Lawrence Berkeley Laboratory
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To be published as a chapter in
Free-Electron Laser Handbook,
W.B. Colson, C. Pellegrini, A. Renieri, Eds.,
Elsevier Science Publishers B.V.,
Amsterdam, The Netherlands, 1988

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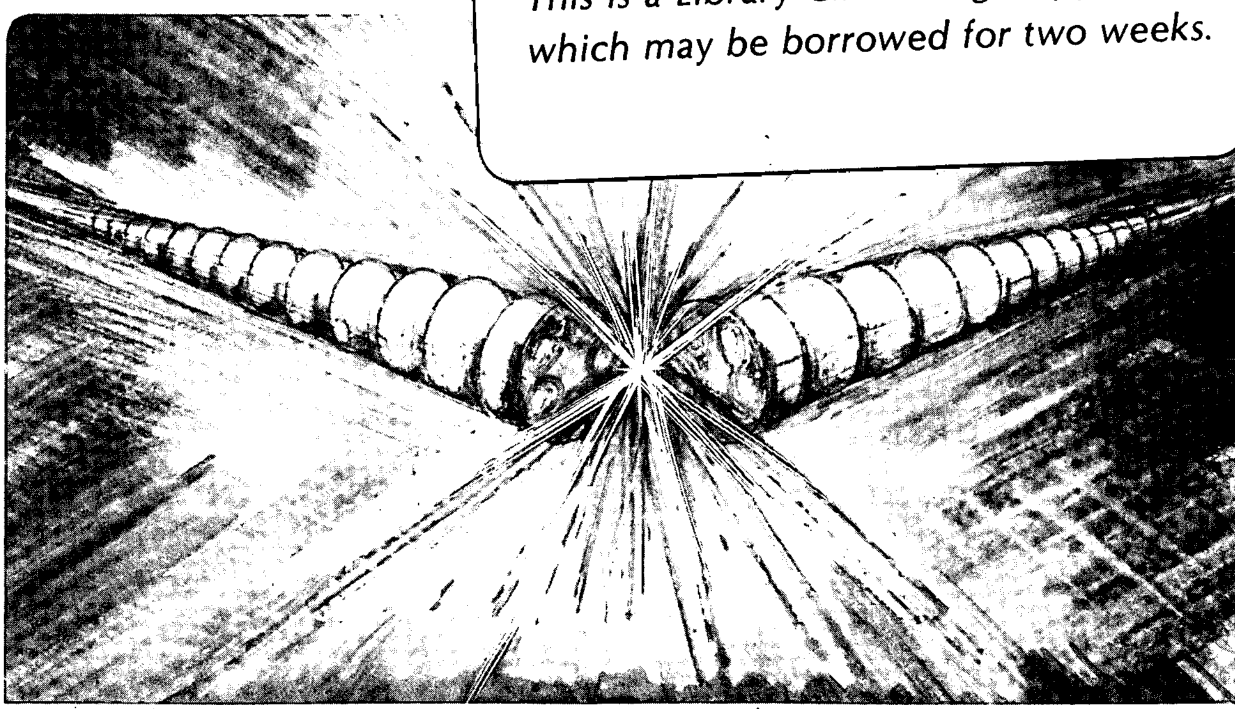
January 1988



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL 24756

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The writing of this chapter was supported by a U.S. Dept. of Defense, Air Force Office of Scientific Research Contract, F49620-87-K-0001, with The Regents of the University of California for performance at the Lawrence Berkeley Laboratory, which is operated under U.S. Dept. of Energy, Office of Basic Energy Sciences Contract DE-AC03-76SF00098.

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Introduction

The extension of cavity free-electron laser (FEL) gain mechanisms into the extreme ultraviolet and x-ray spectral regions will require optics of sufficient reflectivity and durability, both for cavity definition and for applications involving photons thus generated. While single-pass laser amplifiers obviate the need for cavity mirrors, there is a general desire for optics analogous in function to those common in more conventional laser spectral regions. This chapter reviews the status of normal-incidence optics in the extreme ultraviolet (EUV) and soft x-ray regions (collectively referred to as the XUV). Wavelengths under consideration here extend from roughly 200 nm in the far ultraviolet, where optics with high normal-incidence reflectance exist, to several angstroms in the soft x-ray region (see Figure 1). At wavelengths below about 150 nm, high normal-incidence reflectances become difficult to obtain, and research and development remains to ascertain peak normal-incidence reflectances at these wavelengths. This chapter summarizes recent reviews [Attwood et al. 1983, Spiller 1983] which discuss many relevant issues, and also reviews more recent work in this developing area. A brief general discussion of the changing optical properties of solids with wavelength prefaces a review of mirror reflectivities, proceeding from longer to shorter wavelengths. Obstacles encountered or anticipated in this development are considered. Finally, optical elements other than mirrors that may find use in FELs are briefly considered.

The reflectance of cavity mirrors for FELs places a lower limit on the single pass gain of the device necessary for laser oscillation. The higher the normal-incidence reflectance R, the lower the single pass gain required for the FEL to reach saturation. In typical cavity schemes (see Figure 2), two reflections from end mirrors are phased with each pass of the electron bunch, so that the gain per pass of the device must exceed cavity losses at reflection, given by R^{-2}, for overall gain to result. Thus, for a reflectance of 0.5, which is sometimes suggested as a lower useful limit for FEL cavity mirrors, a gain per pass greater than 4 is required for FEL oscillator operation. Even higher gains per pass are required for FEL amplifier operation, i.e., without a resonant cavity. Achieving high single pass gain in the active undulator region becomes more difficult as wavelengths decrease across the EUV and into the soft x-ray, as discussed in Chapters 2 and 5 of this volume. Likewise, normal-incidence mirror reflectances generally decrease across this region. Thus, attainable performance of single pass gain and mirror reflectivity with photon wavelength will ultimately determine the short wavelength limit at which cavity FEL oscillators will operate. FEL amplifier schemes could benefit from even moderate XUV mirror reflectivities (less than 0.5) to aid in reaching saturation in long undulators. High-gain undulator-based amplifier FELs are being considered for operation in storage ring by-passes [Kim] and in rf-linac driven amplifiers [Goldstein et al.].

Optical Properties of Materials in the XUV

Optical properties of solids change dramatically with energy or wavelength from the visible and ultraviolet into the soft x-ray region, resulting from changes in the nature of interactions of photons with electronic states of matter. The challenge of obtaining high reflectance normal-incidence mirrors results directly from these changing optical properties. The complex refractive index, $\hat{n}(\omega) = n(\omega) - ik(\omega)$, provides a general optical description of materials, and reflects these changing optical properties with photon energy, $\hbar\omega$, which is related to the radiation wavelength λ by $\lambda(\mathrm{nm}) = 1239.84/\hbar\omega(\mathrm{eV})$. A material's complex refractive index is related to its complex dielectric constant $\hat{\epsilon} = \epsilon_1 + i\epsilon_2$ by $\hat{n} = (\mu\hat{\epsilon})^{1/2}$. Figure 3 shows the variation of $n(\omega)$ and $k(\omega)$ across the EUV for several materials of interest in for FEL mirrors. Refractive effects are associated with the real part $n(\omega)$, while absorption processes are formally represented by the absorption index $k(\omega)$. The 1/e absorption length for a beam's intensity is given by $\lambda/4\pi k(\omega)$. The normal-incidence reflected intensity at an interface between materials 1 and 2 with radiation incident from material 1 into material 2 is expressed in terms of the materials' complex refractive indices $\hat{n}_1(\omega)$ and $\hat{n}_2(\omega)$ by Fresnel's equation

$$R(\omega) = |[\hat{n}_1(\omega) - \hat{n}_2(\omega)]/[\hat{n}_1(\omega) + \hat{n}_2(\omega)]|^2 .$$

This expression refers to normal-incidence reflectances and can be modified for angles away from normal-incidence [see, e.g., Born and Wolf]. As the complex refractive indices of all materials change rapidly with energy across the EUV, so does their normal-incidence reflectance.

In the visible and ultraviolet spectral regions, metals, semiconductors and insulators have distinctly different optical properties, which in each specific case result from the detailed electronic structure of the material [see, e.g., Wooten, Palik]. In these spectral regions, photons are energetic enough to excite electronic transitions from only relatively high-lying filled electronic states into unfilled states. The nature of these electronic states and transitions is generally associated with the interatomic bonding in the solid. In general the magnitude of $k(\omega)$ depends strongly on the nature of the material, being relatively large for conductors and extremely small for pure insulators. Metals typically have high normal-incidence reflectance associated with their strong absorption. Chemically pure dielectrics with large band gaps retain low absorption into the ultraviolet. However, even the best insulators become absorbing with increasing photon energy in the extreme ultraviolet, as photon energies exceed band gap energies, and by about 100 nm all solids exhibit photo-electric absorption.

