Detection of hidden defects in low-k dielectrics by atomic force microscopy

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Abstract. A new nondestructive technique for detection of latent defects in the interlevel low-k dielectric using atomic-force microscopy in the PFQNM mode with a lateral resolution of 8 [nm] is proposed. It has been established that cavities embedded in the dielectric structure influence the magnitude of the detected deformation (from 1.1 to 3.5 [nm]) and the Young’s modulus (from 5.5 to 1.5 [GPa]). It is shown that this method allows to detect defects in the structure of a low-k dielectric located at a depth of 50 [nm] under the surface.

1. Introduction

One of the key issues of modern micro- and nanoelectronics is the creation of new materials with low dielectric constant (low-k) for their integration into the multilevel metallization system to reduce RC delay [1-2]. The development of new processes and materials is associated with the possible occurrence of unpredictable defects in the low-k dielectric, such as film cracking or internal cavities production [3]. Visual methods, such as optical microscopy or electron one, are used nowadays for the localization of such kind defects [4-5]. However these techniques are well suited for defects located directly on the surface, but they are unsuitable for internal defects located inside the dielectric.

This research presents the results of hidden defects detection in the structure of low-k dielectrics by atomic force microscopy (AFM). The AFM operation is based on the interaction between the surface and the probe-cantilever [6]. The cantilever is a silicon console with a beam attached to it. At the end of the beam, a probe is formed, which has the shape of a cone with a radius of curvature at the end from 1 to 50 [nm] [7]. The force acting on the probe from the surface leads to cantilever bending. The AFM optical system registers the deviation of the laser beam reflected from the cantilever by a photo detector and converts this signal into information about the topography and other surface characteristics [8]. In this work the AFM is used in the mode of nanomechanical mapping.

The PeakForce Quantitative Nanomechanical Mapping (PFQNM) mode also known as quantitative nanomechanical mapping is a new semi-contact AFM mode, which allows to record the power curves at each point of interaction with the sample, in addition to nanometer-resolution topography. Force curves are used to obtain mechanical properties of the sample, including deformation, adhesion strength, dissipation, and Young's modulus (see Figure 1) [9].

Deformation (indentation depth) shows sample ability to change shape when a probe presses on it. The value of the Young's modulus is a mapping of its calculated values along the force curves [10]. The Sneddon and Deryagin-Muller-Toporov (DMT) models are used to calculate the Young's modulus.
The Sneddon model considers interaction with a sample of a rigid spherical probe formed on an elastic surface and it is used in the study of soft materials (e.g. biological ones) if the probe penetrates the sample to a depth of at least 50 [nm] [11]. The DMT model is used for solid materials, in which the conical interaction of the probe with the surface is considered [12].

The result of the study of the surface in the PFQNM mode is a set of illustrations that characterize topography, deformation, and Young's modulus at each point of interaction between the probe and the sample. Lateral resolution of the technique depends on the radius of the probe and varies in the range from 1 to 50 [nm].

![Figure 1. Approach/retract power curves in the PFQNM mode.](image)

2. Experiment details
Spin-on porous OSG (organosilicate glass) low-k dielectric deposited on Al patterns was used as a test vehicle. Preparation of film-forming solutions for the formation of low-k films was carried out by cohydrolysis of silicon alkoxides: tetraethoxysilane (TEOS) – Si(OCH₂CH₃)₄ and methyltriethoxysilane (MTEOS) – CH₃Si(OCH₂CH₃)₃ in the acid conditions. The concentration of porogen Brij 30 was 42 wt. %. Solution preparation is described in more details in [13-14].

Spin-on deposition was performed at the rotation speed of 3500 [rpm] with the help of WS-650-8NPP (Laurell, USA) spin coater. Silicon wafers with the resistivity of 10 [Ohm·cm] and a pre-formed single-level aluminum metallization system were used as substrates. The height of Al conductors was 800 [nm], the distance between Al lines was 800 [nm]. The film was dried in a pulsed infrared (IR) oven at about 200°C [°C] for 5 [min], and then in an isothermal oven in air at T_a = 400°C [°C] for 30 [min].

