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FIB Micro-pillar sampling of Si devices and its 3D observation

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Abstract

A novel technique for three-dimensional structural and elemental analyses using a dedicated focused ion beam (FIB) and scanning transmission electron microscope (STEM) has been developed. The system employs an FIB-STEM compatible sample holder with sample stage rotation mechanism. A piece of sample (micro sample) is extracted from the area to be characterized by the micro-sampling technique [1-3]. The micro sample is then transferred onto the tip of the stage (needle stage) and bonded by FIB assisted metal deposition. STEM observation of the micro sample is carried out after trimming the sample into a micro-pillar 2-5 micron squared in cross-section and 10 -15 micron in length (micro-pillar sample). High angle annular dark field (HAADF) STEM, bright field STEM and secondary electron microscopy (SEM) images are obtained at 200kV resulting in three-dimensional and cross sectional representations of the micro-sample. The geometry of the sample and the needle stage allows observation of the sample from all directions. The specific site can be located for further FIB milling whenever it is required. Since the operator can choose materials for the needle stage, the geometry of the original specimen is not a limiting factor for quantitative energy dispersive X-ray (EDX) analysis.

Introduction

New materials such as electronic and semiconductor devices have been moving toward higher integration and density and their sizes are expected to continue shrinking. In characterization or failure analysis of these materials and devices, requirements for analytical TEMs are rapidly increasing. FIB technique is becoming more prevalent for sample preparation of specific areas of interest for TEM investigation [4]. The FIB technique has advantages in every step of the sample preparation procedure, including specifying the milling area, monitoring the milling procedure, and confirming the finally thinned area. Each step is carried out with the help of scanning ion microscopy (SIM) image observation.

An FIB-based sample preparation technique has the unique ability to make site-specific TEM specimens available directly from bulky samples [1-2]. In addition, the technique allows cross-sectional and plan view TEM sample preparation from the same initial material. Usually a sample should be thinned to a thickness of 0.1 micron or less for TEM observation. However, structural information obtained from such a thin film is two-dimensional, and it is difficult to characterize complicated structures in electronic devices.

This paper describes a novel technique for preparation of a piece of pillar shaped sample (micro-pillar sample) and its three-dimensional characterization using the FIB-STEM compatible 3D-observation sample holder.

Materials and method

Instruments used in the study are the Hitachi FB-2100 FIB system and the HD-2300 200kV STEM. The FIB system is attached with a mechanical probe made out of W, which is used to extract the micro sample. An FIB-STEM compatible 3D-observation holder has been newly developed for this study. An external view of the FIB-STEM compatible 3D-observation holder is shown in Figure 1. The holder can be used for both sample milling in the FIB system, and image observations in the STEM. The holder has a stage rotation mechanism that permits insertion of a needle shaped sample stage on the rotation center. The needle stage has a flat tip with a diameter of about 30 microns for mounting micro-pillar samples (Fig. 2). Since the operator can choose the material used to construct the needle stage on which a micro-pillar sample is mounted, background peaks from the stage will not interfere in quantitative elemental analysis using energy dispersive X-ray (EDX) systems. A schematic of the micro-pillar sample mounted on a needle stage, which is inserted on the rotation mechanism, and its position and orientation relative to the electron beam and the FIB are illustrated in Figure 3. Since the sample is located at the center of rotation and tilting axes, the sample does not shift during rotating or tilting operations.

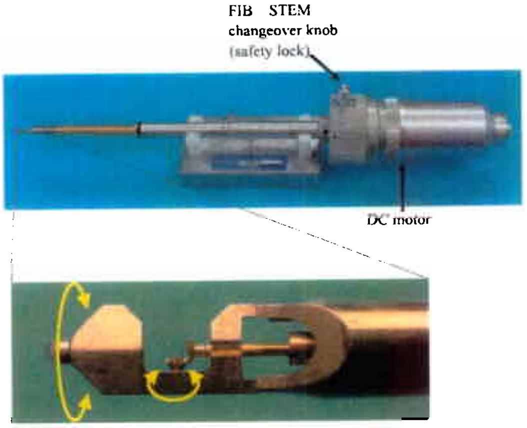

Figure 1: External View of the FIB-STEM compatible 3D analysis specimen holder.