Together with the universal photo-electric absorption of all materials in the EUV and extending to shorter wavelengths, another feature generally associated with the changing optical response of solids in the EUV is the plasma frequency. The plasma frequencies of solids are the resonant frequencies of free-like electrons for collective oscillations, and typically occur somewhere in the spectral region between the visible and the EUV. For photon energies below the plasma frequency, the response of free-like electrons is in phase with the radiation, while above the plasma frequency the response is out of phase. For photon energies below those corresponding to the plasma frequency of a given material, normal-incidence reflectances can be very significant, and are very materials dependent. At the plasma frequency, reflectances begin to decrease, and generally fall rapidly with increasing photon energy for all materials.

A related feature of the changing optical properties of solids with photon energy in the EUV is the onset of the phenomenon of total external reflection with increasing photon energy. This phenomenon occurs when the condition $n(\omega) < 1$ is met. When $n(\omega) < 1$, Snell's law predicts that rays incident on a solid from vacuum are bent towards the surface, rather than away from the surface as they are when $n(\omega) > 1$. As the angle of incidence measured from the surface decreases, an angle is reached below which radiation is totally reflected. This critical angle for total reflection (measured from the surface) is given by $\theta_c = \cos^{-1}(n(\omega))$. For wavelengths greater than those in the EUV spectral region, $n(\omega)$ for solids is greater than or less than 1 depending on the material and wavelength. As plasma frequencies of materials are crossed with increasing $\hbar\omega$ in the EUV, $n(\omega)$ becomes less than one and this condition generally remains to higher photon energies. Thus the phenomenon of total external reflection at grazing-incidence angles is often associated with the x-ray regime where it is exhibited by all condensed matter. Total external reflection has provided the basis for grazing-incidence mirrors to deflect radiation in a variety of situations across the x-ray region, and may find utility in certain FEL applications as discussed in the next section.

In the x-ray regime, the optical constants are more an atomic description, rather than a bulk description, as photon energies become comparable to deeper lying, more atomic-like energy levels of atoms. Here the real and imaginary parts of the optical constants are often referred to as $n(\omega) = 1 - \delta(\omega)$ and $k(\omega) = \beta(\omega)$ [see, e.g., Compton and Allison, James]. The x-ray optical constants $\delta(\omega)$ and $\beta(\omega)$ are expressed in terms of the real and imaginary parts of the atomic scattering factors, $f_o + f'(\omega)$ and $f''(\omega)$, as

$$\delta(\omega) = \frac{N_a r_e \lambda^2}{2\pi} [f_o + f'(\omega)] \quad \text{and} \quad \beta(\omega) = \frac{N_a r_e \lambda^2}{2\pi} f''(\omega) ,$$

where $r_e = e^2/mc^2 = 2.82 \times 10^{-13}$ cm and N_a is the number density of atoms in the sample. Here f_o represents the atomic form factor, which for forward scattering approaches the number of electrons in the atom. $f'(\omega)$ and $f''(\omega)$ represent dispersion corrections to the optical behavior associated with excitation of electronic levels by photons, and thus show strong variation near absorption edges. $\delta(\omega)$ and $\beta(\omega)$ vary to first order as ω^{-2} and become increasingly small with decreasing wavelength in the EUV and x-ray regions. Additional ω-dependencies in $\delta(\omega)$ and $\beta(\omega)$ result from the absorption and resonance effests represented in $f'(\omega)$ and $f''(\omega)$. Figure 3 demonstrates these frequency dependancies for selected elements. In the x-ray region the critical angle for total external reflection is given by $\theta_c = (2\delta)^{1/2}$, and the sharpness of the external reflection cutoff with grazing angle depends on the magnitude of the absorption index $\beta(\omega)$ [James]. As seen from Fig. 3, θ_c can be relatively large (of order tens of degrees) in the EUV, and θ_c decreases to first order as λ in the x-ray regime.

As $\delta(\omega)$ and $\beta(\omega)$ decrease with increasing energy in the EUV, normal-incidence reflectances of all materials decrease dramatically, so that below some wavelength no material exhibits useful single surface normal-incidence reflectances. Figure 4 demonstrates this decrease in reflectance with energy for a clean Al surface in ultra-high vacuum, one of the best reflectors in the ultraviolet. With this general decrease in single surface reflectivities, multilayer structures designed to utilize the constructive interference of reflectance from several properly phased interfaces become an alternative means to increase normal-incidence reflectances. Contrast in either $\delta(\omega)$ or $\beta(\omega)$ in the different layers of these structures result in reflectivity at each interface. These devices function analogously to quarter wave stacks familiar in longer wavelength optics and to Bragg diffraction associated with natural crystals at shorter wavelengths, by increasing reflectance over a limited spectral bandwidth dependant on the number of layers contributing to the coherent superposition of reflectances (which range from several to roughly several hundred in the XUV). Fabrication of multilayer structures having well-defined layers with periods 10 nm and less has recently become possible [Barbee and Keith, Spiller et al. 1980], and advances in ultra-thin film fabrication technology continue to advance the state of the art of this area of x-ray optics. Multilayers have been successfully deposited on mildly curved substrates (required for a focusing FEL cavity) and used in normal-incidence imaging experiments [Underwood et al. 1981]. Multilayer Fabry-Perot etalons have been fabricated [Barbee and Underwood 1983], demonstrating that complex multilayer structures can be fabricated with significant perfection. Recent work in multilayer optics, especially aimed at improving normal-incidence reflectances, is discussed in the following sections.

The design of normal-incidence mirrors and other optical elements in the extreme ultraviolet region can be hampered by the lack of reliable optical constant data. The wavelength region between 200 and 10 nm is a particularly troublesome one in which to find accurate optical properties data. At longer and shorter wavelengths, published data exist which appear fairly accurate for design purposes. While optical constant data are not entirely lacking in the 200-10 nm region (compilations of data are found in, e.g., refs. [Hagemann et al., Weaver et al., Palik]), published data for nominally the same materials and wavelengths can differ significantly. These differences presumably result from difficulties in obtaining accurate measurements from well characterized samples at these wavelengths [Hunter]. In the EUV, photon energies are small enough that optical properties depend strongly on electronic structure influenced by the microstructure of the sample, rather than the atomic-like electronic structure which dominates optical behavior at higher energies in the x-ray region. Significant absorption by all materials in the EUV means that measurements of optical properties sample only very thin regions of material near to the surface, or extremely thin films, which often have microstructures that are not well characterized. The microstructural nature of these thin surface films and the thin layers of multilayers (e.g., amorphous, polycrystalline, single-crystal, surface condition, etc.) and its relationship to optical properties is an area in which understanding remains to be gained.

Survey of Normal-incidence Reflectances across the XUV.

Peak normal-incidence reflectances that have been reported and might be expected across the XUV spectral region are reviewed in this section. Several types of optical structures are of interest in the XUV. These can be classified in idealized form as single surfaces, single-layer coated surfaces, and multilayer coated surfaces, and are shown schematically in Figure 5. For visible and ultraviolet wavelengths greater than about 200 nm, normal-incidence mirrors with reflectances in excess of 0.9 are available and are not considered here. For wavelengths less than about 200 nm, normal-incidence reflectances of good reflectors in the UV begin to fall. Figure 6 is intended to act as a summary of the discussion of peak reflectances in the XUV presented below. Features in this figure in some cases represent measured reflectances and in some cases are predictions or estimations of reflectances.

For wavelengths less than 200 nm but greater than roughly 100 nm, different types of structures yield high normal-incidence reflectances. A clean aluminium surface has $R(\omega) > 0.9$ for $\lambda > 100$ nm [Smith et al.]. However, rapid oxidation of Al generally spoils this reflectance, especially at shorter wavelengths. Dielectric magnesium-fluoride (MgF_2) coatings on clean Al avoid this contamination problem and, being relatively transparent, can be deposited in the appropriate thickness to optimize reflectance at selected wavelengths by interference of reflectance from the two interfaces. Optimized reflectances ≥ 0.8 at wavelengths ≥ 120 nm are obtained in this manner [Hass and Tousey]. At shorter wavelengths, MgF_2 becomes absorbing and $R(\omega)$ falls rapidly. Multilayer dielectric structures have higher $R(\omega)$ than MgF_2 overcoated Al for $\lambda > 145$ nm, with $R(\omega) \geq 0.95$. These structures are multilayer quarter-wave stacks of relatively transparent dielectrics which have high $R(\omega)$ over a limited wavelength range [Malherbe, Stelmack].

As photon energies increase above about 12 eV (100 nm), the bandgaps of the best insulators are exceeded in energy, and all materials become absorbing. Many dielectrics are strongly absorbing at lower energies near 6 eV (or 150 nm). This universal absorption has important implications for optics. One important implication of the universal photoelectric absorption for all materials in the XUV, coupled with decreasing reflectances, is that radiation incident on a mirror that is not reflected will be absorbed, with most of this energy converted into heat. Potential difficulties with absorption-induced heating will be briefly considered in the next section.

