Hitachi's High-end Analytical Electron Microscope: HF-3300

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OVERVIEW: A 300-kV cold FE-TEM, the HF-3300, has been developed by Hitachi High-Technologies Corporation. This TEM has next-generation analytical capabilities and a cold field emission electron source. Available for this TEM is a cold FE gun for higher brightness and added coherency. Functions of cold FE allow for different types of analysis in various fields through the use of unique technologies. As a result, this TEM can meet demands for the advanced analyses for use in developing semiconductor devices, in failure analysis, and process reaction under the material boundary. The HF-3300 TEM will also be useful for various areas of analysis in physical science.

INTRODUCTION

IN recent years, with the high integration and high density of semiconductor devices, clarification in failure analysis and the process reaction have become increasingly difficult using general TEM (transmission electron microscope) methods. Identifying atomic diffusion in the multilayer structure and low-density distribution such as the dopant profile in semiconductor devices has particularly been difficult. We have now developed a 300-kV cold FE-TEM (field-emission TEM) equipped with spatially resolved EELS (electron energy loss spectroscopy) technology and a special electron biprism system for electron holography, as shown in Fig. 1. In this paper, we report on the characteristics of the cold FE electron source and the latest analytical results obtained using the HF-3300.

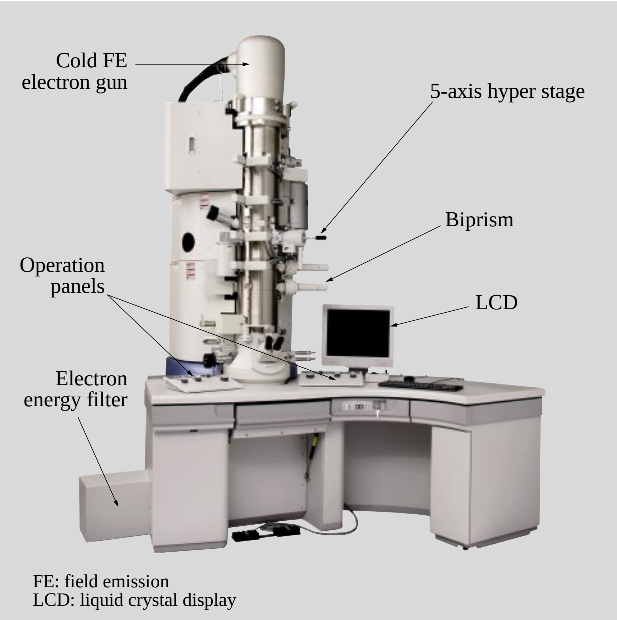


Fig. 1—General View of High-end FE-TEM (HF-3300) Equipped with Cold FE Electron Gun.
HF-3300 is equipped with electron energy filter [GIF (Gatan Imaging Filter)] and the biprism system.

CHARACTERISTICS OF COLD FE ELECTRON SOURCE

On the cold FE gun, an electron beam is extracted from a sharp tip by applying a strong electric field. The size of the emitting area of the electron source is

TABLE 1. Performance Comparison of Cold FE Gun with SE Gun
General operating conditions are shown in gray region.

Emitter	FE W(310)			SE Zr/O/W(100)		
Work function Φ (eV)	4.5			2.8		
Temperature T (K)	300			1700		
Total emission current I_e (μA)	10	30	100	30	100	300
Brightness β (A/cm^{2}sr)	2.9 $\times 10^8$	8.7 $\times 10^8$	2.9 $\times 10^9$	8.8 $\times 10^7$	2.9 $\times 10^8$	8.8 $\times 10^8$
Energy spread ΔE (eV)	0.45	0.55	0.7	1.0	1.3	1.8

SE: Schottky emission

in the order of a few nm and, as a result, the brightness is high. Since the electron can be extracted from the tip without heating a filament, the electron beam has a very narrow energy spread. This results in good interference performance. Table 1 shows a comparison between the cold FE electron gun and SE (Schottky emission) electron gun. The brightness (β) of the cold FE electron gun is about three times that of SE electron gun, and the energy spread (ΔE) of the cold FE electron gun is less than half that of the SE electron gun, as shown in Table 1. The cold FE electron gun is therefore considered the most suitable gun for electron holography, which needs high interference performance, and analysis of the chemical bond state in the nano region using EELS.

