Optical performance of PEEMII microscope

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INTRODUCTION

Photoelectron emission microscopy (PEEM) has become a widely used and prolific tool in studying complex systems. The unique capabilities of PEEM coupled with an SR source combining elemental, chemical, magnetic, and bond orientational sensitivity have made it a valuable tool in studying coupled magnetic systems (e.g. [1] and [2]), self assembled polymer systems (e.g. [3] and [4]), and in a variety of other areas of current scientific interest. The ability to resolve spatial features of microscopic dimension is why we use PEEM, and therefore the spatial resolution of an instrument is of great import both for understanding what questions can and cannot be answered with a given instrument, and in helping to design and build improved instruments for the future. However, there is little documentation of microscope performance and characterization in the literature beyond single measurements that report one number representative typically of a microscope's ultimate performance under an ideal set of conditions. Not only is it then difficult to accurately compare different instruments with different operating parameters, but the performance of any one instrument can vary significantly from the reported performance when an experimenter measures his or her own samples that often differ greatly from the sample used during the performance test. Also, for the next generation PEEMs with highly advanced electron optics, experimental verification of more than a single data point of the complex computer models would help both confidence in and refining of the models. We report here on a more comprehensive measurement of the PEEMII instrument at beamline 7.3.1.1 of the Advanced Light Source (ALS) that examines the response of the instrument to a wide range of experimental conditions and compares this response to both analytic and computer models of the expected performance.

EXPERIMENT

An optical test pattern was made by the Center for X-Ray Optics to use for evaluation of the PEEMII microscope. As a PEEM is surface sensitive (the first 3-5nm depending on sample characteristics) and topographically sensitive, the ideal sample for testing would have features that have high chemical contrast imbedded in an atomically flat surface. To approximate this ideal situation, a pattern was made on a silicon wafer by lithographic means using an e-beam writer capable of producing 20nm features. After developing the resist, Ni was plated to a thickness of approximately 16nm. This procedure produced a pattern with extremely high contrast when viewed with soft x-ray photons at the Ni L3 resonance with an acceptable level of topographic modulation that can be expected to influence the measurement only at the smallest feature size. The test pattern contains a variety of features that allow for optimization of the microscope and measurement of not only the ultimate resolution of the instrument or the smallest distinguishable feature, but of the modulation transfer function (MTF) a measure of the relative contrast of features over a range of sizes. Using the test pattern we were able to measure and calibrate the basic optical properties of the microscope including absolute magnification, the transmission of the microscope with each of its four apertures, and the above mentioned MTF for the four aperture modes and a variety of sample voltages. This range of operating modes will then be compared to both analytic and computer raytrace models.

RESULTS AND DISCUSSION

The performance of the PEEM2 microscope has been previously predicted based on the tabulated experimental values of aberration coefficients of the electrostatic lenses and analytic determinations of the aberration coefficients of the accelerating field of the objective lens. The resolution prediction that results from this analysis was then summed in quadrature with estimates of blurring due to electron diffraction, caused by the selection of a finite range of angles with an objective back focal plane aperture [5]. This type of analysis has a number of fundamental limitations, in particular the summation of non-gaussian ray aberrations in an over-simplified manner. It also leads to a prediction of resolution width, but not the field dependent MTF. In parallel with the experimental study here, the PEEM2 system has been studied by end to end raytracing, combined with a realistic model for the integration of diffraction. The aim is to compare these predictions with the experimental results reported here.

The most basic test of the instrument was to compare the actual magnification of the instrument as a function of the voltages applied to the electrostatic lenses that make up the electron optical imaging system. Unsurprisingly but reassuringly, when measurements were carried out with our calibrated sample the agreement was extremely good. Indeed, beyond the simple optical formula for ideal lenses, the measurements show quantitative agreement with ray trace simulations regarding image curvature due to overfilling of the electron lenses at large fields of view.