Another important implication of the universal photoelectric absorption is that, for a limited range of wavelengths from roughly 100 nm to about 75 nm, multilayer structures cannot increase reflectances. Here absorption is so large that multiple layers cannot be penetrated by the radiation. We can obtain a condition on the absorption index $\beta(\omega)$ (or $k(\omega)$) that must be met for enhanced normal-incidence reflectance by multilayers to be possible. Neglecting refraction, the Bragg condition for constructive interference at normal-incidence is $\lambda = 2d$, where d is the period of the multilayer. Requiring that the absorption length for the electric field amplitude, given by $\lambda/2\pi\beta(\omega)$, be greater than the multilayer period, gives the condition that $\beta(\omega) \leq 0.3$ for multilayers to have a reasonable possibility for reflectivity enhancement. In this argument, $\beta(\omega)$ is assumed to represent some average for both materials which make up the multilayer. In practice, one material in a multilayer has lower absorption than the other. In cases where $\beta(\omega)$ for one material is less than 0.3 while that for the other material is greater than 0.3, it is possible for multilayers to enhance R, as will be seen. For a limited wavelength region starting at about 100 nm and extending to roughly 75 nm, all condensed materials, to the author's knowledge, have $\beta(\omega) > 0.3$ and hence are too absorbing for multilayer interference to increase reflectivities. For many materials, $\beta(\omega) > 0.3$ on one or both sides of this limited range.

Single surfaces have the highest reported reflectances for this limited region from roughly 100 to 75 nm in which multilayers appear unable to increase reflectivities. Silicon carbide (SiC) possesses one of the highest useful single surface reflectances from 60 nm to longer wavelengths. The reflectance of SiC depends somewhat on the method of preparation, with SiC prepared by chemical vapor deposition having the highest reflectances with $R(\omega) \geq 0.35$ for $\lambda > 60$ nm [Choyke and Palik, Mrowka] as shown in Fig. 6. Elemental surfaces of Pt, Ir, Os, and Au have the highest single surface reflectances at shorter wavelengths. Reflectances of these metals no higher than 0.25 extend to 55 nm, again may depend on surface condition, and fall rapidly with shorter wavelength. The collective best measured normal-incidence reflectance of these metals is indicated in Fig. 6.

Multilayer structures have recently begun to be investigated to increase normal-incidence reflectances in the wavelength range from about 60 nm and below. Especially for wavelengths greater than about 10 nm, the design of the multilayers often relies on uncertain optical constants, for reasons mentioned above. Efforts to obtain enhanced normal-incidence reflectivities with multilayers are briefly reviewed with decreasing wavelength. Results from these efforts at wavelengths greater than 15 nm are shown as circles in Fig. 6.

An effort to optimize the Ag-Si multilayer system for normal-incidence reflectance at 58.4 nm was made using two Ag-Si layer-pairs [Scott et al. 1986]. The original design, based on one set of published values of optical constants, predicted a normal-incidence reflectance of 0.38. For these materials, $\beta_{Si} < 0.3$ while $\beta_{Ag} > 0.3$. The measured angular response of the reflectance was obtained, and could be well fit by making several assumptions: that the Ag optical constants were better described by a newly-published, second set of data; that a 1.2 nm oxide layer resided on top of the Si surface; and that a 1.1 nm carbon deposit resided on top of the oxide. A slight multilayer enhancement in the reflectance at normal-incidence of 0.16 was measured. The reflectance of several Al-Nb multilayers was investigated at angles near normal-incidence in the wavelength region between 30 and 45 nm [Kortright]. Published values of the optical constants revealed that $\beta_{Al}(\omega) < 0.3$ while $\beta_{Nb}(\omega) > 0.3$. These measurements show a sensitivity to the type of substrate used and a marked decrease in reflectance after moderate annealing. For one sample, multilayer reflectivity enhancement was observed, with reflectances as great as 0.17. The reflectance for this sample was not more than half of that predicted, based on an ideal structure of pure materials with compositionally sharp, smooth interfaces described by published values of the optical constants. Near 45 nm, reflectances measured near normal-incidence from Al-Al_2O_3 multilayers of no more than about 0.1 have been reported [Vien et al.]. Near 30 nm, the reflectance of multilayers of Pt and Ir layered with Si has been investigated [Keski-Kuha]. Again clear evidence of multilayer interference is demonstrated, with peak reflectances as great as 0.12 at angles near normal-incidence. These structures on Si substrates were observed to be unstable over the time scale of months. Multilayers of the Mo-Si type for use as normal-incidence mirrors in the 14.5-21 nm range have been studied by several groups [Barbee et al. 1985, Keane et al., Kühne et al.]. At these wavelengths both Mo and Si have $\beta(\omega)$ well less than 0.3 so that at least several layers of the sample are penetrated. Experimentally reported reflectances range from 0.12 to 0.70, raising questions about the reproducibility of multilayer fabrication and of measurement in general (not just for this multilayer system). Mo absorption features at 5.5 nm and the Si L absorption edges near 12.3 nm yield rapidly changing optical properties of these materials and limit the range of utility for this material combination. Mo-Si multilayers have been of interest for use as cavity mirrors in plasma-based EUV lasers [Keane et al., Ceglio et al.]. Multilayers of W-Si have shown near-normal-incidence reflectances of about 0.15 in the 15-22 nm wavelength region [Falco].

For wavelengths between 10 and 4 nm, multilayers offer the only hope for normal-incidence mirrors with significant reflectances, as single surface normal-incidence reflectivities become increasingly small and impractical. In this range and to shorter wavelengths, multilayer reflectances have been numerically optimized [Rosenbluth] using published values of optical constants [Henke] for the elements. This numerical work confirms that in this wavelength range, photons are energetic enough so that absorption effects become relatively small, and many (>10) layer pairs of materials can effectively contribute to enhance reflectivities. Multilayer reflectances in excess of roughly 0.5 are predicted in this wavelength range by this optimization approach. These and other predictions of calculated multilayer performance based on ideal models of multilayer structures described by published values of optical constants are represented as a shaded region in

Fig. 6. A growing body of experimentally measured multilayer reflectances in the range 10 nm < λ < 4 nm finds values generally no more than half, and often much less, of the values predicted and are not included as data points in Fig. 6. Possible explanations for why these multilayers in the XUV show lower reflectance than calculated are many. Calculated reflectivities often assume oversimplified ideal models of uniform layers of pure materials with compositionally sharp and topographically smooth boundaries, which become increasingly difficult to obtain experimentally as the layer thicknesses approach only tens of atoms or less across. Experimental work remains to fully understand the limits of multilayer reflectivities in this region.

For wavelengths shorter than about 4 nm, multilayers capable of significant normal-incidence reflectances are not currently practical, as these structures with periods less than about 2 nm are not readily formed with significant composition and optical constant modulation by current techniques. A lack of normal-incidence reflectors exists from these wavelengths to about 1 nm, where the lattice planes of perfect or nearly perfect natural crystals can yield significant reflectances at normal-incidence. The region in which nearly perfect natural crystals can have significant reflectances is shown in Fig. 6. Unlike multilayers, whose lattice periods can be varied essentially continuously, natural crystals present a discrete set of periods suitable for normal-incidence diffraction mirrors. Perfect natural crystals such as Si can have reflectances approaching 1.0. Less than perfect crystals will show lower peak reflectivities.

A method qualitatively different from a single normal-incidence reflection to turn a beam by 180° is that of successive reflections with incidence angles closer to grazing than normal. This approach, illustrated in Figure 7, would utilize the high reflectivities associated with the total external reflection effect. These turning mirrors would be broad band pass devices compared to multilayer mirrors, with a cutoff at short wavelengths but not at long wavelengts. Cylindrical [Vinogradov et al.] and multi-faceted, flat, metal mirrors [Newnam] have been proposed for XUV FEL cavity mirror applications utilizing this scheme. Significant reflectances ≥ 0.5 for wavelengths greater than roughly 5 nm appear feasible based on calculations. Initial experimental data work directed toward exploring and implementing this approach emphasizes the need to carefully model the reflecting surface with respect to contamination [Scott et al. 1988]. Advantages of this technique over single bounce, normal-incidence mirrors include the distribution of absorbed power over a relatively large area and the relatively broader spectral range of high reflectance compared to multilayer mirrors.

