A New Aberration-Corrected Transmission Electron Microscope for a New Era

Michiel van der Stam, Mike Stekelenburg, Bert Freitag, Dominique Hubert and Jan Ringnalda
FEI Company, Eindhoven, The Netherlands

BIOGRAPHY

Michiel van der Stam studied applied physics at the Delft University of Technology, The Netherlands. After receiving his PhD he joined FEI in 1997. Since then he has led various development projects, including HR-STEM development on Tecnai microscopes. He is now in charge of FEI's R and D Electron Columns group and has been responsible for the performance parameters of Titan.

ABSTRACT

Transmission electron microscopy has seen many changes since its invention in 1932. Engineering improvements have advanced system resolution to levels that are now only limited by the two fundamental aberrations of electron lenses: spherical and chromatic aberration. The use of a monochromator significantly reduces the negative effects of chromatic aberration. The spherical aberration can be corrected by multipole systems, but widespread use of this technology has been limited due to limitations in the TEM system. Here we present a new, extremely stable platform specifically developed for corrected optics and demonstrate the first results obtained from this system.

KEYWORDS

scanning transmission electron microscopy, spherical aberration, chromatic aberration, monochromators, Cs correction

ACKNOWLEDGEMENTS

The authors thank the involved employees of CEOS GmbH for their excellent contribution to making this project a success. The Titan platform is the basis of the TEAM project of the USA Department of Energy with the goal to arrive at 0.5 Å resolution in TEM and STEM on a single system, in combination with a Cc corrector developed in cooperation with CEOS GmbH.

AUTHOR DETAILS

Michiel van der Stam, FEI Company, Building AAE, Achtseweg Noord 5, P.O. Box 80066, 5600 KA Eindhoven, The Netherlands
Tel: +31 40 27 66503
Email: Michiel.van.der.stam@feico.com

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INTRODUCTION

The point resolution of transmission electron microscopes is limited by the spherical and chromatic aberration of the imaging lens [1]. Electron microscopes have been at the forefront of the nanotechnology revolution, and it is now widely believed that improvement in the optical performance of these microscopes can only be achieved in correcting for aberrations [2]. The correction of the spherical aberration (Cs) of magnetic lenses of (scanning) transmission electron microscopes is possible by using correctors based on multipole optics. This allows for significantly improved resolution in TEM and STEM and increases the currents in a small electron probe for spectroscopy applications [3,4]. Reducing the energy spread of the electron source with a monochromator down to 0.1 eV effectively reduces the effect of the chromatic aberration [5,6]. Moreover, the monochromator allows high-resolution EELS spectroscopy. This gives new information of the electronic properties of materials such as bonding states or band gaps with unprecedented spatial resolution.

Until now, aberration correction technologies in electron microscopes have been treated as accessory components for standard (S)TEM systems that were not designed for this type of advanced technology. Thus, the integration of these types of correctors for breaking the next resolution barrier as well as high throughput has been met with limited success, since the implementation of correctors brings flaws in the basic platform design to the surface. The new Titan 80-300 (Fig. 1) is designed as a dedicated and upgradeable aberration-corrected system that will enable corrector and monochromator technology to enter into commercial markets and get widespread use. In this article, the key properties and important specifications of this new platform will be described as well as why this platform will allow ultimate performance, flexibility and stability: a new microscope for a new era for new results.

ACCELERATION VOLTAGES

The maximum acceleration voltage of the microscope is 300 kV. The advantages of higher acceleration voltages are both improved spatial resolution and increased current in small probes, since the wavelength of electrons decreases and the brightness of electron guns increase with higher acceleration voltage. In addition, at higher acceleration voltages, the specimen preparation becomes less critical since the mean free path of electrons is increased allowing thicker samples to be examined. Also, amorphous layers on the specimen have a reduced effect on image quality.

The platform is not restricted to work at only 300 kV, but can be switched in acceleration voltage between 80-300 kV. This is an important feature, because sometimes specimens are sensitive to knock-on damage by the high-energy electrons. In this case, it is beneficial to use a lower acceleration voltage. The challenge then becomes clear; the microscope performance has to scale in line with the theoretical performance reduction predicted by the increased wavelength of the electrons, and not more. Furthermore, optical components such as correctors and energy filters should remain useable.

