REALIZATION OF AN ASYMMETRIC MULTILAYER X-RAY MIRROR

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Abstract

Multilayer x-ray optics provide a useful alternative to perfect crystal optics when used as beam conditioners for hard x-rays (~8 keV) in applications that do not require high energy and/or angular resolution. Perfect crystal optics, however, can be cut in such a way that allows one to partially engineer the input and output beam widths and divergence to desired values. Such optics, termed asymmetrically cut crystals, are often used to compress or expand an x-ray beam in one dimension. This trait makes crystal optics far more flexible and valuable in x-ray analysis than they would be otherwise. Due to their layered nature, standard multilayer optics are symmetric and thus, in some ways are less flexible than perfect crystal optics. By depositing a multilayer structure on a triangularly faceted substrate, such as a blazed diffraction grating or an orientation-dependent etched silicon substrate, the multilayer takes on compression/expansion properties similar to those of asymmetrically cut crystal optics and will add a previously unknown level of flexibility to their design and use.

Crystal Collimators

Perfect crystal collimators have been used for many years, and new developments for their exploitation are still being developed. Their use as x-ray beam conditioners in applications that do not require the highest resolution, however, is often unattractive due to the narrow Darwin widths (<20 arcseconds), and thus the low levels of flux that can be passed through them. One method to increase the beam flux through a perfect crystal reflection is to cut the surface of the crystal such that the diffracting planes are at an angle to the surface, \( \alpha \), which is nearly the Bragg angle, as shown in Figure 1.

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Figure 1. Schematic of an asymmetrically cut crystal. If the beam is incident from the left, the reflected beam is expanded, and if incident from the right, the reflected beam is compressed. The angular acceptance and divergence of the reflection is also affected accordingly.

The result for grazing incidence (from the left) is that the acceptance angle of the reflection becomes larger (collecting more photons), and the reflected beam is more parallel than in the symmetric case. The increase in the acceptance angle is proportional to the square root of the beam expansion, while the emitted divergence is proportional to the inverse of the square root of the expansion. If the reverse procedure is used (incident beam from the right), the beam is compressed. The acceptance angle decreases and the emitted beam divergence increases. The compression factor is given by,

$$b = \frac{\sin(\theta + \alpha)}{\sin(\theta - \alpha)}$$

Typical limitations on these techniques for perfect crystal collimators are for beam compressions/expansions of about 10 times, as large absorption losses occur at very small grazing angles (both incident and exit).

**Multilayer Optics**

There are certainly many other types of x-ray optical elements that perform in areas where perfect crystals are insufficient, of which one type is the multilayer mirror. A multilayer mirror consists of a large number of thin, flat layers deposited on a smooth substrate. Typically, the layers are alternating high and low density materials, with uniform thickness for each type. With many bilayers (a single pair of these layers), the structure then behaves as an artificial one-dimensional crystal in the direction normal to the surface, diffracting x-rays over a narrow range of incident angles. For high quality multilayers, the diffraction efficiency can be over 90% and the Darwin width around 0.03 degrees, or 100 arcseconds. Multilayers have recently become the x-ray optical component of choice for many standard diffraction applications, as they provide a reasonably monochromatic the beam and pass far more flux than typical perfect crystal collimators (an order of magnitude or more).

Due to the symmetric layered nature of multilayer structures, however, no one has been able to produce a multilayer with the planes grown at an angle to the substrate surface, which would yield the multilayer equivalent of a beam compressor/expander, as shown...
above for the perfect crystal case. One would like to be able to do this for two obvious cases. The first is as a beam compressor, as the total flux in the beam should increase as the square root of the compression. The multilayer compressor should still collect an order of magnitude more photons than a crystal beam compressor, while compressing a wide beam, and for a compression of 10, yield a beam on the order of 0.1 degrees in divergence, which is suitable for many diffraction applications. The second application is as a beam expander. At an expansion factor of 10, the multilayer expander would collect even more photons than a normal multilayer, and yield a beam with as little as 30 arcseconds divergence, which is suitable for many medium resolution experiments or could be coupled into a secondary crystal collimator for high resolution work. The difficulty is to determine how to make such a structure.

