The Novel Stress Simulation Method for Contemporary DRAM Capacitor Arrays

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***Abstract*— The increasing of aspect ratio in DRAM capacitors causes structural instabilities and device failures as the generation evolves. Conventionally, two-dimensional and three-dimensional models are used to solve these problems by optimizing thin film thickness, material properties and structure parameters; however, it is not enough to analyze the latest failures associated with large-scale DRAM capacitor arrays. Therefore, beam-shell model based on classical beam and shell theories is developed in this study to simulate diverse failures. It enables us to solve multiple failure modes concurrently such as supporter crack, capacitor bending, and storage-poly fracture.**

Keywords—capacitor stress; large-scale simulation; beam-shell model

I. INTRODUCTION

The demands for high-performance DRAM (Dynamic Random Access Memory) with low power consumption lead the continuous development of HAR (High Aspect Ratio) structure capacitor. This HAR structure, however, is the primary source of structural instability and process failure, e.g. top-bridge and capacitor leaning. To prevent these problems, a MESH-type (Mechanically Enhanced Storage node for virtually unlimited Height) capacitor having supporter structure is required and developed [1-4] (Fig. 1).

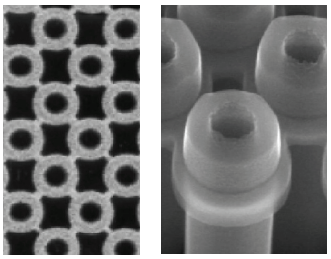

Figure 1: SEM image of MESH type capacitor with supporter.

Recently, multilayered thin film supporter to prevent capacitor leaning becomes the reason of process failures such as storage-poly fractures, supporter crack and capacitor bending. Capacitors can be modeled with simple two-dimensional structure or partial three-dimensional structure until now. However, these methods cannot deal with various failures associated with each other. Moreover, new model should be developed on each occasion. This paper reviews the models and results of simple two-dimensional and localized three-dimensional analysis with conventional method and introduces the novel method of integrated stress simulation that enables to simulate approximately 60 thousand capacitors in maximum based on beam and shell theory.

II. SIMPLE 2D MODEL

Two-dimensional stress analysis using simple composite model focuses on the determination and improvement of process failure. This analysis predicts single capacitor behavior depending on vertical movement of supporter or lateral movement of capacitor i.e. bending and adherent due to capillary force during cleaning process. Fig. 2 shows fragmentary failure analysis of unit block shrinkage after SiGe passivation process and it has enough predictability with very high correlation between simulation data and experiment data.

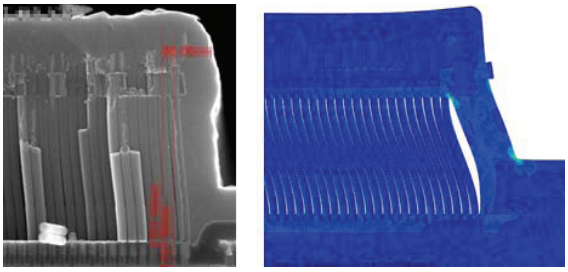

Figure 2: SEM images and simulation results of unit block shrinkage after SiGe passivation process. The Simulation result is magnified by original scale.

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Somewhat, such analyses have a major role in understanding and improvement of the process failures. As to unit block shrinkage, in case of same generation device, it is simulated and verified that the unit block shrinkage is proportional with the number of capacitor, i.e. the size of unit block (Fig. 3). It can be easily observed on cell and peripheral block.

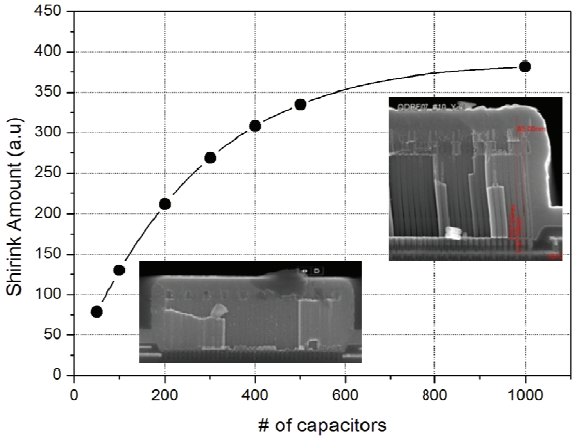

Figure 3: Shrinkage along with various numbers of capacitors is verified by fabrication data.

