Hitachi's Spherical Aberration Corrected STEM: HD-2700

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OVERVIEW: It has been a long-held dream of electron microscopy engineers to correct or eliminate the spherical aberration that theoretically occurs in the electron optics, a development that would dramatically improve the resolution of electron microscopes. Now Hitachi High-Technologies Corporation has developed the HD-2700, a next-generation STEM that is equipped with a spherical aberration corrector. Essentially, the corrector acts as a kind of concave lens that reduces the spherical aberration of the electron optics to the absolute minimum. As a result, a much smaller probe diameter is obtained while keeping the larger convergence angle, and this provides significantly improved resolution and analytical sensitivity. It is anticipated that the HD-2700 STEM will prove to be a powerful analytical tool in researching and developing next-generation semiconductors, materials, and nanotechnologies.

INTRODUCTION

AS VLSI (very large scale integration) technology evolves toward ever smaller features and multilayer designs, analysis and control of structures and compositions at the atomic level is becoming increasingly important. In 1998 Hitachi High-Technologies Corporation released the HD-2000, a STEM (scanning transmission electron microscope) that was very well received for combining the ease of operation of a SEM (scanning electron microscope) with the excellent resolution of a TEM (transmission electron microscope). Now in collaboration with the German company CEOS GmbH, we have developed the HD-2700, a high-end addition to the HD series that effectively eliminates spherical aberration. This paper will provide a summary overview of the development concept, the basic capabilities, and some typical VLSI device analysis results for the HD-2700 STEM.

DEVELOPMENT CONCEPT

The approximate resolution limit, *d*, of a STEM, assuming a point electron source, is given by

$$d = 0.43\ Cs^{\frac{1}{4}}\ \lambda^{\frac{3}{4}}$$

where Cs is the objective lens spherical aberration coefficient, and λ is the wavelength of the electron beam. The wavelength of the electron beam is determined by the accelerating voltage. In HD series STEMs the accelerating voltage is 200 kV which yields a sufficiently small wavelength of about 0.0025 nm, but due to the spherical aberration of the objective lens, a resolution limit of only about 70 times the wavelength can be obtained.

Fig. 1 is a schematic illustrating how spherical

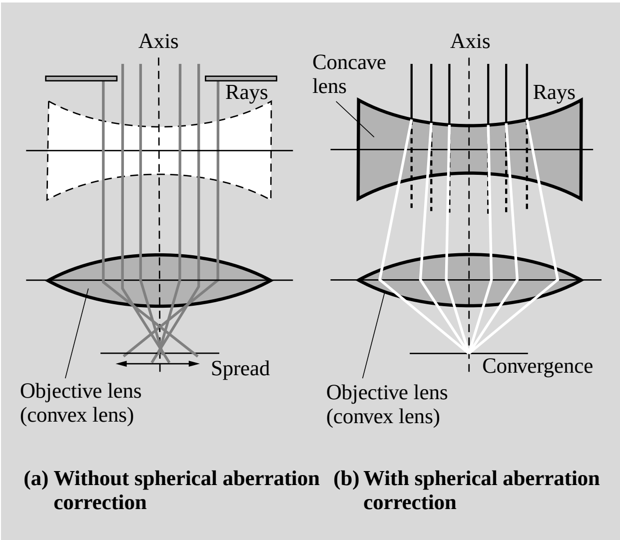

Fig. 1—Spherical Aberration Results in Reduced Resolution. Technology to substantially reduce the spherical aberration of the objective lens is required to improve the resolution of STEMs (scanning transmission electron microscopes).

