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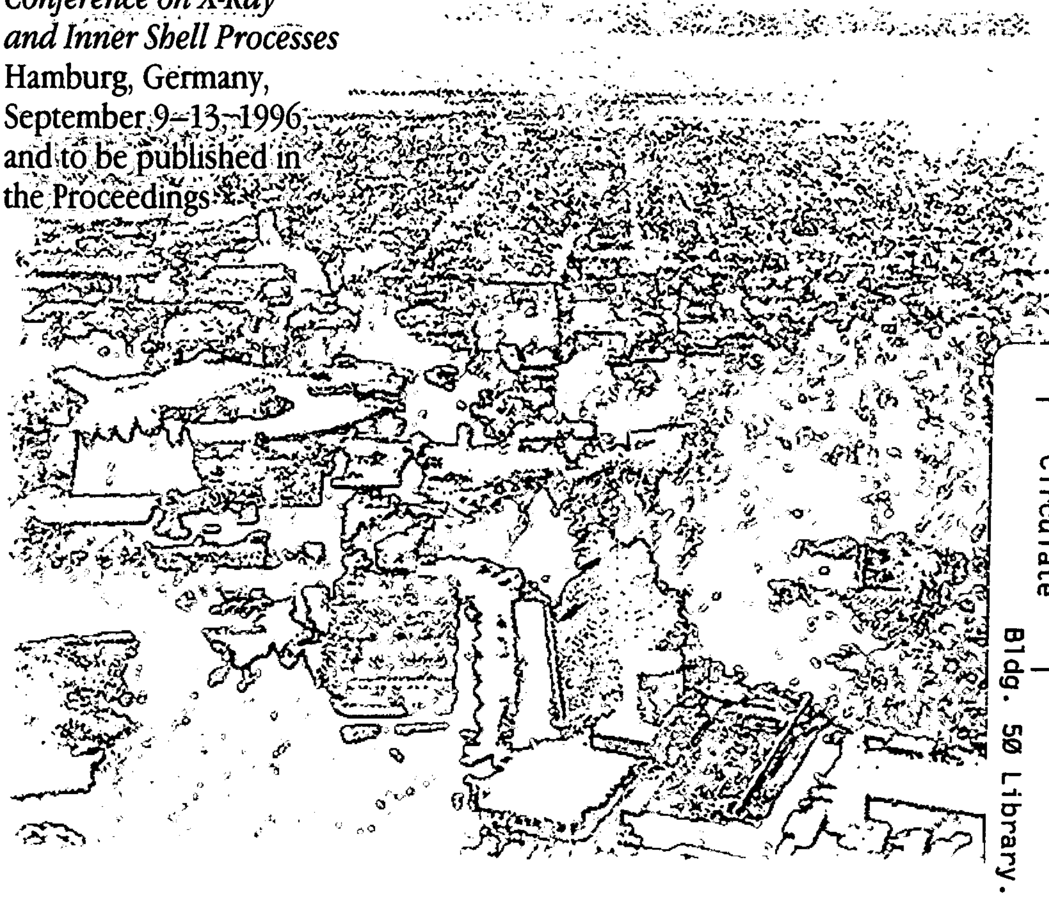

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SOFT X-RAY OPTICS FOR SPECTROMICROSCOPY AT THE ADVANCED LIGHT SOURCE

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Soft X-ray Optics for Spectromicroscopy at the Advanced Light Source

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Abstract. A variety of systems for performing spectromicroscopy, spatially resolved spectroscopy, are in operation or under construction at the Advanced Light Source (ALS). For example, part of our program is centered around the surface analysis problems of local semiconductor industries, and this has required the construction of a microscope with wafer handling, fiducialization, optical microscopy, coordinated ion beam etching, and X-ray Photoelectron Spectroscopy (XPS) integrated in this case with Kirkpatrick-Baez (K-B) grazing incidence micro-focusing optics. The microscope is to be used in conjunction with a highly efficient entrance slitless Spherical Grating Monochromator (SGM). The design and expected performance of this instrument will be described, with emphasis on the production of the elliptically curved surfaces of the K-B mirrors by elastic bending of flat mirror substrates. For higher resolution, zone-plate (Z-P) focusing optics are used and one instrument, a Scanning Transmission X-ray Microscope (STXM) is in routine operation on undulator beamline 7.0. A second Z-P based system is being commissioned on the same beamline, and differs from the STXM in that it will operate at Ultra-High Vacuum (UHV) and will be able to perform XPS at 0.1 μm spatial resolution. Spatially resolved X-ray Absorption Spectroscopy (XAS) can be performed by imaging electrons photoemitted from a material with a Photo-Emission Electron Microscope (PEEM). The optical requirements of a beamline designed for PEEM are very different to those of micro-focus systems and we give examples of bending magnet and undulator based instruments.

INTRODUCTION

The development of spatially resolved spectroscopy, spectromicroscopy, and its use in the analysis of problems in surface and materials science is in its infancy. Although several microscopes have been developed on second generation synchrotron radiation sources, third generation sources such as the ALS were specifically designed to give extremely high brightness, and hence give optimized performance for x-ray microscopy. This is now opening the way for the use of spectromicroscopy as a widely used analytical tool in materials science.