**Multilayer-enhanced Diffraction Gratings**

Over the past decade the fields of multilayer mirrors and optical gratings have joined forces to produce quality dispersive optics for the EUV and VUV the regions, where reflectivity is low and absorption is high in potential optical materials. By depositing a multilayer on top of a diffraction grating, with the multilayer reflecting at the same angle and energy as the diffraction grating substrate, the operation of lamellar, echelle, and blazed gratings have been improved by factors of 2-5. One of the critical enabling technologies for this union has been the development of grating substrates with sub-nanometer roughness. The use of lamellar gratings has far surpassed other types due to the ability to produce well-defined groove frequencies and to easily modify substrates to the required profile, while maintaining low roughness parameters. With enough care, however, blazed gratings and even replicated substrates can be produced with low enough roughness (< 1 nm rms) to enable high efficiency multilayers to be grown on them.

However, the schematics of low angle blazed gratings in these papers are universally distorted. For near normal incidence, this is not much of a problem, but for grazing incidence the distortion can cause an incorrect prediction of the optical behavior. A typical schematic is given below.

![Figure 2. Typical schematic of a multilayer-enhanced blazed diffraction grating, showing deposited layers on the blazed facets.](image-url)
The blaze angle in the above figure is on the order of 20 degrees, while angles actually described and used in the above references are as small as 0.8 degrees. If redrawn to an approximately correct scale, the above figure, with $\phi = 2.5^\circ$, a grating of 1000 lines/mm, and 10 layer pairs of a 5 nm bilayer, would look more like the following:

![Figure 3. More accurate schematic of a multilayer-enhanced blazed diffraction grating. In almost all cases, deposited layers on one facet will not line up in registry with layers on the neighboring facet.](image)

Three items become immediately obvious in the above drawing. First, for an arbitrary bilayer thickness, there will most likely be a registry mismatch at each lateral groove boundary, as is shown. Second, as a photon penetrates into the structure at some grazing angle, it will likely pass through multiple groove regions. Most importantly, however, this structure would look very much like the ideal asymmetrically cut perfect crystal in the first figure, if not for the registry mismatch. Thus, for a structure with good registry match across groove interfaces, an asymmetric reflection is certainly possible. However, even a structure with an arbitrary registry mismatch should yield a useful device, since the coherence length for x-rays is smaller than the facet size in most grating structures. Also, for the same reason, the blaze structure does not even need to have a uniform spacing, as all this would do is create a high probability of registry mismatch. Note: this system is not at all analogous to the use of a multilayer enhanced diffraction grating; the diffraction properties of the grating do not contribute to the operation of this system. The grating structure suggested is used entirely for its geometric properties to tilt the layers of the mirror, and is given as a possible substrate only because it makes the geometry simple to envision and there have already been efforts to deposit multilayers on grating substrates.

**Substrate Quality**

References 6 and 7 studied the surface roughness along each facet of the grating substrates and to a lesser extent, the distribution of facet angles. The results indicate that ruled blazed gratings (and even replicas of master gratings) can be made with roughness of 1 nm or less, which is sufficiently small for growth of reasonably high quality multilayer structures. Alternatively, if one etches an asymmetrically cut silicon crystal, etch rates will be different along different crystallographic planes. Thus, one can produce facets with atomic level roughness and nearly perfect groove tips.
Conclusion

In summary, the current limiting factor in production of an asymmetrically grown multilayer structure on a blazed substrate is the quality of the substrate. Diffraction gratings are an obvious candidate, and currently available master gratings may be suitable, but will be cost-prohibitive for large-scale production. Replicas of master gratings have been used to produce conventional multilayer-enhanced diffraction gratings, but their surface roughness properties may be on the high side for production of quality multilayer beam expander/compressors. Orientation-dependent etched silicon may also be a viable substrate, given the high quality of the surface and the ability to produce sharp, well defined triangular grooves and tips.