Epitaxial c-axis oriented LuNi$_2$B$_2$C thin films on MgO(110)

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Abstract. Epitaxial thin films of LuNi$_2$B$_2$C have been fabricated on MgO(110) substrates using pulsed laser deposition. XRD measurements show almost perfect c-axis texture, a sharply textured Lu$_2$O$_3$ interface and a small amount of a secondary phase, which is assumed to contain Ni and B. The films show good homogeneity, very high in-plane and out-of-plane order and high residual resistivity ratios up to 15 at film thicknesses of 200 – 250 nm. The quality of these films compared to single crystals was tested using a sample in the as-grown state for $H_{c2}(T)$ measurements. Upper critical field values in the <001> crystallographic direction are higher than in single crystals and show a less pronounced S-shape of the $H_{c2}(T)$ behaviour for $H \parallel <001>$.

Keywords: Borocarbides, thin films, PLD, superconductivity

1. Introduction
Since the class of superconducting borocarbides was discovered in 1994, a comprehensive variety of results has completed the picture of the unusual superconductive properties concerning two-band behaviour, magnetic interplay or anisotropy [1, 2]. For $RNi_2B_2C$ ($R$ being a rare earth), single crystals of very high quality became recently available for many borocarbide compounds and alloys, respectively [3]. Most of the results were gained using either polycrystalline or single crystalline bulk samples but also, a significant number of investigations on the superconducting or magnetic properties have been performed on thin films in the past [4-15]. Thin film growth of this system is challenged by high growth temperatures, the lack of metallic buffers for layered growth and the sensitivity of textured growth on the deposition conditions. Therefore, such films are preferentially grown on thermally highly stable oxides such as MgO or sapphire substrates, as the formation of a $R_2O_3$ oxide at the substrate interface can lead to a suitable buffer for textured $RNi_2B_2C$ growth. In this work, growth conditions were optimized for LuNi$_2$B$_2$C to high in-plane order while preserving adequate superconducting properties.

2. Experimental
Epitaxial LuNi$_2$B$_2$C thin films were deposited on one-side polished MgO(110), 10 mm x 10 mm x 1 mm sized substrates (from Crystec company) from a stoichiometric target using a Lambda Physics LPX 305 KrF laser. The films were deposited at a pressure lower than $5 \times 10^{-9}$ mbar. The optimized conditions are as follows: The laser spot size was around 1.5 x 4 mm$^2$ and the laser energy per pulse was about 250 mJ. The laser repetition rate was chosen to 5 Hz resulting in a growth rate of 0.05 – 0.15 nm as estimated with an Inficon rate monitor. During the deposition, the substrate holder was axially oscillating to improve lateral homogeneity. The temperatures were measured from outside directly after the deposition of the film using an Infrarwin infrared pyrometer. The film thickness was aimed at approximately 250 nm and estimated by measuring the step height of a sample edge using atomic force microscopy. The phase and the texture of the films were analyzed with a Philips X’Pert x-ray systems using a Co $K_{\alpha}$ tube for $\theta$-2$\theta$-scans or a Cu $K_{\alpha}$ (Euler cradle) tube. Magnetic field measurements were performed in a Quantum Design PPMS equipped with a 9 T magnet.
3. Phase Formation and Texture

Figure 1 shows an XRD pattern of a LuNi$_2$B$_2$C thin film deposited at 810 °C under optimized conditions as described above. Besides the MgO(220) substrate peak at 2\(\Theta\) = 73.87°, three groups of peaks corresponding to three phases can be distinguished. Firstly, the pronounced c-axis peaks of the LuNi$_2$B$_2$C phase prove almost perfect c-axis textured growth except for a small peak which might be identified as LuNi$_2$B$_2$C(116). Secondly, the sharp Lu$_2$O$_3$(440) peak emerges from an oxide interface layer grown in the <110> direction, forming \textit{in situ} during LuNi$_2$B$_2$C deposition by reaction of Lutetium with oxygen from the substrate [11]. Thirdly, a small amount of a secondary phase is also visible with peaks at 2\(\Theta\) \approx 30°, 2\(\Theta\) \approx 50° and 2\(\Theta\) \approx 62° which is assumed to be a Ni and B containing phase.

The in-plane and the out-of-plane order determined by a series of phi- and psi-scans at 2\(\Theta_{Cu}\) = 40.55° is shown in Figure 2. In the selected film, the in-plane FWHM is < 1.3° only, whereas the out-of-plane FWHM is \approx 2°. The low background proves the absence of almost any misoriented grains.

Figure 1: XRD pattern (Co K\(_\alpha\)) of c-axis textured LuNi$_2$B$_2$C on MgO(110)

Figure 2: (112) pole figure of the LuNi$_2$B$_2$C thin film, measured at 2\(\Theta\) = 40.55° (Cu K\(_\alpha\), square root scaling)
4. Superconducting properties

In the as-grown state, the critical temperature of the samples was resistively determined to around 15.8 K, which is only slightly lower than the highest reported bulk values of around 16.4 K. The superconducting transition measured resistively is only 0.2 K wide in the zero-field state (figure 3(a)) and indicates an adequate chemical homogeneity of the film. Figure 3(b) shows a set of R(T) curves for zero field as well as different magnetic fields up to the maximum of 9 T, measured in 1 T steps on a second film. The dotted line roughly marks the middle of the transition, where the exact temperature values were taken to determine the upper critical field.

![Graph of R(T) curves](image)

**Figure 3:** R(T) curves of two different as-prepared LuNi$_2$B$_2$C layers

A measurement of the upper critical field in <001> direction, taken at 50% of the residual resistance value, is shown in figure 4. The S-shape of the curve, expected for a non magnetic borocarbide and well understood within the two-band theory [17], is weakly visible for the thin film. It is known that single crystals show considerably stronger S-shape and a lower critical field towards zero temperature [2, 16, 17]. This indicates that the superconducting state in the samples is not precisely as clean as in single crystals.
5. Summary
At optimized deposition conditions, superconducting LuNi$_2$B$_2$C thin films were synthesized with adequate quality with respect to phase formation, texture, critical temperature transition and residual resistivity ratio. Due to high in-plane order and reliable superconductive properties, the samples may serve for further investigations on the borocarbide system.

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7. References
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