There are two distinct methods of image formation, scanning and full field imaging. In the scanning method, a monochromatic object is demagnified by an x-ray optical system to a small image at a sample surface, and an image is acquired by recording a response of the sample as a function of the beam position. The demagnification can be done in a number of ways, for example using a mirror, tapered capillary or zone plate (Z-P). Each of these have very different optical characteristics; the Z-P is a circular diffraction grating whose focal length is a function of wavelength, while the other two are achromatic. They also have different acceptances and efficiencies; the reflection systems have a high reflection efficiency as well as a large acceptance, while the Z-P has a small efficiency (although phase shifting soft x-ray Z-Ps can deliver a peak efficiency of 20%) and small acceptance. The Z-P has however the best spatial resolution, approximately equal to the outer most zone width, and a resolution of around 50 nm is becoming routine. With the advent of new electron beam machines dedicated to Z-P writing, we can expect significant improvements in resolution in the next few years, ultimately approaching the limit imposed by the recording medium of photoresist, of around 15 nm.

The full field imaging method requires that a field of view is illuminated, and that either the transmitted or fluorescent photons or the photoemitted electrons are imaged. In the case described later, we are concerned with Photo-Electron Emission Microscopy (PEEM). Unlike the scanning technique described above, the full field methods acquire data in a parallel process. In addition, as only a condensed illumination field has to be produced, we can have an optical system with a large acceptance. Together, this implies that the parallel imaging techniques are intrinsically fast. Moreover, the resolution of the electron imaging technique, PEEM, depends only on the quality of the electron optics. We routinely achieve 200 nm resolution with secondary electron yield x-ray absorption spectroscopic imaging, and recent developments in this field have shown a clear path to achieving < 5 nm resolution.

In this paper, we describe both a bending magnet and an undulator beamline optical system optimized for PEEM and for XPS. In the latter case, the bending magnet beamline uses K-B mirror micro-focusing, whereas for the undulator beamline zone plate focusing is used. For PEEM, in each case mirror condensors are used. These choices are examined in this paper, with emphasis on the use of K-B mirror systems to produce micro-focii on bending magnet beamlines, and on the selection of systems for scanning and full field techniques on an undulator. This discussion is with reference to two new microscope beamlines currently under construction at the ALS, beamline magnet beamline 7.3, and elliptically polarized undulator beamline 4.0.

FOCUSING SYSTEMS

In this section, we restrict discussion to zone plate and grazing incidence mirror focusing systems. Tapered capillary optics however are becoming useful for condensing systems, but although excellent spatial resolution has been achieved (< 1μm), throughput is limited due to roughness of the reflecting glass surfaces. In addition, straight capillaries reduce the brightness of the source, and although not important in terms of flux density, the effect is to produce an image with much greater divergence than a mirror system of equivalent image size. This usually requires that the tip of the capillary be close to the sample to achieve the expected resolution. In addition to the grazing incidence mirror systems discussed later, normal incidence optics can be used, usually arranged in a Schwartzchild configuration of a convex - concave spherical mirror pair. Coated with a metal, the maximum photon energy is set by the reflectivity cut-off at normal incidence of around 25 eV (1). They can also be coated with a synthetic Bragg crystal (multilayer) and by choosing the appropriate materials and periodicity, high reflectivity within a narrow energy range can be achieved (2). Mo-Si multilayers are used for photon energies just lower than the Si $L_{2,3}$ edge (typically 90 - 95 eV), although using boron nitride instead of silicon as the 'spacer' element has recently allowed operation at 130 eV. Using both these types of system, a resolution of around 100 nm has been achieved (1,2).

Although zone plate micro-focusing systems are commonly used, the use of grazing incidence mirrors has been relatively little used due to the problems of fabrication of the optical surface to the required figure tolerance. Mirror systems although not challenging zone plates in terms of resolution, have a role to play where modest resolution at very high throughput is required, and have the advantage of being achromatic. They have been used for soft x-ray spectromicroscopy and achieved μm resolution (3). Recent advances in the production of aspheric mirrors by elastic bending of flat substrates have opened up the possibility of achieving near perfect elliptical surfaces, thus providing a way of producing a high efficiency achromatic system for sub-micron focusing and this methodology is described in detail in a later section (4).

Zone Plate Focusing

In order to obtain a diffraction limited image size, the Z-P can only accept the fraction of the radiation that is spatially coherent, and for practical purposes this means that the product of the object size and divergence (phase space) that can be used is approximately equal to the wavelength. In the absence of electron beam divergence, undulators produce radiation that is transversely spatially coherent and hence are well matched to the requirements of Z-Ps. Third generation sources attempt to have an electron beam emittance less than the photon beams produced by the undulators, so that the fraction of spatially coherent versus incoherent radiation will be high. In the case of the ALS, the vertical emittance is set to around 1×10^{-10} m.rads by skew quadrupoles in the accelerator lattice (to couple a small fraction of the horizontal emitance into the vertical plane to increase the lifetime to an acceptable value), and the horizontal emittance is 4×10^{-9} m.rads. For these values we can expect a high fraction of the light to be spatially coherent for wavelengths greater than 0.6 nm and 24 nm in the vertical and horizontal planes respectively. In general we are concerned with wavelengths from 10 to 1 nm (covering for example the K edges of the light elements and the $L_{2,3}$ edges of the 3d transition metals), and so we can see that over the whole range the ALS will produce spatially coherent radiation in the vertical plane, but in the horizontal plane, except at the longest wavelengths only a small fraction will be coherent. In actuality, the fraction of spatially coherent light is less than is indicated by the simple analysis above as it assumes that the phase space ellipses of the photon beam generated by a single electron passing through the undulator and the real electron beam are concentric. In fact the betatron functions of the ALS are too large to give this optimum matching, and the coherent fraction of the light is less than 1% at 1 nm wavelength. However, the total monochromatized flux can be high and this to some extent offsets the low diffraction efficiency of the Z-P and the low coupling efficiency of the source to the Z-P. For example, the spectromicroscopy beamline BL 7.0 has an 89 period undulator with a period of 5 cm, and together with an SGM beamline produces 10^{12} to 10^{13} photons/sec in a bandpass of 10^{-4} over the wavelength range described above (5,6,7). After spatial filtering, and focusing with an amplitude zone plate, the flux in the center of the wavelength range is typically 10^{7}-10^{8} photons/sec, presently focused into a spot size of around 100 nm.

