3D Nano-analysis Technology for Preparing and Observing Highly Integrated and Scaled-down Devices in QTAT

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OVERVIEW: In regards to structural evaluation and failure analysis of increasingly integrated and scaled-down devices, three-dimensional structural analysis in the submicron range is becoming indispensable. With that fact in mind, we have developed an FIB/STEM (focused ion beam/scanning transmission electron microscope)-compatible specimen-rotation holder — namely, for use with both FIB processing and STEM observation — that is fitted with a mechanism for rotating the loaded specimen. FIB micro-sampling is used to extract the specimen, which is then formed into a column shape containing the region of interest (usually 0.1 – 5-μm square); the specimen preparation time is about 20 to 30 minutes. A key feature of the STEM observation, compared to TEM (transmission electron microscope), is that it can observe thicker specimens because it suffers less chromatic aberration. In addition, by means of SE (secondary electron) imaging — which utilizes electrons accelerated by a high voltage (200 to 300 kV) — information about the specimen surface, as well as the inner structure near the surface, can be obtained. And since the holder can be used for both FIB processing and STEM observation, if necessary, the specimen can be thinned to 0.1 μm, and structural analysis can be performed at the atomic level. Applying the analysis technology developed in this study makes so-called "QTAT (quick turnaround time) 3D nano-analysis" of devices possible.

INTRODUCTION

IN the fields of structural evaluation and failure analysis of increasingly integrated and scaled-down devices, analysis methods for sizes of the sub-nanometer order are needed. In recent times, as such methods, high-resolution observation and analysis technologies that utilize atomic-level techniques like TEM (transmission electron microscopy) are gaining recognition. Regarding analysis by TEM, however, sample preprocessing and skillful observation techniques are required. Accordingly, under these circumstances, conventional TEM methods are not

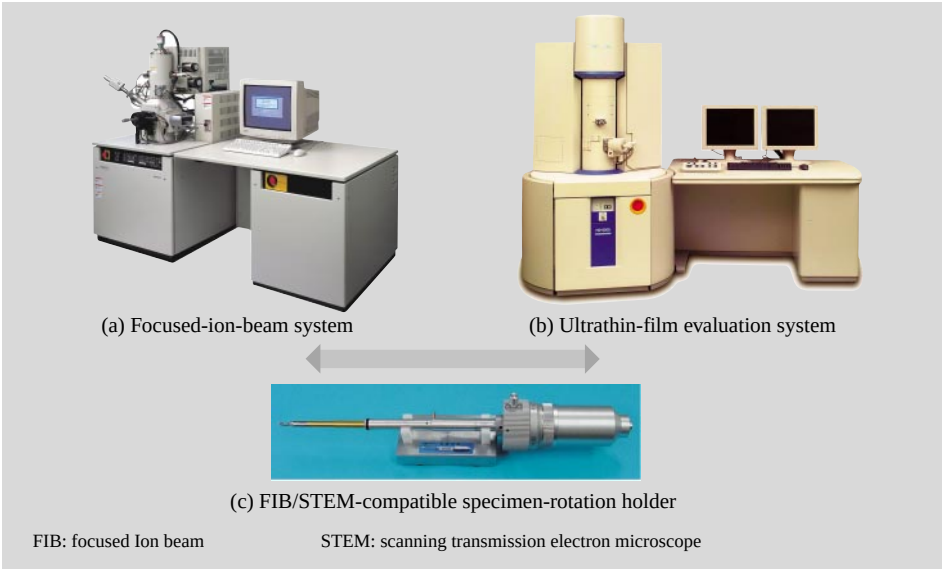

Fig. 1—Semiconductor-device Evaluation System for 3D Nano-Analysis.
A semiconductor device evaluation systems combining (a) focused-ion-beam system and (b) ultrathin-film evaluation system using an STEM both using (c) an FIB/STEM-compatible specimen-rotation holder.

gaining in popularity.