In summary, measured normal-incidence reflectances of 0.5 or greater have not yet been routinely achieved across most of the XUV. As the relatively high reflectivities of UV reflectors drop at roughly 150 nm, absorption is so great that multilayers cannot act to enhance reflectances, leaving single surfaces as the best reflectors down to roughly 70 nm. Multilayers do offer the possiblilty of significant reflectivity enhancements across a broad region in the XUV, for wavelengths from roughly 75 nm to 4 nm. Early experimental results show that multilayers can enhance normal-incidence reflectivities in the range from 60 nm to shorter wavelengths, and point to several limits to multilayer performance and design, some of which are discussed further in the next section. Enhancements in reflectance in cases investigated so far appear modest in many cases, with more dramatic increases apparent in isolated cases. Absorption limits multilayer reflectance by limiting the number of interfaces that can contribute to enhanced reflectivity. Materials suitable for layering with less absorption, and stronger optical contrast, would be desirable for increased multilayer enhancements of reflectance in this and other regions. Uncertainty in optical constants, especially in the 200 - 10 nm region, resulting from differences in values from different published works and from uncertainties in the microstructure of the materials makes optical design here particularly difficult. Better understanding of fabrication tolerances may lead to improved performance. Methods for turning XUV beams by 180° other than normal-incidence reflectance are under investigatation, though are in earlier stages of development than multilayer mirrors.

Degradation of Optical Performance.

The goal of FELs to provide intense radiation in the XUV will result in harsh radiation environments that may degrade the performance of optics. Various physical processes may reduce the performance of optics in the EUV and soft x-ray regions, some of which are considered in this section. Processes which reduce reflectivity can be generally categorized as resulting from absorption or scattering, and different mechanisms may be more relevant to different types of optics. Since all materials are absorbing in the XUV, degradation processes resulting from absorption may be anticipated to be important. Absorption-related degradation may be especially severe in the EUV, where absorption lengths of order 10-100 nm are common.

Scattering of photons into unwanted directions is a mechanism for degradation, and may result from surface roughness or other microstructural features in the optic with size scales of the order of λ. Reduction of the specularly reflected intensity by scattering into unwanted directions resulting from surface roughness is often assumed to follow the functional form $\exp[-(4\pi\sigma\sin\theta/\lambda)^2]$, where σ is the rms roughness and θ the incidence angle from grazing [see, e.g., Bennett and Porteus]. Thus, scattering from surface roughness is a more significant potential problem for normal-incidence optics of various types than for grazing-incidence optics. Surfaces and substrates for all XUV optics must be as close to ideal in their surface finish and figure as possible, and any absorption processes which would roughen or disfigure optics could lead to significant degradation of performance.

In many scenarios, intense pulses of radiation will be incident on FEL cavity mirrors. The ability of optics to survive a single intense pulse of radiation is an important concern that clearly depends on the power of the pulse. These pulsed heating concerns are similar to those encountered in pulsed laser annealing studies of solid surfaces. Typical lengths of FEL pulses (of order 100 picoseconds) are short enough that conduction of heat away from the beam footprint is not a effective cooling mechanism in the duration of the pulse. Thus, pulsed power above some limit will melt or evaporate all surfaces, thereby spoiling optical performance. Experiments and theory on condensed matter and multilayers suggest that 0.1-1 J/cm^2 is enough absorbed energy to melt condensed matter [Larson et al., Hockaday et al., More et al.]. Theoretical predictions of FEL performance in the EUV [La Salla et al.] suggest that under Q-switched operation, these power levels could be reached in practice at 96 nm. Under most proposed operating conditions, however, the energy deposited in the mirrors during one FEL pulse appears likely to be below this catastrophic failure limit. Short of catastrophic failure of the optical surface during a single pulse, many mechanisms triggered by time-averaged absorption of power could limit performance of optics in the XUV.

Single- or multilayer coated optics face another set of possible degradation mechanisms in intense radiation environments. These structures are frequently metastable materials composites, whose equilibrium thermodynamic state is different from that of the designed optic. Thus, energy deposited into these optics may hasten atomic rearrangements towards a lower free energy state. Microstructural changes resulting from photon-induced mechanisms may lead to degraded optical performance in various ways [Deacon]. Thermally or photon-induced interdiffusion or solid-state reaction between layers of a multilayer or a coating and substrate are examples of processes which would likely degrade optical performance, as are crystallization of amorphous layers and grain growth of polycrystalline regions. Roughening of optical surfaces may also result from this deposited energy as a consequence of atomic rearrangements. Delamination or spalling of multilayers or coatings from substrates due to poor adhesion, thermally induced stresses, or shock waves resulting from momentum imparted to the optic during a pulse are other mechanisms that may degrade the performance of optics. Several of these degradation mechanisms were observed to occur in

MgF_2-coated Al mirrors in synchrotron radiation application [Takacs et al.]. Damage mechanisms in multilayers short of catastrophic failure are only beginning to be explored. Because of the metastable nature of single- and multilayer-coated optics, efforts to design optics whose state is close to thermodynamic equilibrium may be of importance.

Absorption of EUV and soft x-ray photons by dielectric thin film optics has been shown to decrease reflectance in cavity mirrors for visible and infrared (IR) FEL applications [Billardon et al., Elleaume et al., Ambrosio et al.]. In these cases, absorption of radiation, with photon energies inferred to be greater than about 160 eV, by dielectric TiO_2/SiO_2 multilayer mirrors optimized for high reflectance in the visible and IR was observed to degrade reflectance in these spectral regions. Some of this degradation of reflectance, if not too severe, was found to be reversible by annealing the optics at moderate temperatures. A proposed mechanism for this absorption-induced degradation is the formation of atomic defect centers (color centers) by the EUV photons, which effectively change the optical properties of the constituent layers of mirrors in the visible and IR spectral regions. This possibility, of altered optical properties at one photon energy due to radiation damage resulting from another (or perhaps even the same) photon energy, may exist in the XUV as well. As photon energies increase across the EUV into the soft x-ray, effects of interatomic bonding on the optical properties become less important in general (except perhaps near absorption edges), so that changes in the effective optical constants due to such point defects might be expected to decrease.

Thermal distortion of FEL cavity mirrors presents another potential mechanism for degraded performance, and again will depend on the energy deposited in the optic. During a single pulse, thermal distortion of the topmost optical surface or coating is of greatest concern, while deformation of both substrate and surface is important for times averaged over many pulses. Distortion during the pulse may be more severe than distortion averaged over time, assuming that heat is effectively removed from the optic. The surface distortion during a pulse may be of order 1-2 nm, assuming typical materials parameters and published values for projected FEL output specifications [La Sala et al., Deacon]. It is unlikely that this thermal expansion will adversely affect the separation of the mirrors. However, the focusing properties of a curved FEL optic could be altered by such distortions, thus degrading the mode defining performance of the cavity. Much thought has recently been given to heat extraction techniques and mirror substrate materials that minimize these potential distortion and other heating concerns [DiGennaro et al.] in synchrotron radiation applications. Judicious choice of substrate materials based on thermal conductivity, thermal expansion coefficient and yield stress, together with appropriate active cooling techniques, is required to provide mirrors capable of handling high average power levels without significant distortion.

Contamination of the optical surface is a general problem across the XUV, and is especially severe in the EUV, where contamination layers of order 1 nm thick can significantly perturb optical performance. Oxidation at surfaces is one type of contamination that can affect performance in the EUV [Hass and Tousey, Scott et al. 1988]. Designing optical surfaces of materials that do not oxidize, incorporating native oxide layers into optical design [Vien et al.], or fabricating optical surfaces in situ in ultra-high vacuum to avoid oxidation may help avoid this contribution to reduced performance. Carbon contamination of optical surfaces in vacuum can also significantly degrade optical performance. This contamination, often observed in synchrotron radiation optics across the XUV [Elleaume et al., Ambrosio et al.], is thought to result from cracking of hydrocarbons present near the surface of the optic catalyzed by photoemitted electrons from the surface [Boller et al.]. Atomic oxygen generated by an RF or DC discharge in low pressure O_2 gas has been found to effectively clean carbon contamination from optical surfaces in situ [E.D. Johnson et al., Koide et al.]. While this approach can effectively regenerate an optical surface after carbon contamination, or clear a volume of carbonaceous compounds, it cannot generally be used during operation to avoid carbon contamination because of the relatively high O_2 pressures required. In this scheme, care must be taken so that reactive atomic oxygen does not oxidize cleaned optical surfaces that are susceptible to such damage. In addition to contamination resulting from photon-stimulated adsorption of carbonaceous material, photon-stimulated desorption of specific species may also change surface microstructure resulting in degraded optical performance [Billardon et al.].

Other optics of interest in the XUV.

In addition to normal-incidence cavity mirrors, other optical elements are of interest for XUV FEL applications. These include optics for output coupling of beams to experimental or diagnostic stations, focusing and dispersing optics, etc. Development of these optics for the EUV spectral region faces many of the same difficulties as development of normal-incidence cavity mirrors, but usually with one important exception--the requirement of high normal-incidence reflectance.

