



Mid-March 2005
Vol 27 No 3

European
semiconductor

Zoom zoom zoom

Zeiss's record breaking
ultra high resolution TEM



Stretched to the limit

Big Blue's strained
germanium technology

New model army

Replisaurus's founders get
into the modelling craze



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Picture perfect

A record-breaking new transmission electron microscope comes close to achieving the theoretical limit of image resolution, write **Drs Peter Schlossmacher, Alexander Thesen** and **Gerd Benner** of **Carl Zeiss SMT**.



Figure 1. Carl Zeiss SMT's new sub-Angstrom UHRTEM with revolutionary column suspension concept

Typical structures in semiconductor devices and advanced nanotechnology are getting smaller and smaller. Since scientists and engineers want to visualise and analyse what they develop and manufacture, their demand for better imaging resolution and improved imaging quality increases rapidly.

The attainable resolution of a transmission electron microscope (TEM) is – like in an optical microscope – mainly determined by the properties of the objective lens. Lenses are never perfect and exhibit a variety of defects. One major lens defect, called spherical aberration and characterised by the spherical aberration coefficient, C_s , causes rays or electrons away from the optical axis to not be focused on the same focal point as those propagating on the optical axis.

In light optics, improved manufacturing quality, sophisticated shapes of lens surfaces and combination of lenses have led to very high optical properties, resulting in a resolution even smaller than the wavelength of visible light.

Since typical lenses in transmission electron microscopy are electromagnetic round lenses, they unavoidably suffer from aberrations and have always had a positive C_s coefficient (1). This explains why the typical (point) resolution of a present 200kV TEM of 0.24nm is about two orders of magnitude worse than the wavelength of the electrons (200kV = 0.0025nm). Only the coefficient C_s and the wavelength determine the (point) resolution. Therefore only two ways for resolution improvement exist (besides different techniques like electron holography): to shorten the wavelength by increasing the accelerating voltage; or to reduce the spherical aberration of the objective lens. Higher accelerating voltages increase the knock-on damage, ie the direct displacement of atoms from

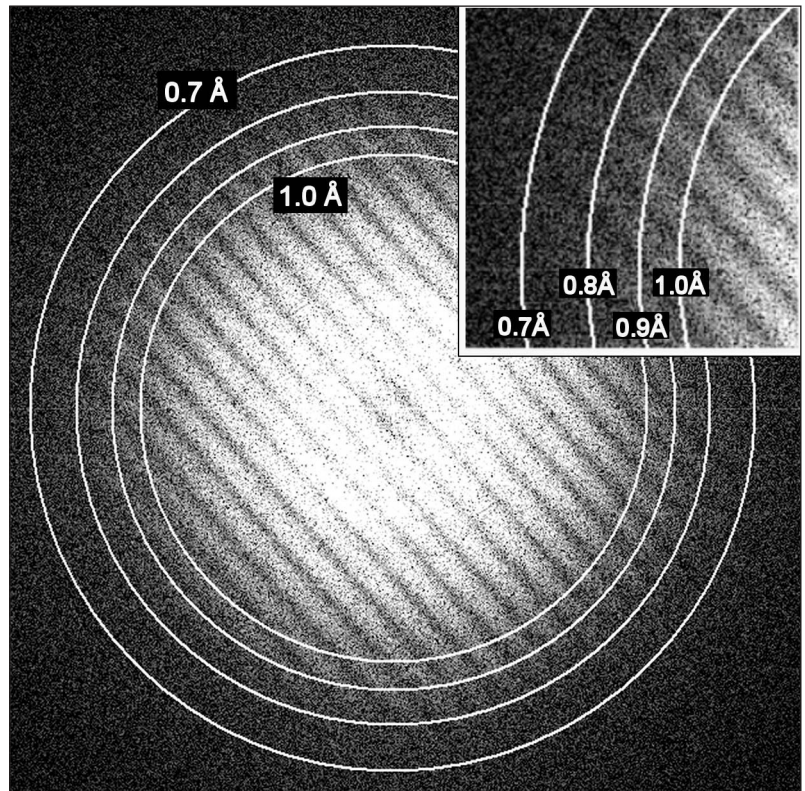
the crystal lattice and, importantly, the costs of such microscopes. In 1990 Professor Harald Rose showed that, in principle, it is possible to correct the spherical aberration of the objective lens of a TEM (2). This discovery paved the way towards sub-Ångstrom resolution for 200kV TEMs.

