Nuclear multilayer structure with antireflecting coating

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A combined application of resonant Bragg diffraction by a nuclear multilayer structure and specular antireflection by a coating film to provide a beam of synchrotron radiation with super narrow, $\Delta E/E = 10^{-11}$, bandwidth has been studied. A proposed structure includes two antireflecting films above and below the nuclear multilayer. Computer simulation shows that a high nuclear reflectivity with a suppression of electronic scattering down to 4×10^{-7} at the angular position of nuclear Bragg reflection can be attained.

Excitation of nuclear ensemble by synchrotron radiation can be used to generate coherent monochromatic *x* radiation.[1] Synthetic nuclear resonant multilayer structures have recently been employed for this purpose.[2,3] A very big enhancement of the radiative channel[4] can be achieved in nuclear resonant Bragg scattering of synchrotron radiation by a nuclear multilayer. It yields a large broadening of the resonance and a speedup[5] of nuclear de-excitation. In the ^{57}Fe/Sc multilayer, for instance, the width of a nuclear γ resonance can be enlarged to 40 Γ_0 (Ref. 3) ($\Gamma = 4.7\times 10^{-9}$ eV is the natural width of a 14.413-keV ^{57}Fe nucleus level) and the effective lifetime of the excited state can be decreased correspondingly to $\sim$4 ns (compared to 141 ns, which is the natural lifetime of ^{57}Fe first isomer state.)[6]

The coherent γ radiation emitted by a nuclear multilayer can be especially useful in application to time domain hyperfine spectroscopy.[7] It can be used as a source radiation which excites in a short time all nuclear transitions between the different sublevels of the ground state and the excited states in the test sample. It also allows one to observe the subsequent evolution of the coherent nuclear fluorescence of the sample, where the quantum beats between the excited transitions should be revealed.[8] An advantage of nuclear multilayer application for these experiments lies in the fact that nuclear reflectivity of a multilayer essentially exceeds the electronic reflectivity. Thus, an energy bandpass of a nuclear multilayer is comparable with the energy of nuclear hyperfine interaction, with a negligible contribution of electronic scattering beyond resonant range. The suppression of electronic scattering is a necessary condition in the case of synchrotron radiation sources of the third generation, which provide very high spectral density of radiation. In the 1-μeV energy band one can expect an *x*-radiation flux of about 10^7 quanta/s. For the modern fast counters of *x* radiation it is the highest limit of operation. Our goal in the present paper is to determine the optimal conditions for suppression of the electronic scattering in a nuclear resonant multilayer.

A nuclear multilayer is a synthetic regular structure in which the electronic and nuclear resonant densities have different periodicities. For this reason the Bragg diffraction of radiation by nuclei and electrons occurs at different angles. Since the spatial arrangement of the multilayer is usually characterized by a large period, the Bragg

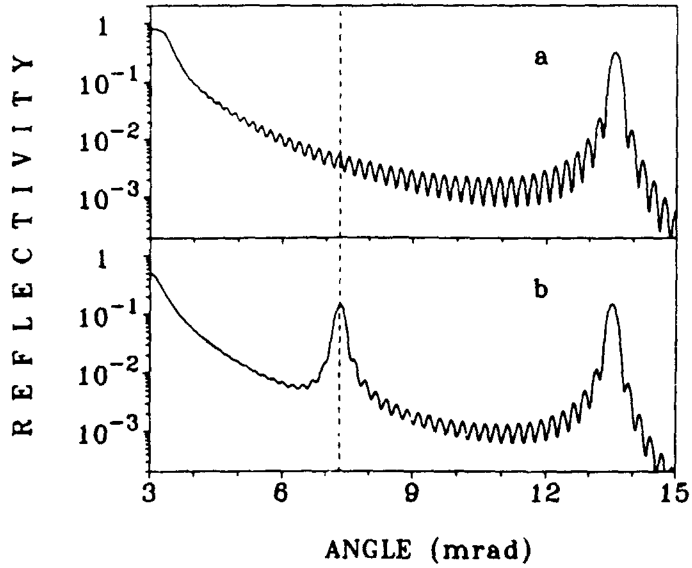

FIG. 1. Computer-simulated angular dependences of (a) nonresonant electronic and (b) resonant nuclear scattering by the [^{57}Fe(22 Å)/Sc(11 Å)/Fe(22 Å)/Sc(11 Å)]·25/glass (NML/glass) nuclear multilayer without antireflecting coating. Dashed line shows an angular position of nuclear Bragg reflection.

diffraction occurs rather close to the forward direction, which is not far from the region of the grazing incidence specular reflection. Therefore, specular scattering from the boundaries (upper and lower ones) of a multilayer still gives weak contribution to the coherent signal. Because of this contribution, one can observe the Fresnel interference pattern in the angular dependence of scattering. Suppression of electronic scattering enables such a structure to provide effective destructive interference in the electronic coherent scattering at the angular position of nuclear Bragg diffraction.