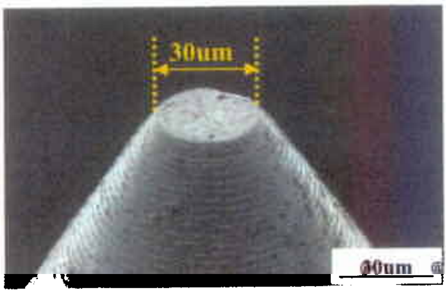

Figure 2: Tip of the needle stage.

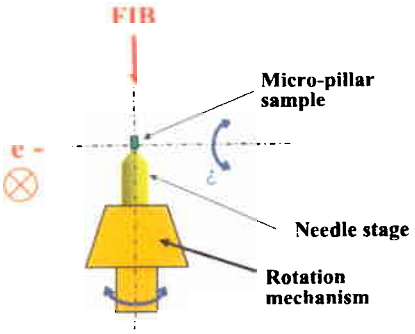

Figure 3: Micro-pillar sample on the FIB-STEM compatible 3D analysis holder.

Figure 4 shows a schematic flow for the FIB micro-pillar sample preparation technique. A micro- sample is extracted from a bulk material (a). The micro sample is then transferred onto the tip of the needle stage and bonded by FIB assisted metal deposition (b). The sample is then trimmed in the form of a pillar-shaped sample (micro-pillar sample) of 2-5 micron square and 10 -15 micron long (c). All of these operations are accomplished inside the FIB system. In the case of a Si-device, it takes less than 30 minutes to prepare. A secondary electron (SE) image of a micro-pillar sample of a Si device mounted on the needle stage is shown in Figure 5.

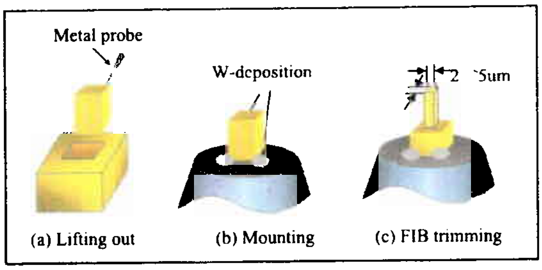

Figure 4: Schematic flow for the FIB micro-pillar sampling technique.

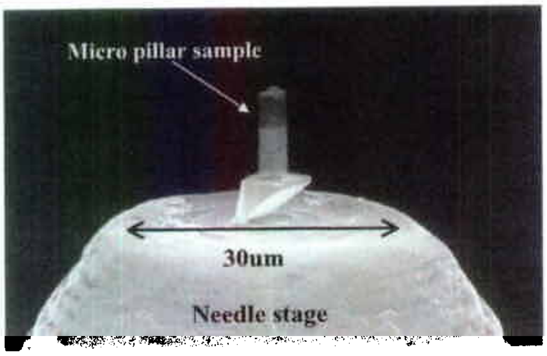

Figure 5: SE image of a micro-pillar sample of a Si-device.

Results and discussion

The method described above was applied to characterize DRAM device. The micro-pillar sample was about 2.5 micron square in base area. Figure 6 shows a series of SIM images showing the procedure for the FIB micro-pillar sample preparation. Firstly, the surface area to be characterized is coated with an FIB assisted W deposition (a). A groove surrounding the area to be examined is milled leaving a micro-bridge (b). Next, the sample is tilted and the bottom is milled by FIB (c). The sample is tilted back, and the W-probe of the micro-sample unit is bonded on the surface of the sample by W-deposition (d). The micro-bridge is then cut off for lift out (e) and the micro-sample is transferred onto the tip of the needle stage by manipulating the W-probe. The micro-sample is bonded onto the tip of the needle stage by W-deposition (f). After bonding, the W-probe is cut off by FIB milling (g). The micro-sample is then trimmed for making a micro-pillar sample suitable for 3D observation. (h).

Figure 7 shows a dark field (DF) STEM (a) and SE (b) images of a 2 micron-square micro-pillar sample of a DRAM structure observed from the same direction. Though the sample is 2 microns thick, DF-STEM image provides fine structures of capacitors as well as the metal lines inside the sample (a). SE image (b) offers cross-sectional structures of components near the cross-sectional surface clearly.

Figure 8 shows a piece of hemi-spherical grain (HSG) capacitor by SE (a, d, g), DF-STEM (b, e, h) and BF-STEM(c, f, i) viewed from three different directions. The shape and fine structures of a capacitor are obtained three dimensionally.