This flux allows Scanning Transmission X-ray Microscopy (STXM) at high spatial resolution and with fast frame speeds. The ALS beamline 7.0 STXM uses a piezo driven x-y stage for fast scanning, a flexure z stage to allow the focus position to be tracked as the photon energy is changed during local area spectroscopic measurements, and a selection of pulse counting and analog detectors. The system is operated at 1 atmosphere of helium or at rough vacuum. It has been mostly used for studies on polymeric systems, and a review of recent work can be found in (8).

A second system that operates at UHV and uses an XPS detection system has been constructed and is presently being commissioned. This is far more demanding in terms of flux, as the XPS analyzer only integrates over a small fraction of solid angle and over a very small fraction of the whole photo-electron energy spectrum. For many practical experiments, the available flux will in fact limit the achievable resolution, set by the maximum time allowable to acquire an image. In a later section, we describe a system in which the optical system is designed to optimally couple the source to the zone plate focusing system, in this way maximizing the coherent flux, and allowing the full high resolution capabilities of the zone plate to be utilized for XPS imaging.

Grazing Incidence Mirror Focusing

The two main types of grazing incidence mirror arrangement are the K-B system consisting of two crossed mirrors, and systems in which only a single reflection is used. Usually, in order to avoid or minimize aberrations, an elliptical or ellipsoidal surface is used, or a close approximation to this surface. In the case of single mirror systems, complete surfaces of revolution of an ellipse (2) or sections of a complete surface of revolution (9) have been used and good resolution has been achieved, albeit at modest collection aperture.

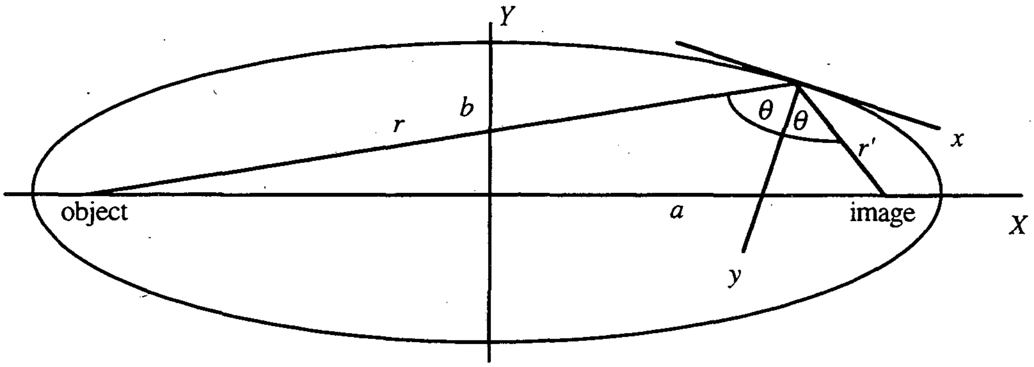

FIGURE 1.. Geometry of the Ellipse

As it is extremely difficult to produce aspheric surfaces at the required figure tolerances, we have adopted an approach in which one starts with a 'perfect' flat substrate, and produce the desired elliptical shape by elastic bending, and this approach is described in detail later. The bending action is produced by the application of unequal couples to the ends of the beam in a method originally devised for the production of collimators (9). The main advantages of a grazing incidence system is that it is achromatic, and can collect a large solid angle. The maximum collection aperture is essentially limited by the critical angle of reflection for the maximum photon energy to be used. This can be seem in Fig. 1, in which the geometry of a grazing incidence ellipse is shown. If a beam of angular width ϕ from the object is collected and focused by the ellipse, the convergence at the image is $\phi'=\phi r'/r$. If this convergence angle becomes similar to the critical angle, it implies that at one end of the mirror light is propagating almost parallel to the surface, and at the other is becoming close to the critical angle, and hence reflectivity efficiency is being lost. A further decrease in the image distance will simply result in only the upstream end of the mirror reflecting light. As a general rule, the maximum convergence is restricted to half of the critical angle of reflection for the maximum photon energy in the design range. It can also be seen that as we demagnify more, this implies that less angular aperture can be accepted, and so we can say that the product of image size and divergence is constant. For example, in the case of a system we are building for μ-XPS on a bending magnet, we are aiming for an image size of 1 μm, and with a grazing incidence angle of 1.6° dictated by the upper working photon energy of 1.2 KeV, we can say that the convergence angle is limited to around 14 mrads. The acceptance aperture is then set by the required demagnification which is set from the source size and required image size. In the case of the ALS which has a vertical source size of around 30 μm FWHM, it can be seen that for the 30:1 demagnification needed to produce a 1 μm focus size, 14/30 or approximately 0.5 mrads vertical aperture can be collected from the source. This is a little larger than the vertical angular distribution (fwhm), and so we can say that it is possible to demagnify the ALS source for 1.2 KeV photons to a 1 μm spot size without geometrical loss. In the horizontal direction however, the ALS source is approximately 7 times larger than in the vertical direction, and hence only 1/7 of the angular aperture can be taken if the objective is to demagnify to a 1 μm image. In this case therefore, a horizontal aperture of only around 70 μradians can be accepted. This emphasizes the importance of the brightness of a source, and the fact that even with a 3rd generation bending magnet source, only a relatively small aperture can or needs to be taken.

