ESRF	**Experiment title:** Surface enhanced magnetic ordering of the europium surface by in-situ ^{151}Eu nuclear resonant scattering	**Experiment number**: SI-2546
Beamline: ID18	**Date of experiment**: from: 4/11/12 to: 4/12/12	**Date of report**: 29/08/13
Shifts: 15	Local contact(s): Rudolf Rüffer	*Received at ESRF:* *30/08/13*

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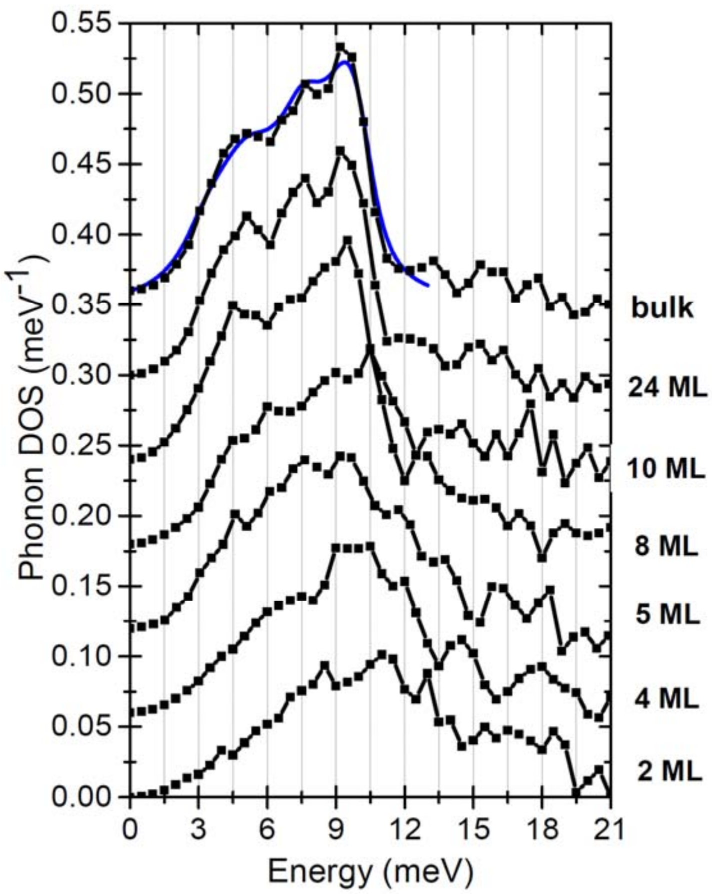
Report:



The aim of this experiment was to investigate the intriguing surface enhanced magnetic ordering effect at the surface of epitaxial Europium films by nuclear forward scattering of synchrotron radiation on ^{151}Eu *in-situ* (i.e. under ultrahigh vacuum). However, because of unforeseeable technical problems (most likely due to a bad thermal contact) the Néel temperature of bulk Eu (91K) could not be reached. This did not allowed us to fulfil the original proposal. Therefore, in this beamtime we investigated the thickness evolution of the density of states (DOS) of fcc Eu islands.

In a recent experiment [1] we have investigated the phonon DOS of thin Eu films. The measured spectra revealed a significant phonon hardening, which needed more systematic investigation.

Fig. 1. *The phonon density of states of fcc Eu islands with the indicated nominal coverage in monolayers (ML). 1 ML = 0.33 nm. The experimental and ab initio calculated DOS of bulk bcc Eu is also shown*

The experiment was performed at ID18 of

the ESRF using the ultrahigh vacuum facility [2] installed in the second experimental hutch. We point out that this is the only place worldwide where thin films and nanostructures can be grown, characterized, and investigated by *in-situ* nuclear resonant scattering methods. We used the 16-bunch filling mode of the ESRF storage ring operation. The final energy bandwidth of 1.0 meV (at the resonance energy of 21.5 keV) was obtained using a dedicated high-resolution monochromator. The vertical beam size was reduced down to 20 μm using Kirkpatrick-Baez focussing mirror.

Europium islands with nominal thicknesses of 2ML, 4ML, 5ML, 8ML, 10ML and 24ML were grown epitaxialy on Nb buffered Al_2O_3 following an elaborated procedure [3]. The fcc structure was proven by the reflection high energy electron diffraction (RHEED) measured after the samples growth and before the nuclear inelastic scattering experiment. Due to the significant multiphonon contribution to the measured signal at room temperature [1], the samples were measured at 100 K.