The PeakForce QNM technique is implemented on a *Bruker Dimension Icon* atomic force microscope. The measurements were carried out using the *RTESPA MPP-13100* cantilever (Table 1).

| Table 1. Characteristics of the cantilever RTESPA MPP-13100. |
|-------------------------------------------------------------|
| Probe height | Beam length | Beam width | Probe radius | Stiffness coefficient of cantilever (nN) | Resonant frequency (kGz) |
| (μm)         | (μm)        | (μm)       | (nm)         |                                      |                          |
| 20           | 125         | 40         | 8            | 200                                    | 525                       |
The measurements of the Young’s modulus were carried out with the following parameters: scan area – $1 \times 5$ [$\mu$m], image resolution – $256 \times 256$ [points], impact force 100 [nN].

3. Experiment results and discussion of them

Figure 2 shows AFM mapping of the same surface area with lateral dimensions $1 \times 5$ [$\mu$m] of Al structures with OSG low-k dielectric layer, including images of the topography, deformation and Young’s modulus.

Analysis of the surface topography shows that the dielectric material is uniformly deposited on the aluminum structures, the surface roughness is less than 1 [nm]. The height difference in the area above and between the conductors is 50 [nm] and does not change over the entire area (Figure 2a). Thus, the analysis of the surface topography indicates the absence of defects in the low-k layer deposited on Al structures.

Figure 2. AFM image (1x5 µm) mapping: a) topography; b) deformations; c) Young’s modulus.

Strain distribution map shows that the deformation is the same in the areas above and between the conductors and approximately equals to 1.1 [nm]. However, the deformation increases on the boundary of the conductors be as great as 2 [nm] for the left border and 3.5 [nm] for the right one (Figure 2b). In general the change in deformation on the conductors boundaries can be explained by the fact that in these areas the probe interacts with the sample at an angle (due to change in topography), which contributes to a change in the contact area between the probe and the sample. The difference in strain values for the opposite edges of the conductor is presumably caused by the choice of scanning direction, but its changes do not affect the result.

The map of the Young’s modulus distribution shows correlation with the deformation distribution. For the areas above and between the conductors, the value of $E$ is 5.5 [GPa], which corresponds to the $E$ value obtained for the low-k film deposited on silicon wafer without Al relief. However, there is significant distinction between the $E$ value on the left and right conductor boundaries: 4 [GPa] and 1.5 [GPa] respectively (Figure 2c).

The anomalous values of the deformation and the Young’s modulus are observed on the right conductor boundary. It may be suggested, that the reason lies in some kind of defects located in this region. To check this suggestion a cross section was made using the focused ion beam method (Figure 3a). The corresponding Young’s modulus distribution map is shown in Figure 3b.
Figure 3. Cross-sectional view (a) and corresponding Young’s modulus distribution map (b).

The cross-sectional image shows that cavities were formed on the right conductors’ edges during the low-\( k \) dielectric film preparation. The lateral dimensions and location of the cavities well correspond to the Young’s modulus and deformation maps obtained by AFM in the PFQNM mode. The cross-sectional image illustrates that the cavities are separated from the surface by a dielectric film with the thickness of about 50 [nm]. For this reason it is impossible to detect them by optical techniques.

It should be noted that the part of the cavity located at the bottom of the gap between Al conductors does not affect the Young’s modulus and deformation values obtained in the PFQNM mode. The low-\( k \) film thickness over the cavity in the scanning area is about 800 [nm]. So it can conclude that the proposed technique has limitation on the depth of defects location.

4. Conclusion
A new nondestructive technique for detection of internal hidden defects in the low-\( k \) dielectric structures is proposed. It is shown that formation of cavities inside the low-\( k \) film leads to change of the Young modulus value (decrease from 5.5 to 1.5 [GPa]) and deformation value (increase from 1.1 to 3.5 [nm]) obtained by AFM in the PFQNM mode. The proposed method can be considered as nondestructive due to very low impact on the sample (100 [nN]).

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