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PHOTOELECTRON X-RAY MICROSCOPY

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Abstract: The soft-X ray range, between 1-10 nm wavelength, is highly interesting for X-ray microscopy. Taking advantage of it requires, however, to operate a high resolution instrument at a variable wavelength. We describe here an image converter X-ray microscope which is based on secondary photoemission. This instrument is now developed at the Institut d'Optique (Orsay); it will be installed near ACO storage ring (LURE, Orsay) and should have a 50 nm resolution.

INTRODUCTION

It is well established that the soft X-ray range (1-10 nm wavelength) is the most favorable for imaging biological objects \cite{1,2}. The reasons can be shortly summarized as follow. The image contrast is dominated by photoelectric absorption and scattering is negligible; thus the resolution is only limited by the wavelength and the energy dose in the sample can be minimized. Moreover, the penetration depth of soft X-rays is in the order of 1 µm and enables the observation of rather thick sections or whole cells. Besides, the attenuation cross section changes quickly with the wavelength according to the chemical composition. The K edges of Carbon to Aluminum and the L\textsuperscript{2,3} edges of Phosphorus to Bromine are situated in the 8-9 nm wavelength range. Differential absorption analysis can be done \cite{3}, or more simply, the contrast of a particular feature can be enhanced by a convenient choice of the illuminating wavelength – for instance, wet biological tissues can be imaged in a living state \cite{1}.

At present however, no instrument can actually offer the characteristics that one can hope from soft X-ray microscopy. The situation is expected to change rapidly. The synchrotron radiation has practically satisfied the need for polychromatic X-rays; undulators and multilayer mirrors should give new solutions for monochromatic illumination. The lack of high resolution soft X-ray optics is a more fundamental problem. Direct solutions are experimented with focusing gratings (Fresnel zone plates) \cite{1,4} or multilayer optics \cite{5}, either for image and for scanning microscopy. These elements however are highly dispersive; their efficiency and resolution fall down rapidly with shorter wavelengths, and, in practice, the instruments which use them work at fixed wavelengths.

The difficulty is eluded with contact microscopy, and we describe an image converting X-ray microscope similar in its principles, to the instrument formerly designed by HUANG and MOLLENSTEDT (1956) \cite{6}.
PRINCIPLES OF THE PHOTOELECTRON X-RAY MICROSCOPY

The object, as shown on Fig.1, is fixed on one side of a thin support film (.1 to .5 \( \mu \)m of polyimide which is coated on the other side by a thin layer of a high Z photoemissive material. This assembly is illuminated by a small aperture X-ray beam. The photons which are not absorbed in the object are stopped in the photocathode and generate photoelectrons. Electrons of very low energy only, can be focused accurately and make a magnified image; but up to 90% of the total yield is emitted as secondary electrons, the energy of which is under 10eV.

The resolution of the instrument is limited by several factors which can be separated in two classes. The first one includes the limitations introduced by the cathode and sample holder geometry. The supporting foil maintains a distance \( t \) between the object and the cathode. The resolution is therefore limited by Fresnel diffraction around \( \delta = \sqrt{\lambda t} \) and penumbra remains negligible if the aperture of the X-ray beam is kept lower than \( \theta = \sqrt{\lambda t} \) (viz. \( \lambda = 5 \text{ nm}; \ t = .5 \text{ \( \mu \)}\text{m}; \ \delta = 50 \text{ nm}; \ \theta = .1 \text{ rd}). The resolution is also limited by the diffusion of the photoelectrons in the cathode layer. An estimation of this effect is given by the cathode thickness which is typically 10 nm.

Aberrations of the electron optics are the second class of resolution limitations. In fact, spherical and chromatic aberrations are so important that only the regions where the electrons aperture and energy spread are large, must be considered. The problem is then restricted to the accelerating lens (also called immersion or cathode lens). Even, assimilating the lens field to the superposition of the uniform field which reign near the cathode, and an aberration free lens, is an excellent approximation. Then, the longitudinal aberration is given by \( \zeta = 2d \left( \frac{\theta}{V} \right)^{2} \sin \alpha \) (1).

where \( d \) stands for the cathode-anode distance; \( V \), the accelerating potential ; \( \alpha \) and \( \phi \), the emission angle and energy of an electron. This aberration is commonly reduced by limiting the image aperture \( \alpha' = \left( \frac{\phi}{V} \right)^{2} \sin \alpha \) (2) in the cross over (1). This operation is a filtering of the lateral energy; total energy filtering can equally be done. Evaluation of their influence requires a good criterion; it has been found that the modulation transfer function (M.T.F.) was well adapted (8). It can be calculated from the energy \( N(\phi) \) and angular \( K(\alpha) \) distribution (9).

\[
F(V) = 2\pi \int_{0}^{\phi_{\text{max}}} N(\phi) \int_{0}^{\alpha_{\text{max}}} (\phi) \sin(\alpha) \ J_{v} (v, r(\alpha, \phi)) \ d\phi \ d\alpha
\]

where \( r(\alpha, \phi) \) is the distance from the paraxial image to the intersection of the image plane with the ray \( (\phi, \alpha) \). Computations have been done with the energy distribution given by HENKE et al(9) and assuming a lambertian angular distribution (10). Figure 2 shows the relative influences of angular and energy filtering, on the resolution and the collection efficiency for a gold cathode.
ELEMENTS FOR THE DESIGN OF AN INSTRUMENT

From Eq.1 and 2 it appears that the lateral aberration of the rays is in inverse ratio to the strength of the cathodic field. In a positive immersion lens, the Wehnelt electrode always lowers the field in the vicinity of the cathode. It is therefore convenient to separate the accelerating and focussing functions. The electrostatic immersion lens is then designed independently from its focussing properties, to maximize the cathode field and reduce as possible the field aberrations [11]. The resulting element is slightly divergent and must be completed by magnetic lenses.

It is clear from Fig.2 that the presence of a velocity filter (dotted curves) can significantly enhance the resolving power. In our instrument we shall use a magnetic filter of CASTAING-HENRY (Fig.3 et 4.).

**Figure 2:** Modulation transfer function in different filtering conditions

**Figure 3:** Diagramme of the electron optics.

**Figure 4:** Diagrammatic drawing of the photoelectron X-ray microscope.
The presence of this element requires a proper conjugation of the image and pupil planes with the stigmatic points of the prism. As shown on Fig.3, a first lens of low power is needed between the immersion lens and the objective. It plays the double role of conjugating the image plane with the objective focal plane, and of giving the enlarged image of the cross-over where aperture filtering can be achieved.

The X-ray microscope is planned to work with synchrotron radiation (ACO, LURE, Orsay) and therefore must have an horizontal axis. It results in particular problems of design in order to keep at the same time, the necessary alignment and adjustment facilities and a sufficient stability. A condenser X-ray mirror is nevertheless necessary to ensure a reasonable illumination at high magnifications. It also suppresses the hard X-ray component of synchrotron radiation.

CONCLUSION

This photoelectron X-ray microscope is presently under realisation at the Institut d'Optique (Orsay). Its expected characteristics, 50 nm resolution (with velocity filter) and about 1% efficiency are quite similar to those of the existant zone plate imaging microscopes. But, in opposition to zone plates, the detection efficiency of a gold cathode for instance, is not very sensitive to the illuminating wavelength. The advantages of the instrument will become significant, when the condenser mirror will be replaced by a monochromator, and it appears to be realistic within a few years. The aim is of course absorption microanalysis, but, even with a rather broad monochromatic band, wavelength tuning should provide very helpful variation of contrast to image biological objects.

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