Contrastively, the shrinkage of two 2x nm generation capacitor blocks in DRAM devices are predicted differently and it makes useful guide for chip size design. Also, this result shows us fabrication difficulty is going higher than ever (Fig. 4).

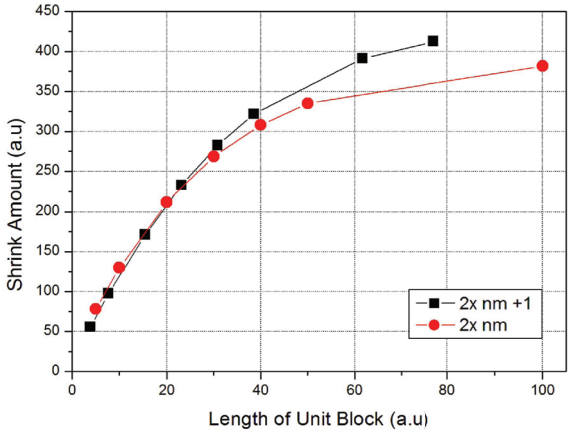

Figure 4: Shrinkage along with two kinds of design rule. It shows fabrication condition is getting worse along with generation development.

III. LOCALIZED 3D MODEL

Reasonably, simulation with full three-dimensional structure about whole area is ideal; however, localized i.e. partially discretized three-dimensional model composed from 3 by 3 to 8 by 8 unit size is simulated due to the limitation of computational resources like the limitation of memory and simulation time. The major failure analyses of localized three-dimensional model are storage-poly fracture, supporter crack and capacitor bending. Since three-dimensional model cannot be simulated with large-scale capacitor unit, the failure structure should be simplified or partially modeled with small unit. Storage-poly fracture and capacitor bending are analyzed with intrinsic stress value and Young's modulus of various supporter materials. These kinds of failure are improved by optimization of stress value and thickness of supporter.

Furthermore, the idea of small size discrete supporter is developed to optimize capacitor modulus and prevent bending and crack. The size of discrete supporter is well optimized together to avoid capacitor leaning and bending (Fig. 5). Based on this simulation, the fabrication of discrete supporter structure is obtained successfully without any failures.

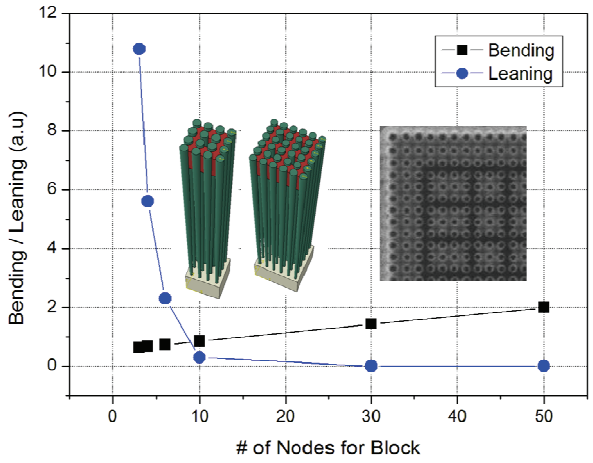

Figure 5: Discrete supporter size optimization between capacitor leaning and bending. And top-view SEM image of its fabrication.

As mentioned earlier, above simple two-dimensional and localized three-dimensional model are very useful to understand mechanical failure in a point of view local stress-engineering and optimization of thin film intrinsic stress. But, they have a limitation that they cannot simulate complicate phenomenon of capacitor with full three-dimensional structure. Also, these methods cannot analyze various correlated failures. So we propose the novel method of stress simulation with large-scale capacitor as below.