PRODUCTION OF ELLIPTICAL MIRRORS BY CONTROLLED BENDING OF FLAT SUBSTRATES

One of the key technologies that we are developing for a range of applications, including μ-XPS, is the production of highly accurate elliptical surfaces by the controlled deformation of flat mirror substrates. The reason for developing this approach over conventional grinding and polishing methods is that the latter are difficult to make accurate enough particularly in the case of highly aspheric surfaces, while the production of flat surfaces to the required tolerances is routine. The remaining problem is to produce a mirror bender capable of exerting the right combination of couples and forces to produce the desired shape. If we take a mirror substrate of length L and apply couples C_1 and C_2 respectively at the two ends, the bending of the substrate is given by the Bernouilli-Euler equation (10),

$$EI_0 \frac{d^2y}{dx^2} = \frac{C_1 + C_2}{2} - \frac{C_1 - C_2}{L} x \tag{1}$$

where E is Young's modulus, I is the section modulus which is equal to $bh^3/12$, where b is the substrate width and h is the substrate thickness. The second derivative is effectively the curvature of the ellipse, and as this is a function of displacement along the beam from the center (x=0), a variable in (1) has to be controlled to give the required value. C_1 and C_2 are independent of x, and so clearly the section modulus I has to be varied, either by changing the width b(x) or the thickness h(x). In the present arrangement we have chosen to vary the width. The individual couples C_1 and C_2 are chosen assuming a rectangular beam of width b_0 and this ensures that the smallest variation of b(x) has to be made to give true elliptical bending. These couples are given by (4),

$$C_1 + C_2 = 4EI_0a_2 = \frac{2EI_0}{R_0} \tag{2}$$

$$C_1 - C_2 = -6EI_0La_3 = \frac{3EI_0L}{R_0}\frac{\sin\theta}{2}\left(\frac{1}{r} - \frac{1}{r'}\right) \tag{3}$$

where R_0 is the radius of curvature at x=0, and θ is the angle of incidence.

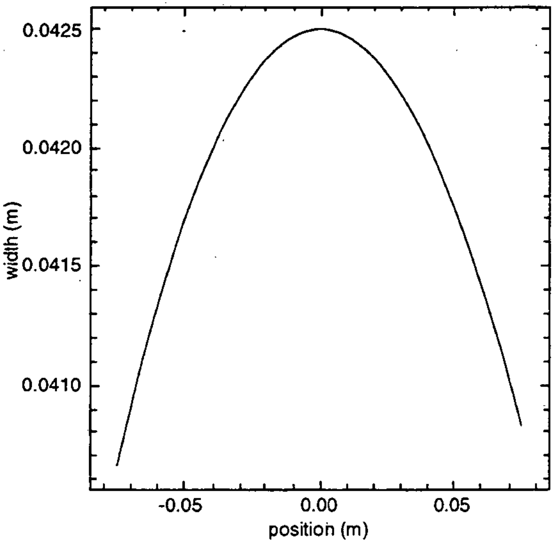

FIGURE 2. Width of a mirror substrate as a function of displacement from the center; r= 31 m, r' = 0.5 m, θ = 89.67°, b_0 = 42.5 mm, L = 150 mm.

The design process first fixes the width and thickness of the substrate at the center, the couples are calculated from (2) and (3) and then these values are used in (1) together with the known curvature of the required ellipse to calculate the variation of width with displacement. As an example, Fig. 2 shows the substrate width b(x) as a function of displacement x, for a mirror to be used for hard x-ray focusing, with $r = 31\text{m}$, $r' = 0.5$ m and $\theta = 89.67°$. This edge profile is produced by computer controlled grinding. The most important aspect of this approach is the method of applying couples. The method we have been developing for both hard and soft x-ray micro-focusing is shown schematically in Fig. 3.

