

The Next Generation of TEMs

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A selection of the more common questions arising during a typical lab course for materials majors learning to use a TEM is as follows:

- 1) Why must I insert the objective aperture, which governs *image* contrast, in the *diffraction* plane?
- 2) Why must I insert the selected area diffraction aperture, which governs the *diffraction pattern contrast*, in the *image* plane?
- 3) Why is the TEM relatively useless if both apertures are in at the same time or both are out?
- 4) Why is the contrast in my images always greatest when the beam is parallel - which makes the screen intensity so weak, I sometimes can't see the contrast anyhow?
- 5) Why, when I need to record a diffraction pattern, do I have to learn to estimate exposure time from the analog screen, rather than just push a button and get a correct exposure, as in most other optical instruments and cameras?
- 6) Why are my centered dark-field images all weak?
- 7) Why do my (zone-axis) diffraction patterns, which contain the most useful crystallographic information, provide the worst image contrast?
- 8) Why are my two-beam diffraction patterns that create the best image contrast, usually impossible to index?
- 9) Why is the spherical-aberration limit of resolution of the TEM given by so many different equations, including: a) the diameter or b) the radius of c) the disc of least confusion or d) the Gaussian image with a "constant" of proportionality that is A, B, 1, 0.91 or 0.43?

These fundamental questions are asked by students today, as they were thirty or more years ago. Most of these questions relate simply to the operation of the TEM column, not to the use of the TEM to solve materials problems. Can a TEM be developed to the point where most of these questions are redundant because the instrument takes care of the answers for the operators and allows them to concentrate on extracting useful information from their images and diffraction patterns?

Unfortunately TEMs cost so much that we can't convince the funding agencies or our university administrators that \$1 M only buys us a routine instrument. So we have to make every TEM purchase a top-of the line instrument. With apologies to Thomas R. Marshall, what this country needs is a good "nickel" TEM. The large majority of routine TEM users that don't need or can't apply high-resolution imaging need an inexpensive TEM (~\$250-300,000 range). It needs to have no better than 5Å resolution, which is still well below the chromatic-aberration limit of ~2 nm that applies to any specimen >100 nm thick, (even when it is viewed in a high-resolution instrument). Relaxing the resolution needs from 2Å to 5Å will reduce the mechanical demands and complexity of stage design and create plenty of space in the stage to traverse, tilt, rotate, strain, heat and cool the specimen under computer control, while having one or more X-ray detectors available. All these useful tools for materials characterization are usually compromised in current TEM stages by the demands of high resolution.

Such an instrument will simplify the teaching of TEM. Laboratories that are currently priced out of the market will be able to afford a TEM. Some aspects of such a TEM might comprise:

- a) A sealed, bakeable UHV gun chamber with multiple tips (FEG or LaB₆) that remains sealed for the life of the instrument.
- b) A compact column, using mini-lenses (e.g., sextupoles and octupoles) - constructed in VG mode (i.e., gun on the floor) or horizontal, to maximize the

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mechanical stability, and small enough for rapid pumping to UHV.

c) Computer-driven apertures and stage with a mechanically-isolated piezo-driven specimen holder, and an environmentally-isolated column, far from the operator.

d) Digital recording, storage and printing, with direct internet access at the operating console to the ICDD file, and useful TEM web sites, such as the Lausanne TEM yellow pages, or the Argonne software library, etc. Diffraction patterns can then be indexed on line and combined with X-ray spectra to give automatic phase identification on line - as is feasible on many modern SEMs.

Current TEMs have locked themselves into costly designs that are the consequence of incremental improvements on proven concepts (e.g., the manually operated goniometer stage). A modern TEM needs several pumps to evacuate a total volume of about 1 ft³ to a vacuum of ~10⁻⁶ Pa. In any surface-analysis instrument that volume would be at < 10⁻⁸ Pa or better. The problem is that sliding o-rings, essential for mechanical side-entry goniometers, leak and photographic emulsions outgas. Obviously the solution is to remove the mechanical drives, replace them with piezo drives, which operate very well at the atomic level in UHV scanning probe microscopes (SPMs). Also the photographic film should be replaced with digital recording which, while not yet at the resolution of Ag-halide, is still more than sufficient for the vast majority of microscopists who don't need atomic resolution (see article by Alwyn Eades in *Microscopy Today*, December 1998).

One consequence of such a radical change in TEM design will be that, like a modern SEM, the TEM will become completely remotely controllable (apart from loading the specimen). The prime advantage of remote operation is that it isolates the TEM column from the most dangerous object in a lab - *the user*.