IV. LARGE-SCALE INTEGRATED MODEL

In DRAM capacitor, the stress analysis for structural stability is getting complicated. Since the localized three-dimensional model has abovementioned limitations in analysis and prediction of stress failure, integrated large-scale simulation should be introduced. Therefore, a novel method of stress simulation is developed for contemporary DRAM

capacitor arrays based on the beam theory of Euler-Bernoulli and Timoshenko and shell theory of Kirchhoff-Love and Mindlin-Ressner [5-8]. The essential method of this model is capacitors are described as beam elements from the elastic theory point of view and supporters are simplified as shell elements (Fig. 6).

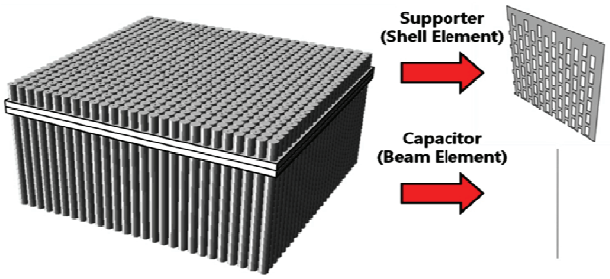

Figure 6: Beam and shell elements are modeled for large scale capacitor simulation.

Three-dimensional capacitor shapes can be substituted to beam element as below. After modeling of detailed capacitor shapes surrounded dielectric film on top and bottom electrode, measure the displacement and deformation applying force with axial and lateral direction. And calculate equivalent Young's modulus from capacitor with single material to get same displacement and deformation. In other words, an equivalent Young's modulus for the beam element is derived by homogenizing the material property of full three-dimensional model, and validated by comparing its deflection behavior (Fig. 7). In our study, error between three-dimensional shape and beam element is less than single figure percentage.

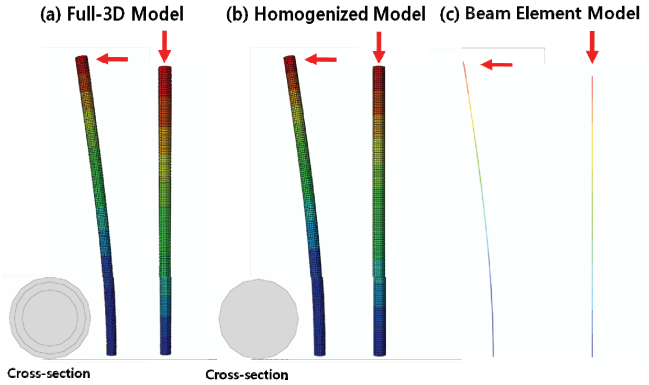

Figure 7: An equivalent Young's modulus is derived by homogenizing the material property of full 3D model.

In the same way, the shell element model considers the behavior of multiple composite layers [9].

Through this one-step integrated method, up to 120 by 120 array capacitors can be simulated and various stress induced failure modes can be detected at a time, i.e. 60 thousand capacitors with symmetry condition (Fig. 8).

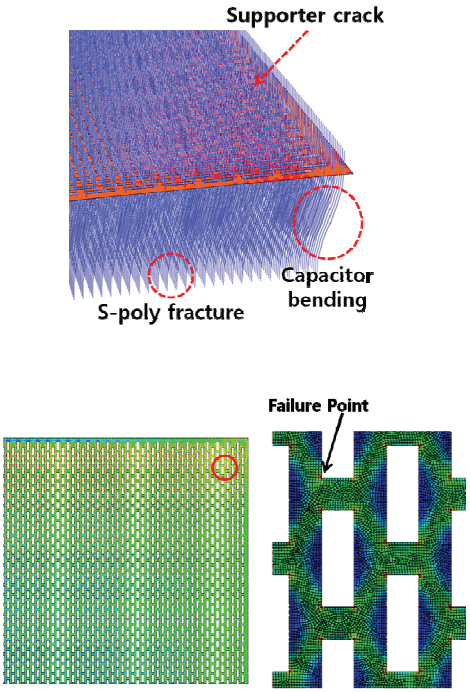

Figure 8: Large-scale simulation is able to analyze integrated various stress failure like crack, fracture and bending at a time.