ELECTRON HOLOGRAPHY

Electron holography is a useful technique for observing the phase change of the electron beam by the electric and magnetic fields in the sample[1]. Fig. 2 schematically shows the principle of electron holography. The electron wave is affected by a phase shift resulting from the electrostatic and/or magnetic potential in the sample. With the electron biprism, the modulated wave coherently interferes with the electron reference wave. In electron holography, the phase change of the electron beam is recorded as a shift of the interference fringes in the electron hologram. The amplitude and phase of the modulated wave are extracted from the recorded electron hologram. The Fourier analysis method is used to reconstruct the image from the hologram.

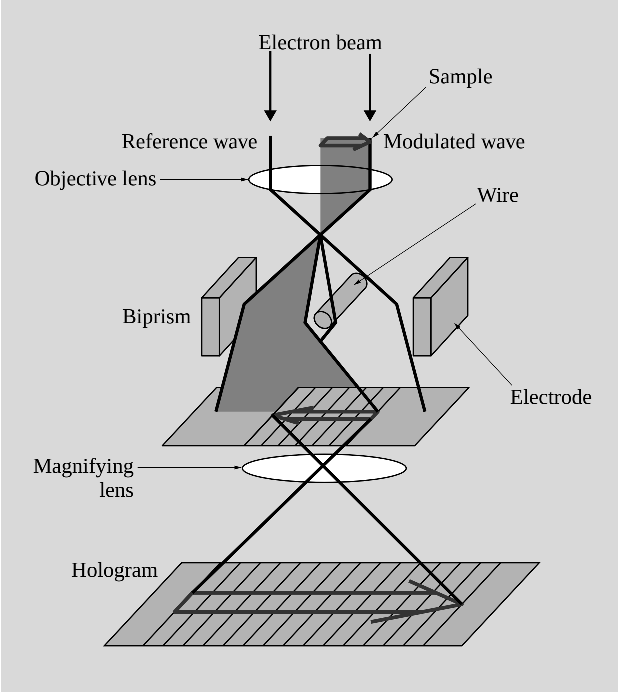


Fig. 2—Scheme Showing Principle of Electron Holography. Modulated wave passes through sample, such as doped semiconductor, and reference wave passes through vacuum region.

ELECTRON HOLOGRAPHY APPLIED TO SI DEVICE

We used electron holography to observe the internal electrical potential in a Si device. The sample was fabricated using an FIB (focused ion beam) with an FIB micro-sampling mechanism and an FIB/TEM compatible rotation holder[2]. Fig. 3 (a) shows a bright field STEM (scanning transmission electron

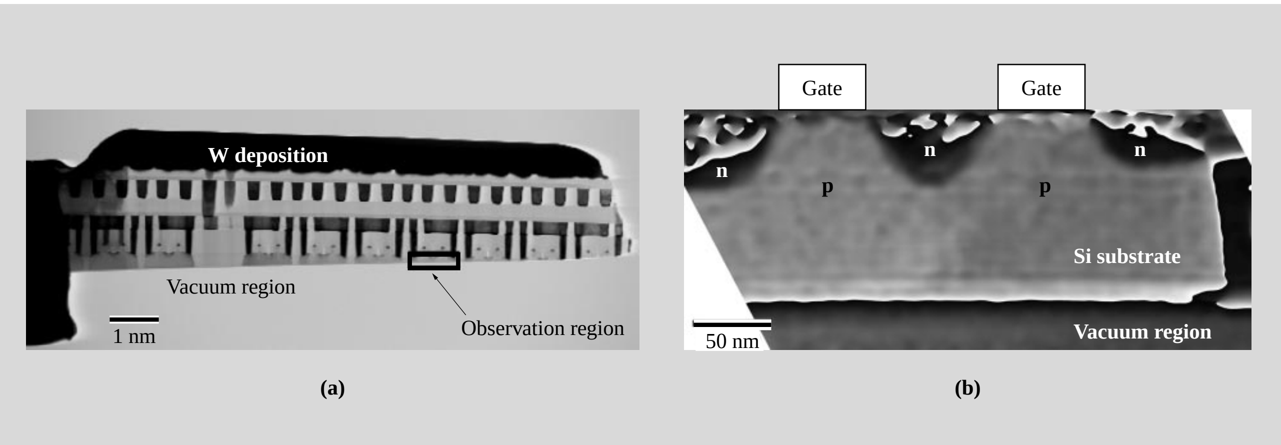


Fig. 3—Result of Applied Electron Holography for Analysis of Si Device.
STEM (scanning transmission electron microscope) image of sample prepared for electron holography observation (a), and phase image of N-MOS (negative-channel metal oxide semiconductor) doped with arsenic (b) are shown. Gate length of sample is 50 nm.