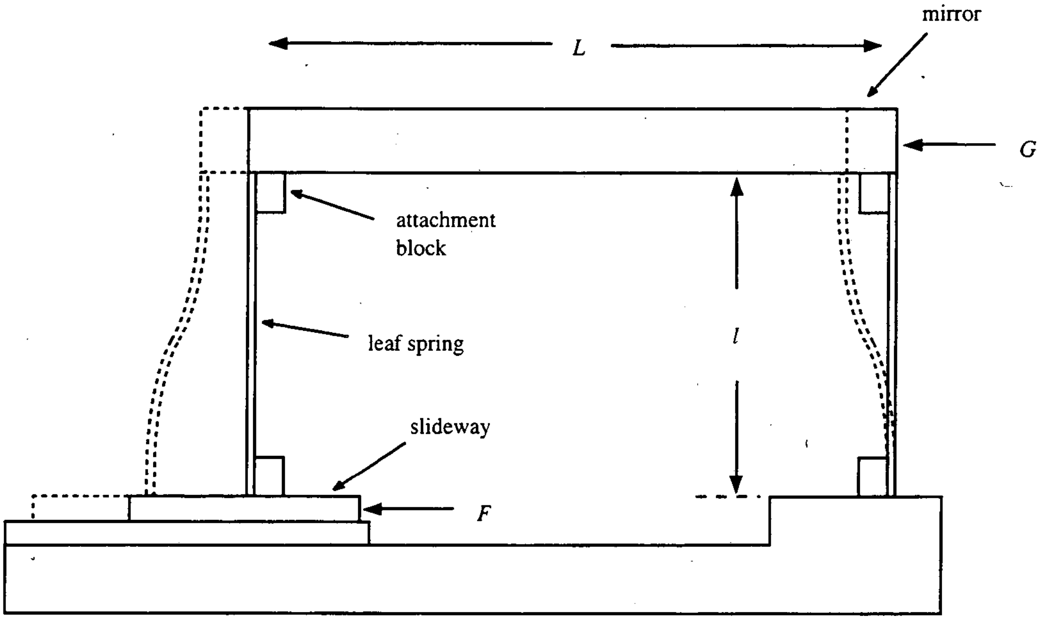

FIGURE 3. 's' spring bender shown in the relaxed and extended positions.

The mirror substrate is attached to two blocks which are joined to leaf springs at either end. At the right hand end, the other end of the leaf spring is rigidly attached to a base, and at the left hand end is attached to a slideway. If a force F is exerted on the slideway to move it to the left, the springs are deformed in a symmetric manner and exert equal and opposite couples on the ends of the beam. If the mirror substrate is pushed left by the application of a force G, the extension of the right hand spring increases, and the extension of the left hand spring decreases, resulting in a linear change in moment as required along the beam. The system is highly controllable and insensitive to temperature due to the large extension of the springs. Typically we use an extension of around 1/5 of the length of the spring, and in many cases this amounts to around 1 cm. The mirror substrates are made of glass or steel, and polished by conventional techniques to sub-microradian flatness, and a few Å rms roughness.

In order to adjust the couples to the correct values, and to measure the deviation of the surface from the required elliptical shape, we use a slope measuring device known as a Long Trace Profiler (11). The results of this measurement for a mirror with parameters given in Fig. 2 is shown in Fig. 4.

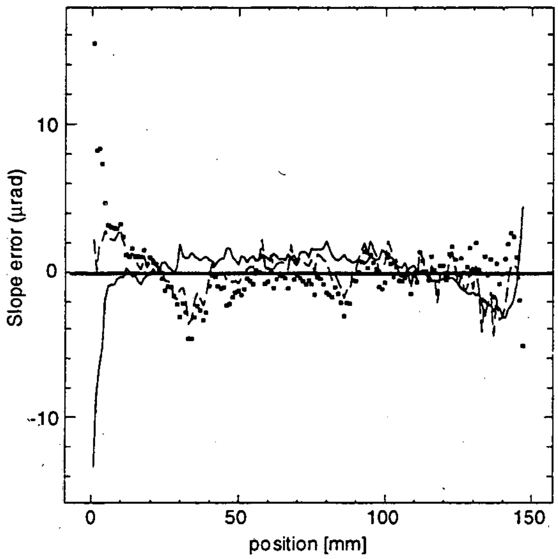

FIGURE 4. Solid line gives the slope error of the unbent surface from a flat, the dotted line shows the error from the defined ellipse, and the dots give the difference.

It can be seen that the slope error deviation from the required ellipse is small, and in fact has a standard deviation of only 1.2 µradians. The details of production of this class of mirror are given in reference (4). In using the same approach in the production of mirrors for µ-XPS, the main difference is that the radius of curvature has to be much less, due to the increased grazing angle that is used. Of course, the maximum grazing angle is used commensurate with obtaining good reflectivity in order to collect the maximum angular aperture. In the case of a Kirkpatrick-Baez system we are building for µ-XPS on a bending magnet source, the horizontally focusing mirror has the following parameters; r= 4m, r'=0.1m, θ = 88.4° and an optical length of 50 mm, giving a central radius of curvature of 7 m. This contrasts to the case described above for hard x-ray micro-focusing in which the radius of curvature is around 150 m. In that case the beam thickness was 9.5 mm, and therefore if the stress in the µ-XPS mirror substrate were to be the same, the thickness would have to be 0.45 mm. Clearly this is impractical, and so the thickness has to be increased to a level where it is stiff enough to be polished flat to µradian slope tolerance, and still have a stress that is reasonable. For metals, it is relatively easy to decide what is a reasonable stress based on the yield strength, micro-yield point and creep. For brittle materials such as glass and silicon, the behavior of the material depends on such things as micro-crack density and length, as well as in the case of glass materials, moisture content. Based on this information we are using a thickness of 2 mm of glass for the horizontal focusing µ-XPS mirror. In order to reduce the crack density, the machined edges are optically polished, and the back surface is acid etched (12). Using this approach we have successfully obtained micro-radian flatness and have bent the material to the desired radius without failure. We are currently performing bending tests to assess residual slope errors.

An alternative to glass is to use a metal substrate material. The advantage is that they can withstand much higher stress, and so can be made substantially thicker. This in turn makes them easier than glass to fabricate to the required flatness, but more care is required to produce the required micro-finish. In fact, using a precipitation hardened steel, we have obtained mirrors for this application 4mm thick, polished to around 1 μradian flatness and with a micro-roughness as measured with an optical profiler (Micromap) of < 3Å rms (13). Bending tests of these mirrors is underway.

