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EXAFS Studies of Multilayer Interfaces

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ABSTRACT

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INTRODUCTION

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$\chi(k)$ is the EXAFS interference function after the smooth absorption background is removed, and the energy has been converted to the photoelectron wave vector k. The EXAFS contains information about the interatomic distances R_j for the first few atomic shells about the absorbing atom. Each shell give rise to a characteristic frequency, and can often be isolated by Fourier transform techniques. The amplitude functions A(k) and σ_j give information about the types of atoms in a shell, and the disorder in the bond lengths. The advantage of EXAFS is that no long range order is required, a situation which often in interfaces.

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The fluorescence technique has high sensitivity, but still has problems for single crystal substrates. If the multilayers are thin such that the X rays penetrate to the substrate, then Bragg reflections can enter the fluorescence detector and distort the data. For the above mentioned W-C results this problem was avoided by using amorphous substrates. Bragg peaks can also minimized by using glancing angles to reduce the penetration of the X rays to the substrate. However, since the components in multilayers are generally present in concentrated amounts, self absorption will then give significant reductions of the EXAFS amplitudes as will be discussed below.

A better technique is to detect the electron yield from the sample. Since the electrons can be collected from an $\simeq$1000Å surface layer, the technique is well matched to typical multilayer samples. In addition, self absorption corrections are eliminated, and Bragg peak interference is greatly reduced. Figure 1 shows examples of data collected using electron detection for a W-C multilayer consisting of 10 bilayers with a W thickness of 43Å and a C thickness of 40Å. The

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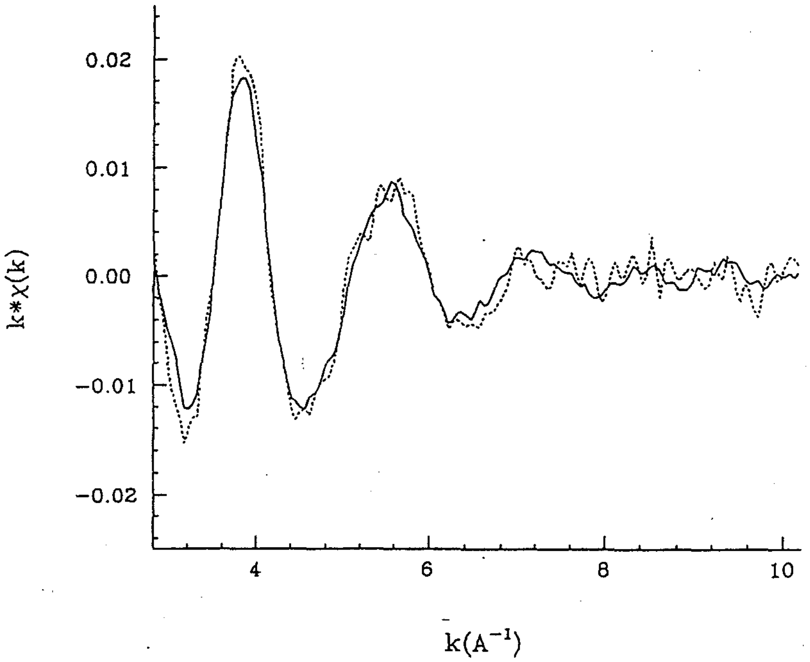

Figure 1: Comparison of EXAFS $\chi(k)$ for a W(43Å)-C(40Å) multilayer before(solid line) and after(dashed line) exposure to NSLS bending magnet radiation for 12 days.

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An enhancement of the fluorescence technique can be made by taking advantage of the standing wave fields set up in a multilayer structure when the multilayer Bragg reflections are excited[5]. The basic principle is shown in Fig. 2. This shows a calculation of the electric field intensity in a Ni-Ti multilayer for incident angles near the first order Bragg peak. Strong modulations of the electric field are produced, which means that the fluorescence signal is no longer being excited uniformly throughout the sample. Thus, the EXAFS measurement can be enhanced from selected regions of the sample by an appropriate choice of incidence angles. As the data show this is possible even if there is substantial interfacial roughness. Fig. 2(a) shows the reflectivity from an actual Ni-Ti multilayer prepared by sputtering[6]. The reflectivity is substantially reduced by interfacial roughness. This reduction can be modeled by $\simeq$17Å of roughness. The standing wave modulation for this amount of roughness, however, is only slightly affected as the calculation in fig. 2(b) shows.