Optics for output coupling of the photon beam will be required for extraction and utilization of beams generated by cavity-based XUV FELs. Several types of output couplers have been proposed. Perhaps the simplest idea is that of a scraper mirror that directs the outer periphery of the beam out of the cavity while allowing the central portion of the beam to continue contributing to FEL oscillation (see Fig. 7). Multilayers on ultrathin transparent substrates have been proposed as beam splitters [Attwood et al. 1982] for inclusion in the cavity. A beam splitter consisting of essentially a free-standing Mo/Si multilayer has been demonstrated in the 16-22 nm region [Hawryluk et al.]. Such a multilayer beam splitter could be placed at the end mirror position and would allow for transmission of a fraction of the beam intensity out of the cavity while at the same time acting as a mirror for cavity definition. This mirror/beam splitter combination has the advantage of avoiding perturbations of the beam by an additional optical element in the form of a beam splitter in the cavity. Another proposed output coupler is a multilayer coated grating at the position of one of the cavity end mirrors [Hawryluk et al.]. In this scheme, the zero order reflection from the multilayer coated grating would act as the normal-incidence mirror for cavity definition, while the diffraction orders would direct beams out of the cavity. To date these multilayer-coated beam splitter and gratings suffer from reduced multilayer reflectances resulting presumably from less than ideal multilayer substrates.

A variety of optics exist, and continue to be developed, that are suited for applications of photons generated by XUV FELs (other than for cavity mirrors). Detailed consideration of these optics is beyond the scope of this chapter. Optics for synchrotron radiation EUV, soft x-ray and x-ray applications are directly transferable to XUV FELs (reviews can be found in, e.g., refs. [R.L. Johnson, Matsushita and Hashizume]). Beam transport mirrors based on total external reflection are common, and can be figured to provide focusing in one or two dimensions. Focusing can also be achieved using Fresnel zone plate lenses [Rarbach and Kirz, Schmahl et al.], multilayer-coated figured mirrors in a Kirkpatrick-Biaz geometry [Underwood et al. 1986], and multilayer-coated Schwartzschild objective lenses [Lai et al.]. Diffraction gratings of various types are useful in the EUV and soft x-ray in applications where spectral dispersion is of interest. Reflection gratings can be ruled on figured surfaces and with variable spacing, thus enabling focusing applications with high resolution [Hettrick]. Transmission gratings may also find uses in various applications [Dijkstra et al.]. Multilayer structures operating away from normal-incidence can be applied on the surfaces of various optics to increase reflectivities. Combinations of these elements can deliver highly coherent XUV FEL beams to a variety of experiments.

<u>Summary</u>

In summary, achieving high normal-incidence reflectance FEL cavity mirrors at wavelengths below about 150 nm remains in general a challenge because of the nature of the optical properties of materials in the XUV. In the region between 150 nm and about 10 nm, design of optics is especially difficult because optical constants for thin films or surfaces of many materials are poorly determined. Much recent work has focused on the use of multilayer structures, which offer potential normal-incidence reflectances of 0.5 or greater in a broad range from roughly 70 nm to about 4 nm. A growing body of experimental results have generally found reflectances less than 0.5 across this region, though in isolated cases reflectances greater than 0.5 have been reported. Mirrors based on successive grazing-incidence reflection are being investigated for cavity mirrors. The environments of FEL cavities present various possible mechanisms that would result in degradation of optical performance of cavity mirrors. Active research continues in these areas to better understand the limitations of performance of multilayers and other optics in XUV FEL and other applications. Gains in the performance of these optics are to be expected, and will ultimately help determine the short wavelength limit at which XUV FELs will operate.

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FIGURES

Figure 1. The spectral range of interest in this chapter is from about 200 nm in the ultraviolet (UV) to several angstraoms in the x-ray. The divisions between the different regions are not sharp. Between the UV and extreme ultraviolet (EUV) are regions sometimes referred to as the far UV and the vacuum UV (VUV). Photon energy, $\hbar\omega$, is related to photon wavelength, λ, by λ (nm) = $1239.84/\hbar\omega$ (eV).

Figure 2. A free-electron laser oscillator is defined by cavity mirrors. Radiation intensity accumulates and saturates after many passes of the electron beam bunch through an undulator and phased with the mirror feedback. High reflectance mirrors at normal-incidence are desired. Features are not drawn to scale.

Figure 3. Variation of the optical constants $n(\omega) = 1 - \delta(\omega)$ and $k(\omega) = \beta(\omega)$ with photon energy across the EUV. Data for molybdenum, amorphous silicon, silver and aluminum are taken from ref. [Palik]. A wide variation in $n(\omega)$ in the visible and UV becomes a trend toward 1 in the EUV for all materials as photon energies exceed resonances of free-like valence electrons. The λ^2 first order variation in $\delta(\omega)$ and $\beta(\omega)$ for $\lambda \lesssim 50$ nm is modified by resonances from bound atomic electrons.

Figure 4. Normal-incidence reflectance of a clean Al surface in ultra-high vacuum decreases rapidly in the EUV above the plasma frequency for Al at roughly 15 eV. Data are taken from ref. [Smith et al.]. All condensed

materials show a similar trend of decreasing $R(\omega)$ through the EUV and into the x-ray.

Figure 5. Types of normal-incidence reflectors of interest in the XUV include single surfaces, single-layer coated surfaces, and multilayer coatings, shown here as idealized structures. Each different material is described by its optical constants $\delta(\omega)$ and $\beta(\omega)$. Surface contanimation and the microstructural nature of thin films may mean that published values of bulk optical constants do not adequately describe a real structure's optical behavior. Natural crystals are of interest at wavelengths < 1 nm.

Figure 6. Normal-incidence reflectances of various types of mirror structures as a function of wavelength across the XUV are shown here. See text for discussion.

Figure 7. Successive reflections at angles far from normal incidence, where relatively high reflectances are associated with the total reflection phenomenon, has been proposed as a means to turn a beam by 180° with good efficiency. (After [Newnam])