In the usual case of observing the fine structure of the interior of materials by electron microscopy, the sample is processed into a thin film approximately 100-nm thick. However, in regards to devices with fine, 3D structures in the nanometer to sub-nanometer order, even at such a thickness, overlapping of heterogeneous materials can be seen, so it is becoming difficult to grasp the true structure of such devices. Particularly, in the case of 90-nm-node technologies and beyond, because many additional device elements are contained in 100-nm-thick samples, this difficulty can no longer be neglected.

To address the above-mentioned difficulties, we have developed a method for forming a sample with a sub-micron-square pillar structure and then observing the sample while inclining and rotating it. And we have applied this method to the failure analysis of electronic devices[1]. A key feature of this method is that it allows the sample to be observed from different directions, so it is easy to grasp the 3D structure of the analysis area of interest.

This paper first describes a sample preparation method (which requires about 30 minutes) for extracting a minute sample from a specific part of a device and processing it into a columnar structure. It then introduces a 3D nano-analysis technology for high-resolution observation and elemental mapping of the interior structure of this sample at the atomic level.

FEATURES OF SEMICONDUCTOR-DEVICE EVALUATION SYSTEMS

For the analysis of future scaled-down devices, the following three requirements must be satisfied.

(1) High-resolution observation and sensitivity analysis of minute defects of the sub-nanometer order.

(2) High-positional-accuracy processing to extract specimens from specific sites of interest.

(3) High-throughput analysis from specimen preprocessing up to analysis.

With satisfying these requirements as our goal, Hitachi Group has developed a semiconductor-device evaluation system that combines a focused-ion-beam system [Fig. 1(a)] and an ultrathin-film evaluation system using an STEM (scanning transmission electron microscope) (previous model). This system can extract ultra-thin specimens from specific sites and perform observation and analysis of these specimens at sub-nanometer resolution. As regards forming a thin specimen, a specific area is extracted from a bulk sample placed in the FIB system and formed into a thin film by a widely used FIB micro-sampling technique[2], which takes about 30 minutes at present. The transfer of the formed specimen between the two apparatuses shown in Fig. 1(a) and 1(b) is performed by an FIB/STEM-compatible specimen-rotation holder and, as a result, overall analysis throughput is improved. Moreover, the ultrathin-film evaluation system —which superceded the previous model — shown in Fig. 1(b) is equipped with automatic control functions such as autofocus and auto stigma correction. It is thus fast and easy to operate[3].

In the current study, aiming to meet requirements (1) to (3) and to handle the increasing scaling down and complexity of future devices, we developed an FIB/STEM-compatible holder with a mechanism for rotating the specimen through 360°.

3D NANO-ANALYSIS TECHNOLOGY

Micro-pillar Sampling Using Specimen-rotation Holder

An external, side view of the FIB/STEM-compatible specimen-rotation holder is shown in Fig. 2. The sample is fixed to the tip of the needle-type specimen stage (called a stub)—fitted in the center of the rotation mechanism—by an FIB micro-sampling technique. The needle stub can be rotated by 360° in the specimen chamber of the FIB or the STEM apparatus.

The specimen-processing procedure is shown schematically in Fig. 3, steps (a) to (c). First, in step (a), the desired specimen is extracted by a standard micro-sampling technique; then in step (b), it is fixed to the tip of the needle-type stub by tungsten deposition; lastly, in step (c), the desired area of the specimen including the region of interest is trimmed into the required size of 0.1– 5 μm by FIB processing

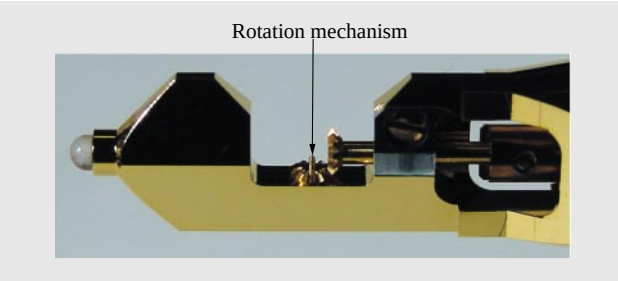

Fig. 2—Side View of FIB/STEM-compatible Specimen-rotation Holder.
A needle-type specimen stage (stub) is fitted in the center of the rotation mechanism. The specimen is fixed to the tip of the needle stub by an FIB micro-sampling technique.

