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SONOS memories with embedded silicon nanocrystals in nitride

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Abstract
We have successfully demonstrated SONOS memories with embedded Si-NCs in silicon nitride. This new structure exhibits excellent characteristics in terms of larger memory windows and longer retention time compared to control devices. Using the same thickness 2.5 nm of the bottom tunneling oxide, we found that N_2O is better than O_2 oxide. Retention property is improved when the thickness of N_2O is increased to 3.0 nm.

(Some figures in this article are in colour only in the electronic version)

Silicon–oxide–nitride–oxide–silicon (SONOS) non-volatile memories have been proposed to overcome the oxide thickness limit of a conventional floating gate structure [1, 2]. In SONOS, charges can be stored in the nitride which offers several advantages over the traditional floating gate flash memory: simple process, higher density, no floating gate coupling effect, multi-bit operation and elimination of the drain-induced turn-on effect [3–5]. Although scaled SONOS can be operated at a low bias, endurance and data retention are still challenging [6]. Recently, metal-oxide-semiconductor (MOS) memories with embedded silicon nanocrystals have attracted a great interest to mitigate the problem of retention and endurance [7–11]. In this paper, SONOS memories with embedded silicon nanocrystals (Si-NCs) are proposed. Si-NCs are introduced inside the silicon nitride film of SONOS structure [12]. We found that the memory window of SONOS with Si-NCs can be increased 2.5 times and the endurance can also be increased significantly.

Figure 1 shows the device's structure. P-type silicon (1 0 0) wafers were used. After the local-oxidation-of-silicon, or LOCOS, isolation step, a tunneling oxide was first thermally grown in N_2O (2.5 and 3.0 nm) or O_2 (2.5 nm). Then, a 3 nm thick silicon nitride film was deposited in a low-pressure chemical vapor deposition (LPCVD) system using SiH_2Cl_2 and NH_3 at 780 °C. Wafers were deposited on a thin amorphous silicon layer which was grown in LPCVD by using SiH_4 (85 sccm, pressure ∼100 mTorr, at 550 °C). This amorphous silicon layer was crystallized into Si-NCs in the following elevated temperature step of nitride deposition. To sandwich Si-NCs, a top 4 nm silicon nitride was capped on the amorphous silicon nucleation. A blocking oxide about 20 nm was then deposited using high-density plasma chemical-vapor-deposition (HDPCVD). A 200 nm thick poly-Si film was deposited as the control gate. Standard MOSFET fabricating steps were followed to complete final devices.

The formation of Si-NCs was confirmed by atomic force microscopy (AFM) as shown in figures 2(*a*)–(*c*). Compared to the control one (figure 2(*a*)), the roughness was increased as the deposition time of SiH_4 was increased from 1.5 min to 2 min. The average size was estimated to be around 8–10 nm and the density can be as high as 3–7 × 10^{11} cm^{-2}. Si-NCs distribution and sizes obtained with AFM were verified using HR-TEM (results to be published elsewhere). These Si-NCs are well separated with an average distance of >6 nm, which ensures electrical isolation between two NCs. The *C*–*V* was measured from the transistor with a W/L of 100 × 100 μm^2 when source/drain were grounded. Figure 3 shows program window of all samples. The programmed state was achieved by a constant $V_G = 25$ V for 10 s. The program windows of SONOS, SONOS with Si-NCs deposited for 1.5 min and

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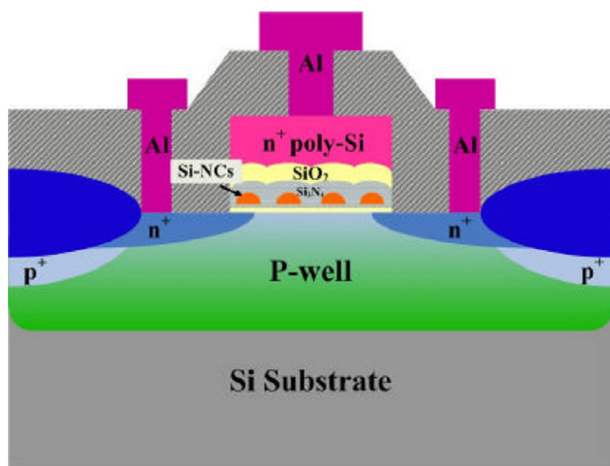

Figure 1. The cross-sectional scheme of a Si-NCs SONOS memory structure with the nitride film embedded with the silicon nanocrystals.