NEXT GENERATION CORRECTORS

The Cs correctors are of the dual hexapole type and were developed for the new TEM column by CEOS GmbH in close collaboration with FEI. Figure 2 shows schematically how they work. The first hexapole of the corrector deforms the beam. This deformed beam is then projected into a second hexapole that compensates for this deformation leaving only a higher order effect. This effect acts like a negative Cs: the electron rays further away from the center leave the corrector seemingly coming from a point source closer to the corrector. This compensates for the opposite effect (positive Cs) in the objective lens. The aberrations of the two components are simply added together, so the total Cs of the two modules can be tuned to various values.

Figure 1:
Titan™ 80-300

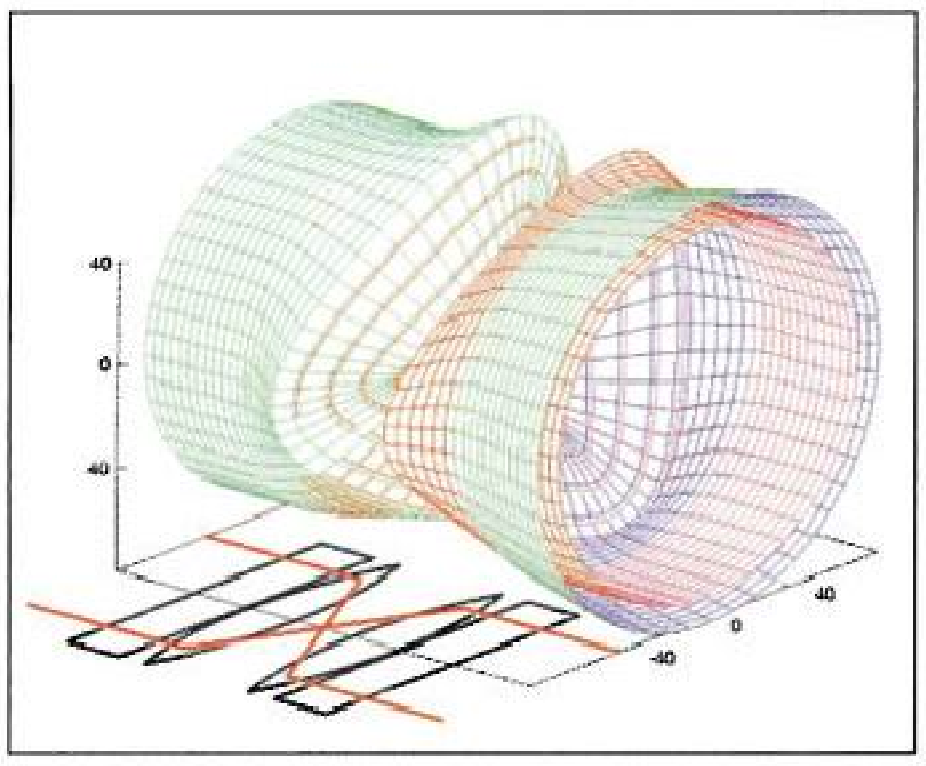

Figure 2:
Principles of a spherical aberration (Cs) corrector. Courtesy of Dr Stephan Uhlemann, CEOS GmbH.