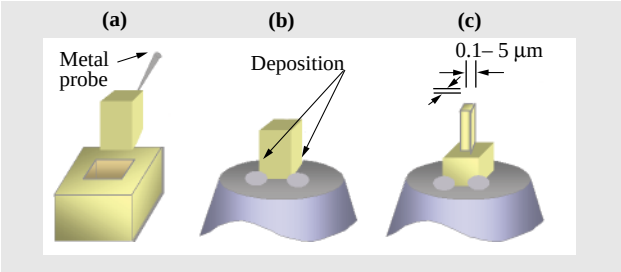

Fig. 3—Micro-pillar Sampling Procedure.
First (a) the specimen is extracted; then (b) the extracted specimen is fixed to the needle-type stub by tungsten deposition; lastly (c) the observation area of interest in the specimen is trimmed by FIB processing.

and a columnar structure (called a pillar-shaped specimen) is formed. The time required for the whole procedure — from extraction of the minute specimen to forming the columnar structure — is about 30 minutes.

Advantages of Observing Thick Specimen by STEM

Compared with TEM, STEM suffers from less chromatic aberration; therefore, even without forming a film specimen down to a 100-nm thickness, it is possible to clearly observe the interior of the specimen. Furthermore, in the case of dark-field-STEM images, which are formed only by using scattered electrons from a specimen, because scattered electrons are utilized as the detection signal, even thicker specimen can be observed. Moreover, SE (secondary electron) images of the specimen surface (and the internal structure near the surface) formed at 200 kV can be recreated in 3D.

If observation of thick specimens were possible, the pre-processing time for specimens before observation and analysis could be shortened. And if the 3D structure of specific specimen areas could be left as it is, structural analysis and elemental mapping of that area could be performed. In regards to materials analysis by electron microscopy used up till now, because a thin-film specimen is used, the information obtained about the specimen is limited to two dimensions. For this reason, evaluation of the 3D structure of a device based on such 2D (two-dimensional) electron-microscopy images has been simply a matter of guesswork. In contrast, as for the observation method developed in the current study — which observes a STEM image of the specimen formed as a columnar structure — 3D structures can be observed as they are, and guesswork is thus eliminated.

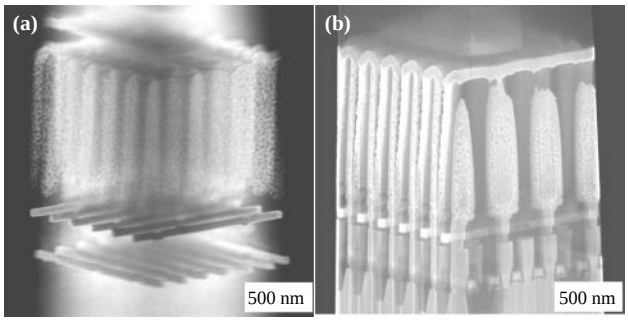

Fig. 4—Observation Examples of DRAM Capacitor Plug (2-µm square).
The dark-field STEM image (a) three-dimensionally shows the uniform appearance of the bit lines and word lines. The SE image (b) shows the cross-sectional structure of the specimen in detail.

As a consequence, the reliability of structural analysis has been significantly improved by this new method.