BEAMLINE 7.3.1 for μ-XPS and PEEM

Beamline 7.3.1 was specifically designed to be optimized for Photo-Electron Emission Microscopy (PEEM), with emphasis on the application of the technique to the study of magnetic materials using Magnetic Circular Dichroism (MCD) spectroscopy (14, 15). The beamline layout is shown in Figure 5.

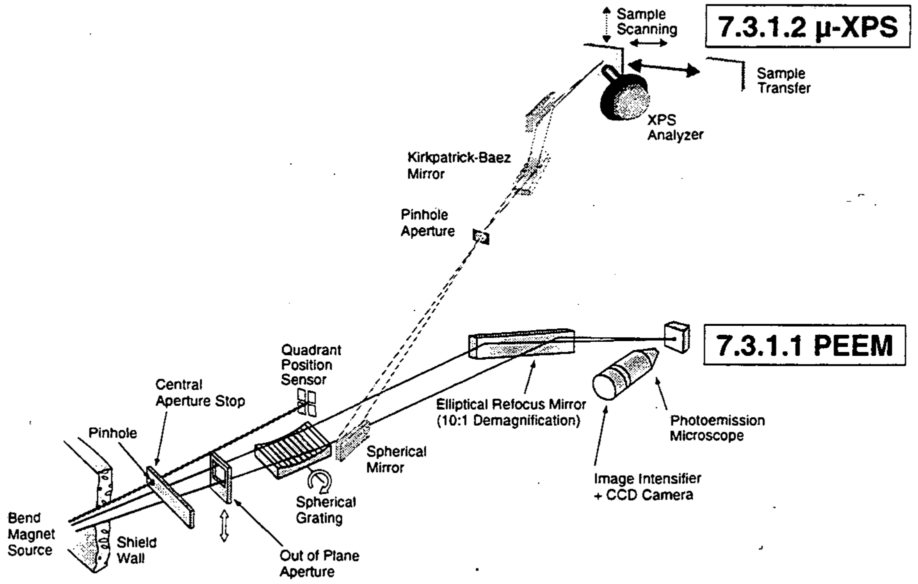

FIGURE 5. Beamline 7.3.1 for μ-XPS and PEEM.

The monochromator is entrance slitless, and produces a monochromatic image of the source at the position of the sample in the case of the PEEM beamline and at a pinhole aperture in the case of the μ-XPS branch. The system is designed to cover from 280 eV to around 1200 eV. The vertical source size at the center of the central bending magnet of the triple bend achromat structure of the ALS is less than 30 μm (FWHM). The required field of view of the PEEM imaging microscope is around the same value, and so it allows us to directly image the source to the sample. In addition, as the source size is small, this allows us to use a low line density grating, and this in turn results in a high diffraction efficiency (16). It also leads to a very slow variation of focal length with wavelength, and therefore it is not necessary to track the focus with the sample position. In the horizontal direction, a 1m long elliptical mirror is used to collect 2 mrads of horizontal aperture at a grazing angle of 2°, and to demagnify it by 10:1 onto the sample. As before, this demagnification and aperture are simply dictated by the critical angle of reflection for the highest photon energy within the design range, in this case 1200 eV. The design is simple, and by optimizing each component for a specific experimental requirement, extremely high performance can be achieved. In a design bandpass of 1 eV at 1 KeV, the predicted photon flux is expected to be 3 x 10^{12} ph/sec, with the storage ring running at 1.9 GeV 400 mA, and this flux will be contained in a monochromatic spot size of around 30 μm diameter. This not only will allow rapid spectroscopic PEEM imaging, but should also allow us to undertake time-resolved studies at standard video frame rates.

In the case of μ-XPS, the optical requirements are significantly different. In this case, the grating together with a horizontally deflecting spherical mirror produce a monochromatic image of the source at an adjustable pinhole aperture. In the vertical direction the grating produces a 1:1 image, and in the horizontal direction, the mirror produces a 2:1 demagnified image. The monochromatic image size at this point is therefore 30 by 120 μm (FWHM) in the vertical and horizontal direction respectively. The slit is set to 20 μm by 40 μm (v, h) and the following Kirkpatrick-Baez (K-B) mirror pair image at 20 and 40 :1 respectively. The K-B system uses a pair of elliptically bent mirrors, as described in the previous section. From consideration of the critical angle for our upper photon energy (1200 eV), we can determine as previously described that the convergence onto the image should be a maximum of 14 mrads. If we assume that the K-B mirrors are at 100 and 200 mm from the sample, and we assume a 1.6° grazing angle, we can see that the mirror lengths are approximately 50 and 100 mm (horizontal and vertical respectively). If we set the object aperture as above to 40 by 20 μm (h, v), then we need 40:1 and 20:1 demagnification to achieve our aim of a 1 μm image, and hence the angular acceptance from the object aperture is 0.35 and 0.7 mrads respectively (h, v). As the monochromator operates at almost 1:1 magnification, the 0.7 mrads in the vertical direction corresponds to the acceptance from the source. This compares to the divergence from an ALS bending magnet source at 1.2 KeV of 0.5 mrads (FWHM), and so we can say that at this energy, our K-B mirror system can demagnify the source to a 1 μm image with only the geometrical loss caused by reducing the vertical monochromatic image size by a factor of 2 to 20 μm. In the horizontal case, the 0.35 mrads divergence from the object slit corresponds to 0.175 mrads from the source due to the 2:1 demagnification of the horizontally focusing and deflecting mirror. This mirror is at 11 m from the source at a grazing angle of 2°, and is therefore only 55 mm long. The acceptance from the source is 0.175 mrads, and as the image size at the object slit is 120 μm in comparison to the horizontal slit size of 40 μm, only around 1/3 of the focused beam is transmitted. The photon flux in this case is expected to be around 2 x 10^{10} ph/sec in a focused spot of 1 μm diameter. This flux is commensurate with that necessary for X-ray Photoelectron Spectroscopy (XPS), and we are presently completing a microscope with XPS detection specifically designed to meet the needs of the semiconductor microstructure community. Images are created by scanning the sample in the fixed micro-focused beam, and recording some response function of the sample. In order to get topographic information, or to measure x-ray absorption related features, we will record the total electron yield as a function of position. Once the area of interest has been identified, we will measure high resolution XPS data from that position, or create local area maps by choosing a particular photoemission feature and recording its intensity as a function of position. In order to investigate microstructured surfaces that have been examined in other microscopes, the system has a rapid sample introduction system, optical registration with a high resolution in-situ optical microscope, and a laser interferometer to record the sample position. In this way, we will be able to go directly to features previously identified to micron precision. This system is in the final stages of construction and will be commissioned from November 1996.

