Phonon Density of States in Tb/Fe Multilayers

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Introduction

Nuclear resonance inelastic x-ray scattering (NRIXS) of synchrotron radiation at the 14.4125 keV nuclear resonance of ^{57}Fe is an efficient and unique method for the direct measurement of the Fe-projected vibrational density of states (VDOS) of thin films that contain this Mössbauer isotope. In this contribution we will demonstrate that the VDOS is a sensitive probe of the crystallographic structure in nanoscale multilayers (MLs). Our samples are UHV-deposited Tb/Fe MLs with different layer thicknesses (t_{Tb} = 14-50 Å, t_{Fe} = 10-50 Å). Tb/Fe MLs may exhibit perpendicular magnetic anisotropy and are known to undergo an amorphous-to-crystalline structural transition upon increasing layer thickness.[1]

Methods and Materials

The following types of Tb/Fe MLs (labeled A-F, respectively) were prepared in UHV by thermal evaporation on Si(111) substrates held at 300K:

A: [Tb(50 Å)/Fe(10 Å)]*20, B: [Tb(50 Å)/Fe(20 Å)]*10,
C: [Tb(50 Å)/Fe(35 Å)]*8, D: [Tb(50 Å)/Fe(50 Å)]*8,
E: [Tb(14 Å)/Fe(20 Å)]*10, F: [Tb(14 Å)/Fe(35 Å)]*10.

The pressure during growth was < 1 x 10^{-9} mbar. All Fe layers were enriched with 20% ^{57}Fe. X-ray diffraction and Mössbauer spectroscopy (CEMS) confirm that crystallographic structure of the Fe depends of the Fe layer thickness.[1]

The inelastic nuclear resonant absorption experiments were performed at the undulator beamline 3-ID of SRI-CAT at the Advanced Photon Source. Details of the technique are described in refs. 2-5. The synchrotron radiation had an energy bandwidth of 2.3 meV after monochromatization.

Results and Discussion

Distinct differences in the VDOS have been observed by varying t_{Tb} and t_{Fe} (Fig. 1). For larger t_{Fe} values (samples C, D and F), the VDOS exhibit the typical phonon peaks between 23 to 28 meV (transverse phonons) and 36 meV (longitudinal phonons) of bcc-Fe, and the derived Debye-Waller (f-) factor is close to its bulk value. For the thinnest Fe layers (samples A, B and E), the VDOS extends up to ~ 40 meV and shows a maximum at ~ 20 meV, and the broad and structureless feature is similar to that observed in amorphous (a-)$Tb_{1-x}Fe_x$ alloy films, yielding a smaller f-factor.[5,6] With increasing Fe layer thickness, the VDOS provide evidence for the typical amorphous-to-crystalline transition of Fe near $t_{Fe} \approx 25$ Å. The VDOS does not depend on the Tb layer thickness in this thickness regime (compare samples B and E, and F and C, respectively).

Summarizing, we have demonstrated that NRIXS is a useful method for the measurement of the structural state in multilayer samples. Vibrational dynamics opens a new domain in thin-film research.

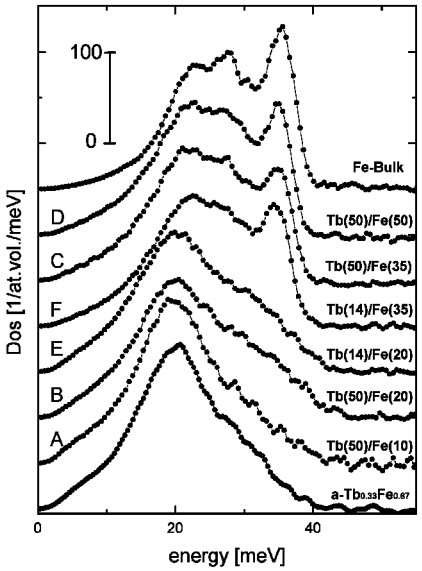

FIG. 1: Fe-projected vibrational density of states (VDOS) of the Tb/Fe samples (labeled A – F). The phonon DOS obtained from a bulk-Fe sample (top)[3] and a 175-Å-thick a-$Tb_{33}Fe_{67}$ alloy film (bottom)[6] are shown for comparison. (For clarity the different curves are offset along the vertical axis.)

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