Fresnel interference on interfaces is widely used in conventional optics. It was applied[9–11] to suppress x-ray scattering by GIAR (grazing incidence antireflecting) films. However, the decrease of electronic scattering by a factor of about 25 is rather small compared with the required value (about 10^{-6}). As is shown below, strong suppression of electronic scattering can be achieved on the way to combined usage of pure nuclear x-ray diffraction and Fresnel interference; in other words, with an antireflecting nuclear multilayer.

The antireflecting nuclear multilayer was analyzed by a computer simulation of the angular and energy spectra of the γ-ray scattering. As a base for the present studies we used the previously investigated [^{57}Fe(22 Å)/Sc(11 Å)/Fe(22 Å)/Sc(11 Å)]·25/glass nuclear multilayer (denoted below as NML/glass). The actual parameters of the quality of layers, such as the interface roughness and inhomogeneity of the layer thickness, were those obtained from the fit of the experimental data with the nuclear multilayer mentioned above.[3,6] Mean roughness was assumed to be 4 Å. The influence

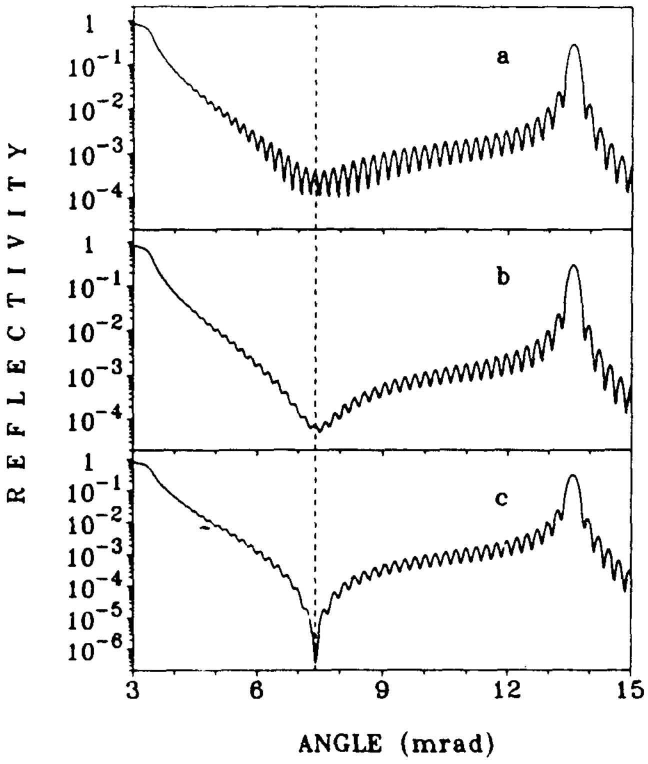

FIG. 2. Computer-simulated angular dependences of electronic scattering by the (a) Ti(40 Å)/NML/glass, (b) Ti(40 Å)/NML/Te(20 Å)/glass, and (c) Ti(18 Å)/B(14 Å)/NML/Te(20 Å)/glass antireflecting nuclear multilayers. Dashed line shows an angular position of nuclear Bragg reflection.

of the thickness inhomogeneity of about 1% was considered as a convolution of angular dependences with 15 arc sec Gauss distribution (FWHM). An impedance-match solution of the antireflecting film theory[9] was analyzed. We were looking for the antireflecting film of proper impedance, which the waves scattered by the top and bottom interfaces of the film to the direction of pure nuclear reflection of equal amplitudes but shifted in phase by 180°.

Figure 1(a,b) shows the rocking curves of the nuclear multilayer without an antireflecting film for the radiation (a) off and (b) on resonance with nuclear levels. An electronic reflectivity of nonresonant radiation at the angular position of nuclear Bragg reflection is about[12] 5×10^{-3}. The oscillations of reflectivity resulting from the Fresnel interference are seen in the two rocking curves.

