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Advances in monochromators and aberration correctors

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Electron-optical instrumentation and its applications have advanced rapidly in the last few years. Particularly noteworthy progress has taken place in the areas of low kV imaging and analysis, spearheaded by the SALVE project [1], the CREST triple-C project [2] and work by Nion, in rapid elemental mapping using either electron energy-loss spectroscopy (EELS) or energy-dispersive X-ray spectroscopy (EDXS) signals, in improved performance environmental microscopy, and in ultra-fast imaging and analysis. In this paper, the Nion contribution to the general progress is reviewed.

The scanning transmission electron microscope (STEM) which we recently introduced combines a bright, stable and mono-energetic cold field emission electron gun (CFEG) with an ultra-stable probe-forming column corrected to 5^{th} order and a high-stability sample stage operating in an ultra-high vacuum [3,4]. It has allowed experiments to be carried out that seemed unthinkable only a few years ago. Examples include the determination of the position and type of every atom in a monolayer material [5], detecting single atoms by X-ray spectroscopy [6], and even exploring the atomic environment of single atoms, based on their near-edge EELS fine structures [7,8].

More recently still, we have developed a High Energy Resolution Monochromated EELS-STEM (HERMES) system that uses several new design principles [9-11]. The monochromation is carried out at the ground potential (i.e., at the full primary energy) rather than inside the electron gun, with an all-magnetic monochromator (MC) consisting of a main energy-dispersing prism, spectrum-magnifying quadrupoles, auxiliary prisms that bend the beam into an alpha-type trajectory, an energy-selecting slit equipped with current sensing, and aberration-correcting sextupoles and octupoles. The MC uses dispersing-undispersing optics such that the energy dispersion of the beam is precisely cancelled at its exit. The MC's main prism winding is connected in series with the prism of an all-magnetic EEL spectrometer, which means that the energy spectra formed at the slit and at the EELS detector track each other, and small instabilities in the prism supply current do not change the position of the spectrum on the final detector. The high tension (HT) of the microscope is stabilized by sensing the electron current falling on the two halves of the MC's slit in a feedback scheme that adjusts the HT such that the energy-dispersed beam remains precisely centered on the slit opening.

The above approach is roughly equivalent to two parallel EELS systems running back-to-back and thus more complicated than other MC designs. However, it provides several key advantages. First, because the beam traverses the MC at the full energy and the beam intensity is reduced by a pre-MC beam-defining aperture, statistical Coulomb interactions between the beam electrons are greatly reduced, allowing good energy resolution to be reached without broadening the beam unduly. Second, connecting the MC and EELS prisms in series, which is possible precisely because the MC operates on the full-energy beam, results in very good short- and especially long-term energy stability. Third, full energy electrons are less sensitive to effects such as charging at the slit edges, and this allows the system to achieve very good spatial resolution while monochromating.

HERMES has been able to reach 12 meV full-width at half-maximum (FWHM) of the EELS zero loss peak (ZLP) in a short-exposure spectrum at a primary energy of 60 keV (Fig. 1), and 20 meV FWHM in spectra acquired for several seconds. Fig 2. shows a low-loss spectrum of an SiO_2 layer in a MOSFET device acquired at about 40 meV energy resolution at 60 keV. Fig. 3 shows Si L-edges in elemental Si and in SiO_2. Further improvements in energy resolution should become possible once the detector part of the column and the EELS are brought up to the ultra-stable design standards used in the probe-forming part of the column, and we are now working in this direction.

When the energy-selecting slit is opened to admit an electron beam about 100 meV wide at 60 keV primary energy, the spatial resolution of the system is improved compared to running with the MC turned off (and the beam going straight through it), or the MC on and the energy-selecting slit withdrawn from the beam [10]. This is because at primary energies <100 keV, the size of the unmonochromated probe in the Nion STEM is mainly limited by chromatic aberration (C_c), and decreasing the beam energy spread reduces C_c's influence. Bypassing the chromatic resolution barrier shifts the attention back to geometric aberrations. We are presently working on incorporating extra sextupoles in the Nion C3/C5 quadrupole-octupole probe corrector [12] for more flexible control of parasitic aberrations. The sextupoles work together with other multipoles of the corrector and produce a rich set of combination aberrations, which allows all the important parasitic aberrations up to fifth order to be adjusted via a small subset of controls that addresses each aberration in turn [13]. This should allow HERMES to form aberration-corrected electron probes with semi-angles of up to about 50 mrad, and to reach probe sizes of about 0.8 Å at 60 keV and about 1.2 Å at 30 keV.

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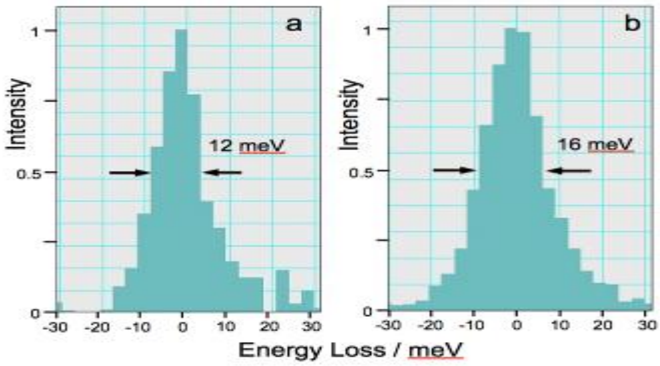

Figure 1. Zero Loss Peaks (ZLPs) acquired in a) 2 ms and b) 55 ms at 60 keV. Nion HERMES, Gatan Enfinium EELS.

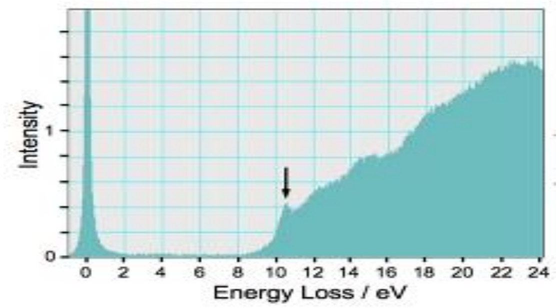

Figure 2. Low loss spectrum of SiO_2 acquired in 0.2 s at 60 keV. The ZLP maximum intensity is 302. Band edge exciton is marked by an arrow.

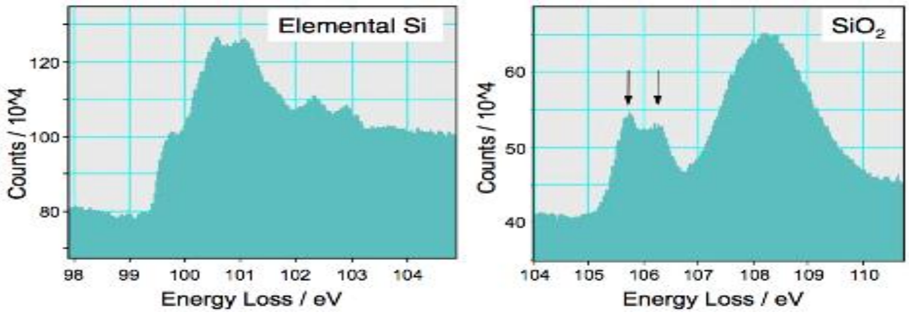

Figure 3. Si $L_{2,3}$ electron energy loss spectra in crystalline Si and in SiO_2. Nion HERMES, Gatan Enfinium EELS, 100 keV. L_3/L_2 splitting of 0.6 eV is marked by arrows in the SiO_2 spectrum.