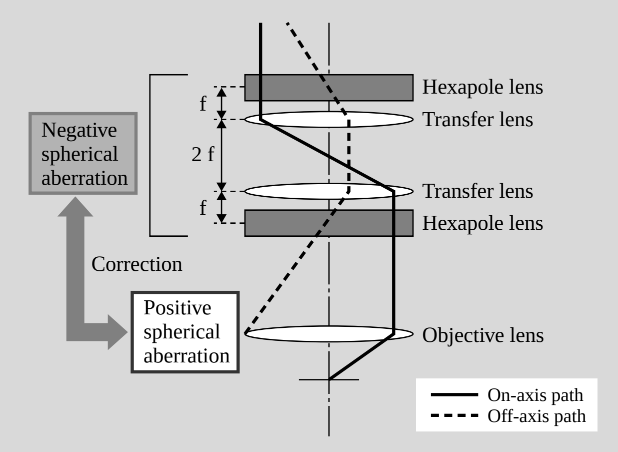

Fig. 2—Configuration of Spherical Aberration Corrector.
Two transfer lenses that cancel higher order aberration sandwiched between two hexapole lenses that produce negative spherical aberration.

Fig. 3—Photograph of HD-2700.
The high-end Cs (objective lens spherical aberration coefficient)-corrected HD-2700 STEM is shown.

aberration reduces the resolution. When the objective lens is convex as in Fig. 1(a), rays which pass close to the optical axis of the lens (paraxial rays) converge at a single focal point, while rays striking the lens away from the axis toward the edge of the lens do not converge at the focal point, thus producing a spread of the focal point.

In theory, this spherical aberration is unavoidable because the rotational symmetric electromagnetic lenses used by electron microscopes must be convex lenses, so finding a way to correct for the spherical aberration has been a long-standing issue. A method of directly correcting the spherical aberrations by combining a multipole lens that acts as a concave lens with the rotational symmetric lens was investigated back in the 1940s, but it was not until fairly recently that a practical working prototype of this approach was demonstrated at the research level.

Now, in a collaborative effort with CEOS GmbH, we have succeeded in eliminating spherical aberration on the HD-2700 model STEM by equipping it with a hexapole aberration corrector. The spherical aberration corrector essentially acts like the concave lens in Fig. 1(b), causing the off-axis electron beams to diverge. Combining the corrector with a conventional spherical objective lens, the off-axis electron beams are also brought into convergence at the focal point. This not only reduces the diameter of the electron beam (i.e. the probe size), it also takes advantage of the larger convergence angle beams to greatly increase the probe current density.

Fig. 2 shows a schematic cross-section of the spherical aberration corrector. As one can see in the figure, it consists of two transfer lenses that cancel higher order aberration sandwiched between two hexapole lenses that produce negative spherical aberration. By adjusting the strength of the hexapole lens, the spherical aberration of the overall electron optics can be reduced to close to zero.

Fig. 3 is a photograph of the HD-2700 STEM. The spherical aberration corrector is mounted between the condenser lens and the objective lens. On the HD-2700, the body of the microscope has been enclosed in cover considering its higher resolution, and to reduce potential adverse effects of noise and temperature changes on imaging to an absolute minimum. The HD-2700 can be fitted with EDX (energy dispersive x-ray spectroscopy), EELS (electron energy-loss spectroscopy), and other attachments, and is thus fully compatible with legacy analysis utilities. Adjustments to the spherical aberration corrector are done on screen using an intuitive graphical user interface, and every effort has been made to not impair the excellent operability of former HD series STEMs.

BASIC PERFORMANCE

Fig. 4 compared dark-field STEM images of gold (100) crystal and power spectra captured using Hitachi's former STEM and HD-2700. In the former STEM images, 0.2-nm cross stripe patterns can be observed, and (200) diffraction spots can be seen in the power spectrum that corresponds to the diffraction pattern. Turning to the HD-2700 images, the STEM image is much clearer, and we can see that the cross-

