O-1-4

Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp1148-1149

Analysis and Experimental Proof of Deterioration-free Memory Device Using CAAC-IGZO FET

Masashi Tsubuku, Toshihiko Takeuchi, Kazuaki Ohshima, Tsutomu Murakawa, Masashi Fujita, Daigo Shimada, Shota Sambonsuge, Tomoaki Atsumi, Masayuki Sakakura, Kiyoshi Kato, Yoshitaka Yamamoto and Shunpei Yamazaki

Semiconductor Energy Laboratory Co., Ltd. 398 Hase, Atsugi-shi, Kanagawa, Japan
Phone: +81-46-248-1131 E-mail: mt0924@sel.co.jp

Abstract

A field effect transistor (FET) using a c-axis aligned crystalline In–Ga–Zn–O (CAAC-IGZO) for an active layer has an extremely low off-state current. Connecting a CAAC-IGZO FET to a storage capacitor, it is realized that the device behaves as a nonvolatile memory since electric charges are kept. From the results of retention test, data "0" and "1" are distinguishable for more than 2000 hours at 85°C. In addition, test at higher temperature and analysis of the results elucidate that data retention lifetime of this memory device using a CAAC-IGZO FET is estimated over 100 years.

1. Introduction

C-axis-aligned crystalline In–Ga–Zn–O (CAAC-IGZO) is an oxide semiconductor [1]. When it is used as an active layer in a transistor, the off-state current of the transistor is of the order of yA/um, which is much lower than an off-state current of a silicon (Si) transistor. Therefore, various applications using such a field effect transistor (FET) made with a CAAC-IGZO (referred to as a CAAC-IGZO FET), such as memory devices or ultra-low power consumption devices, have been proposed [2-4].

A memory device in which a CAAC-IGZO FET is connected to a storage capacitor behaves as a nonvolatile memory. The retained data is decided by reading charge accumulated in the storage capacitor. This device is referred to as a non-volatile oxide semiconductor random access memory (NOSRAM)". A simple operation of switching the FET allows the NOSRAM to read and write data, and the device has high read/write endurance and low power consumption.

Although operation of the nonvolatile memory device with low leakage is simple, it is difficult to completely prevent leakage of current in actual devices. We evaluated and analyzed leakage of electron charge in order to validate whether this device endures being used practically.

2. Experiment and Result

For measurement, we fabricated 1-kbit-NOSRAM modules. Figure 1(a) shows a circuit of a cell, and Fig. 1(b) is a timing chart. A CAAC-IGZO FET with a channel length of 200 nm was used to write and retain data. Peripheral circuits and readout transistors were configured by Si FETs.

When the voltage applied to the WWL connected with the gate electrode of a CAAC-IGZO FET is "H", the voltage applied to the BL is written in the floating node connected to the storage capacitor. The charge can be retained when the voltage applied to the WWL is "L". We can estimate the amount of the charge from current of the readout transistor.

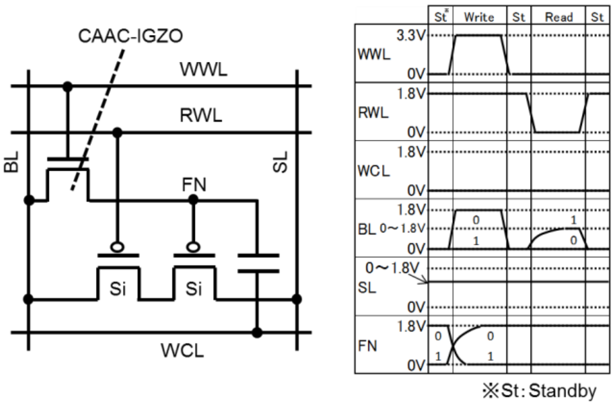

Fig. 1 (a) NOSRAM cell circuit (b) Timing chart

Figure 2 shows the I_d-V_g characteristics of the CAAC-IGZO FET with a 200-nm channel length. In order to retain the data even when V_g (the gate voltage) is 0 V, the threshold voltage was controlled and V_g when I_d is 1 pA was shifted to 1.2 V.

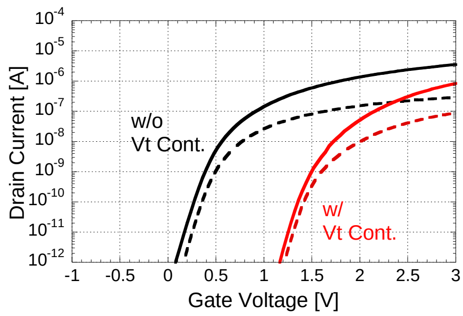

Fig. 2 I_d-V_g characteristics of CAAC-IGZO FET
(Solid Line: V_d = 1.8 V, Dashed Line: V_d = 0.1 V)

In the previous report, the characteristics of the NOSRAM module did not vary after 10^{12} times of rewriting [2]. We have not obtained data indicating that the retention characteristics of the NOSRAM module are sufficient for a nonvolatile memory.

In this paper, we carried out a retention test and the newly obtained results are shown in Fig. 3. In a usual operation, data "1" and "0" are read by determining whether the voltage of the floating node is higher or lower than the voltage of the SL. However, to analyze the retention characteristics, we varied the voltage of the SL and measured the voltage at which the readout transistor was switched from "on" to "off" (maximum read voltage, V_{RM}) to indirectly evaluate the distribution of the electric charges accumulated in a storage capacitor.