Figure 3 shows the results of a calculation of the contribution to the EXAFS signal from interfacial regions under standing wave conditions. For the case shown the total interface contribution can be enhanced by almost a factor of two for the appropriate choice of incidence angle. Of equal importance is the fact that the signal from interface type (1) can be almost completely eliminated. This makes it possible to look for differences in the two types of interfaces present in multilayer samples.

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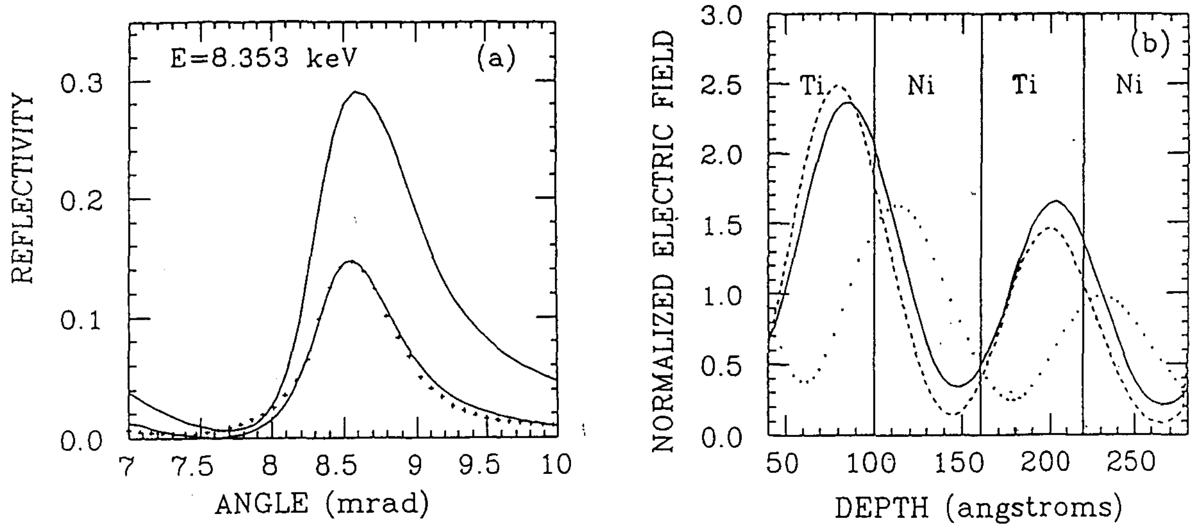


Figure 2: a) Reflectivity near the first order Bragg peak for the Ni-Ti multilayer described in the text (crosses). The solid lines are calculated reflectivities assuming no roughness (large amplitude) and 17Å rms roughness (smaller amplitude). b) Calculated electric field intensity for the near surface region in a Ni-Ti multilayer with d=120Å at 8.353 keV. The interface roughness is 17Å rms, and the curves are calculated for 8.23 mrad (solid line), and 9.0 mrad (points). The dashed line is the result for 8.23 mrad assuming no roughness.

absorption coefficient by the relation[1]

$$\mu' = \frac{I_f}{I_0} = \frac{\mu sin(\theta)}{\mu_t/sin(\theta) + \mu_f/sin(\phi)} \tag{2}$$

where $\mu_T = \mu + \mu_B$ is the total absorption of the sample including the other components, μ_B, and μ_f is the absorption for the fluorescence photons. The incidence angle is denoted by θ, and the fluorescence photon exit angle by ϕ. For glancing angles $\theta \ll \phi$ and the μ_f term can be ignored. Thus, eq. 2 can be simplified to $\mu' = \mu/(\mu + \mu_B)$ where it is easily seen that if $\mu \simeq \mu_B$, modulations in the measured μ' will be strongly reduced in amplitude. EXAFS spectra, however, are normalized relative to the step in the absorption edge which is also reduced. Taking this into account the reduction in the normalized EXAFS signal can be calculated for a two component system as

$$\frac{\chi'}{\chi} = \frac{\mu_{1L} + f\mu_2}{\mu_{1K} + f\mu_2}, \quad f = \frac{1 - x}{x} \tag{3}$$

where μ_{1L} and μ_{1K} are the absorption of the element being measured below and above its absorption edge, μ_2 is the absorption of the other component, and x is the concentration of element 1.

