Heterostructures and superlattices of transition metal oxides are potential candidates for a new generation of electronic devices because exciting phenomena can occur at their interfaces which are absent in the bulk components. In addition, epitaxial strain, the layer thickness and external fields allow tuning their properties [1]. However, besides these intrinsic parameters, the microstructure of the entire films can also affect the properties, e.g. in form of dislocations or planar faults [2,3].

Here we report about the characterization of LaNiO$_3$/LaAlO$_3$ superlattices (LNO/LAO SLs) with two or four unit cell thick single-layers, which were grown on (La,Sr)AlO$_4$ (LSAO) substrate by pulsed laser deposition. Transmission electron microscopy in combination with electron energy-loss spectroscopy (EELS) is used to study the defect structure on the atomic scale for different layer thicknesses.

The films contain extended planar faults whose origin are surface steps of the LSAO substrate resulting in a relative vertical lattice translation on the two sides of the surface step as envisaged in Figure 1a by the overlaid LNO unit cells. In addition, the elemental EELS map (Figure 1b) shows that one NiO plane is missing along the planar fault (see black arrow). Such a structure is known from Ruddlesden–Popper phases (RP phases) which is why these defects are called RP faults and can be classified as a two dimensional (2D) defect [4].

Beside these extended planar RP faults, rectangular blocks exist in the films as can be seen in the high-angle annular dark field image in Figure 2a. The intensity of the atom columns is very similar within the blocks indicating that the average atomic number is similar because the atom columns are mixed, as shown in Figure 2b. For example, the atom column marked by an arrow consists of Al and La atoms. The source of these cuboid-shaped blocks is a strongly localized stacking fault (see blue arrow in Figure 2b) which propagates in growth direction through the film. The zigzag arrangement of La atoms along the borders of the block is characteristic of RP faults showing that the blocks are terminated by RP faults on all faces. Therefore we call this defect type in the following 3D RP fault. In contrast to the planar RP faults which are induced by the surface steps of the substrate, no correlation with the substrate could be found for the 3D RP faults which therefore rather seem to be the result of small irregularities, i.e. the formation of stacking faults, during the growth process.

The phase behavior of LNO/LAO SLs differs in dependence of the thickness of the individual layers because of the confinement of the conduction electrons in the thinner single layers [5]. However, both defect structures are found irrespective of the single-layer thickness of the SL. Hence, the microstructure cannot be the decisive factor for the property change of SLs with different single-layer thickness.

In conclusion, we have found two different types of RP faults in LNO/LAO SLs: extended 2D defects which are induced by surface steps of the LSAO substrate and nanometer-sized 3D defects whose origin are local stacking faults. However, it turned out that thickness-dependent differences in the phase behaviour of LNO/LAO SLs are not caused by the defect structure but they are an inherent phenomenon of the SLs.
References


Figure 1. a) A high-angle annular dark field image of a planar Ruddlesden-Popper fault (marked by the upper arrow) starting at a surface step of the LSAO substrate. The LNO lattice is overlaid (La is blue, Ni yellow and O grey) to illustrate the shift of the two sides against each other. b) Elemental EELS map showing a Ruddlesden–Popper fault (La is blue, Ni yellow, and Al red).

Figure 2. a) A high-angle annular dark field image showing a single block which consists of columns with similar brightness. b) Cross-section of the TEM sample (the electron propagation direction is from left to right) in the direction of the yellow arrow in a). La atoms are blue, Ni yellow, Al red, and O is neglected. The arrow points to the stacking fault which induces the growth of the 3D Ruddlesden–Popper fault.