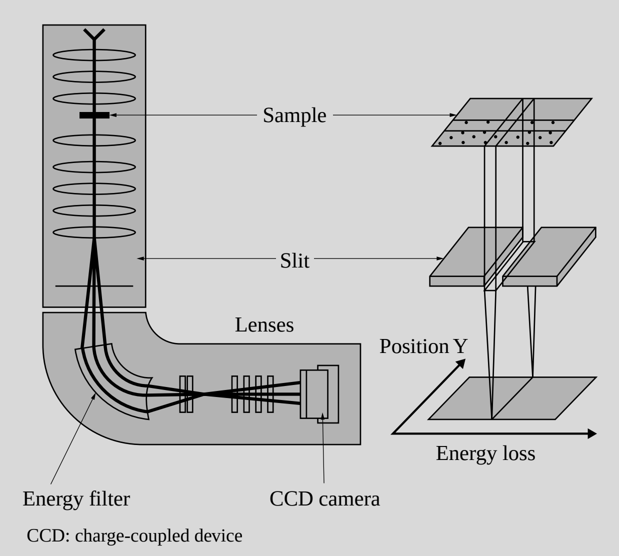


Fig. 4—Scheme Showing Principle of Spatially Resolved EELS Technology.
The electron-energy filter is composed of an EELS (electron energy loss spectroscopy) slit, lenses, and a CCD camera.

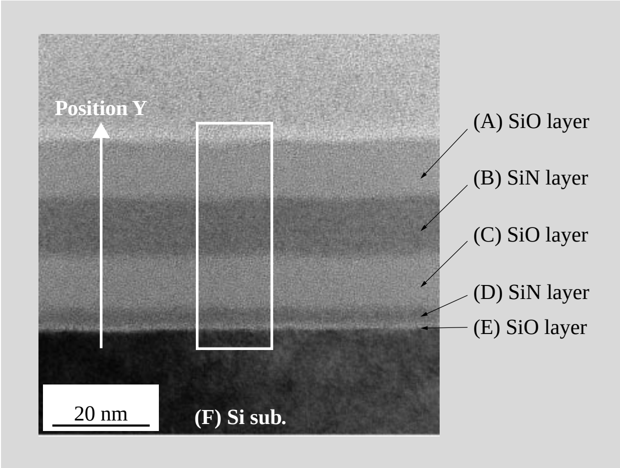


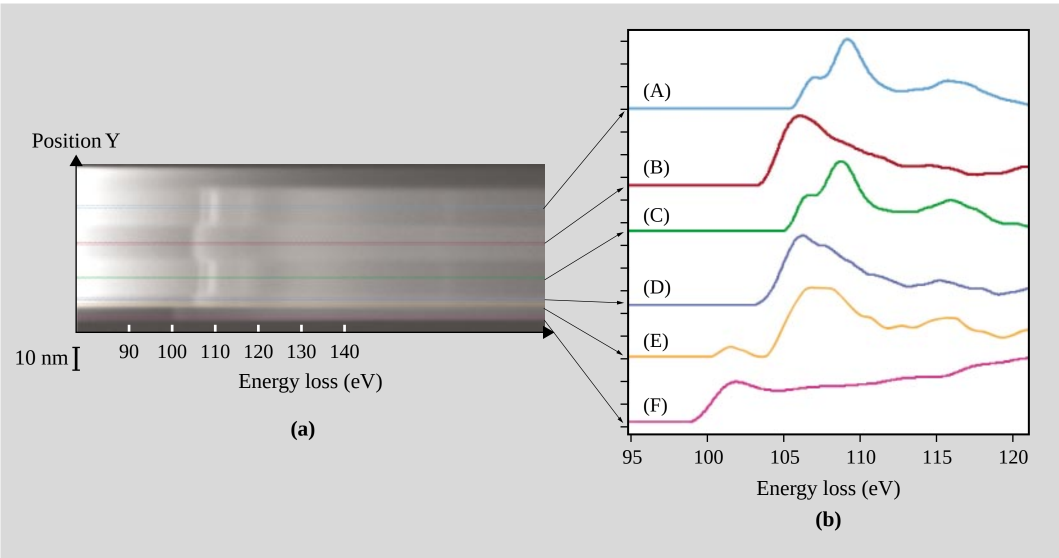
Fig. 5—TEM (transmission electron microscope) Image of Sample.
This multilayer film of SiO and SiN was fabricated using FIB (focused ion beam) with FIB micro-sampling mechanism. Slit position is white rectangular area.

