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

\[
d = 0.43 \frac{1}{Cs^2 \lambda^3}
\]

where \( Cs \) is the objective lens spherical aberration coefficient, and \( \lambda \) 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 aberration affects the resolution of a STEM. The aberration causes the rays to spread out, reducing the convergence angle and thus the resolution. The corrector acts as a kind of concave lens that reduces the spherical aberration of the electron optics to the absolute minimum, allowing for a much smaller probe diameter 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.
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 high-end Cs (objective lens spherical aberration coefficient)-corrected HD-2700 STEM is shown.

**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-
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/SiO₂ interface observed by the HD-2700 in bright-field STEM mode. The silicon crystal lattice and the amorphous structure of the SiO₂ are clearly visible, so this tool should be highly effective in analyzing thicknesses of gate 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
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 than 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.

GMR: giant magneto-resistance
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

ABOUT THE AUTHORS
Kuniyasu Nakamura
Joined Hitachi, Ltd. in 1992, and now works at the Advanced Microscope Systems Design Second Department, Naka Division, Nanotechnology Products Business Group, Hitachi High-Technologies Corporation. He is currently engaged in the design and development of scanning transmission electron microscopes. Mr. Nakamura is a member of the Japanese Society of Microscopy and the Japan Society of Applied Physics.

Hiromi Inada
Joined Hitachi, Ltd. in 1998, and now works at the Advanced Microscope Systems Design Second Department, Naka Division, Nanotechnology Products Business Group, Hitachi High-Technologies Corporation. He is currently engaged in the design and development of scanning transmission electron microscopes. Mr. Inada is a member of the Japanese Society of Microscopy.

Hiroyuki Tanaka
Joined Hitachi, Ltd. in 1993, and now works at the Advanced Microscope Systems Design Second Department, Naka Division, Nanotechnology Products Business Group, Hitachi High-Technologies Corporation. He is currently engaged in the design and development of scanning transmission electron microscopes. Mr. Tanaka is a member of the Japanese Society of Microscopy.

Mitsuru Konno
Joined Hitachi Instrument Engineering Co., Ltd. in 1993, and now works at the Naka Application Center, Naka Division, Nanotechnology Products Business Group, Hitachi High-Technologies Corporation. He is currently engaged in the development of applications to expand sales of TEM, STEM, and FIB systems. Mr. Konno is a member of the Japanese Society of Microscopy.

Taro Ogawa, Dr. Eng.
Joined Hitachi, Ltd. in 1984, and now works at the Product Marketing Department, Advanced Equipment & Systems Sales Division, Hitachi High-Technologies Corporation. He is currently engaged in developing markets for TEM, STEM, and FIB systems. Dr. Ogawa is a member of the Japanese Society of Microscopy and the Japan Society of Applied Physics.