This means the relationship between these various failures and quantitative simulation based on material properties can be also simulated. In addition, the reliability error and convergence of simulation is enhanced according to the increase of simulation domain. And it shows our domain size is enough to represent full size of capacitor (Fig. 9).

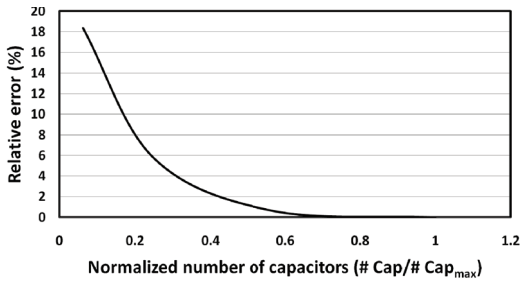

Figure 9: Solution convergence result in accordance with number of capacitors.

Lately, we predict the crack stress with new supporter materials using the beam-shell model. Thinner supporter can improve capacitance of DRAM, but this makes the structure more vulnerable supporter crack. Therefore, supporter thickness, material property and pattern of open area should be optimized.

Fig. 10 shows crack stress change with supporter thickness and two kinds of supporter material. It shows thicker supporter lead to less crack stress and material 2 is more stable to crack. Fig. 11 shows crack stress change with intrinsic stress of supporter material. Normally intrinsic stress of material can be controlled by process temperature and deposition rate. Critical stress is measured at the point of crack occurred in fabrication. With this result, we can choose supporter material and optimize thickness and intrinsic stress.

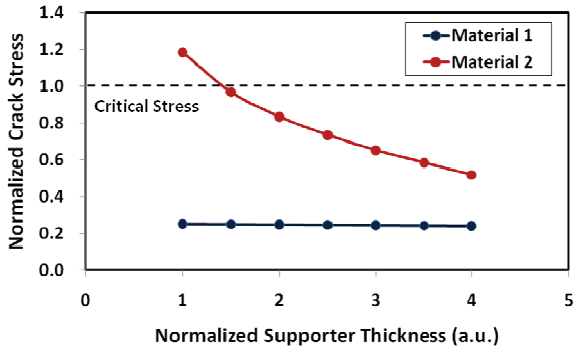

Figure 10: Crack stress change along with supporter thickness and material.

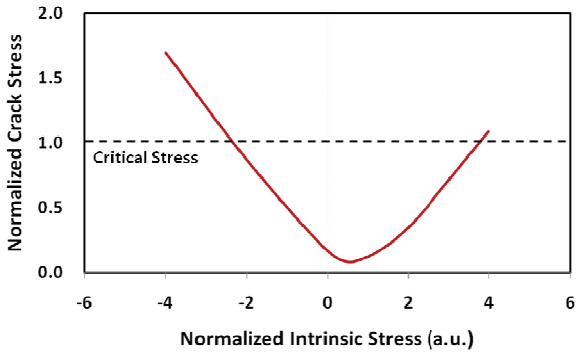

Figure 11: Crack stress change along with supporter intrinsic stress.

With this method, we can solve various problems associated with HAR structure capacitor and prevent various stress-induced failures with structurally stable capacitor block. We can also enhance capacitance with minimal supporter thickness to maximize area of surface.

V. Conclusions

A various failure in capacitor with HAR structure that increase upon DRAM scaling causes delay of development period and rising of development cost. To minimize stress-induced failures we have optimized processes and analyzed various failures through two-dimensional and three-dimensional simulation model. Due to the increase of complexity in capacitor structure and stress analysis, large-scale simulation is needed. Therefore, we developed an integrated analysis model with up to 60 thousand capacitors based on the beam and shell theory. As a result, process yield and capacitance are enhanced and verified successfully through fabrication.

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