The concept of the Ultra High-Resolution TEM (UHRTEM)

The key elements of a UHRTEM (Figure 1) are three new electron-optical components. The C_s corrector – based on Rose's concept (2) – was developed by German company CEOS (Corrected Electron Optical Systems GmbH, Heidelberg) (3,4). It consists of two hexapole elements and two lens doublets that provide complete compensation of the spherical aberration (of the imaging part) of the objective lens. Only this hexapole corrector is able to correct for large image sizes typical for the image mode in transmission electron microscopy.

The second component is a monochromator, which was also developed by CEOS and is entirely integrated in the electron source – nowadays a field emission [FE] system. The monochromator reduces the inherent energy spread in the electron beam from typically 0.7eV to values smaller than 0.2eV depending on the setting. As soon as the spherical aberration of the objective lens is fully corrected (C_s drops by three orders of magnitude to a few microns compared to a value of about 1mm without correction) the second largest lens defect, the chromatic aberration, C_c , comes into play. For monochromated electrons, the influence of the chromatic aberration is smaller. Since correction of C_c requires a rather complex arrangement of even more electron-optical elements compared to the C_s corrector, reducing energy spread is the method of choice. The combination of the monochromated FE source with a C_s corrector for the objective lens has allowed the sub-Ångstrom imaging resolution barrier to be broken.

Last but not least, the UHRTEM comprises an In-column energy filter of the corrected Omega design (5). An In-column Corrected Omega filter disperses the electrons according to their energy (like a prism disperses the different colours of visible light). This provides an electron energy loss spectrum (EELS) of the specimen in the dispersive plane revealing detailed information on the chemical elements and their bonding. Furthermore, the In-column Corrected Omega filter is also an imaging unit since it generates an achromatic image of the specimen (to which electrons of all energies contribute). By selecting a certain energy range by inserting a slit in the dispersive plane, the image only contains information of specific electron energy losses within the specimen (EFTEM = energy filtered TEM). This can be used to remove inelastically scattered electrons (for contrast enhancement) or to select



element specific energy losses for elemental distribution images (electron spectroscopic imaging). Therefore, the In-column Corrected Omega energy filter adds analytical capabilities to the UHRTEM without influencing its outstanding imaging resolution.

The three new electron-optical components are integrated into a new unique TEM platform, which is also used for Carl Zeiss SMT's new series 200kV FE-TEM – the LIBRA 200FE (6). A proprietary support frame (concept of a "hanging" column), together with an ultra-stable high voltage supply and very stable current sources for the objective lens and the in-column energy filter, complete the UHRTEM.

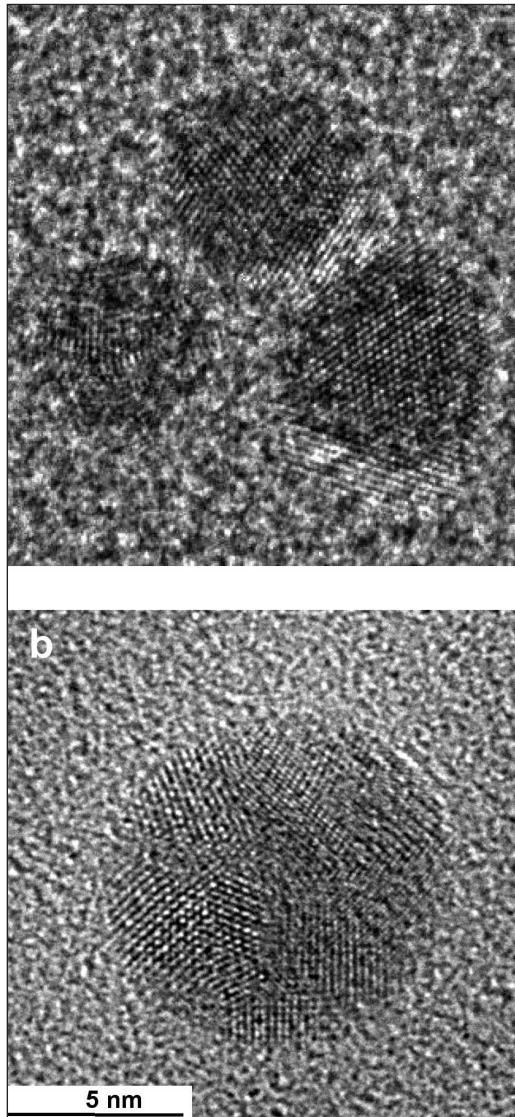
A new record in sub-Ångstrom TEM imaging