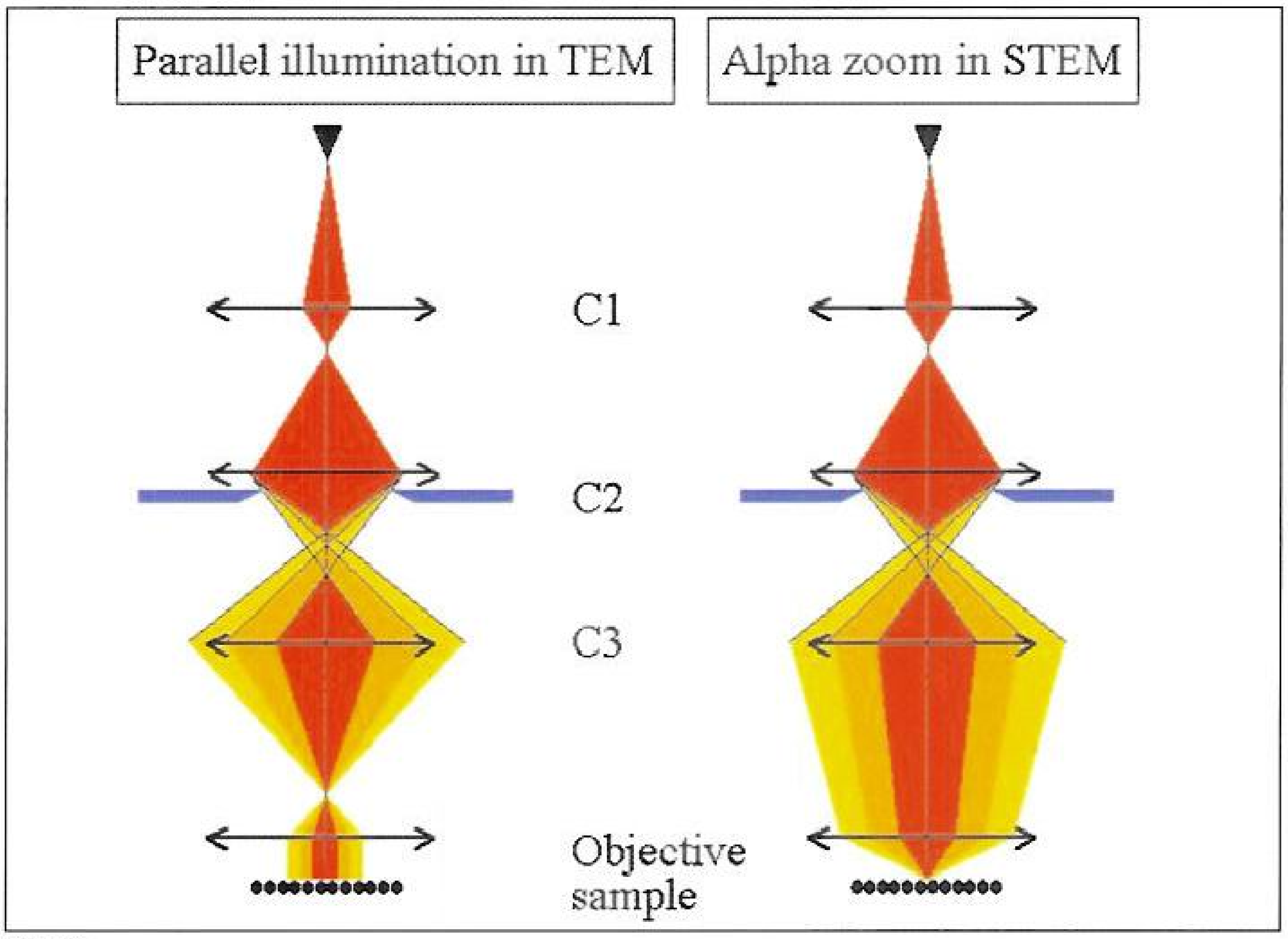

Figure 3:
Principle of three-lens condenser system.

The newly developed correctors offer a full 80-300 kV range with lower noise electronics, have better temperature stability and intrinsic to the microscope, modules have a better mechanical alignment. In addition, a new transfer lens was designed that allows for improved resolution.

NEW CONSENSER SYSTEM

The TEM is equipped with a new three-lens condenser system. Figure 3 shows the basic optical setup. The C2 aperture has a dominant role. The three condenser lenses together form a double zoom system giving increased flexibility in both TEM and STEM modes. In TEM mode, parallel illumination can be achieved over a wide field of view. In STEM mode, a large variety in probe angles and probe currents are supported. In combination with a monochromator, the monochromatic spot can be demagnified to the angstrom level to allow for high-resolution EELS with very small probes. The new 300 kV monochromator is of a Wien filter type and follows the same principles as the successful 200 kV monochromator of the Tecnai series [5].