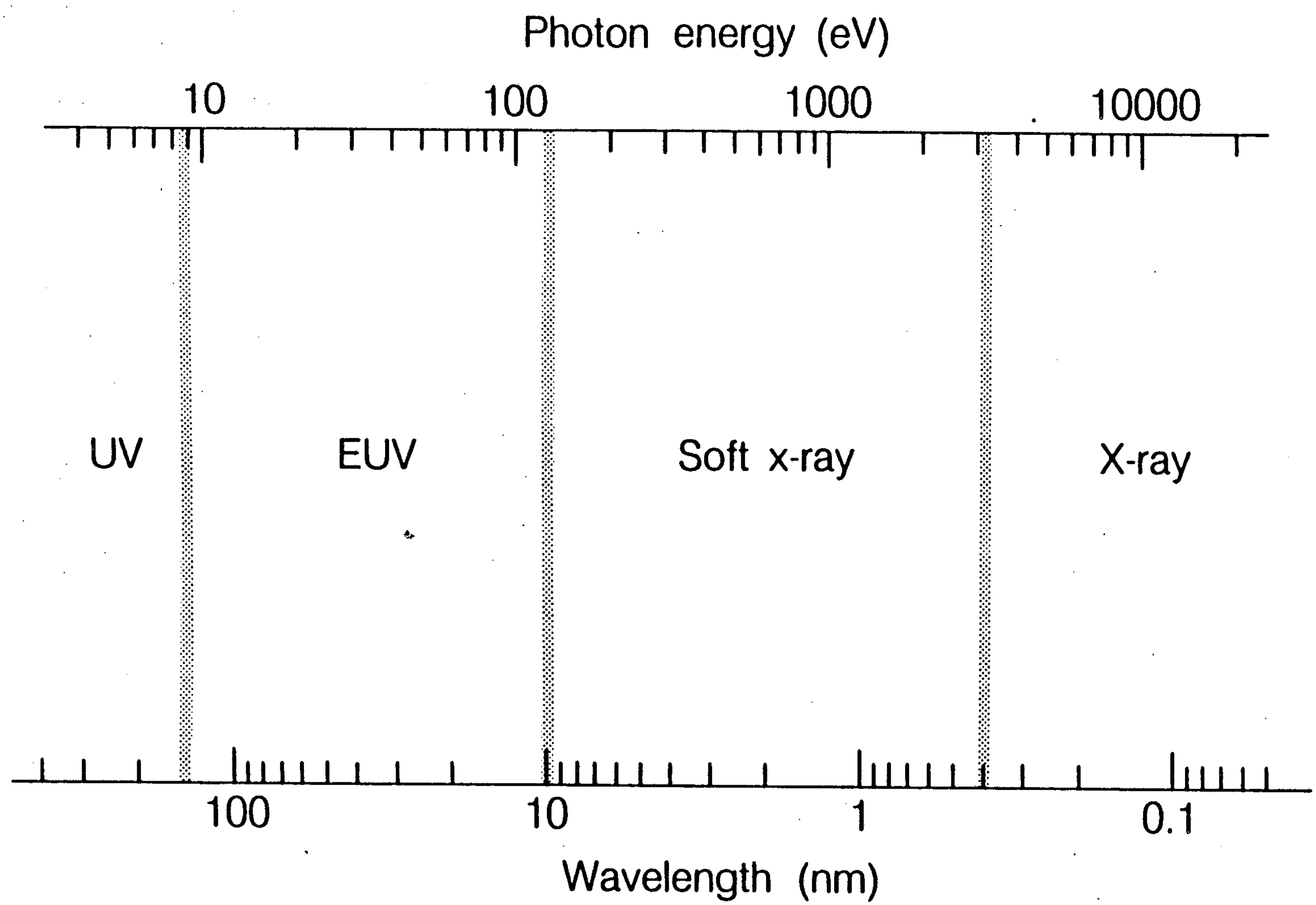
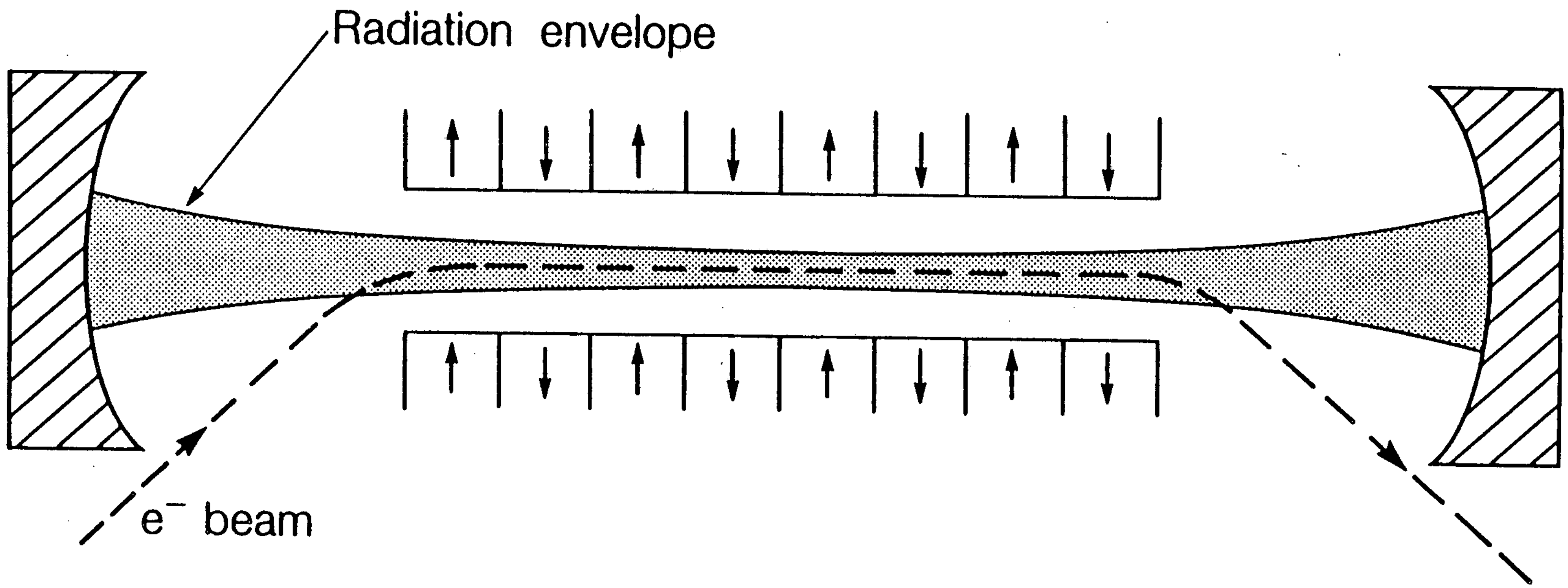