An insertion of a Ti(40 Å) antireflecting layer above the nuclear multilayer results in an attenuation of the wave scattered by the top boundary of a sample: A broad minimum of electronic scattering occurs at the nuclear Bragg angle, and electronic reflectivity decreases to 2×10^{-4} (Fig. 2a). However, the suppression of scat-

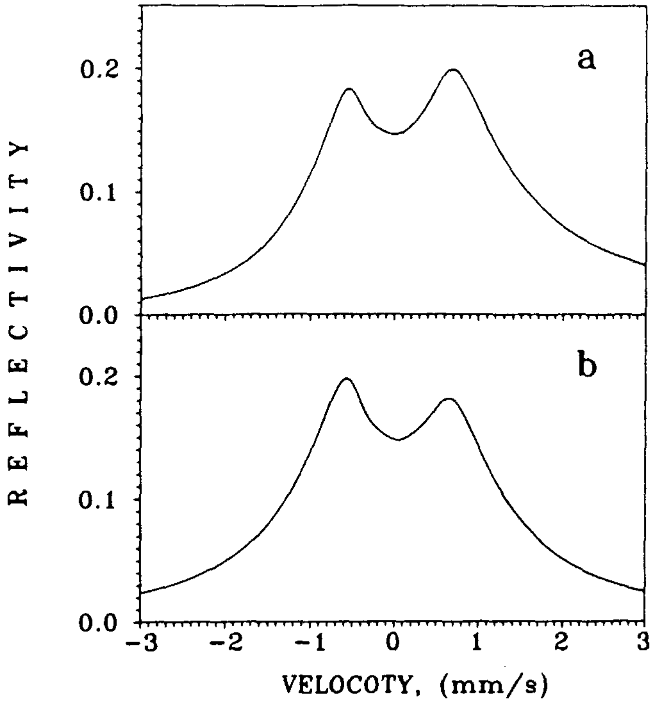

FIG. 3. Mössbauer spectra of nuclear diffraction by (a) NML/glass and (b) Ti(18 Å)/B(14 Å)/NML/Te(20 Å)/glass multilayers.

tering from the top boundary results in a strong increase of the reflectivity oscillation, because now the waves which are scattered by the two boundaries of the nuclear multilayer have similar amplitudes. An increase of these beats should be regarded as a disadvantage, because the probability that the detector would overload due to a minor shift of the angular position of the multilayer is high. An obvious solution is to employ another antireflecting layer below the nuclear structure to suppress the reflection from the bottom boundary as well. An insertion of a Te(20 Å) antireflecting layer between nuclear structure and glass substrate smooths the angular curve at the nuclear Bragg position and decreases electron reflectivity further to a value of about 5×10^{-5} due to the suppression of scattering from the bottom boundary (Fig. 2b). Thus, the antireflecting Ti(40 Å)/NML/Te(20 Å)/glass multilayer results in a reduction of nonresonant scattering by about two orders of magnitude as compared with the nuclear multilayer without antireflecting films.

In order to obtain a stronger reduction of electronic scattering, we need to use an antireflecting film of more complex structure.[9] This is especially important for the top antireflecting layer which suppresses the main contribution of specular scattering. The optimal solution for this film was found to be the Ti(18 Å)/B(14 Å) bilayer. Figure 2c shows that the electronic reflectivity of the Ti(18 Å)/B(14 Å)/NML/Te(20 Å)/

glass structure is about 4×10^{-7} at the angular position of nuclear Bragg reflection. It should be stressed that this value was calculated with due account of the mentioned roughness and layer inhomogeneity parameters, which were proved to be available in practice.

An important question is how does an addition of the antireflecting films affect the resonant reflectivity of a nuclear multilayer. Figure 3 shows that a Mössbauer spectrum of nuclear diffraction is affected only slightly, but neither the mean nuclear reflectivity nor the energy bandpass undergoes significant changes. The reason is that in the entire resonant energy range a nuclear contribution to a refractive index is sufficiently large to destroy the impedance-match solution and to prevent the reduction of nuclear reflectivity. Photoabsorption in the top antireflecting film is also of minor importance for the proposed multilayer.

Thus an application of an antireflecting technique is predicted to be very promising for the suppression of electronic scattering by a nuclear multilayer. The combination of antireflecting films and a nuclear multilayer seems to be much easier in practice as compared with GIAR films due to the larger scattering angle of the nuclear multilayer. Hence the angular extension of the antireflecting minima on the rocking curves is also larger, and they are not so sensitive to the multilayer quality. An optimal level of nonresonant electronic scattering of about 10^{-6} seems to be possible for this approach, while the parameters of nuclear resonant reflectivity are not affected by the introduction of the antireflecting layers.

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[12] Experimentally measured[4] lower value of about 1×10^{-3} seems to be caused by the lower electron density of sputtered materials in the multilayer as compared with the nominal values used in the simulation.

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