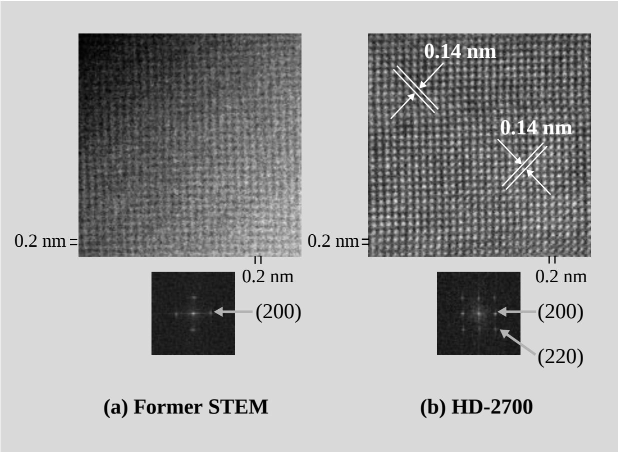

Fig. 4—Dark-field STEM Image of Gold (100) Crystal.
Comparison of dark-field images: Hitachi's standard former STEM (a), and HD-2700 STEM (b). Smaller images show the respective dark-field image power spectra.

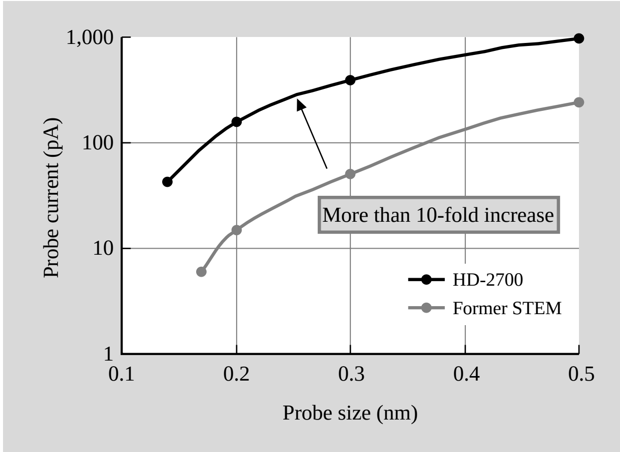

Fig. 5—Probe Size as Function of Probe Current.
Probe sizes are estimated; probe current densities are measured.

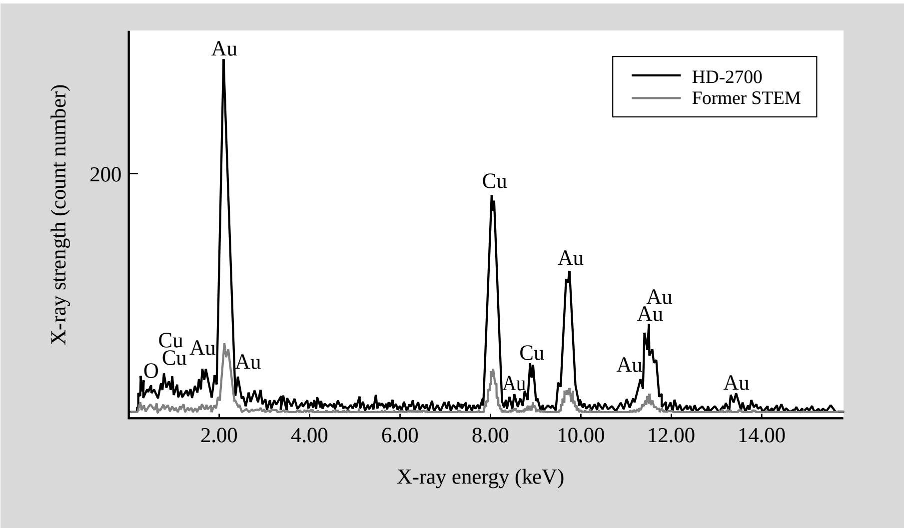

Fig. 6—EDX (energy dispersive X-ray spectroscopy) Spectrum.
Using a sample of gold particles on copper mesh/carbon-supported film, the probe size was 0.2 nm and the capture time was 20 s.

stripe patterns correspond to a period of 0.14 nm [corresponding to (220) diffraction spots in the power spectrum], and the resolution limit is markedly improved.