2 min are 3.85 V, 6.25 V and 8.98 V, respectively. It is noted that the program window of Si-NCs is larger than that of the control sample. And large Si-NCs size (2 min) results in a large memory window due to the increased trapping site. The Si-NCs memory window of 8.98 V is large enough for multi-level operation. For this sandwiched structure with embedded Si-NCs, the electrons could be stored in Si-NCs, or at the interface of silicon nitride and Si-NCs. However, from a rough calculation, the charge in each dot would be around 10, which could not result in such a memory window. An alternative explanation is trapping by nitride traps, while Si-nanodots facilitate injection of electrons from the substrate. Therefore the relatively large resultant memory window can be obtained for SONOS with embedded Si-NCs.

The threshold voltage shown in figure 4 is extracted from the constant drain current at 10^{-7} A. The data retention characteristics of the different Si-NC memories at a high temperature of 250 °C are shown in figure 4(*a*). SONOS with Si-NCs exhibits a good performance than the control one.

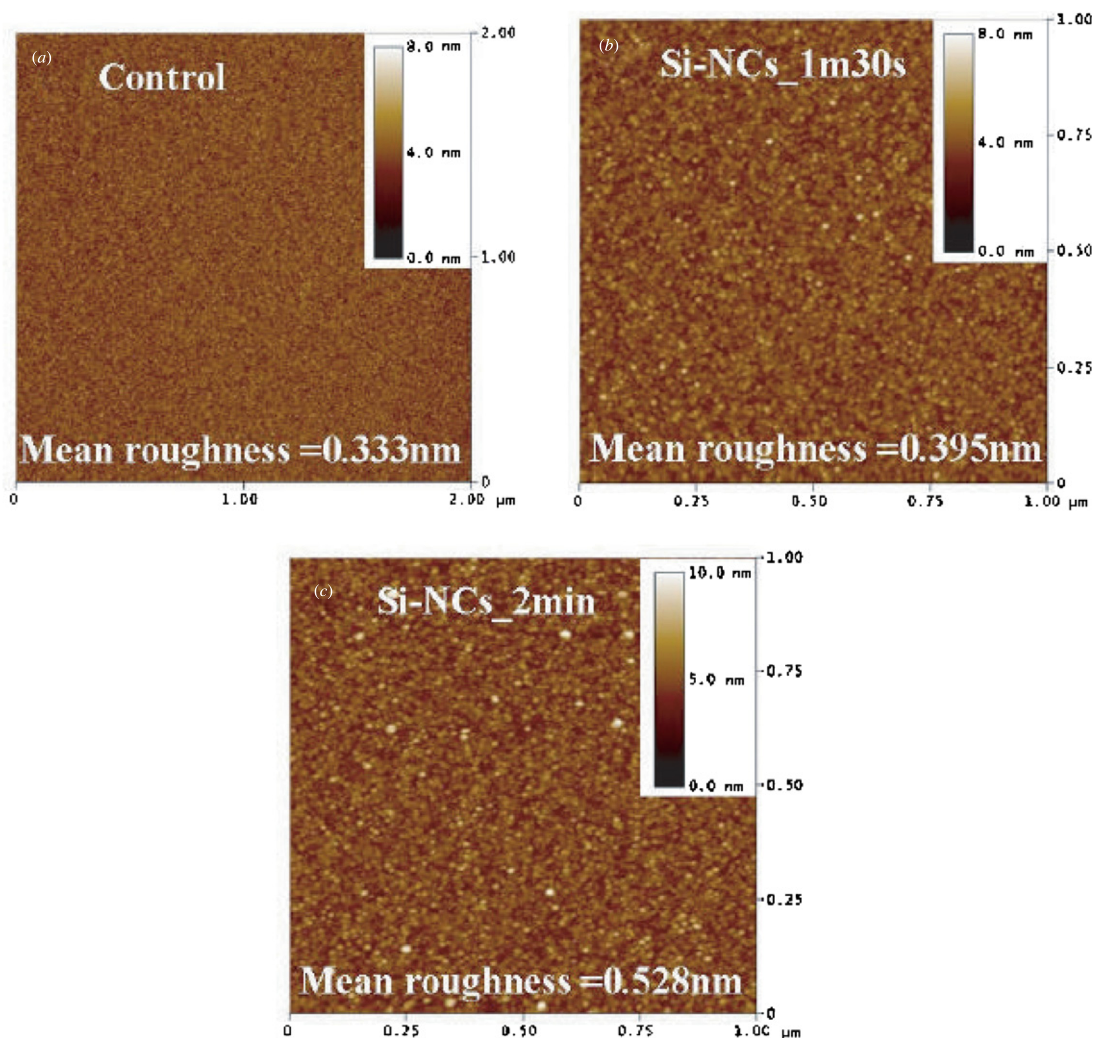

Figure 2. AFM pictures of Si nanocrystals deposited on Si_3N_4 (*a*) control sample, (*b*) Si-NCs_1m30s sample and (*c*) Si-NCs_2 min sample, with the same growth conditions. The densities are, respectively, 6.7×10^{11} and 3×10^{11} cm^2. The diameters are about, respectively, 8 and 10 nm.

