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# Hydrogen-and-Stress-Induced de-lamination in an $IrO_2$ layer of FRAMs

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## 1. Introduction

FRAMs (ferroelectric random access memories) draw much attention as a NVRAM (non-volatile random access memory) device due to the fact that they have ideal memory properties such as a fast READ/WRITE speed (200 MB/s in bandwidth), low power consumption (~μA in stand-by current), and reasonable memory density (several ten megabit or more)[1]. To meet the requirement of customers' need in a package level, several acceleration tests such as HTOL (high temperature operational life) test and HTS (high temperature storage) test, has long been applied to ensure a device lifetime. During the high temperature tests, in our case, a few defective points have appeared and localized in specific cell arrays. The main cause of the imperfection turns out to be physical de-lamination of the $IrO_2$ layer in vertical conjunction to pulsed plate-line, so-called here ATE, additional-top-electrode (see Fig.1) In one hand, $IrO_2$ can, in general, be readily affected by many ambient conditions such as temperature, pressure, and hydrogen or its related materials[2-4]. On the other, reduction of the $IrO_2$ layer often become metallic Ir, stress value of which is approximately one order of magnitude larger than that of conventional metals. Thus, in this paper, we present how heat treatments of BEOL (backend of line) integration influence $IrO_2$ to be reduced. Also, we simulate stress distribution in cell arrays depending on how many dummy cells have been taken into account. Along with this, we suggest a schematic model to describe the possible paths of hydrogen involvement during the BEOL integration.

## 2. Results and Discussion

*Experiments*

Capacitor-level reliability tests is carried out on the cell arrays of test-element-group (TEG) in fully integrated wafers[5-6]. Package-level reliabilities have also been evaluated thoroughly and analyzed in detail <see reference[6]>. After wafer-level tests, individual prime dies have proceeded to a conventional packaging process for the standard qualification tests. 2-dimensional stress simulation in cell arrays has been done by utilizing a commercial tool, ABAQUS CAE ver. 6.7.1.

*Results and Discussion*

Despite satisfying results from retention and endurance characteristics obtained in a capacitor level, 64 Mb FRAMs in device-level packages have failed in the HTS and HTOL tests. The defective cells in function-failed packages during the tests are localized at the corner of the memory cell arrays. Fig. 1(a) represents a plan view of the failed cell capacitor by FIB. Note that we investigated a FIB-focused ion beam, tool for a structural analysis of a bit failure because FIB is in general useful to track a failed cell in scramble of entire memory cells.

Fig. 1(b) is a STEM (scanning transmission electron microscope) image of the dashed rectangle in Fig. 1(a). As shown in Fig. 1(b), the $IrO_2$ layer disappeared and formed a gap between ATE Ir and TE Ir. The gap was confirmed by rastering of EDX (Energy Dispersive X-ray) between 'A' and 'B' as marked in Fig. 1(a). Fig. 2 describes the mapping results of Ir and oxygen through this EDX spectroscopy. An Ir density profile between 'A' and 'B' has a dip while an oxygen profile does not have any prominent peaks and dips but shows a plateau over a scanned region. This suggests that the interface region between ATE Ir and TE Ir is an empty gap. This empty space could come from the two kinds of origin. One is the reduction of $IrO_2$ with involvement of hydrogen-related products contained in the inter-layer dielectric (ILD) and inter-metal dielectric (IMD)

$$\langle IrO_2\rangle \rightarrow \langle Ir\rangle + (O_2) : Kp = P_{O2} \qquad (1),$$

↑ Hydrogen-related products

where angular bracket denotes solid state and parenthesis bracket represents the gaseous state. From this reaction formula, $IrO_2$ is readily reduced to Ir. Also, atomic hydrogen or hydrogen- related products may accelerate this dissociation process, combine with oxygen, and then finally make gaseous phase of water. We make a model for the diffusion paths of atomic hydrogen during BEOL processes to the $IrO_2$ layer as shown in Fig.3. The path 'A' is a route from the IMD to the $IrO_2$ layer via Metal 1 and ATE Ir. The path 'B' is for the hydrogen in the ILD formed after etching process of ATE Ir. The path 'C' is in the ILD after the capacitor-patterning process. All the paths are connected each other because the EBL (encapsulated barrier layer) is covered the ferroelectric capacitor. The other is the de-lamination by the opposite state of stress distribution between ATE Ir and TE Ir. From the two-dimensional stress simulation at the very edge of the suspected cell arrays, we can obtain a S22 value defined by stress projected on the surface normal, the $IrO_2$ layer. Fig. 4 show stress projected on the $IrO_2$ layer as a function of memory cells located from the very edge boundary. In case of having a couple of dummy cells, the stress S22 is relatively uniform. By contrast, S22 distribution in case of no dummy cell shows not only an abrupt change in the stress at the boundary but fluctuates so much that the value of the stress has one or two ups and downs even on the middle of memory cells in location. Combined with the reduction of $IrO_2$ layer by hydrogen and its related products, we think that the dummy-cell absence could cause a de-lamination between the two.