The optimized design of 7.3.1, together with the high brightness of an ALS bending magnet source allows us to achieve high enough flux density to permit PEEM imaging at < 1000Å resolution at normal CCD frame rates (30 frames/sec), and to permit XPS imaging at 1 µm spatial resolution. The optical systems are simple and relatively inexpensive, and this should in turn allow us to duplicate the apparatus when demand requires. This opens the way to solving one of the problems that has emerged in synchrotron radiation microscopy, that of having sufficient time to solve real world materials science problems. The traditional approach of either sharing beamlines with a multiplicity of other users, or bringing a microscope to a beamline for specific run are not practical, and we have been driven to conclude that microscopes should be developed for specific purposes on dedicated beamlines. There will be some systems where the higher resolution afforded for zone plate microscopes, or aberration corrected PEEMs require the far higher brightness of undulators and one new system we are developing is described in the following section.

ELLIPTICALLY POLARIZING UNDULATOR BEAMLINE 4.0

Undulators produce quasi-harmonic radiation, and radiate over a narrow range of angles. If one observes the undulator at the energy of the peak of an odd harmonic, the angular emission cone has a width (1 sigma) of approximately $(\lambda/L)^{0.5}$ where λ is the energy of the harmonic, and L is the length of the undulator. For example, at 1 KeV, a 2.5 m long undulator will radiate in a cone width of 22 µradians (1 sigma). This narrow angular range, combined with the addition of flux from each pole results in extremely high brightness when used in conjunction with the small electron beam emittance of a third generation source such as the ALS. For the case of any micro-focusing system, brightness translates directly into the flux available in the focus.

Because of the small angular width of undulator radiation, traditionally a single monochromator has been used to provide light to different end stations for both spectroscopy and microscopy. An example is beamline 7.0 at the ALS, in which a watercooled SGM is used in conjunction with a 5 cm period length, 89 period undulator to provide light to a range of experimental stations including high spectral resolution XPS, PEEM, and zone plate based microscopes (5,6,7). Inevitably in designing an optical system to satisfy several different requirements, many compromises in performance have to be made.

We are presently constructing undulators and optical systems for both spectroscopy and microscopy on a new line at the ALS, beamline 4.0. The layout of the system is shown in Figure 6. The main difference in comparison to existing systems is that we have designed two beamlines, one for spectroscopy, one for microscopy, both with highly specific design constraints. In addition, we are using two undulators in the straight section that can supply beam to both of the beamlines simultaneously. As we only have 10 straight sections available, doubling the number of available undulator beamlines is a significant benefit at the cost of a modest reduction in the already extremely high brightness of full length 4.5 m undulators.