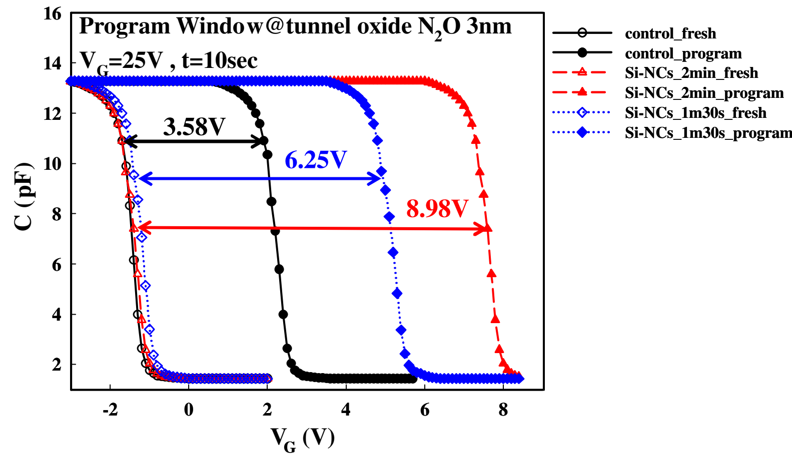

Figure 3. Program window characteristic was a different sample. The program windows of control, Si-NCs_1m30s and Si-NCs_2 min sample are about 3.58 V, 6.25 V and 8.98 V, respectively.

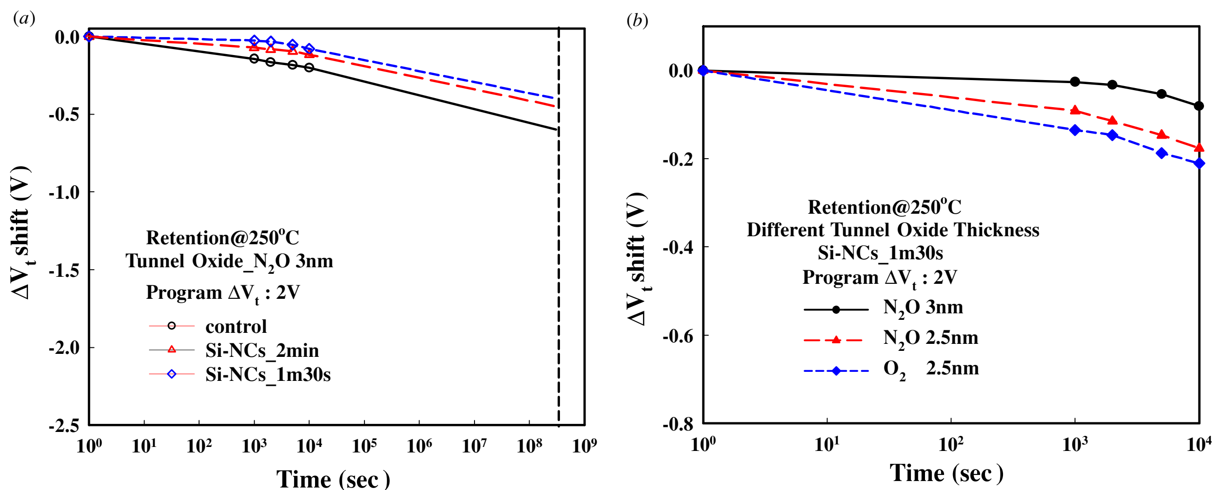

Figure 4. (*a*) Data retention characteristics of different Si-NCs sizes when programming $\Delta V_t = 2$ V at $T = 250$ °C. (*b*) Data retention characteristics of different tunnel oxide films when programming $\Delta V_t = 2$V at $T = 250$ °C.

SONOS with Si-NCs shows only about 0.08 V degradation for 10^4 s. Only 14% charge loss when extrapolates to 10 years. It is known that data loss of SONOS is mainly due to thermionic emission and direct tunneling of charges [13]. The retention performance was not degraded though the trapping efficiency of the memory media with Si-NCs strongly improved. Figure 4(*b*) shows the data retention characteristics of different tunnel oxides with an initial programming $\Delta V_t = 2$ V at $T = 250$ °C. It is found that, with the same thickness of 2.5 nm, N_2O is better than 2.5 nm O_2 oxides due to better quality [14, 15]. On the other hand, retention property is improved when thickness of N_2O is increased to 3.0 nm, resulting from the reduction of direct tunneling probability.

In conclusion, we have successfully demonstrated SONOS memories with embedded Si-NCs in silicon nitride. Based on the above result, embedded Si-NCs in silicon nitride of SONOS memories exhibit excellent characteristics in terms of larger memory windows and long retention time.

Acknowledgments

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