Fig. 5 compares the probe size and probe current density of the former STEM and the HD-2700. It is apparent that probe current density is improved by more than an order of magnitude for the HD-2700 at probe sizes ranging from 0.2 nm to 0.3 nm, the typical size used in EDX analysis.

Fig. 6 compares EDX spectra for the former STEM and the HD-2700 using gold particles on carbon mesh/carbon-supported film as a sample. Using the HD-2700, it was confirmed that the intensity of the characteristic X-ray spectrum was increased by approximately an order of magnitude.

APPLICATION TO THE ANALYSIS OF ELECTRON DEVICES

Finally in this section we present the results of trials to assess the usefulness of the HD-2700 in analyzing actual electronic devices. Fig. 7 shows a low-magnification image of a Si semiconductor device and a high-resolution image of a Si/SiO_2 interface observed by the HD-2700 in bright-field STEM mode. The silicon crystal lattice and the amorphous structure of the SiO_2 are clearly visible, so this tool should be highly effective in analyzing thicknesses of gate dielectric films.

Fig. 8 shows dark-field STEM images of a Si semiconductor device cross-section and EDX elemental mapping images. Despite the very low concentration of As (arsenic) dopant of less than 2 at.%, the arsenic distribution is already starting to become apparent in the EDX elemental mapping image in only 5 min, and a strong clear image is obtained in 20 min. These elemental distribution image capture times are more than 10 times faster `that on the former STEM, and clearly demonstrates the potential of the HD-2700 for high-throughput high-sensitivity EDX analysis.

Fig. 9 shows a bright-field STEM image of a cross-section of a GMR (giant magneto-resistance) head and an EDX elemental mapping image. The EDX elemental mapping image and GMR compositional elements can be clearly identified, and one can even see the 0.4-nm-thick Ru (ruthenium) layer. These results also demonstrate the excellent spatial resolution of the HD-2700 for EDX analysis.

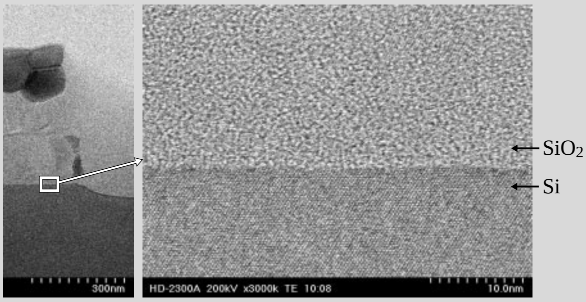

Fig. 7—Bright-field STEM Image of Si Semiconductor Device Cross-section.
Capture time is 10 s. The Si crystal lattice and SiO_2 amorphous structure can be clearly observed, indicating that HD-2700 will be a valuable tool for analyzing thicknesses of gate dielectric films.

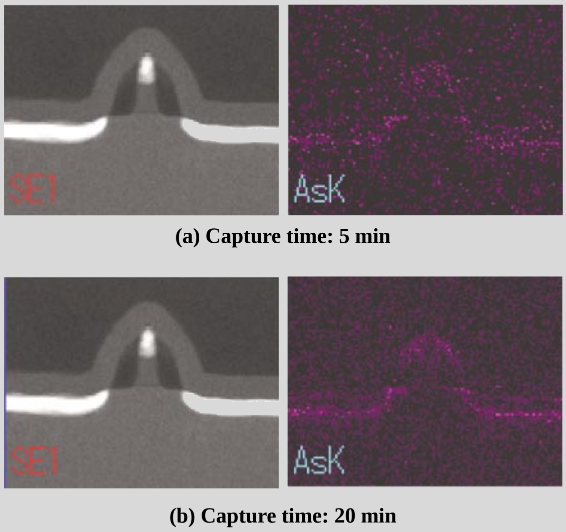

Fig. 8—Dark-field STEM Images of Si Semiconductor Device Cross-section and EDX Elemental Mapping Images.
Elemental distribution images are captured 10 times faster using HD-2700 than the former system, so it should prove to be a high-throughput and highly sensitive tool for EDX analysis.

