Charge Localization During Program and Retention in NROM-like Nonvolatile Memory Devices

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1. Introduction

An alternative solution to standard Flash memories is represented by nitrile-trap memories as SONOS or NROM memories. NROM in particular can be operated in 2-bit/cell mode using localized trapping in SiN film [1]. Therefore it can comply with the increasing demand of bit density. However these structures are facing retention issues at high temperature and a quantitative analysis of the charge distribution during program and retention is required.

Various techniques have been employed to deduce the distribution of trapped charges injected by channel hot electrons in the Oxide/Nitride/Oxide stack (ONO) of standard NROM devices. Among them we find charge pumping technique [2], GIDL and subthreshold slope monitoring [3], or analyses based on the surface potential model [4] and the measure of reverse/forward programming windows \(AV,R,AV,F\); Fig. 1). In this work the method described in [4] will be used on experimental data in order to evaluate the trapped charge distribution in program and retention conditions. The lateral migration (i.e. inside the trapping layer) and vertical migration (i.e. charge loss) of the trapped charges during retention will be quantitatively evaluated. Other trapping layers such as AlOx and HfO2 are also investigated.

2. Samples Description and Methodology

The devices under analysis are presented on Fig.2. The gate stack is composed by 5 nm tunnel SiO2 plus 6 nm charge trapping layers: SiNx deposited by LPCVD or HfO2 or Al2O3 deposited by ALCVD at 350°C. Then, a 10 nm thick High Temperature Oxide (HTO) is deposited as top oxide plus N+ Si-poly gate. After gate etching, standard processing steps include NiSi silicidation. Using the method presented in [4], the charge density \(Q_{\text{densio}}\) and the effective charged length \(L_{\text{charged}}\) are extracted (Fig.3), based on \(AV,R\) and \(AV,F\) measured during program and retention.

3. Results and Discussions

Programming dynamics - Fig. 4 shows that the programming dynamics are dependent on the trapping layers and this even for short programming pulses, as shown in [6]. However, as shown in Fig. 5 the location of the charge is independent of the material: indeed \(L_{\text{charged}}\) is equal to 40 nm for \(Q_{\text{densio}}\) smaller than \(10^{13}\) cm\(^{-2}\) (stress time of the order of 0.01 s). This can be explained by the fact that all devices have the same junction profile thus they have identical injection efficiency of accelerated carriers by the electric field [3]. Then when \(Q_{\text{densio}}\) reaches \(1.4\times10^{13}\) cm\(^{-2}\) (stress time over 0.01 s), \(AV,R\) continue to increase (Fig. 4) due to the increase of \(L_{\text{charged}}\) (Fig. 5). Seemingly the traps over drain junction becomes saturated, thus newly injected charges can redistribute in the trapping layer farther from the junction. We conclude that the charge distribution behavior during programming is similar for the three materials, even if the device with SiN shows the best capture efficiency during the programming dynamics.

Retention and model - Fig. 7 shows data retention characteristics of devices at 25°C and 125°C. In Fig. 8, the extraction of \(Q_{\text{densio}}\) and \(L_{\text{charged}}\) shows that the \(AV,R\) shift is only due to the lateral charge migration at low temperature (excepted for Al2O3 at 125°C, where the vertical charge loss is the dominant mechanism). We stress that at high temperature (200°C) \(AV,R\) decreases mainly because of vertical electron loss (not shown here). To simulate the lateral migration of the trapped charges the numerical resolution of 1D Drift-Diffusion system is adopted (Fig. 9-10). From Fig. 11 we notice that the diffusion process is negligible with respect to drift, and the drift of charged particles is found equal to \(L_{\text{charged}}\sim L_{\text{charged}}+A\ln(t)\) (Fig. 11) with \(A\) linearly dependent with \(\mu_{\text{eff}}Q_{\text{densio}}\tau_{\text{evp0}}\) and independent of the shape of the injected charge. \(\mu_{\text{eff}}\) corresponds to an effective mobility that includes the trap/detrap process plus the drift in the conduction band [7]. Fig. 12 quantifies the lateral migration of trapped charges \(L_{\text{charged}}\) for Al2O3, HfO2 and SiN. The lateral migration follows a logarithmic law and the lowest drift is observed for SiN.

4. Conclusions

In this paper, we have quantified the localization of the charges during programming and retention in NROM-like devices, based on experimental measurements (in particular of \(AV,R\) and \(AV,F\)) and a surface potential model [4]. It appears that during programming the charge is injected on a 40nm-length region in the trapping layer, with a charge density up to \(1.4\times10^{13}\) cm\(^{-2}\). Then the injected charge density saturates and the trapped charge region broadens. During retention, the lateral migration of the charge appears to be the dominant mechanism of the \(V_s\) shift at room temperature. We have been able to quantify this shift based on a 1D drift model (diffusion being negligible).

References
Fig. 1: ΔV'R (ΔV'F) is the programming window in reverse (forward) read condition.

Fig. 2: Devices under analysis. The devices are 10 µm large and 350 nm long.

Fig. 3: Qdensity and Lcharged as described in [4]. The total charge trapped in the stack is equal to Qdensity x Lcharged.

Fig. 4: ΔV'R dynamics as a function of stress time for virgin devices. Stress parameters V0=10 V, VD=5 V, VS=VB=0 V.

Fig. 5: Extracted Qdensity and Lcharged as a function of time from the dynamics of Fig. 4.

Fig. 6: Qdensity as a function of Lcharged extracted from the dynamics of Fig. 4. VQ=10 V & 12 V, VD=15 V, VS=VB=0 V.

Drift-Diffusion equations

\[ \frac{\partial n(x,t)}{\partial t} = D \frac{\partial^2 n(x,t)}{\partial x^2} \]

Diffusion equation: \( \mu_d=0 \)

\[ \frac{\partial n(x,t)}{\partial t} = \frac{\partial}{\partial x} \left[ D \frac{\partial n(x,t)}{\partial x} \right] \]

Drift equation: \( D=0 \)

\[ \frac{\partial n(x,t)}{\partial t} = A' \frac{\partial}{\partial x} \left[ n(x,t) \int_{x}^{x_e} d\xi \right] \]

where

\[ A' = \frac{\mu_d}{\epsilon} \int_{x}^{x_e} d\xi \]

Fig. 7: ΔV'R evolution at 25°C and 125°C during retention for Si3N4, Al2O3 and HfO2 trapping layers.

Fig. 8: Total charge variation in the trapping layer \( Q_{\text{density}} \times L_{\text{charged}} \) extracted during retention (Fig. 7) at 25°C and 125°C.

Fig. 9: 1D Drift-Diffusion equation and approximations to a perfect diffusion or drift process.

Fig. 10: Explanation of 1D model used to model the lateral migration of the charge. Shapes 1 & 2 are used as initial conditions for simulations of Fig. 11.

Fig. 11: Numerical resolution of the 1D Drift-Diffusion equations. To note that we obtain a perfect fit with a law equal to \( L_{\text{charged}} = L_{\text{charged,0}} + A \ln(t) \)

Fig. 12: Lcharged extracted during retention (Fig. 7) at 25°C for Si3N4, Al2O3 and HfO2 trapping layers. \( A \) is in nm/s.