COLUMN DESIGN

Ultrahigh performance dictates ultrastable behavior of the entire system for the duration of the experiment: mechanical stability, low noise performance of the electronics and thermal stability of the column are all key factors. All these critical parameters have been addressed in the design of the new platform. The stiffness of a microscope column improves with the 4th power of its diameter, but it deteriorates by the 3rd power of its length. Increasing the microscope length by adding correctors and energy filters therefore has a dramatically negative effect on the stiffness of the column, while, at the same time, resolution and stability requirements become much more stringent. The new microscope's column has an increased diameter of 30 cm which gives the required stiffness. It is also equipped with a patented new method for accurately aligning column modules, since mechanical alignment of the microscope lenses with respect to each other is a key element to arrive at a high-performance system. This new method also offers this high accuracy in the field. As a result, a stepwise approach to corrected microscopy becomes possible: the TEM system, when originally delivered without correctors, can be upgraded in the field with a single corrector.

CONSTANT POWER

As these platforms with aberration correctors have to use multipole optical elements to make them work, aberration corrected systems have very strict demands on the mechanical and thermal drift of the relative position of the various optical axes in the system. For this reason, a constant power solution for all major lenses of the column has been designed. Figure 4 shows how this works. Every lens is equipped with two coils with the same number of windings. The magnetic field that is generated by the lens is proportional to the sum of the currents flowing through the individual coils ($I_1N + I_2N$). The power dissipation of the lens however, is proportional to the sum of the second power of the individual currents ($I_1^2R + I_2^2R$). In combination with a dual bipolar power supply, this yields the possibility to vary the magnetic field over a large negative and positive range while the power dissipation of the lens stays completely constant.

Even though the power dissipation of both coils together is constant, the individual coils do not have a constant dissipation. This effect is addressed by winding both coils together in a bifilar manner. This completely couples the two coils so one single unit is formed with constant power dissipation regardless of the magnetic field. This power scheme for ultimate stability with flexibility allows changing the optical conditions of the microscope without affecting the thermal equilibrium. Even the low-mag range (typically only possible by switching the objective lens off) can be achieved by having the two coils excited at the same strength in opposite sign.

STATUS AND FIRST RESULTS

In the fourth quarter of 2004 the platform was released for production, and the first uncorrected systems have been built for delivery to customers in the USA and Europe. In Figure 1, an image of the basic column, which is

