Depth resolved hyperfine interactions with standing waves in [W/Si]_{10}/Si/Ag^{57}Fe/Ag/Si multilayer

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Abstract. Delayed nuclear resonant reflectivity (NRR) of [W/Si]_{10}/Si(z nm)/Ag^{57}Fe/Ag/Si multilayer as well as the time spectra at several grazing angles have been measured at the nuclear resonance beamline ID18/ID22N of the ESRF. NRR of ^{57}Fe layer has been enhanced by standing waves created by Bragg reflection from [W/Si]_{10} backing and by multiple reflections from Ag adjacent layers. Fitting of the data was done with the program package REFTIM. The reconstructed HFI depth distributions show an essential asymmetry of the ^{57}Fe interfaces. The total ^{57}Fe density depth-profiles turn out to be in a good agreement with the measured Fe K_{α} fluorescence curve.

1. Introduction
Standing wave method has been successfully used for depth resolved investigations of different processes: atomic migration in multilayers, the interface structure in thin film nanostructures, magnetic structure of interfaces, position of a marker layer inside the waveguide, structure changes during post-growth annealing steps, the intermixing of layers induced by irradiation [1-8]. Resonant methods combined with standing wave technique enrich obtained information. Nuclear resonant reflectivity (NRR) also undergoes the standing wave influence [9,10]. An enhancement of NRR by the standing waves has been used for depth profiling of the hyperfine interactions (HFI) in multilayers [10-12] and also for investigation of ^{57}Fe monolayers or islands inside waveguides [13-14].

Here we report the results of the NRR and Fe K_{α} fluorescence measurements from a thin ^{57}Fe layer under the influence of standing waves created by the periodic multilayer backing [W/Si]_{10} for the same sample. In such a way the influence of the standing waves on two different processes: incoherent secondary radiation emission and coherent NRR is compared.

2. The sample description
The samples [W(2.1 nm)/Si(3.1 nm)]_{10}/Si(z nm)/Ag(1.9 nm)/^{57}Fe(4 nm)/Ag(2.2 nm)/Si(9.8 nm) were deposited on a float glass substrate using electron beam evaporation in an UHV environment with the base pressure in the chamber being 3x10^{-9} mbar. The buffer internal Si layer had a wedge profile and allows one to change the distance z of ^{57}Fe layer from [W/Si]_{10} periodic structure. A standing wave amplitude in the thin ^{57}Fe layer is enhanced by the Bragg reflection from [W/Si]_{10} backing and by the multiple reflections from the Ag adjacent layers (like that in waveguide). Here we investigate a sample...
having \( z = 1.9 \) nm to study the standing wave influence on the NRR. The investigation was supported by angular dependence measurements of the Fe K\(_\alpha\) fluorescence excited by Cu K\(_\alpha\) X-rays.

3. **Nuclear resonant reflectivity measurements**

Usually X-ray standing waves are used to get a depth selectivity in secondary radiation (photoelectrons, fluorescence) excitation. The intensity of a secondary radiation \( I_f(z) \) created at a depth \( z \) is proportional to the square module of the total field amplitude \( E(z) \)

\[
I_f(z) \sim N_f(z) |E(z)|^2 = N_f(z) \left( E^+(z) + E^-(z) \right)^2
\]

(\( E^+(z) \) and \( E^-(z) \) are the amplitudes of waves in the forward and backward directions). Positions of standing wave antinodes can be shifted by small variations of the angle, so the angular dependency of the fluorescence signal determines the depth profile of the density \( N_f(z) \) of fluorescent atoms.

The influence of the standing waves on reflectivity has been also proved [9-11]. In the simplest case the reflectivity \( I_R \) from an ultrathin layer placed at a distance \( z \) atop a multilayer is given by

\[
I_R = |r E(z)|^2,
\]

where \( r \) is the reflectivity amplitude from the same layer placed in vacuum. It follows from (2) that the reflectivity from an ultrathin layer is enhanced by the fourth power of the standing wave amplitude \( E(z) \). That takes place in general case also. So the influence of the standing waves on the reflectivity is even more effective than that on the secondary radiation emission. The problem how to extract the contribution of a selected layer to the total reflectivity can be solved by resonant techniques.

NRR is measured with synchrotron radiation in the time domain. Reflectivity amplitudes in the energy \( R(\omega) \) and time \( R(t) \) domains are connected by the Fourier transform. Integration of \( |R(t)|^2 \) over the delay time \( t \) for each grazing angle \( \theta \) gives the delayed NRR curve \( I_R(\theta) \).

This curve characterizes the depth position of the resonant nuclei. In experiment the integration limits are restricted by the interval \( T \) between synchrotron radiation sequent pulses (176.06 ns at 16 bunch mode of ESRF). Besides there is a “dead time” \( \delta \) of a detector, overloaded by the huge prompt pulse. The calculations show that the exclusion even a small initial delay times 0-\( \delta \) from the time integration leads to a considerable change of the delayed NRR curve [15]. In our experiment \( \delta = 10.17 \) ns, \( T = 161.4 \) ns. The tail of a previous pulse has been also included in calculations.