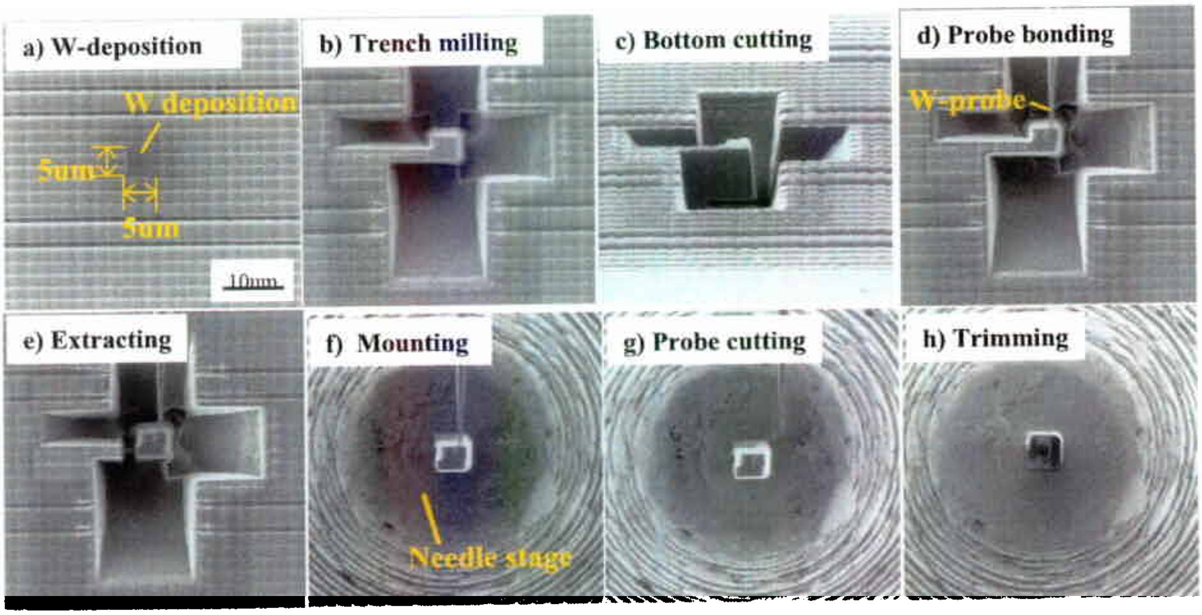

Figure 6: Series of SIM images showing the procedure for the FIB micro-pillar sampling.

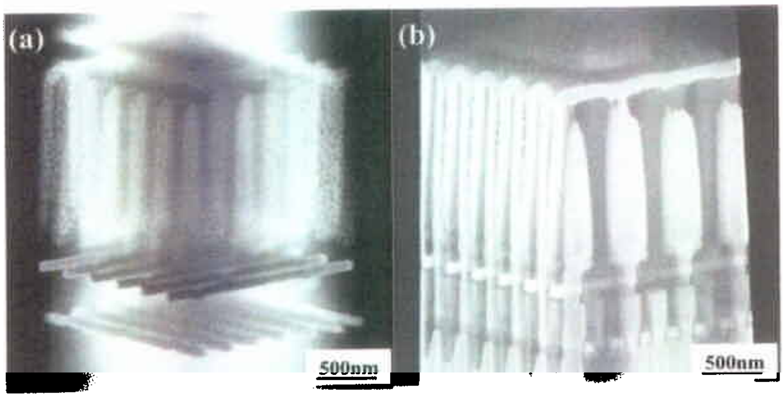

Figure 7: DF-STEM(a) and SE(b) images of a 2 micron-square micro-pillar.