When standing waves are excited in a multilayer structure, the concentration must be adjusted to account for the fact that the components no longer contribute to the absorption in direct relation to their average concentration. This can be done by integrating the electric field intensity over the individual layers and summing to determine the contribution of each element. The variation of the EXAFS amplitude with the standing wave pattern can also be used to verify that standing wave fields are being excited, as will be shown in the next section.

RESULTS FOR NI-TI

Figure 4 shows results obtained for the Ni K-edge in the same sample for which the reflectivity data is shown in Fig. 2 (60Å Ti and 60Å Ni layers). In this case the comparisons are most easily made using the Fourier transforms of the EXAFS. A strong amplitude variation is seen indicating that standing wave affects are being observed, but the overall shape of the spectra are very similar to data obtained on a bulk Ni sample. This immediately indicates that there is not substantial

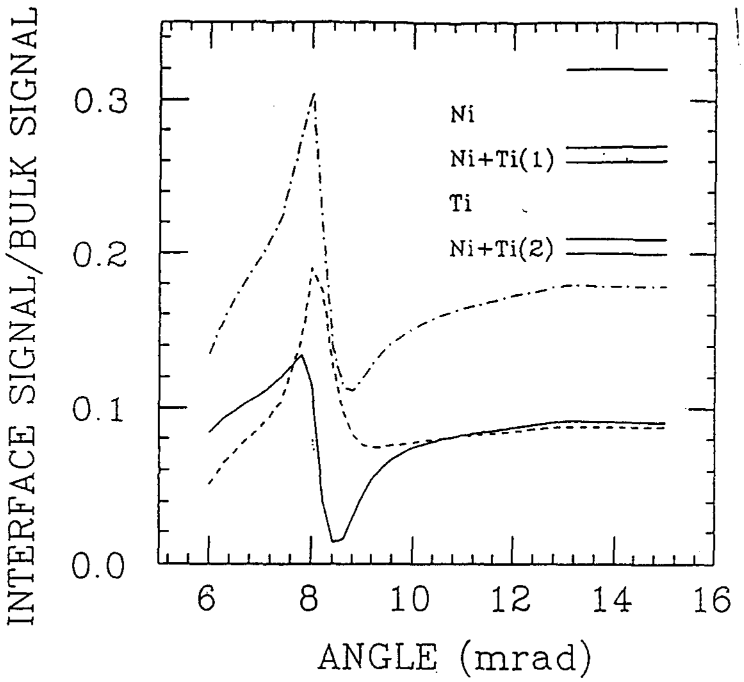


Figure 3: The ratio of the interface signal to the bulk Ni signal for the multilayer shown in the inset. Compared are the signals for interface (1) (solid line), interface (2) (dashed line), and the total interface signal (dot-dashed line)

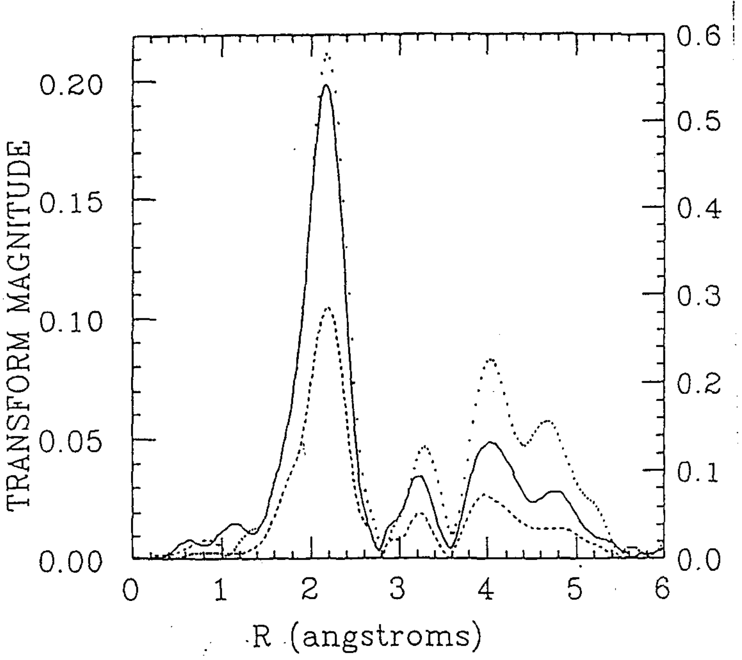
intermixing between the Ni and Ti. Further analysis indicates that Ni-Ni bond length in the multilayer is the same as for the bulk metal to 0.01Å, and the EXAFS Debye-Waller factor is increased over the metal by $\simeq$0.0015 Å^2.