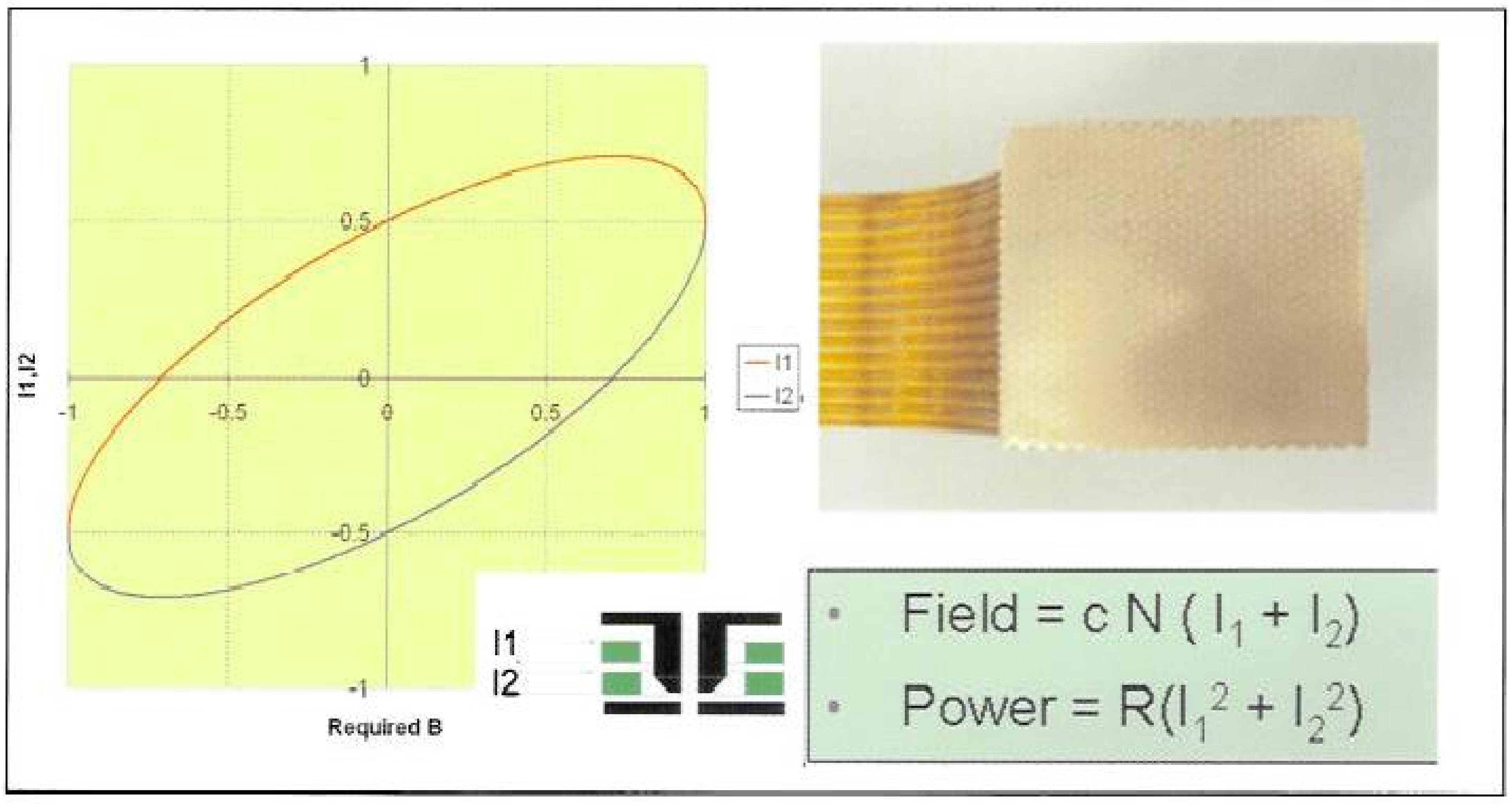

Figure 4:
Constant power scheme of lenses. The X-axis refers to the required field. The red (I1) and blue (I2) lines show the coil current values (Y-axis) for this field strength. Power dissipation is constant regardless of the required field.

installed in the Nanoport in Eindhoven, is shown. The performance of the new microscope's column in TEM/STEM and spectroscopy has been tested.

Figure 5 shows the fast Fourier transform (FFT) of a Young's Fringe experiment taken from a polycrystalline gold sample on a carbon film in high resolution TEM. This experiment determines the information limit of the platform in TEM, which proves the highest lateral resolution the microscope can transmit. As can be seen from this FFT, the Young's fringes extend to 0.7 Å which is remarkable considering this system was equipped with an S-TWIN pole piece having a relatively large gap (5.4 mm) which allows tomography and cryo experimentation to be performed. In the magnified section of the FFT in Figure 5 all the lattice spacing of gold below 1 Å down to below 0.7 Å can be indexed. This illustrates that the new (S)TEM system features high overall stability to break the 1 Å barrier as a base system before the addition of aberration correctors.

In March 2005 the new 300 kV monochromator was tested for the first time. Application results on GaAlAs show its value for bandgap studies on semiconductor devices, shown in Figure 6. The band gap of pure GaAs and GaAlAs has been measured at 300 kV. A shift in the bandgap due to the 50% Al concentration can be observed in the spectra. The bandgap energy of GaAs can be measured to 1.42 eV and the band gap energy of the GaAlAs to 1.72 eV. This is in accordance to theory, which predicts 1.45 eV and 1.75 eV. Moreover, a shift of the plasmon loss peak is noticeable, which is a topic for further investigation.