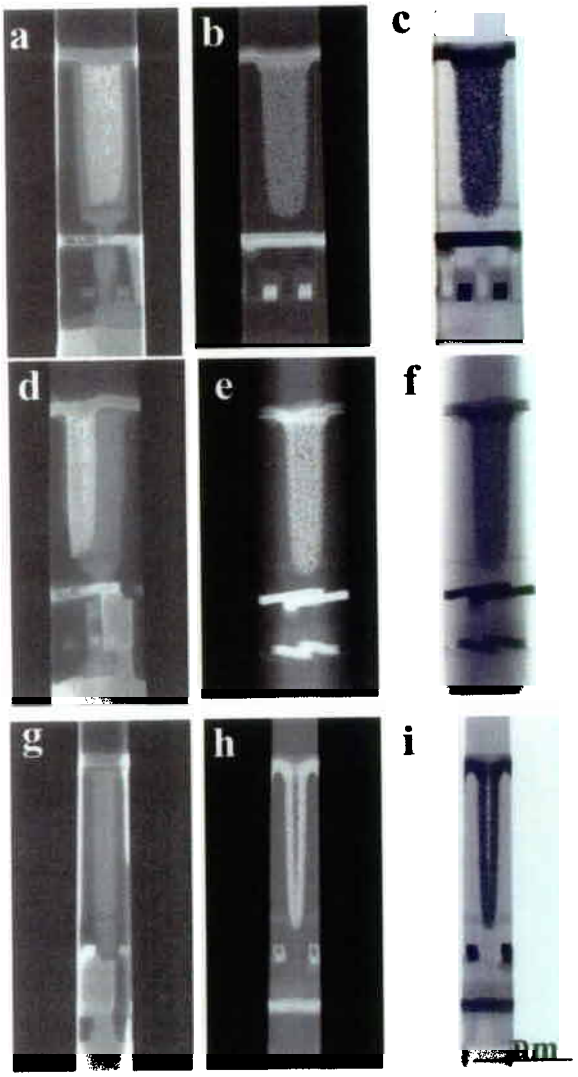

Figure 8: SE(a,d,g), DF-STEM(b,e,h) and BF-STEM(c,f,i) images of 1 micron wide x0.5 micron long -square micro-pillar were observed at different rotation angles(0deg.:a,b,c, 45deg.:d,e,f, 90deg.:g,h,i).Micro-pillar sample on the FIB-STEM compatible 3D analysis holder.

EDX analysis of micro-pillar samples of 3 different thicknesses was also carried out. Figure 9(a), (b) and (c) show EDX spectra obtained from an Al wire in a micro-pillar sample of Si-device with a thickness of 2microns, 1micron and 0.5microns. The center of Al wiring was analyzed. Low signal of Si-K originating from Si-substrate is detected on the 2micron-thick-sample. However, no Si signal is detected on thinner samples. This result suggests that the volume of Si-substrate in the micro-pillar sample is small and the shape of the micro-pillar sample is suitable for quantitative EDX analysis.

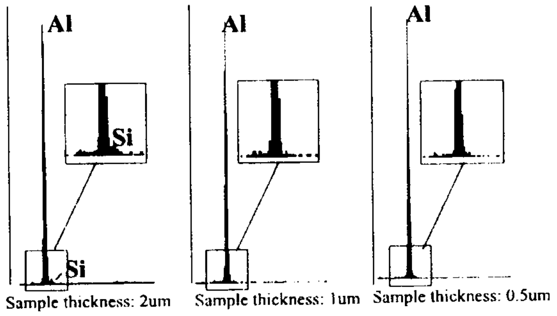

Figure 9: EDX spectra obtained from Al wire in a micro-pillar sample of Si-device with thicknesses of 2 micron (a), 1 micron (b) and 0.5 micron (c).

Figure 10 shows DF-STEM image (a) of the 2-micron-pillar sample of Si device and its EDX elemental maps of N-K (b), Al-K(c), and Ti-K (d). The elemental maps of Al wirings between TiN barrier-metal were obtained three dimensionally, even with this thick sample.

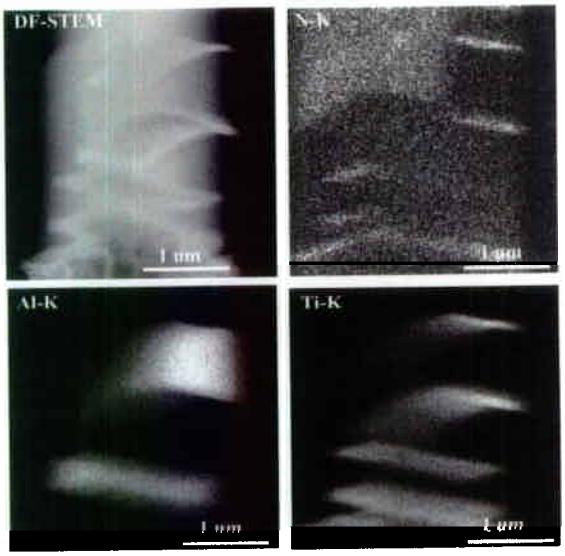

Figure 10: DF-STEM image (a) of the 2-micron-pillar sample of the Si device and its EDX elemental maps of N-K (b), Al-K(c), and Ti-K (d).