The situation for the Ti K-edge is quite different as shown in Fig. 5. Again amplitude variations indicative of standing wave affects are present, although the increased absorption near the Ti edge reduces their amplitude. The most striking feature is the presence of a low-R peak not seen in the pure standard. Detailed analysis indicates that this peak is due to low-Z neighbors such as C or O located at distance of 2.15±0.05Å. Subsequent Auger analysis identified these to be due to C and O in about a 2:1 ratio. The reactivity of Ti is well known, and the contaminates were undoubtedly picked during the deposition process. The observed distance is in good agreement with the first neighbor distance in TiO at 2.09Å and TiC at 2.16Å. TiO_2 with a Ti-O distance of 1.92Å seems to be ruled out. In addition by carrying out calculations similar to those shown in Fig. 3, it was determined that the low-Z impurity is distributed relatively uniformly throughout the Ti layers.

To further investigate the presence of the standing wave fields, the amplitude of the Ni EXAFS was determined at a variety of angles. The results are shown in Fig. 6, and compared to two calculations using equation 3. The solid line assumes 17Å rms roughness and ideal Ni and Ti layers. The dashed line includes the fact the density of the Ti layer is reduced by the presence of low-Z impurities. The results clearly verify the presence of standing wave fields in about the expected amplitude. The only discrepancy is small and systematic reduction in the overall amplitude. This could be caused by a small amount of intermixing (1-2 monolayers) at the interfaces. Model calculations indicate that since the Ni and Ti backscattering functions are similar, such a small amount of mixing would not result in an observable Ni-Ti bond, but would manifest itself mainly in a reduction of Ni-Ni signal. Note, however, that mixing on the 17Å level as indicated by the interface roughness would be clearly observable, and would cause serious disagreement between the Ni-Ni EXAFS amplitude and the calculations. Thus, we conclude that the reflectivity reduction is due to a rough interface with only small amount of intermixing.

CONCLUSIONS

This paper has reviewed the application of EXAFS techniques to multilayer systems. EXAFS



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is seen to be valuable complement to other techniques, and is particularly suited for studying interfacial mixing or reactions between layers. It can also determine the role of impurities in modifying the layer structure as the results on the Ti edge demonstrated. The paper also introduced the standing wave enhancement of EXAFS measurements on multilayers, and has shown that they can be applied to multilayers with substantial interface roughness. This technique can substantially enhance the sensitivity to interface regions, and offers the possibility of probing structure within the multilayer unit cell. The present case of Ni-Ti is far from optimum, since x-ray optical systems such as W-C have much stronger standing wave fields, and W and C backscattering are much easier to distinguish.

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References

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[3] T. Claeson, J. B. Boyce, W. P. Lowe, and T. H. Geballe, Phys. Rev. **B29**, 4969 (1984).

[4] G. M. Lamble, S. M. Heald in *Multilayers, Synthesis, Properties, and Non-electronic Applications*, edited by T. W. Barbee, F. Spaepen, and L. Greer (Mat. Res. Soc. Proc. **103**, Pittsburgh, PA 1988) pp. 101-07.

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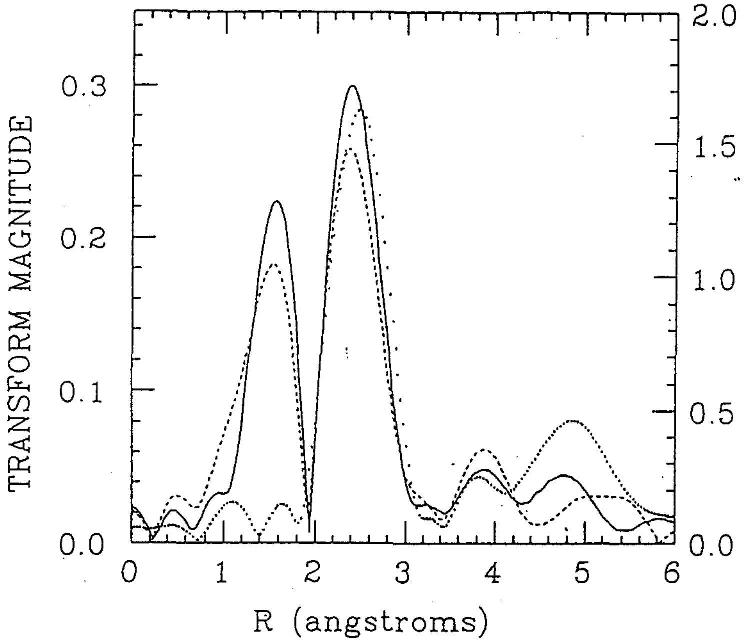