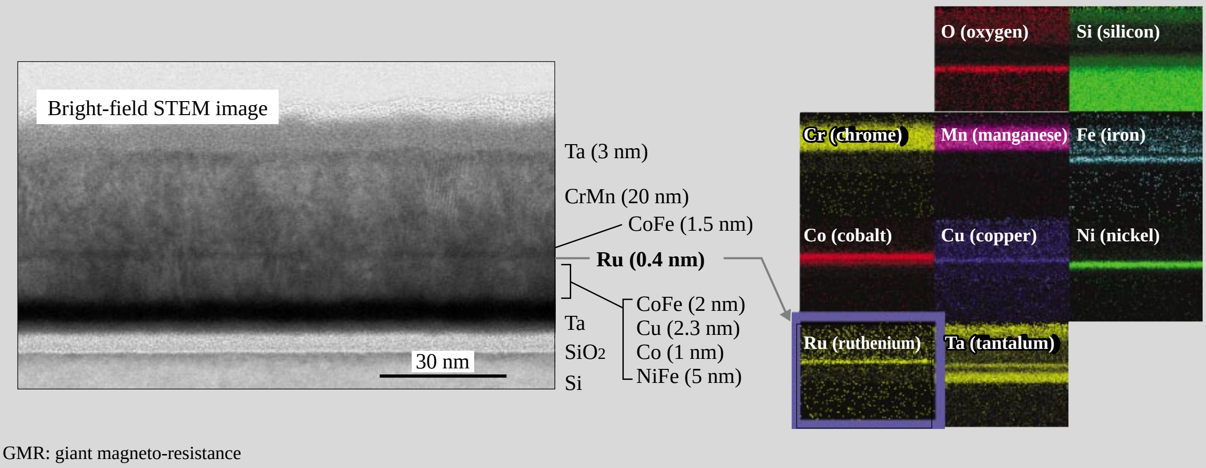

Fig. 9—Bright-field STEM Image of GMR Head Cross-section and EDX Elemental Mapping Image.
Probe size is 0.2 nm, probe current density is 150 pA, and capture time is 15 min.

CONCLUSIONS

This paper provided a summary overview of the development concept of the Hitachi's HD-2700 STEM with spherical aberration corrector. The HD-2700 delivers excellent performance with a resolution of 0.14 nm and more than an order of magnitude increase over the former STEM in probe current density. Finally, we presented some typical VLSI device analysis results obtained by the HD-2700 STEM. The Cs-corrected HD-2700 is a high-end system that fully exploits Hitachi High-Technologies' special expertise with STEMs. HD-2700 was unveiled last year at the 16th International Microscopy Congress held in Sapporo, Japan in September 2006. The system will see extensive application to materials science, semiconductors, and nanotechnology, both in research and development and quality control.

REFERENCES

(1) K. Nakamura et al., "Scanning Transmission Electron Microscope Spherical Aberration Correction and Applications," *Microscopy* **41**, 1, pp. 16-20 (2006).

(2) K. Nakamura et al., "Development of a Cs-corrected dedicated STEM," Proc. 16th International Microscopy Congress. p.633 (2006).

(3) T. Yaguchi et al., "Application of a Spherical Aberration Corrected Dedicated 200 kV STEM to Structural and Chemical Analyses of Nano-materials at Near Atomic Resolution," Proc. 16th International Microscopy Congress. p.1155 (2006).

(4) H. Inada et al., "Diffraction Capability with Cs-corrected STEM," Proc. 16th International Microscopy Congress, p.622 (2006).

(5) K. Kaji et al., "Development of an EELS with a Cs-corrected Dedicated STEM," Proc. 16th International Microscopy Congress, p.859 (2006).

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