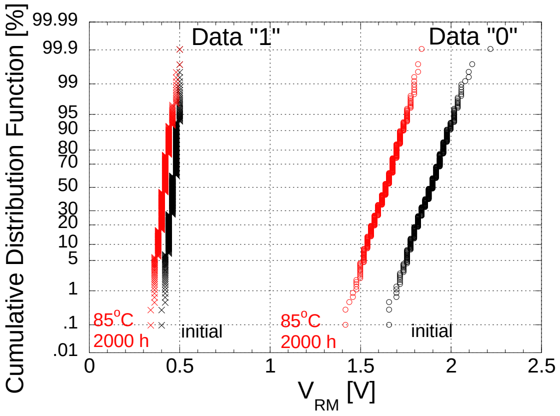

Fig. 3 Distribution of electric charges in retention test

As a result, it was confirmed that the data "1" and "0" were sufficiently distinguishable for 2000 hours at 85°C, and reading margins between "1" and "0" were reserved sufficiently.

3. Discussion

As shown in Fig. 4, the off-state leakage current of the CAAC-IGZO FET is 100 yA/mm at 85°C[5]. This indicates that the electric charge stored in a capacitor hardly varies due to the leakage current of the CAAC-IGZO FET.

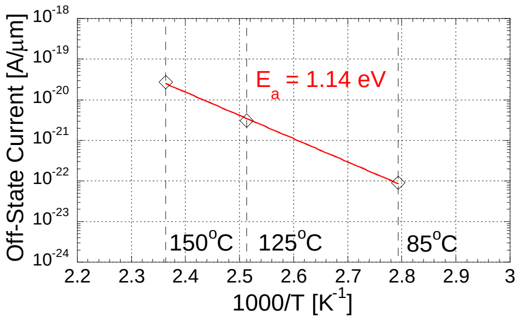

Fig. 4 Off-state current of CAAC-IGZO FET

From this result, the activation energy of the off-state leakage current is estimated to be as large as 1.14 eV. In order to calculate the data retention lifetime of the NOSRAM, we carried out an acceleration test at 175°C, 150°C and 125°C. The average of the voltage of floating node (FN) at each of the temperatures was plotted against time in Fig. 5.

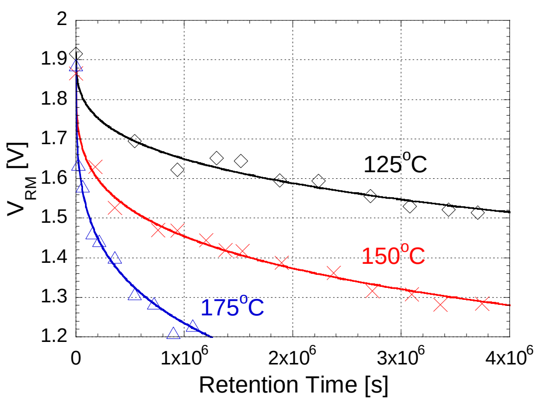

Fig. 5 Voltage drop of FN in acceleration test

From this result, it is confirmed that the voltage drop due to leakage current is approximated to the stretched exponential function expressed by eq. (1).

$$V(t) = V_0 \times \exp\left\{\left(-\frac{t}{\tau}\right)^{\beta}\right\} \quad (1)$$

(V_0 : initial voltage, τ : relaxation time, β : power law)

The aforementioned stretched exponential function is known as the Kohlrausch–William–Watts function [6,7]. This function is an empirical description of the relaxation of polarization or charge distribution of a dielectric, and is used to explain long time decays in trapping processes, non-radioactive exciton recombination, etc. The fitting parameter calculated from this equation is shown in Table I.

Table I Parameters calculated from KWW function

	V_o [V]	τ [s]	β
175°C	1.89	1.8×10^{7}	0.30
150°C	1.87	1.1×10^{8}	0.30
125°C	1.91	6.1×10^{8}	0.29

With this parameter, the relaxation time τ at 85°C, which is proportional to the memory retention time, was calculated according to Arrhenius' law. The result is shown in Fig. 6. The obtained activation energy was 1.08 eV and the same as that of the off-state leakage current of the CAAC-IGZO FET. From this result, the relaxation time at 85°C was estimated to be 2.1×10^{10} s, and it was found that the memory retention lifetime of the NOSRAM could be over 100 years.

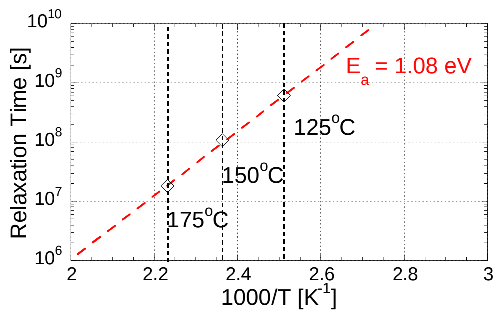

Fig. 6 Arrhenius' plot of relaxation time in NOSRAM

4. Conclusions

We evaluated the retention characteristics of the NOSRAM module using a CAAC-IGZO FET, and the retention characteristics sufficient for a nonvolatile memory could be obtained. Application to an ultra-low power consumption device can also be expected due to its read/write endurance and simple operation.

References

1. S. Yamazaki et al., Jpn. J. Appi. Phys., 53, 04ED18 (2014).
2. T. Matsuzaki et al., IEEE Int. Memory Workshop, 183(2012).
3. H. Inoue et al., IEEE JSSC, 47, 2258 (2012).
4. T. Ohmaru et al., Ext. Abst. SSDM, 1144 (2012).
5. K. Kato et al., Jpn. J. Appi. Phys., 51, 021201 (2012).
6. R. Kohlrausch, Annalen der Physik und Chemie (Poggendorff), 91, 179 (1854).
7. G. Williams and D. C. Watts, Trans. Faraday Soc. 66, 80 (1970).