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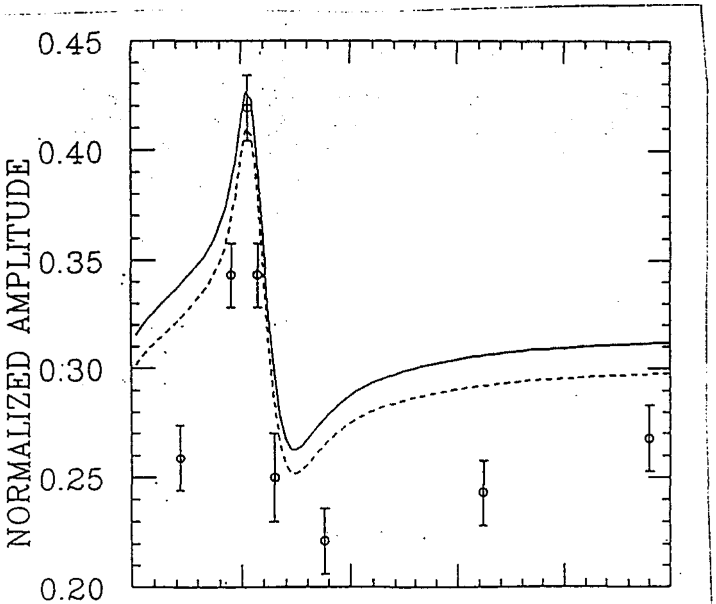

Figure 6: Reduction of the EXAFS amplitude for the Ni first shell in the multilayer as compared to Ni foil. The points ar the data and the curves are calculated reduction factors for a 120Å period multilayer with equal thickness Ni and Ti layers, and 17Å rms roughness. The solid line assumes that the Ni and Ti densities are the normal metal values, while the dashed curve is for a Ti density of 90% of the metal.

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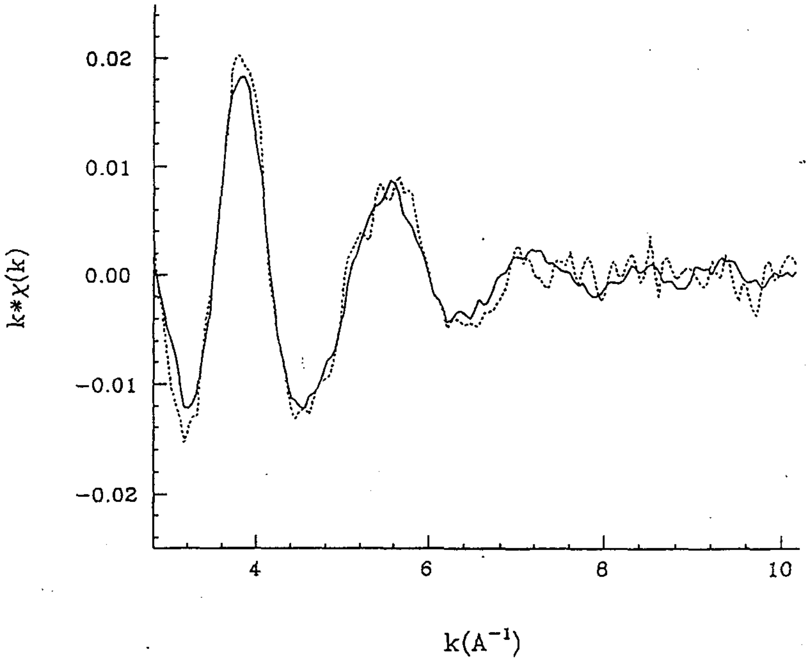