This method was applied for observation of metal line failures caused by electro-migration in test elements group (TEG) pattern. An optical photo of the TEG pattern is shown in Figure 11. The portion used for the electro-migration testing of the Cu wire was a circled area in Figure 11.

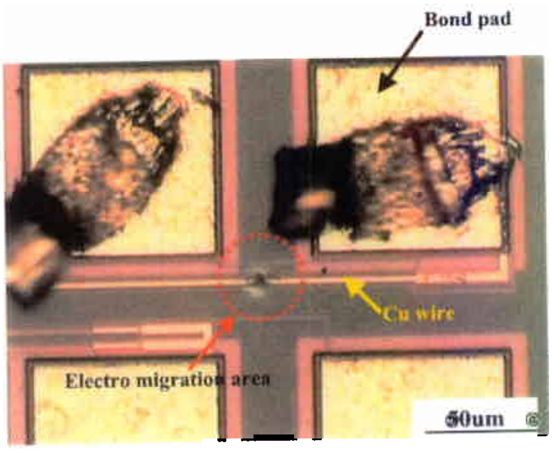

Figure 11: Optical photo of the area where the electro migration occurred. Applied voltage across bond pads was 5V and the current density was 2.5MA/cm^2 .

The surface of the area was covered with W-deposition prior to extraction of a micro-sample. The area was extracted using the micro-sampling technique. A series of SIM Images of the sample preparation process and the corresponding milling conditions are shown in Figure 12.

Figure 13 shows SE images of 18 micron wide, 6 micron long, and 20-micron high micro-pillar sample of TEG pattern. The broken parts of the Cu-wire were located by DF-STEM image observation prior to further FIB milling.

Figure 14 shows DF-STEM images recorded at different rotation angles at intervals of 30 degrees. The size of the failure as well as deformation of the Cu wire and formation of voids at the center of the electro-migration pattern is clearly observed.

Figure 15 shows a close-up DF-STEM image of the void. Dark dots assumed to be debris of the Cu wire are observed. Although the thickness of the sample is 2 microns, small debris of about 100nm(indicated by arrows) is found near the void.

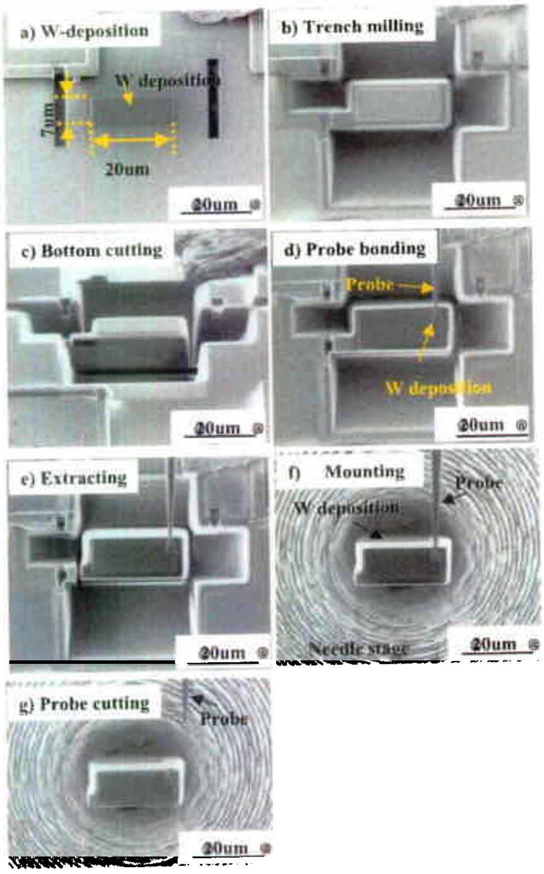

Figure 12: Series of SIM images of sampling process.