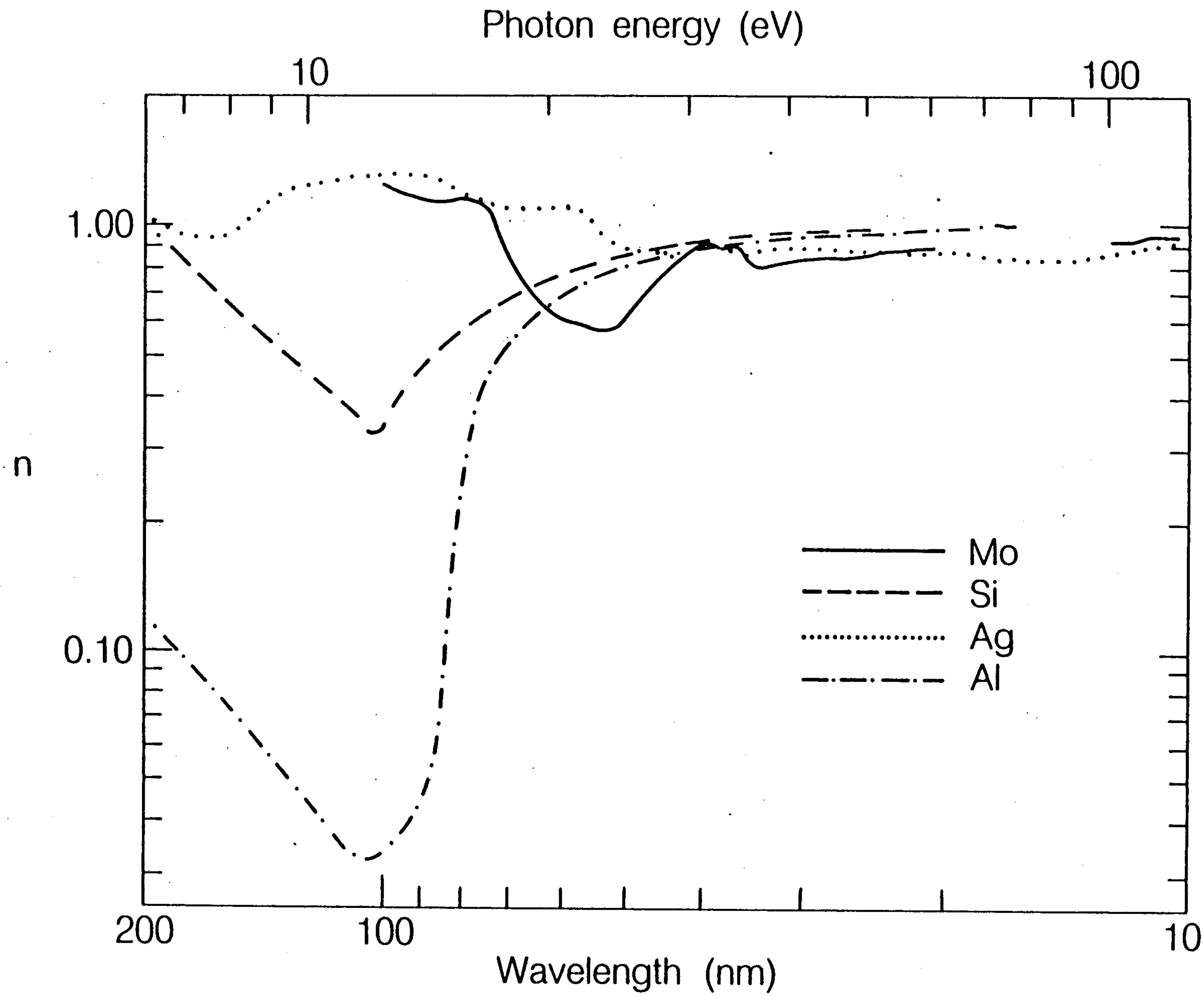
Figure 1

XBL 8711-11292



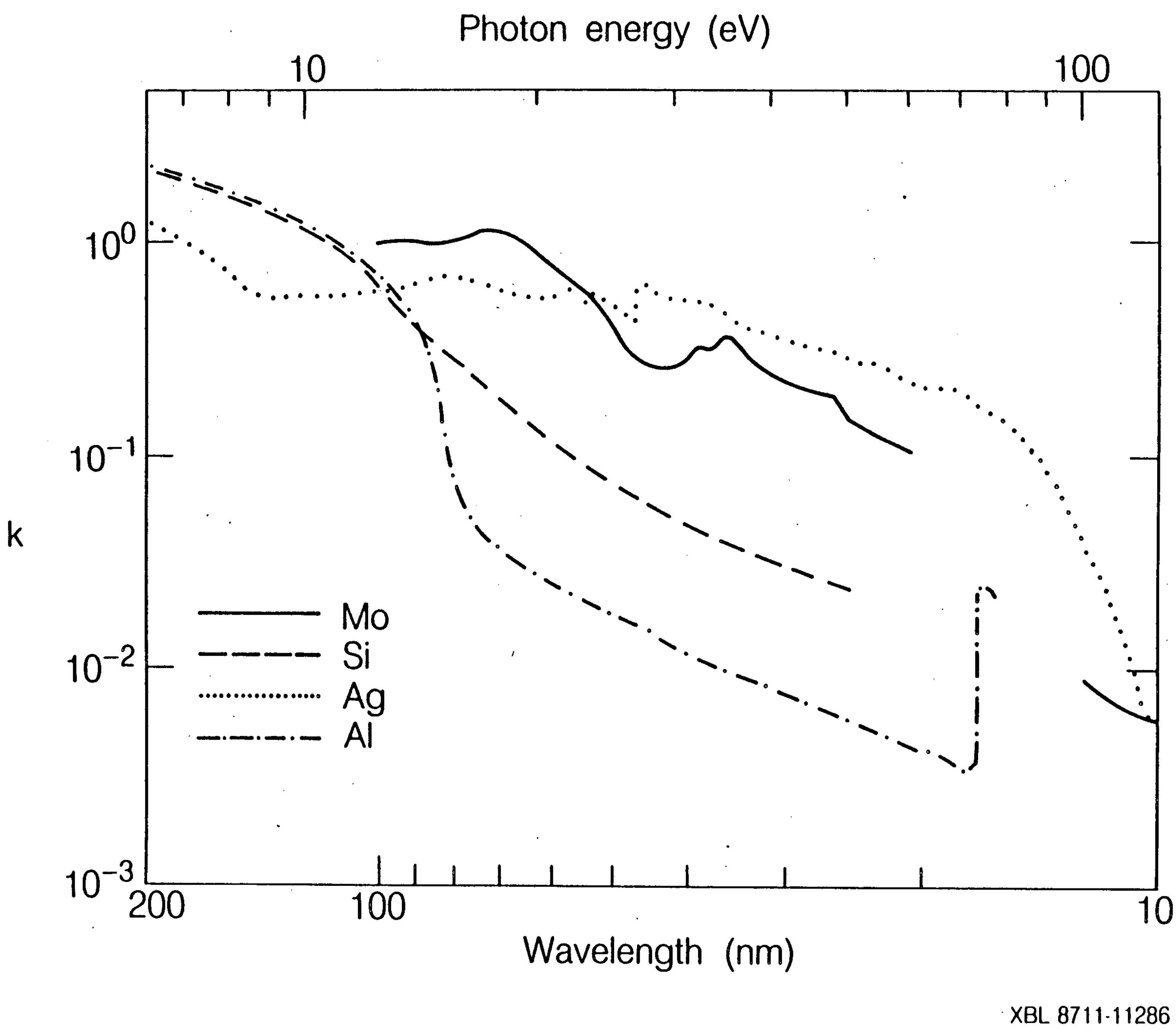
XBL 8711-11291

Figure 2



XBL 8711-11287

Figure 3a



Photon energy (eV)
10
100
10^0
10^{-1}
10^{-2}
10^{-3}
k
Mo
Si
Ag
Al
200
100
10
Wavelength (nm)
XBL 8711-11286