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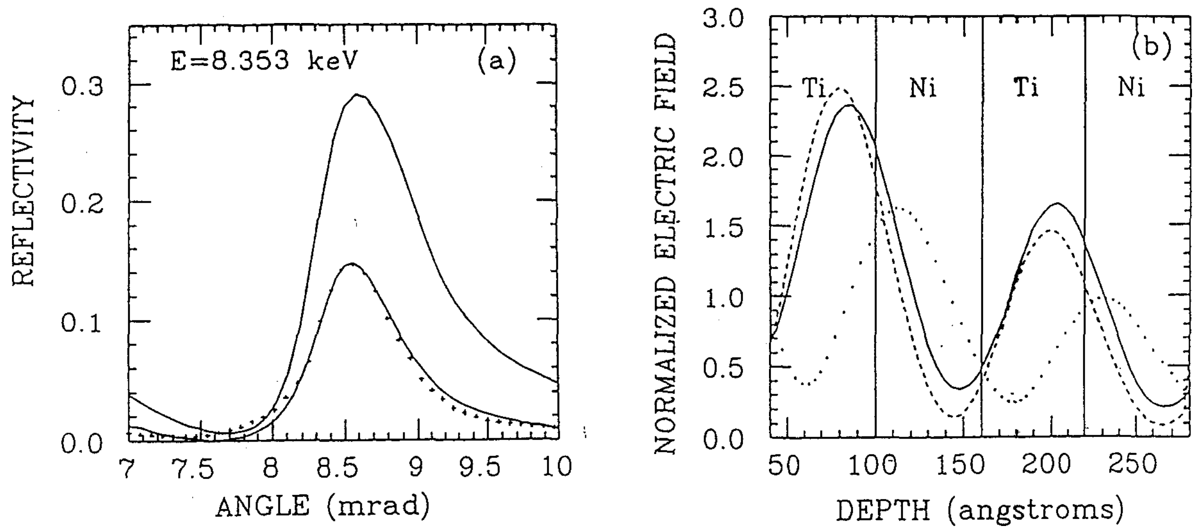

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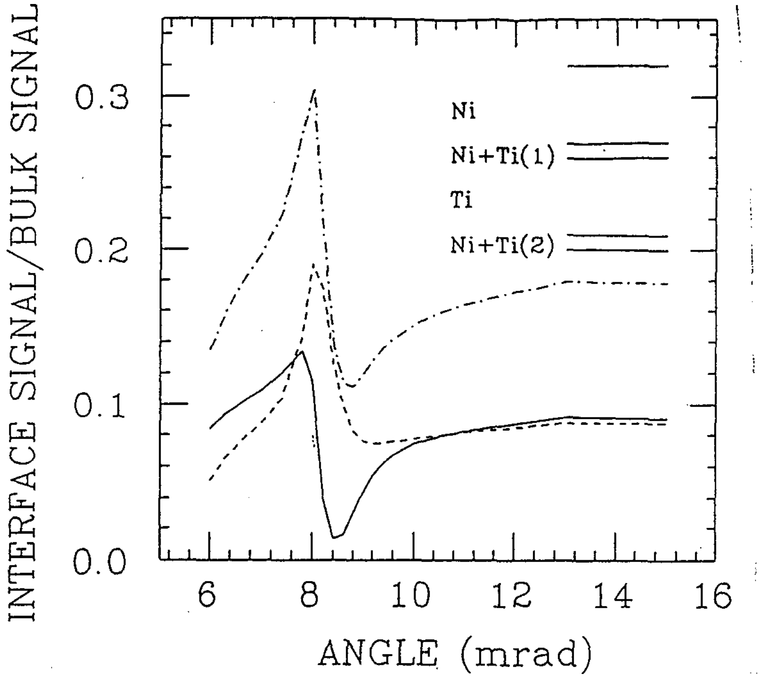

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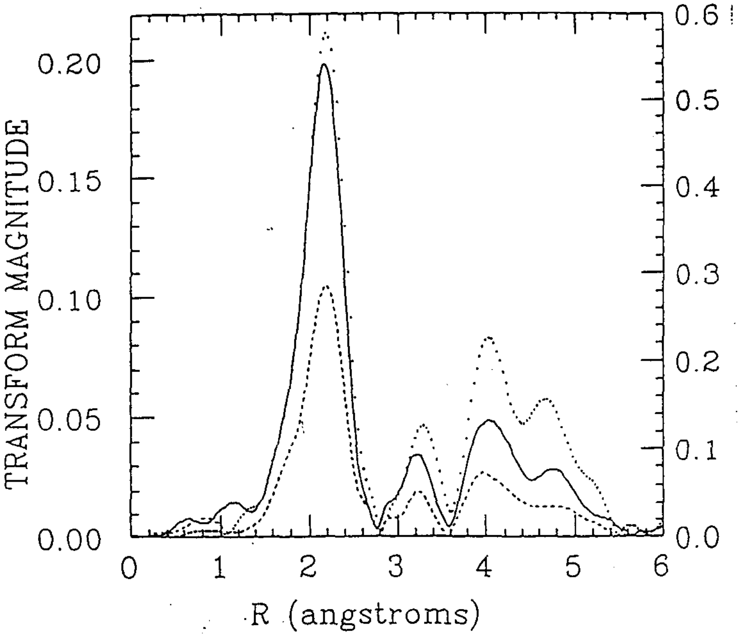

