}}$ represents the resultant sigma of Vt variability after the calculated sigma value of subgroup cells at time t, i.e. $\sigma_{\mathrm{Vt}}(t)$ is subtracted with the sigma at time zero at 25 °C, i.e. $\sigma_{\mathrm{Vt,0}}$. Sigma at time zero of 25 °C represents the Vt variability effect contributed by sensing noise and random telegraph noise (RTN). Thus by applying Arrhenius model as shown in Eq. (2), apparent activation energy (Eaa) of anomalous Vt variability effect can be derived based on the time to achieve arbitrarily identical degradation levels, i.e. 25/30/35 mV. In Eq. (2), t_f, A, k, T are time to achieve arbitrarily identical degradation level, constant, Boltzmann's constant, and temperature of each subsequent bake respectively. Therefore, the relationship between apparent activation energy (Eaa) and P/E cycle count can be obtained and physical interpretation of the results can be made.

$$\Delta\sigma_{Vt} = \sqrt{(\sigma_{Vt}^2(t) - \sigma_{Vt,0}^2)} \tag{1}$$

$$t_f = Ae^{\frac{Eaa}{kT}} \tag{2}$$

3. Results and discussions

In order to ensure the functional samples of nanoscale nitride based CT NVM are fully annealed, Vt distribution data was collected for each time slice at each subsequent bake. Fig. 2 exhibits the normalized Vt distribution measured at each time slice for each bake temperature for various P/E cycle counts. Fig. 2 have shown stable Vt distributions for various P/E cycle counts with no significant shift in subsequent bake and Vt distribution saturates at Vt level higher than its native Vt which is the Vt level of fresh cells without any history of P/E cycling stress. This indicates that all cells from the functional samples of nanoscale nitride based CT NVM have reached steady phase where there is no significant shift in Vt distribution of subsequent bake for various durations.

In order to take a closer look into the variability effect exhibited by cells Vt at steady phase as exhibited in Fig. 2, the sigma values of Vt variability effect of cells with initial identical Vt level were computed based on Eq. (1). Furthermore, the sigma values computed were found to increase along bake temperature and time. In other words, Vt of all program cells were observed to fluctuate anomalously and continuously at different rate for various bake temperatures and bake durations while there is no significant shift observed on Vt distribution of all program cells. By applying Arrhenius plots as shown in Fig. 3, Eaa of the anomalous Vt instability exhibited by program cells can be derived based on the time for each sigma value to reach the arbitrarily selected degradation levels, i.e. 25, 30 and 35 mV. It is imperative to compute Eaa because the derived Eaa is the minimum energy required for program cells to exhibit anomalous Vt instability to reach the selected degradation levels. Moreover with various P/E cycle stresses of different P/E cycle count administered onto these functional samples, relationship between Eaa of anomalous program state Vt instability and P/E cycle count is established for the first time on nitride based CT NVM. Fig. 3 show that this anomalous Vt instability of program cells continues to increase even though Vt distribution have reached steady phase as shown in Fig. 2 and thus this is in agreement with findings reported in [13]. Since the samples were fully annealed, P/E cycling induced interface states and bulk oxide traps were assumed to be annihilated during preparation bake of 175 °C for 100 h as evidently shown in Fig. 2 where there is no significant shift in Vt distribution data for each subsequent bake [6,25]. Furthermore, the saturated Vt level of these functional samples of nanoscale nitride based CT NVM at steady phase clearly exhibit no temperature dependence but depends on P/E cycle count. This phenomenon is difficult to be elucidated by using vertical charge transport model. Moreover if the anomalous Vt instability is dictated by vertical charge transport model, then there should not be any Vt fluctuations exhibited by nanoscale nitride based CT NVM cells since both P/E cycling induced interface states and oxide traps at tunnel oxide should have been annihilated [8–13]. However, this phenomenon was not observed. In addition to that, all cells within program state Vt distribution exhibits certain degree of Vt fluctuations throughout all subsequent bake administered to the samples. This finding is not feasible to be elucidated by using trap-assisted-tunneling (TAT) model attributed for stress-induced-leakage-current (SILC) phenomenon [2,3]. Thus at steady phase with no apparent contribution from P/E cycling induced interface states and bulk oxide traps, the findings shown in Figs. 2 and 3 indicate that the anomalous Vt instability exhibited by program cells favors lateral redistribution of trapped charge model.

As shown in Figs. 2 and 3, anomalous Vt instability of program cells and P/E cycle count favor lateral redistribution of trapped charges model [14–16]. To evaluate the relationship between