Figure 1 shows the phonon DOS of the fcc Eu islands. The figure reveals, in agreement with our earlier results, that by reducing the size of the Eu islands a significant hardening of the phonon spectra is observed. Namely, a shift of the phonon DOS to high energies, suppression of the phonon modes and low energy and high-energy phonon peak appears. Most likely this is a result of the significant compression of the Eu lattice, i.e. by 9% in comparison to the native for Eu bcc unit cell. In addition, the surface atoms contribute to the observed shape of the phonon DOS. In order to disentangle the contribution from the compressed lattice, the fcc structure, and the surface effects, a first principle phonon calculations in the filling-slab approach are in progress.

In addition, during this beamtime we have measured the Eu-projected phonon DOS in 20 nm thick film $EuSi_2$ and in $EuEi_2$ nanoislands. The interest to investigate rare earth silicides (RESi) stems from the fact that they form self-organized nanostructures with very low Schottky barrier height, which makes them highly attractive for applications in the near-future nanoelectronics.

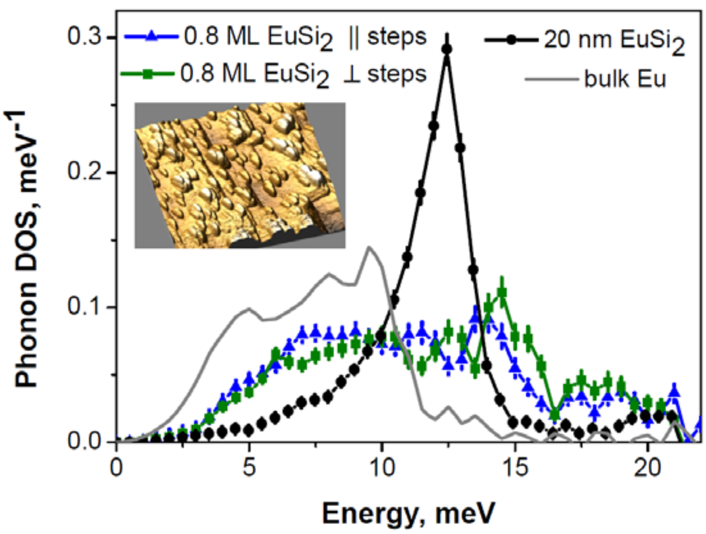


Fig. 2. *The partial Eu-projected phonon DOS in 20 nm thick $EuSi_2$ film (bulk), 0.8 ML islands, measured parallel and perpendicular to the atomic steps of the vicinal Si(001). The inset shows the AFM image of the 0.8 ML islands. The phonon DOS of metallic bcc Eu is also shown.*

Figure 2 summarizes the phonon DOS of the bulk-like $EuSi_2$ and of 0.8ML (monolayer) $EuSi_2$ islands grown on a vicinal Si(001) substrate. The DOS was measured with the X-ray beam being parallel (blue triangles) and perpendicular (green squares) to the steps of the Si substrate. For comparison the phonon DOS of bcc Eu is shown with solid grey line. The inset in Fig. 2 depicts an AFM image of the $EuSi_2$ nanoislands. The experimental data reveal a significant difference of the lattice dynamics between the nano-islands and the 20 nm thick bulk sample. An enhancement of the phonon DOS at low energies as well as at high energies has been detected in the DOS of the nanoislands, revealing the presence of size effects. While the soft phonon modes arise from the atomic vibrations of surface atoms, the high energy phonon states can be attributed to the vibrations of Eu atoms located at the Eu-Si interface and/or at the grain boundaries between adjacent nano-islands. The *ab initio* calculations for the $EuSi_2$ bulk and nano-island surface morphology will shed more light on the observed changes.

These results demonstrate the importance of the systematic lattice dynamics investigations in ultrathin films and nanostructures with various shapes, such as islands, clusters, and wires.

References:

[1] S. Stankov et al., Experimental Report SI-3174

[2] S. Stankov et al., Rev. Scientific Instr. **79**, 045108 (2008).

[3] T. Gourieux et al., Phys. Rev. B **62**, 7502 (2000).