Figure 1 shows a PEEM image of a star pattern of converging lines and spaces. The pattern allows for real time optimization of the astigmatism of the microscope and the image presented here displays the resolving power of the microscope in all directions at once, and demonstrating balanced performance and hence optimized alignment. The solid circle in the image is at a point where the lines and spaces are 100nm, and one can clearly resolve the lines more than 2/3 of the way towards the center of the pattern where the optical lithography ultimately breaks down at approximately 20nm.

The PEEMII microscope utilizes a changeable aperture in the back focal plane of one of the imaging lenses as an energy and angle filter of the secondary electrons that escape from the surface of the sample and are imaged by the microscope (see [5] for details on the PEEMII theory of operation). Depending on the size of the signal one is attempting to measure, the sensitivity of the sample to photon damage, and the resolution one needs, different apertures are used. Smaller apertures are used to improve the spatial resolution of the instrument at the price of throughput.

Depending on the sample being measured, often it is not possible to run the PEEMII at the highest sample voltages. This non-ideal situation results in a degradation of the optical performance and can be modeled using ray trace simulations. Figure 2 shows the measured MTF for one aperture and one sample voltage. As mentioned earlier we measured the MTF for all four apertures and at a variety of sample voltages. The MTF of an instrument provides the contrast in the measured image as a function of the spatial frequency of the object. Armed with this information one can then predict not only the smallest feature one can expect to resolve in ideal conditions, but the smallest feature one can expect to resolve at a wide variety of microscope conditions. In addition, if the contrast of the effect which is to be studied is known, one can also convolute this information into the measured MTF and predict the smallest feature one can expect to resolve both for a given contrast mechanism, and for the variety of microscope conditions which in real experiments are often less than ideal.

Detailed comparison with the simulation discussed above is work in progress, but initial indications are that we have good agreement, both in the MTF itself, and the throughput of the microscope as a function of back focal plane aperture size.

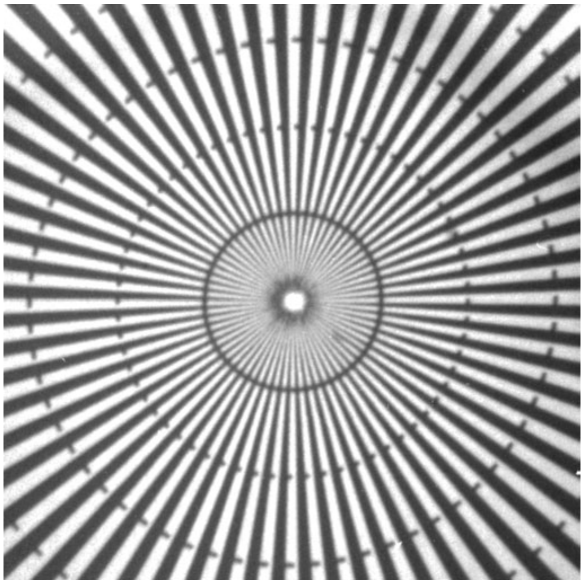

Figure 1: Star optical pattern showing resolution performance in all optical axes at once. The solid circle is at a point where the lines are 100nm thick.

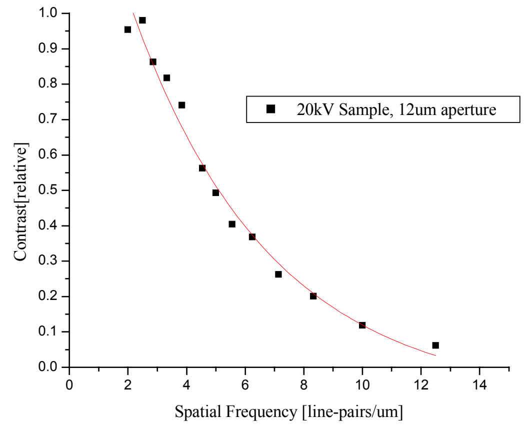

Figure 2: Modulation Transfer Function (MTF) for one set of microscope conditions. The curve is a fit as a guide to the eye. X-axis is in units of line pairs per micrometer, for example 10 lp/um corresponds to 50nm lines and spaces.

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