Figure 3b

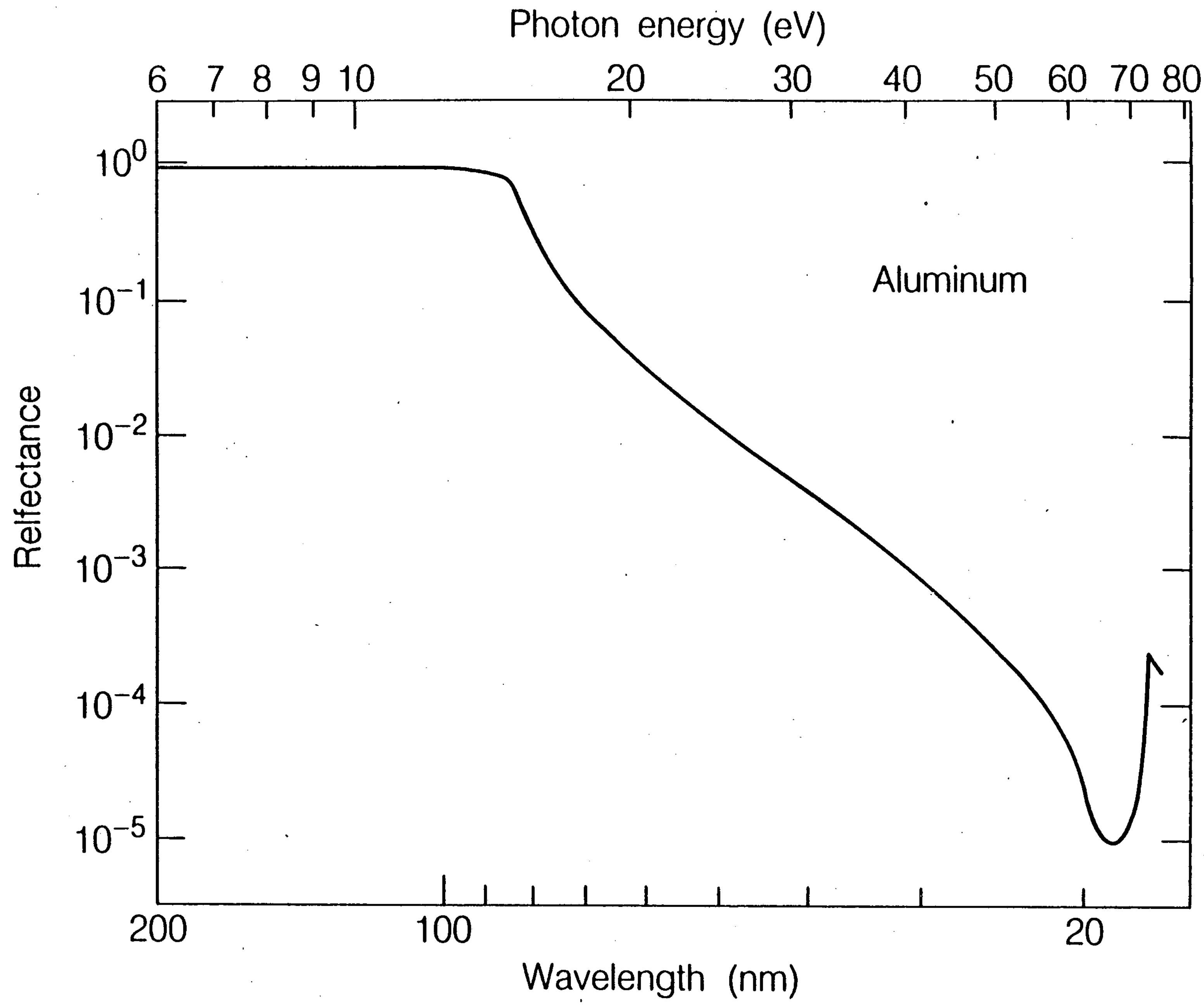


Figure 4

XBL 8711-11289

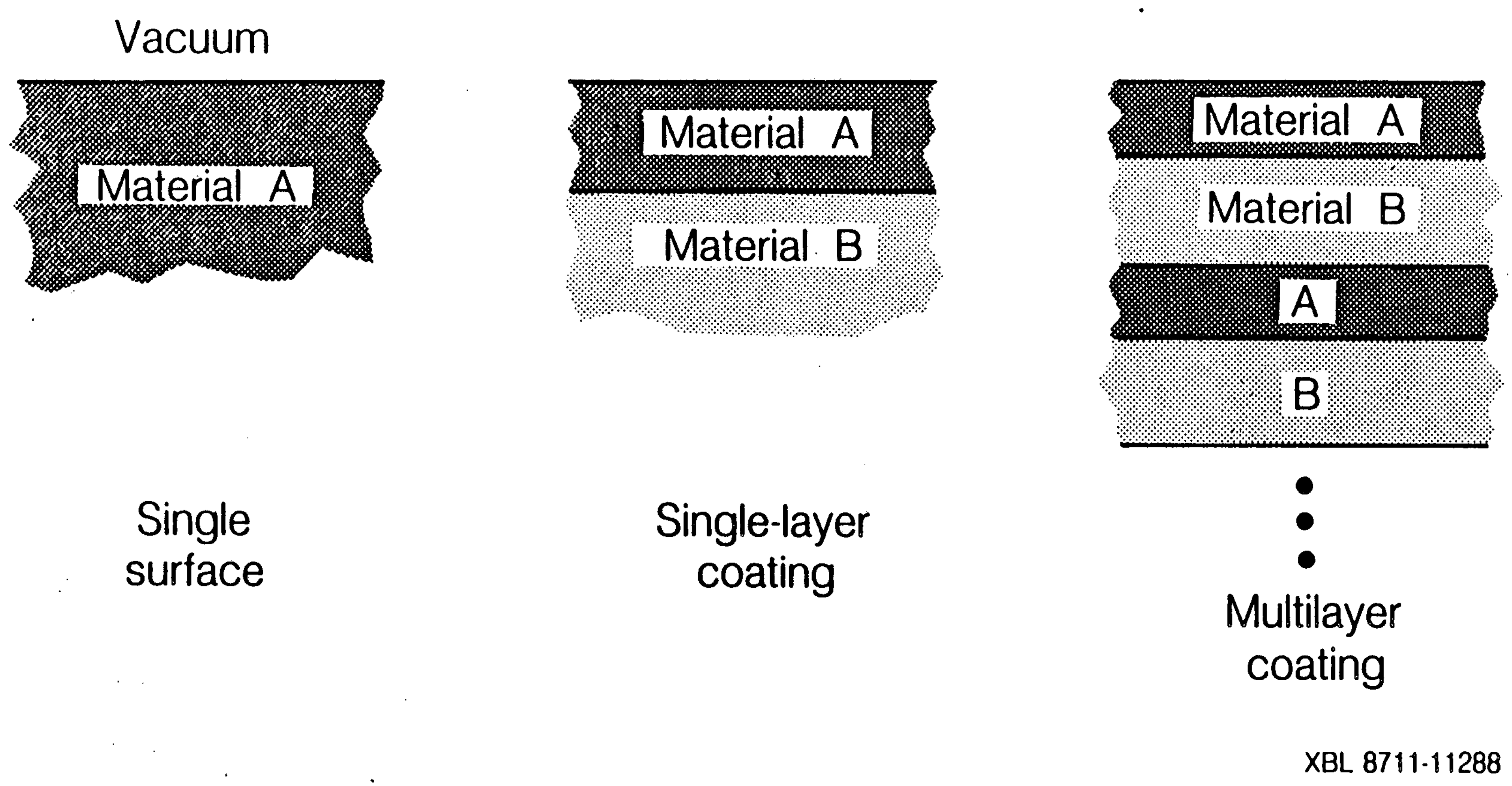
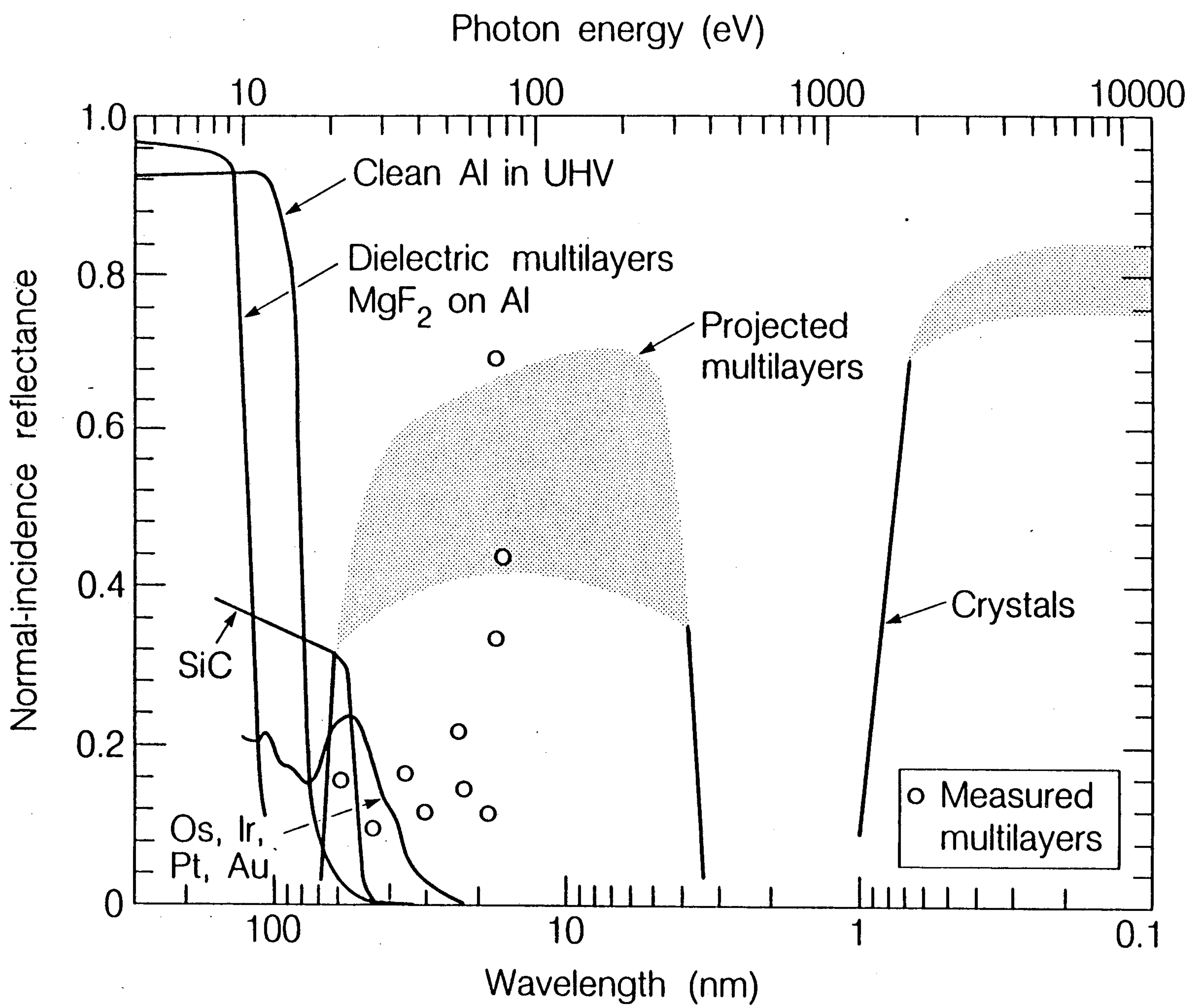

Vacuum
Material A
Material A
Material B
Material A
Material B
A
B
Single surface
Single-layer coating
Multilayer coating
XBL 8711-11288

Figure 5



XBL 8711-11296

Figure 6

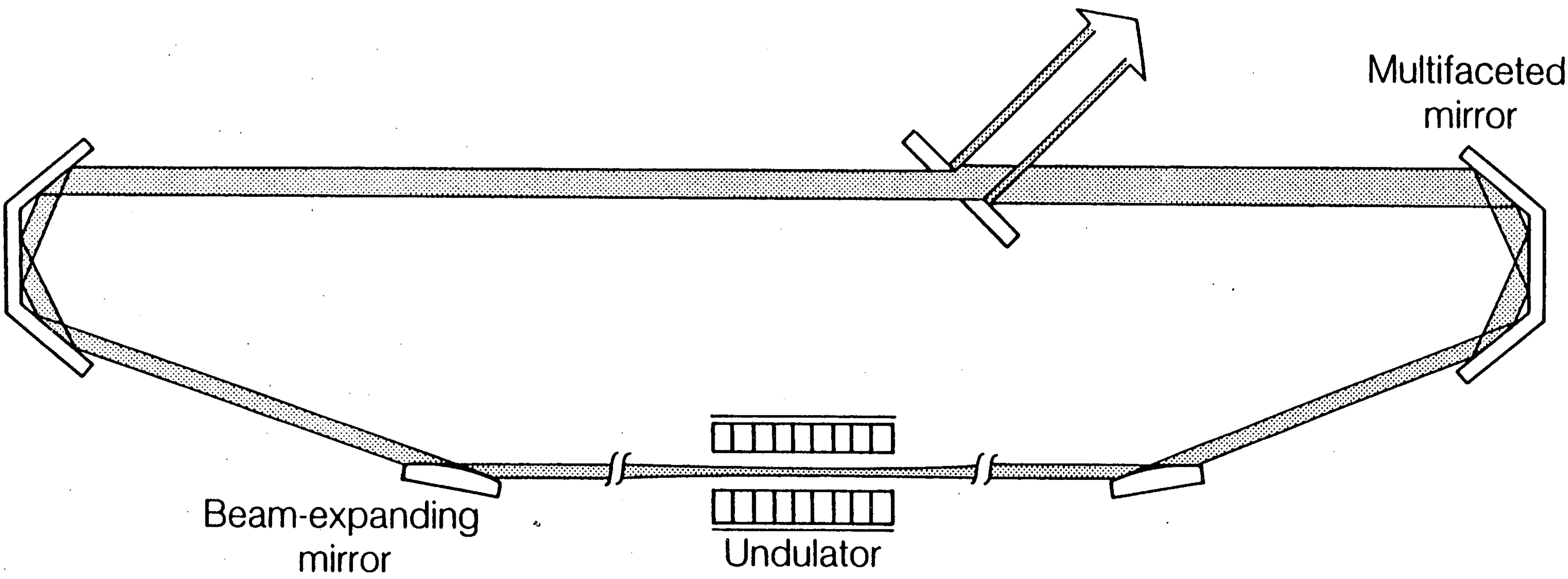

Output beam
Multifaceted mirror
Beam-expanding mirror
Undulator
XBL 8711-11290

Figure 7

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