Accordingly, it is desirable to make the remaining hydrogen-related products as low as possible during the BEOL integration and the stress distribution in the $IrO_2$ layer as uniform as possible. Based on the model suggested

here, we apply a certain number of dummy cells surrounding the cell arrays and additional heat treatments to each process step of the BEOL integration: ILD, ATE, and IMD.

Fig. 5 shows *P-V* (polarization-voltage) hysteresis curves of the edge region of the cell arrays with and without dummy patterns. As seen in Fig.5, in contrast to the well-saturated *P-V* loop in case that dummy cells exist, the *P-V* loop in case of no dummy is not only slanted under the positive switching condition due to a large amount of depolarization, but also slightly rounded under the negative switching. We think that the latter is because of an increase in interfacial imperfection.

Fig. 6 shows a STEM micrograph of the $IrO_2$ layers after applying several anneal processes. No gap between the ATE Ir and the TE Ir has been observed. After the HTS and HTOL tests after 500 hours, the $IrO_2$ layer has a crystalline phase, which is different evidently from the case in which none of heat treatments has been applied.

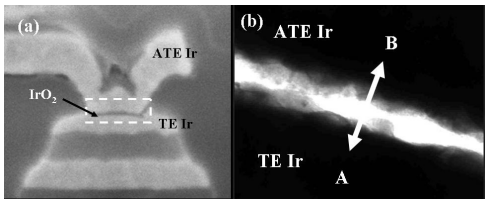


Fig. 1 (a) Micrographs of the failed cell capacitor after an HTS test during 500 hours in package-level and (b) a STEM image of the dashed rectangle in Fig. 1(a).

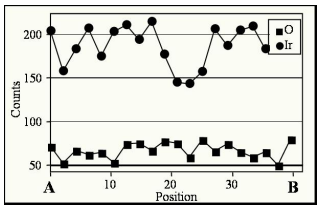


Fig. 2 The scanning profiles of an EDX spectroscope at the ATE Ir/$IrO_2$ /TE Ir layer from A to B in Fig. 1(b).

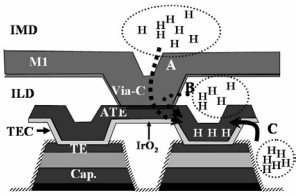


Fig. 3 The possible diffusion paths of atomic hydrogen for a path 'A' arising from forming-gas anneal processes, for a path 'B' resulted from ILD processes after the ATE formation, and for a path 'C' due to ILD processes after formation of the cell capacitors .

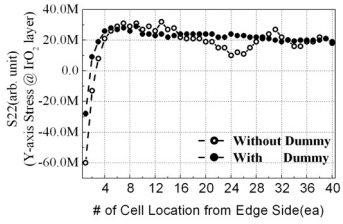


Fig. 4 Stress projected on the $IrO_2$ layer as a function of the number of memory cells located from the edge boundary.

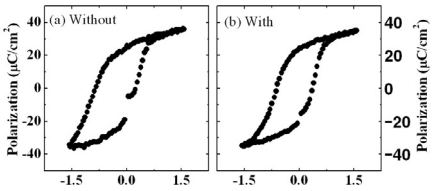


Fig. 5 *P-V* hysteresis loops of the edge cell (a) without and (b) with dummy cells applied.

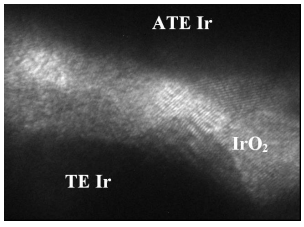


Fig. 6 A STEM image at the $IrO_2$ interface between ATE Ir and TE Ir after the HTS and HTOL test.

## 3. Conclusions

In the BEOL integration for a ferroelectric memory device, several anneal processes including forming gas anneals play a considerably critical role in device lifetime tests such as HTOL and HTS tests. It is essential to consider a deliberated anneal procedure in the BEOL integration. This is because otherwise case may provoke a contact failure in pulsed plate-line node of cell arrays. We think that this failure stems either from the reduction of $IrO_2$ by the penetrated hydrogen at the interface between ATE Ir to TE Ir or from lack of dummy cells applied, or both. We also think that both may give rise to a gap at the interface. To rid the gap of $IrO_2$, the remaining hydrogen should be burned out at each step by introducing additional heat treatments and the fluctuation of the stress projected on the $IrO_2$ layer should be controlled uniformly by adding a certain number dummy cells.

## References


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