![Figure 1. Time spectra of NRR. Symbols are experimental data, lines are the fits. Curves are vertically shifted.](image)

![Figure 2. Prompt and delayed reflectivity for our sample. Symbols are experimental data, lines are the fits.](image)
Measurements were done at the beamline ID22N/ID18 of the ESRF. The time spectra of NRR were measured at several angles in vicinity of the Bragg peak. Results are shown in figures 1-2. Notice that the maxima on the delayed curve at ~3.5 and ~5.4 mrad coincide with minima on the prompt reflectivity curve. This can be explained by the enhancement of the radiation field inside the sample at the resonant layer position. The standing waves created by the prompt Bragg reflection from [W/Si]₁₀ backing produce the delayed peak at ~9.24 mrad. The shift ~0.23 mrad between the delayed “Bragg” peak and prompt Bragg peak is seen. It is obvious that this shift is determined by the relative position of the $^{57}$Fe layer and of the standing wave maximum at different angular shifts.

4. Fit results and discussion

Fit of the delayed NRR and prompt reflectivity curves as well as the time spectra of reflectivity, measured at several angles near the Bragg angle, have been performed with the program package REFTIM [16]. The initial step of the calculations includes the fitting of the CEM spectrum measured for that sample (figure 3 a). HFI parameters obtained by this fit were kept for the fitting of the time spectra. The fit of the prompt reflectivity curve (figure 2) gives the exact period of the [W/Si]₁₀ backing and depth profiles for the real and imaginary parts of the susceptibility in the whole sample (figure 4).

The main parameters used for the fit of the time spectra were the depth distributions of different HFI in $^{57}$Fe layer. The time spectra measured at different angles are not essentially different “by eye” (figure 1), however the reasonable correspondence of the calculated and measured spectra can be achieved just at the very special (but unfortunately not unique) distributions of different HFI across the $^{57}$Fe layer depth. The obtained profile of the $^{57}$Fe total density and profiles of the partial contributions from different HFI are presented in figure 3 b. The mixture of different HFI in each artificially selected sublayer testifies that $^{57}$Fe layer is not homogeneous. Magnetic hyperfine fields have smaller values in the interfaces. A doublet contribution predominates in sublayers with lower $^{57}$Fe density. The figures 3 b and 4 show that the real structure of the sample differs from the nominal one. The most interesting result of the fit is the revealed asymmetry of interfaces of $^{57}$Fe layer (including the difference of HFI in the two interfaces) and a visible destruction of the top Ag layer and the top bilayer of [W/Si]₁₀ backing.

The obtained model of the electronic structure and z-position and depth profile of the $^{57}$Fe density were used (with proper renormalization of the absolute values of sublayer susceptibilities accordingly to the change of the radiation wavelength) for calculations of the reflectivity and Fe Kα fluorescence curve, measured with Cu Kα radiation (figure 5). We immediately get surprisingly good agreement with experimental data. So our depth profiling of the $^{57}$Fe density performed by the analysis of the NRR data were confirmed.
In conclusion, we should emphasize that the NRR supplies us with more detailed information about $^{57}\text{Fe}$ layer than a fluorescence curve. Namely the fit of the NRR delayed angular curve and the time spectra measured at different grazing angles makes possible to follow the depth distribution of different HFI and hence different chemical states of iron across $^{57}\text{Fe}$ layer (figure 3 b).

![Figure 4](image1.png)  
**Figure 4.** Depth profiles of the electronic density and absorption coefficient. Filled curve gives the position and profile of $^{57}\text{Fe}$ density in the structure.

![Figure 5](image2.png)  
**Figure 5.** Reflectivity and Fe $K\alpha$ fluorescence curve measured with Cu $K\alpha$ radiation. Theoretical curves (solid lines) are calculated with the electronic and Fe density depth-profiles (figure 4), obtained by the fit of the NRR.

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**References**

[1] Ghose S K, Dev B N and Gupta A 2001 Phys. Rev. B 64 233403
[2] Kim S-K and Kortright J B 2001 Phys. Rev. Lett. 86 1347
[3] Gupta A, Rajput P, Saraiya A, Reddy V R, Gupta M, Bernstorff S and Amenitsch H 2005 Phys. Rev. B 72 075436
[4] Holý V, Matěj Z, Pacherová O, Novák V, Cukr M, Olejník K and Jungwirth T 2006 Phys. Rev. B 74 245205
[5] Bera S, Bhattacharjee K, Kuri G and Dev B N 2007 Phys. Rev. Lett. 98 196103
[6] Gupta A, Kumar D and Meneghini C 2007 Phys. Rev. B 75 064424
[7] Gupta A, Rajput P and Meneghini C 2007 Phys. Rev. B 76 195401
[8] Andreeva M A, Odintsova E E, Semenov V G, Irkaev S M and Panchuk V V 2008 J. of Surface Investigation. X-ray, Synchr. and Neutron Techn. 2 564
[9] Andreeva M A and Lindgren B 2002 JETP Letters 76 704
[10] Andreeva M A 2004 Hyperfine Interactions 156-157 595
[11] Andreeva M A and Lindgren B 2005 Phys. Rev. B 72 25422
[12] Andreeva M A, Monina N G, Häggsström L, Lindgren B, Kalska B, Kamali-M S, Vdovichev S N , Salashchenko N N, Semenov V G, Leupold O and Rüffer R 2008 Nuclear Instruments and Methods in Phys. Res. B 266 187
[13] Röhlsberger R, Thomas H, Schlage K, Burkel E, Leupold O and Rüffer R, 2002 Phys. Rev. Lett. 89 237201
[14] Röhlsberger R, Bansmann J, Senz V, Jonas K L, Bettac A, Meiwas-Broer K H and Leupold O 2003 Phys. Rev. B 67 245412
[15] Andreeva M A, Monina N G and Stankov S 2008 Moscow Univer. Physics Bulletin 63(2) 132
[16] http://www.esrf.eu/computing/scientific/REFTIM/MAIN.htm