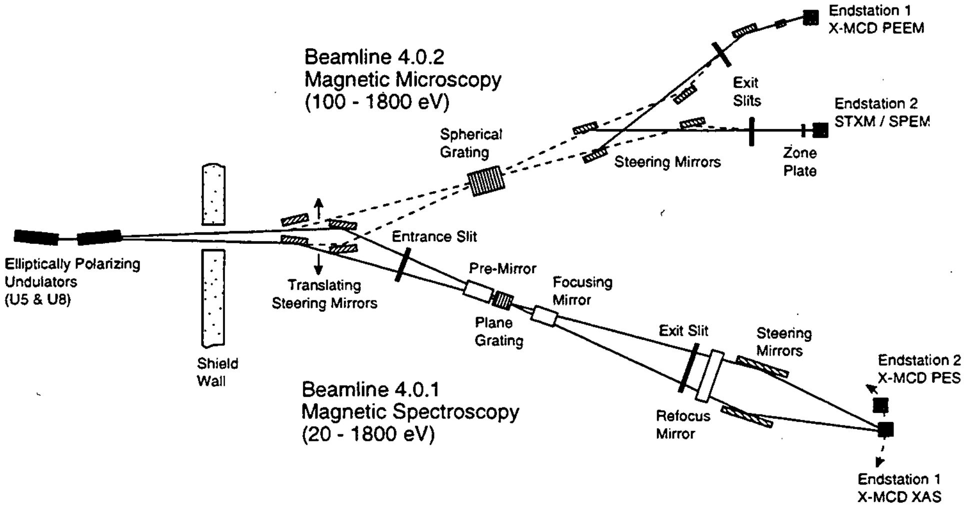

FIGURE 6. Elliptically polarizing undulator beamlines

The electron beam in the straight section is deflected before, between and after the undulators so that the two beams will be separated by an angle of 2.5 milliradians. The undulators are elliptically polarizing (19,20) and by correct phasing can produce radiation that is linearly polarized in-plane, out of plane, and circularly polarized. Initially we are building a 5 cm period device to cover up to 1.8 KeV, followed by an 8 cm period device to cover down to 15 eV. A third 5 cm period device will be built at a later date and installed in the upstream end of the straight. This will be used for experiments in which the two 5 cm undulators will be tuned to the same photon energy but opposite helicity, and the two beams will then be directed by a mirror switchyard into one beamline. The two beams will be alternately chopped by a mechanical disc, thus causing the helicity of the light at the sample to reverse. This will be used for magnetic circular dichroism experiments in which the dichroism to be measured is very small and by changing the beam helicity at high rates (KHz), noise introduced by motion of the beam or the optical system can be minimized.

The mirror switchyard is designed to direct light from either undulator to either beamline, or both undulator beams to one beamline. The 4.0.1 beamline is designed for high resolution circular dichroism spectroscopy, and a design requirement was that the photon energy range should cover 20 eV - 1.8 KeV. This very wide energy range can only be covered if the monochromator uses a grating arrangement in which the deviation angle can be changed as a function of photon energy (16). We have chosen to base our design on the SX 700 (21) design in which a plane mirror and plane grating establish the variable deviation angle, but in which a spherical mirror at low demagnification is used to produce a monochromatic astigmatic image (22). The 4.0.1 switchyard mirrors (one for each of the two beams) are horizontally focusing toroids, and focus in the saggital direction onto the entrance slit of the monochromator, and in the tangential direction onto the sample. Although the beams focus in the horizontal direction at the sample, they are directed to cross at the grating, and are redirected by plane mirrors after the exit slit to cross at the sample focus. The reason for the crossing at the grating is that we will then illuminate the same optical area for each of the two beams for the resolution determining optics. This should help to eliminate the small energy shifts that afflict other beamlines in which 2 beam mode chopping has been attempted. A further innovation is that the grating is designed to have multiple stripes with differing groove depth. In this way, a diffraction efficiency of greater than 15% is predicted throughout the whole energy range from 20 - 1.8 KeV. This possibility is allowed by the fact that we will be employing a lateral grating interchange mechanism, so that changing areas on the grating is straightforward, and that the undulator beam size is typically only millimeters wide compared to the grating width of many centimeters.

The mirror switchyard can also direct beams into the 4.0.2 beamline. This optical system is specifically designed for PEEM and zone plate based microscopy. The energy range is more restricted, 100 - 1.5 KeV, and so a less complex optical arrangement can be used. This system is still being studied, but either a multi-grating SGM will be used, or a plane grating arrangement as in 4.0.1 with only a single variable line spaced (VLS) grating. The VLS arrangement has the advantage in this case that it allows an arbitrary choice of incidence and diffraction angles, and thus allows a choice of dispersion to be made. In many cases in microscopy, we wish to image a fixed pinhole, but to vary the energy bandpass, and this VLS plane grating design should allow us to do so. The system will be entrance slitless as small electron beam induced wavelength shifts are less important in this case than on 4.0.1, as almost all the magnetic systems to be studied are concentrated, but of small area. The switchyard mirrors will focus only in the horizontal direction, and will form an image at the exit slit of the monochromator. Another switchyard will then relay light either to a zone plate based microscope, or to a PEEM microscope. The choice of magnification of the relay optics is not so important in the case of the zone plate microscope, but they must preserve the beam brightness and so near unity magnification will be used. In the case of the PEEM system however, it is very important to produce the highest flux density on the sample. With the advent of a practical scheme for chromatic and spherical aberration correction in emission microscopes (23), in order to utilize the extremely high spatial resolution that such systems will achieve (<5 nm), and to obtain statistically significant data in a reasonable time (seconds / frame), we need to achieve very high flux density at the sample. We will do this by using a Kirkpatrick-Baez mirror pair as described previously to demagnify to a point that maximizes flux density. Our initial design shows that it should be possible to achieve a spot size of less than 1 μm without geometrical loss in both the vertical and horizontal directions, if the system is optimized for 1 KeV operation (ie., between the 3d transition metal $L_{2,3}$ edges and the rare earth $M_{4,5}$ edges). To view wider regions for initial survey work, the mirror system will be slightly defocused, thus achieving the coordinated condensing and magnification action used in a transmission electron microscope.

We have attempted to show that by optimized optical design, bending magnet sources can be used for a wide range of demanding microscopy, such as 1 μm scanning XPS, and 0.1 μm resolution PEEM. The use of such systems will help to solve the problem of providing an adequate number of microscopes at modest cost. In addition, where the ultra-high brightness of undulator sources is needed, we have also shown that the use of two undulators in one straight section and separate optimized beamlines for spectroscopy and microscopy results in a highly effective overall solution. In addition, in order to achieve optimum optical coupling, the refocus systems for zone plate and electron emission microscopes need to be separated and individually optimized.

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