Last but not least, in May of this year, the first probe-corrected system was operational and shows 0.8 Å resolution in STEM mode. Figure 7 shows the image obtained from silicon (110) with a dumbbell spacing of 1.36 Å. An intensity line profile across the dumbbell structure shows clearly the split between the silicon atoms. The noise level of the baseline in the profile shows that the transfer down to 0.8 Å is not due to artifacts in the setup of the detector electronics [7]. The FFT of the image proves a resolution of 0.83 Å, furthermore the FFT shows the reduced intensity in spots which are 'forbidden', such as the <002> reflections, indicating correct experimental procedure.

These results show the effects of the improvements in the column design described above and demonstrate that the microscope is capable of transferring information well below 0.1 nm in both STEM and TEM modes.

CONCLUSIONS

A new corrected (S)TEM platform has been developed capable of the highest performance in TEM and STEM. It is a revolutionary design based on successfully addressing all key requirements for corrected microscopes to obtain a lateral resolution far better than 1 Å and an energy resolution down to 0.1 eV. Its stability, performance and usability will allow corrected microscopy to be taken to the next level where new discoveries on the structure-property relationships of materials become possible at ever decreasing scales.

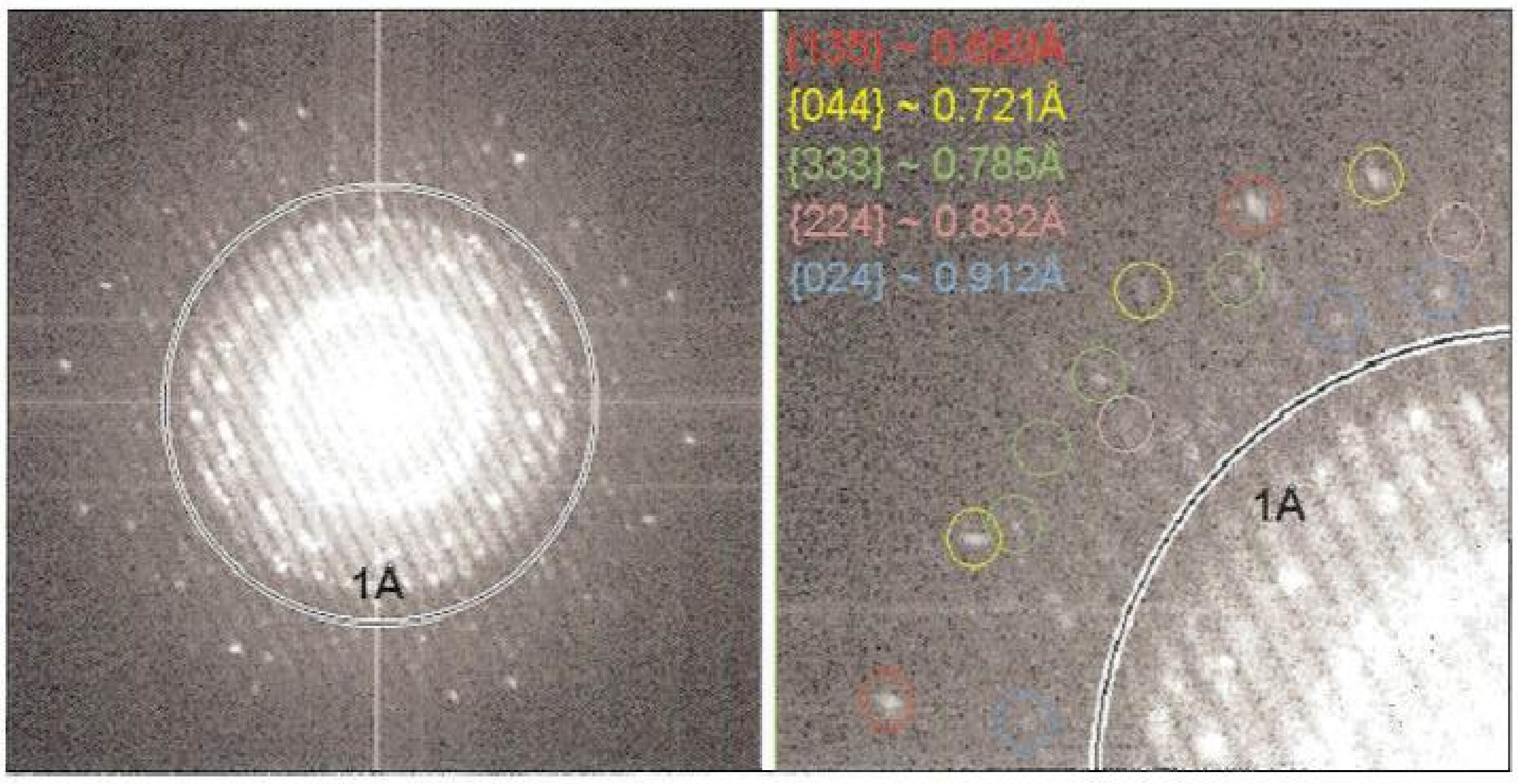

Figure 5:
Young's fringe experiment in TEM mode shows the information limit. On the right side a magnified section of the left image is shown.