During the qualification phase for the UHRTEM, a new record resolution was achieved (7). In order to demonstrate the achieved imaging resolution, so-called Young's fringes patterns (Figure 2) were generated from two micrographs recorded at 800,000 times magnification and image acquisition times of one second. The two images were taken from slightly different locations of an amorphous tantalum thin film, subsequently added and Fourier transformed to generate the fringe pattern. The fringe patterns help to distinguish signal from noise.

The energy spread of the field emission source

Figure 2. Young's fringe pattern revealing useable image resolution of 0.8 Ångstrom. Inset shows image resolution of even down to 0.7 Ångstrom for certain image directions, nearly equaling the theoretically achievable resolution limit.

Figure 3. Image of Au particles on carbon support film. With an uncorrected objective lens (a) string delocalisation (fringe contrast outside the particles) is visible. In the C_s -corrected case (b) the delocalisation has disappeared and the Au particle is imaged artefact free



References

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7. EUROSEMI Bulletin, Issue 570 (January 26, 2005), page 3

was reduced by the monochromator to 0.2eV, and a residual spherical aberration of the objective lens (C_s value) of about $-3\mu\text{m}$ was obtained. Four ring insets, calibrated by gold lattice reflections, indicate the 1.0, 0.9, 0.8 and 0.7 Ångstrom resolution limits (from inside to outside in Figure 2). For all image directions, the fringe contrast clearly extends to the 0.8 Ångstrom ring and even to the 0.7 Ångstrom ring for certain image directions. This is close to the theoretical limit for a 200kV FE-TEM.

The benefit of artefact-free imaging and ultimate resolution

Reducing the main lens defect, the spherical aberration, by three orders of magnitude to a value close to zero not only increases the resolution but it also improves the image quality in general since other effects are closely related to the C_s value. Here, we take a look at two of these effects.

The first one is so-called delocalisation. Due to a non-zero C_s value, electrons from one point of an object are not imaged into a single point but rather into a small disk smearing out the information (the information is no longer "localised" but "delocalised"). In atomic resolved images of periodic structures, delocalisation, although present, is not easily visible. However, as soon as non-periodic structures are imaged or the periodicity is terminated in at least one direction (eg by an interface or surface) the effect of delocalisation is striking (Figure 3). This is the case when interfaces of thin layers – epitaxial layers, nano-particles or grain boundaries in semiconductor devices – have to be investigated.

Eliminating delocalisation allows for the first time certain interfaces – such as the CoSi_2/Si interface in semiconductors – to be visualised in unprecedented detail (3,4). Only aberration corrected imaging of this interface revealed its atomic structure and showed that the CoSi_2/Si interface is atomically flat. Therefore, for all kinds of thin film research – including the latest gate oxide structures – artefact-free imaging is prerequisite for a successful process development. Since any kind of process control has to give a clear feedback to process engineers, whether the selected parameters lead to satisfactory results or not, the new class of C_s -corrected TEMs could become the standard tool for process control in semiconductors in the future.

Secondly, in a TEM with aberration correction of the objective lens, a small beam tilt does not cause other image faults like astigmatism or coma. High-resolution TEM imaging of crystalline structures requires their precise orientation to the optical axis. To achieve this by tilting the sample is in many cases time consuming. In a C_s -corrected TEM this final alignment of the sample towards the electron beam direction can be reversed by tilting the axis of the electron beam towards the orientation of the crystalline sample. This makes it much easier to precisely align a specimen area – eg close to a defect of interest – just by tilting the beam and leaving the specimen stage untouched. As a consequence, specimen throughput can be increased.

Outlook

After almost no improvements in imaging resolution during the 1990s, the correction of the spherical aberration of the objective lens of a TEM has opened up a new era in transmission electron microscopy. Artefact-free imaging up to the utmost imaging resolution with the freedom to tilt the beam without deteriorating effects on the image quality will find many new applications and provide unprecedented insights into materials. Although the full potential of this new technology is far from being exploited, the impact that transmission electron microscopy could have on process control and research in semiconductors should not be underestimated.