microscope) image of a sample prepared for electron holography. The sample thickness was approximately 300 nm. A phase image of the N-MOS (negative-channel metal oxide semiconductor) transistor is shown in Fig. 3 (b). In the phase image, the contrast change in the Si substrate is clearly visible. This change is attributed to the internal electrical potential at the p-n junction. Since the electron holography directly depends on the electromagnetic field and does not depend on the kind of dopant atom, the electrostatic field derived by a light element, such as boron, can be successfully detected.

SPATIALLY RESOLVED EELS

Fig. 4 shows the principle of the spatially resolved EELS technology. A post-column energy filter (Gatan, Inc., GIF 863 Tridiem) was used. The GIF was specially aligned to keep positional information perpendicular to the energy loss axis in the spectrum plane. Therefore, the vertical axis of the spatially resolved EELS image corresponds to the sample position, and the horizontal axis corresponds to the energy loss. The slit is used to select the rectangular area of the sample. Line profiling analysis can easily obtain high-energy resolution because converging and scanning the electron beam is not necessary. In

Fig. 6—Result of Spatially Resolved EELS of Multilayer Sample.
Spatially resolved EELS image of Si-L edge (a), and extracted line spectra (b) from EELS image (a) are shown. Energy dispersion is 0.05 eV/ch. In this measurement, acquisition time was 30 s, and 10 pixels correspond to 1 nm.



addition, because the line spectra of different sample positions are measured simultaneously, the shift of origin of the energy axis in each spectrum can be neglected; therefore, chemical analysis at less than 0.5 eV can be achieved[(3), (4)].

SPATIALLY RESOLVED EELS APPLIED TO MULTILAYER SAMPLE

Fig. 5 shows a TEM image of a sample with a multilayer structure (Si/SiO/SiN/SiO/SiN/SiO). The SiO and SiN layers are clearly visible, as shown in Fig. 5. Fig. 6 shows the results of the spatially resolved EELS on the sample. Fig. 6 (a) shows a two-dimensional spectrum image recorded on a CCD (charge coupled device) camera. The vertical axis corresponds to the Y position in the white rectangular area, as shown in Fig. 5. The horizontal axis corresponds to the energy loss, which is calibrated using Si-L edge (99 eV). Fig. 6 (b) shows the energy loss spectra obtained in each layer. Since all spectra were acquired simultaneously, the energy shifts across the multilayer materials can be measured with high accuracy, and they can also be distinguished with a high spatial resolution (in the Y direction) of about 1 nm, as shown in the extracted spectrum (E) of Fig. 6 (b).

CONCLUSIONS

We reported the latest application results of electron holography, used for observing the dopant profile of a Si device. We also reported on the spatially resolved EELS, used for evaluating a multilayer structure. The HF-3300 TEM has new analytical capabilities that can be used for evaluating various types of materials. Applications of the HF-3300 will be extensively used for semiconductors, materials science, and nanotechnology.

REFERENCES

(1) A. Tonomura, Electron Holography Springer Series in Optical Sciences 70, Springer-Verlag, Heidelberg (1993).

(2) T. Sato et al., M&M proceedings (2008).

(3) K. Kimoto et al., “Chemical Shift Mapping of Si L and K Edges Using Spatially Resolved EELS and Energy-Filtering TEM,” *Journal of Electron Microscopy* **46**, 369 (1997).

(4) T. Sekiguchi et al., “Nitrogen Distribution and Chemical Bonding State Analysis in Oxynitride Film by Spatially Resolved Electron Energy Loss Spectroscopy (EELS),” *Japanese Journal of Applied Physics* **37**, L694 (1998).

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