OBSERVATION EXAMPLE

3D Observation of DRAM Capacitor Plug

Fig. 4 shows (a) a dark-field STEM image and (b) an SE image of a DRAM (dynamic random-access memory) capacitor plug (2-µm square) formed as a columnar specimen. The images were taken at 10° inclination and 45° rotation relative to the silicon substrate. In the STEM image, it is possible to observe 3D internal structure of the capacitor and the straight contours of the bit lines and word lines. In the SE image, the cross-sectional structure of the specimen can be seen in detail. Moreover, in the case of this

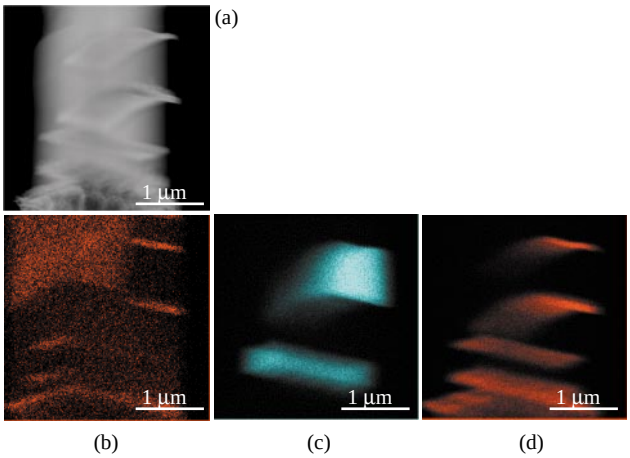

Fig. 5—Elemental Maps of Aluminum Metal Lines in DRAM (2-µm square).
(a) Dark-field STEM image and (b) nitrogen, (c) aluminum, and (d) titanium elemental maps. The distributions of nitrogen, aluminum, and titanium can be observed in 3D.

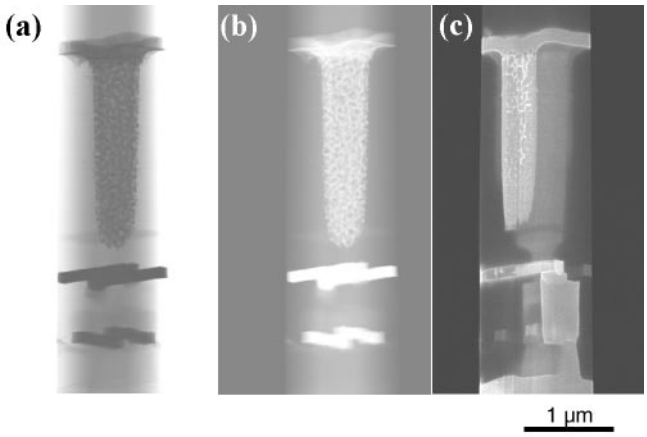

Fig. 6— (a) Bright-field Image, (b) Dark-field Image, and (c) SE Image of DRAM Capacitor Plug (size: 0.5 × 1 μm).
The fine structure of the insides and surface of the capacitor, interconnections, and plug can be seen in detail.

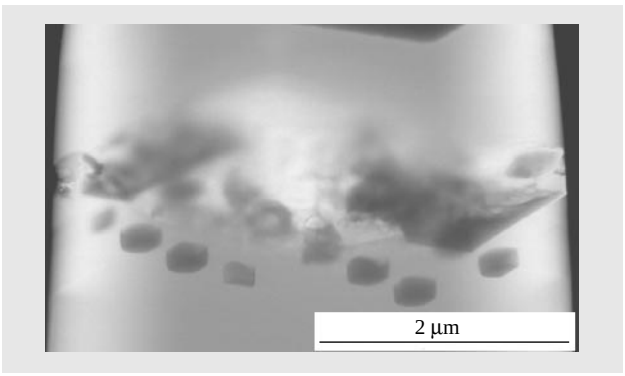

Fig. 7— Observation Example: Dark-field Image of the Cause of Interconnection Failure (Electromigration).
In this specimen (size: 4 × 2 μm), voids are generated in the central area with white contrast by electromigration; in this dark-field STEM image, the contrast is proportional to the product of atomic number and density.

method, since the columnar-formed specimen is affixed to the tip of the needle stub, there are few obstructions between the specimen and the detector of the EDX (energy-dispersive X-ray) system, and elemental analysis with low noise is possible. Fig. 5 shows elemental-analysis map images taken by EDX of aluminum metal lines of a DRAM formed as a columnar specimen (2 μm square). The distributions of nitrogen, aluminum, and titanium can be clearly observed in 3D.