Computer software and hardware exist such that TEM operation, after specimen insertion, can be truly remote. The following steps need full computer

control:

- a) Turning on and optimizing the gun
- b) Finding the hole in the specimen
- c) Focusing to the eucentric height,
- d) Insertion, centering and removal of apertures
- e) Astigmatism and spherical-aberration correction
- f) Tilting to specific orientations
- g) Recording of digital images and transfer to central data archive
- h) Routine checking of the alignment and on-line correction of any drift

Many of these steps are already implemented on SEMs or SPMs. There is no reason they cannot *all* be implemented on a TEM. The next step is then to take the routine operational and alignment steps out of the hands of the operator (as they have been removed on the SEM) and give them to the computer. Such steps include:

- a) Automatic BF, CDF, WBDF, phase contrast imaging, simply by pointing and clicking
 - b) Compensation for changes in eucentricity during automatic tilting to specified orientations
 - c) Remote image/DP recording and storage in digital form
- Automatic compensation of alignment for changes in probe size, and magnification

Other, more advanced possibilities include:

- a) An in-column energy filter to remove chromatic aberration and ensure all

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The Next Generation of TEMs

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images and diffraction patterns are automatically zero-loss images

b) Automatic thickness determination as the specimen is traversed, with indications when limits are reached for EELS and X-ray analysis

c) Automatic orientation determination, as the specimen is traversed, through rapid intermittent collection of Kikuchi maps in CBED mode

Then we can get sophisticated and start to envisage the kind of experiments that are virtually impossible to do today with human operators. Already SEMs are being controlled by software that could be described as artificial intelligence. Perhaps the TEM field can take the lead this time and go straight towards expert-systems control?

Such complete control of the TEM column can also be applied to the seriously expensive research instruments located at National Centers, National Labs, etc., with good internet2 access and real time imaging. This is already done with the Antarctic telescopes, which can be run remotely from the University of Arizona. Such advanced TEMs can be as expensive as they need to be, but remote operation brings advantages and may yet replace the current practice of sending graduate students to Berkeley, Arizona State or ORNL for long periods of time. However, if the TEM is to continue to grow, I believe the marketing emphasis must be returned to attracting the general user, not providing TEMs principally for the high-end market.

If there is no major change in the design of TEMs, if all TEMs remain very expensive and difficult to operate, the market will not expand. Then we face the prospect of possibly losing the instrument, and certainly losing our choice of instruments. With the recent demise of VG Microscopes, only four commercial manufacturers remain [Hitachi, JEOL, Philips/FEI and Leo (formerly Zeiss)]. Within these companies, there are both reassuring develop-

ments and some potentially dangerous possibilities for the TEM community.

Hitachi has just brought out a dedicated STEM for the semiconductor market, offering complete mouse-based operation. It is basically a 200 kV FEG SEM operated and marketed as such. The dedicated STEM will sell for significantly less than a modern TEM - but still offers 2Å STEM images and great X-ray analysis performance. If it succeeds, Hitachi will sell dozens to the semiconductor market. Will this affect their interest in the traditional TEM market?

JEOL has just announced the field-emission filter (FEF) series of in-column energy-filtered, remotely controlled FEG-TEMs with no conventional analog viewing screen. All images and diffraction patterns are viewed via a CCD or high definition TV camera. This is a real step in the right direction but is only offered at top-end prices and will not find a way into all materials departments.

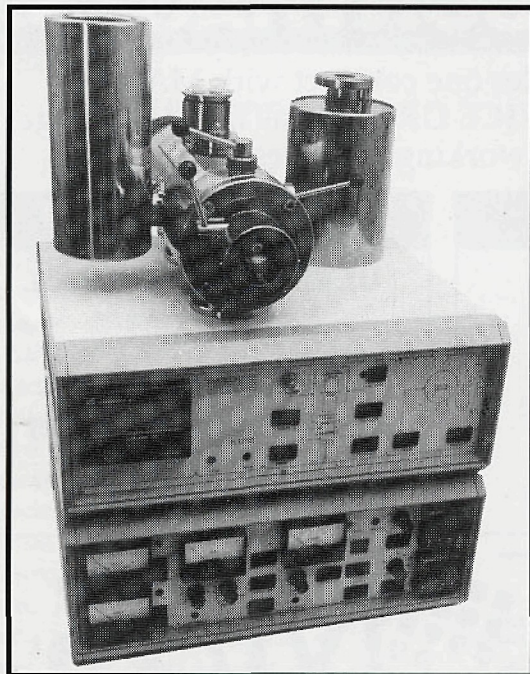
Philips/FEI has just announced the Tecnai series of computer-controlled TEMs, but the column is still firmly in front of the operator. The stage drives have gone, but the apertures are manual and the analog screen is still there. If this doesn't sell, will Philips/FEI decide that ion columns are more profitable than electron columns?

Leo has announced a 200 kV FEG version of their omega-filter 912-series instruments but the degree of computer control and remote operation capability characteristic of the other instruments, are not yet proved. For historical reasons, Leo TEMs remain rare sights in materials departments.

Aspects of all the above instruments, if designed and priced for the routine-user rather than the top-end user, may cause the resurrection of a truly modern TEM and its re-appearance in every materials department, and many more industries. I believe that we as users must push for radical changes in the design and marketing of TEMs so that they can become more routine instruments for materials analysis, requiring no more education to use than a current SEM. ■

This article is based on a talk given at a symposium on "The Future of Remote Microscopy in Materials Education" at Carnegie-Mellon University, Oct. 25, 1998.

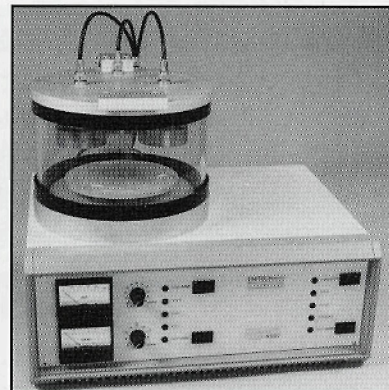
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