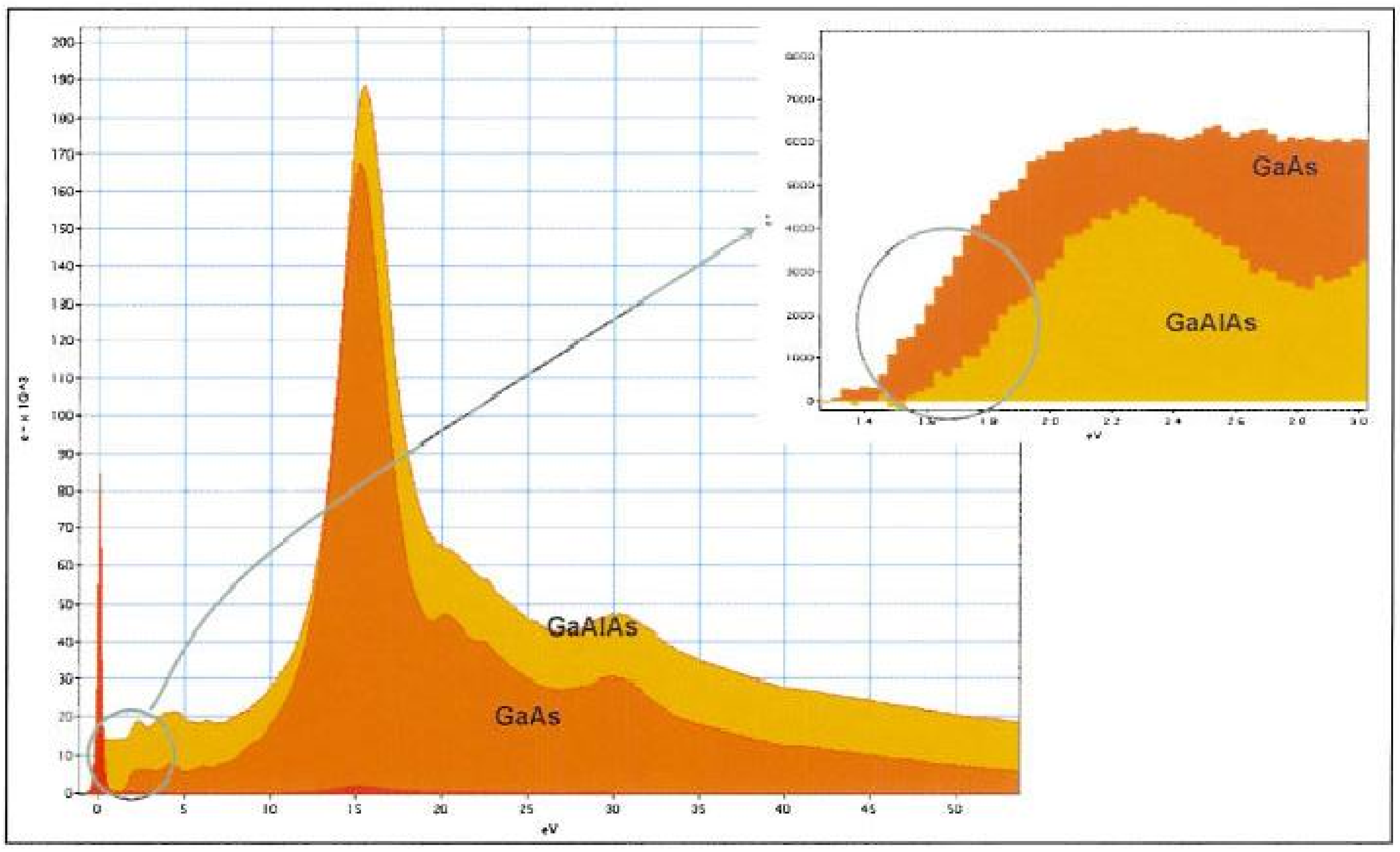

Figure 6:
Low-loss EELS spectrum of GaAs and GaAlAs. The band gap is visible next to the zero-loss peak. The insert shows the shift of the band gap of GaAs and GaAlAs.

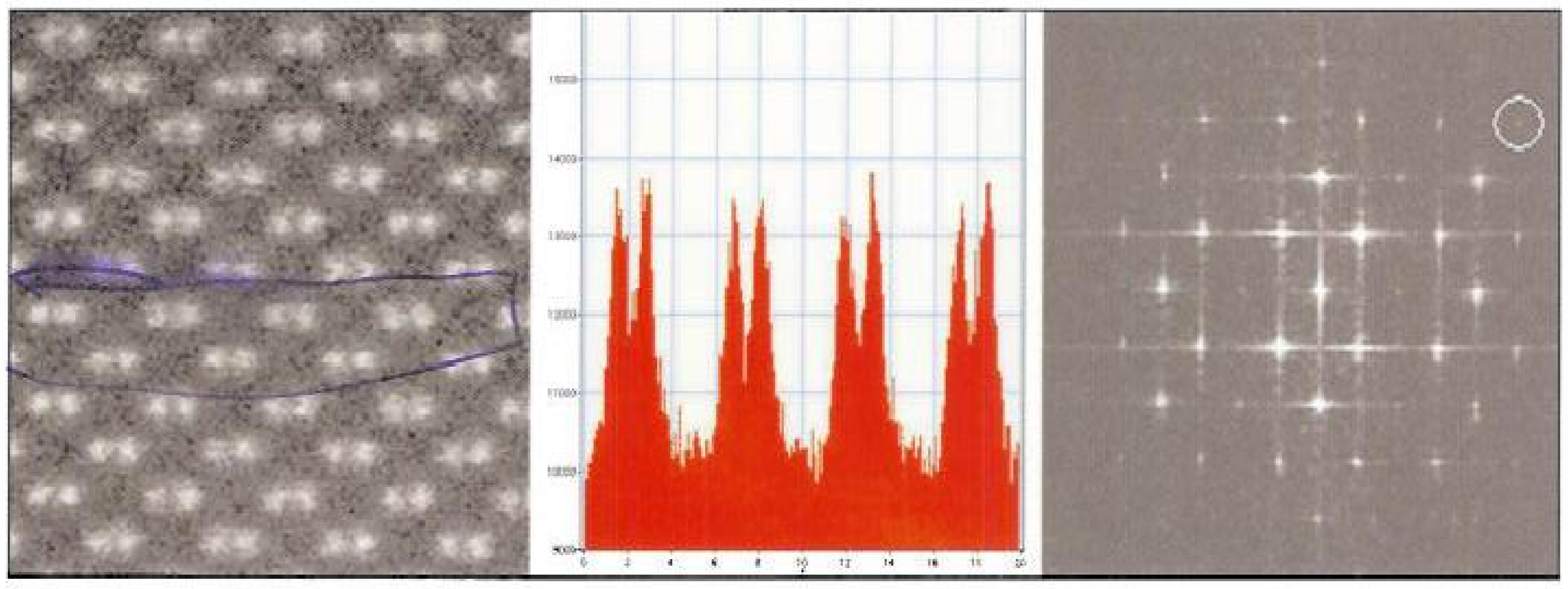

Figure 7:
Left: HR-STEM image of Si (110). The intensity profile across the dumbbell structure is shown on the middle. In the Fourier transform of the image, right, 0.83 Å distance can be observed (circle).

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