From the one remaining capacitor plug, a columnar specimen with a size of 0.5 × 1 mm was formed and a bright-field image, dark-field image, and SE image were taken (Fig. 6 (a) to (c), respectively). The fine structure of the interior and surface of the capacitor, metal lines, and plug can be seen in detail in these images. As regards our ultrathin-film evaluation system, it is possible to switch between bright-field, dark-field, and SE images by one mouse click and, thus, obtain a wide variety of information in a short time.

3D Observation of Interconnection Failure

The newly developed method was used to observe a TEG (test elements group) pattern — used for evaluating reliability of interconnections — in order to study the cause of interconnection failure, i.e. electromigration. Under an applied voltage of 5 V and a current density of 2.5 MA/cm^2, part of the copper metal lines in this pattern failed. After confirmation of the failure region by optical microscope, a columnar specimen (4 μm wide × 2 μm deep × 20 μm high) was formed from this region, and dark-field STEM images of the specimen were taken (see Fig. 7). As shown in the image, the damage covers a region spanning about 2 μm, the metal lines in which migration occurs are significantly damaged, and the generation of voids between metal lines is clearly shown.

High-resolution 3D Observation of Silicon Single-crystal Substrate

From now onwards, with further scaling down of devices, it will become necessary to observe the interfaces between multi-layer thin films as well as the defects at interfaces and in the bulk of crystals. With this in mind, we formed a columnar specimen on a 0.1-μm-square single-crystal silicon substrate, and took high-resolution images at 0° and 90° to the

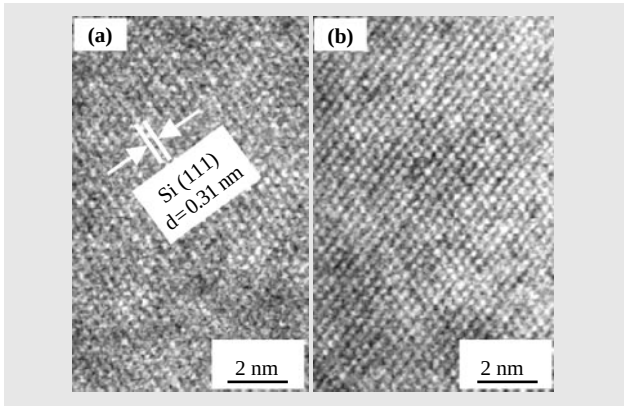

Fig. 8—High-resolution Observation of Single-crystal Silicon Substrate.
A columnar specimen was formed on a 0.1-mm square silicon single-crystal substrate, and high-resolution images were taken at 0° and 90°. The 0.31-nm spacing of the silicon-crystal lattice fringe can be clearly seen.

substrate (see Fig. 8). The 0.31-nm spacing of the silicon-crystal lattice can be clearly seen in these images. To reduce the damaged layer caused by FIB processing, an ion beam with an accelerating voltage of 10 kV was used for the FIB finishing process.

CONCLUSIONS

Since the developed method described here is based on a system that combines a processing apparatus and an observation apparatus, it allows processing and observation to be repeatedly performed in a short time. Furthermore, by changing the specimen from a thin-film to a pillar-shaped specimen, we have been able to improve the analysis method; in other words, we have upgraded conventional observation in 2D to observation of solid structures in 3D. With this new method, we are now able to get more tangible information from specific sites within specimens taken from semiconductor devices. As for the future, while aiming at further improving analysis throughput, Hitachi will strive to further develop high-precision analysis technologies.

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