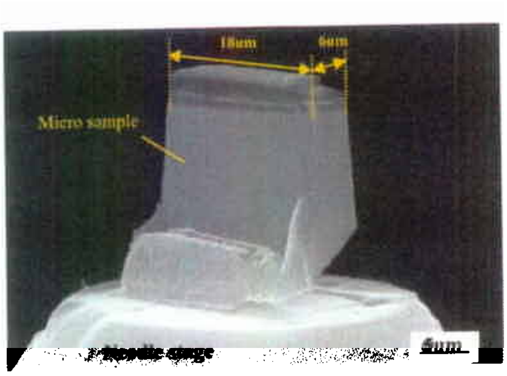

Figure 13: SE image of an 18 micron wide x 6 micron long x 20 micron high micro-sample.

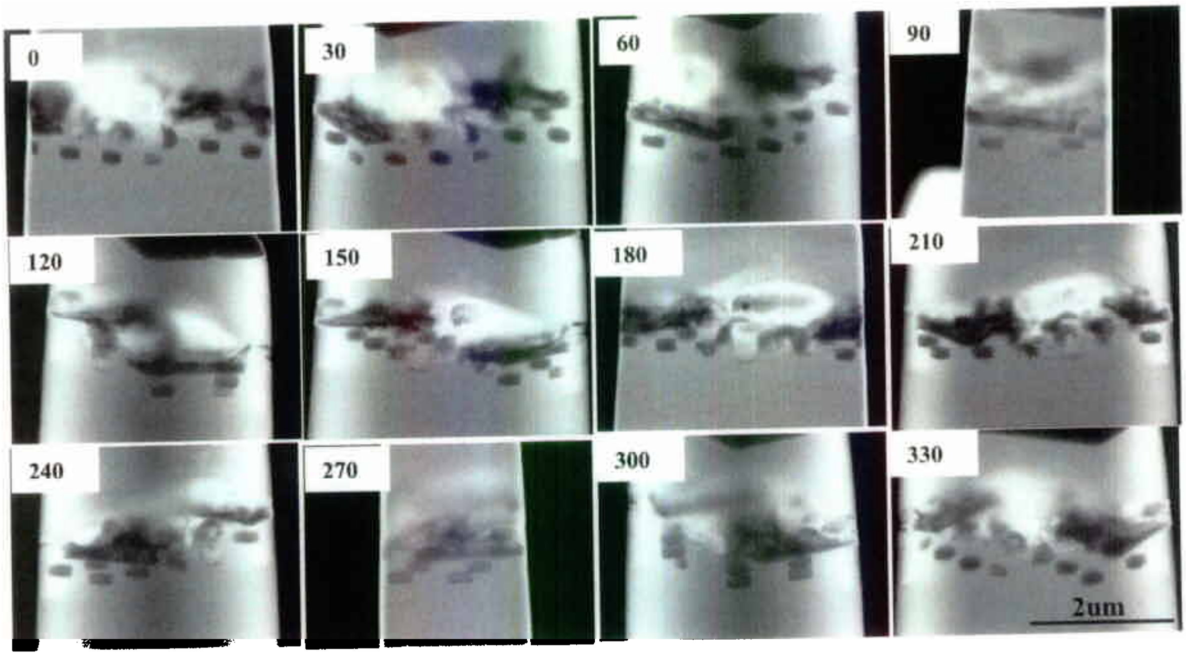

Figure 14: DF-STEM images of 4micron wide x 2micron long micro sample recorded at different rotation angles and at intervals of 30 degrees.

Figure 15: Close-up DF-STEM images of 4 micron wide x 2 micron long micro sample.

Conclusions

We have described an FIB micro-pillar sample preparation technique for three-dimensional characterization of specific-sites. In this technique, a combination of FIB, high voltage STEM and an FIB-STEM compatible sample holder with stage rotation mechanism plays an important role. The technique was applied for observation of fine structures of a Si device and characterization of metal line failure caused by electro-migration.

The results revealed that the micro-pillar sample preparation technique enabled us to observe three-dimensional structures of a specific site without preparing electron transparent thin foil sample. This technique could be applied for the failure analysis or evaluation of a wide range of materials.

References

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2. T.Onishi, H.Koike, T.Ishitani, S.Tomimatsu, K.Umemura and T.Kamino: Proc. 25 th Int. Symp. for Testing and Failure Analysis 449-453 (1999).
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