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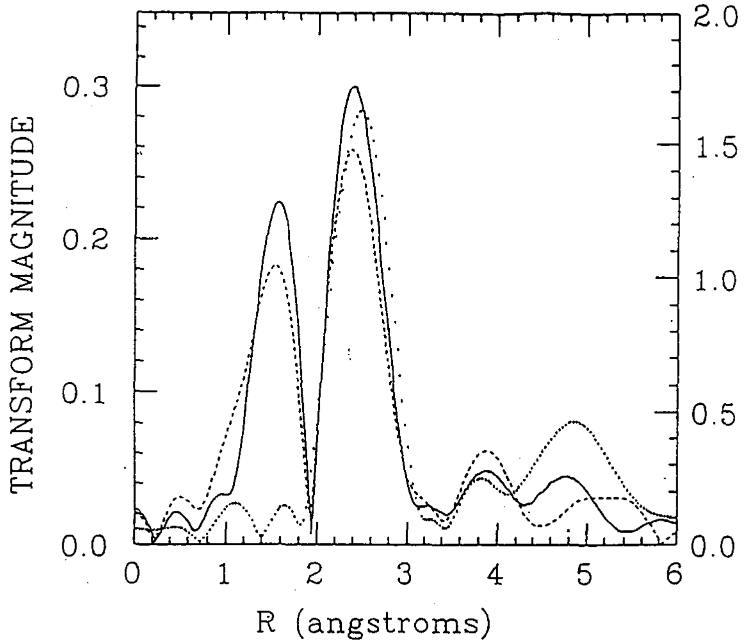

Figure 5: Fourier transform of the Ti EXAFS for a Ni-Ti multilayer at 14.6 mrad (solid line) and 15.0 mrad (dashed line) compared to dat obtained on a pure Ti foil (points). The scale for the multilayer is on the left, and for the foil on the right.

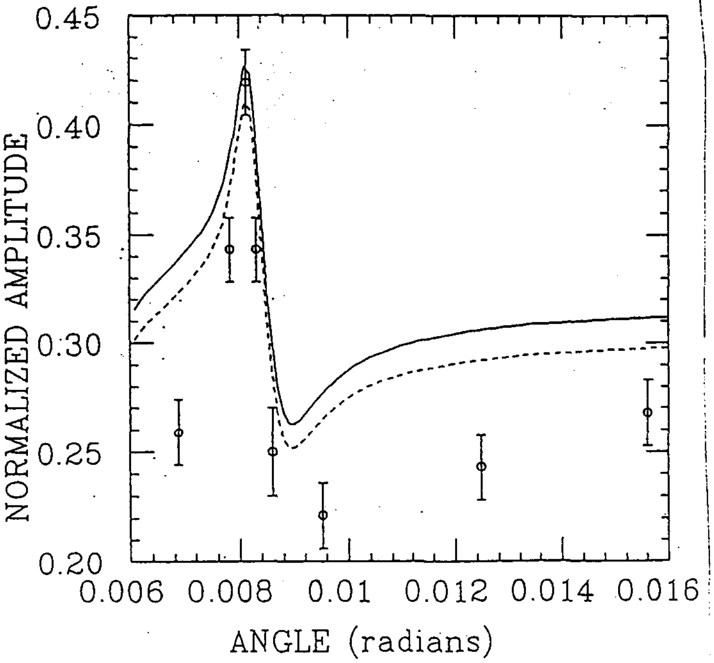

Figure 6: Reduction of the EXAFS amplitude for the Ni first shell in the multilayer as compared to Ni foil. The points ar the data and the curves are calculated reduction factors for a 120Å period multilayer with equal thickness Ni and Ti layers, and 17Å rms roughness. The solid line assumes that the Ni and Ti densities are the normal metal values, while the dashed curve is for a Ti density of 90% of the metal.