Our interest in the physical properties of nanostructures is fueled by the insight that novel phenomena emerge when materials are composed in an atomically controlled way to form nanostructures with spatial extensions in the nanometer (nm) range. These structures contain hundreds to thousands of atoms, and their physical and chemical properties deviate sharply from that of larger sized samples.

One reason for the peculiar properties is that in nanostructures electrons are confined along all spatial directions, and unique quantum phenomena may arise, which are absent in larger structures.

Here we present a result on nanomagnetism where we show how quantum phenomena influence the electronic and magnetic properties of a nm small Co island [1].

One of the quantum phenomena which we exploit is the particle-wave dualism of the electron. The electron is not only characterized by its charge and spin, but also by its wavelength. The wave properties are revealed in our experiments where electrons are confined within a nanostructure. We observe spatial modulations of electronic properties on a length scale which is related to the electron wavelength.

We apply scanning tunneling microscopy (STM) at a low temperature of 7 K to image individual nm small Co islands which were prepared by room temperature Co deposition on a Cu(111) surface. Figure 1 shows an overview STM image of several Co islands on the Cu substrate. Linescans through the islands reveal a height of 0.4 nm, which indicates that the islands are only two atomic layers thin. Their base length varies between a few up to ten nm.

To explore the electronic and magnetic properties of an individual Co island, we perform spin-polarized scanning tunneling spectroscopy in magnetic fields [2]. We use a Co/Cr covered W-tip with a magnetization direction along the tip axis [3]. This tip gives us access to the magnetic properties of the nanostructure. Tunnel current and differential conductance $dI/dV$ depend on the relative orientation of the tip and sample magnetization direction.

The magnetism of our system is largely given by the electron spin. Electrons with opposite spin orientation are called majority and minority electrons, depending on their spin orientation with respect to the magnetization direction of the sample. Thus, measurements of the differential conductance for different magnetization states of the nanostructure give access to its spin-dependent electronic density of states. This establishes a link to theory, which we follow below.

We apply a magnetic field of $-4$ T perpendicular to the surface of the Co island to switch the Co magnetization direction from pointing upwards to downwards [4], while a smaller magnetic field of $-1.1$ T is applied to ensure a fixed magnetization direction of the tip. Thus, we obtain maps of the differential conductance $dI/dV$ for an anti-parallel and a parallel align-
Selected Results

ment of sample and tip magnetization directions, as shown in Fig. 2 A and B, respectively, for measurements close to the Fermi energy. Both maps A and B reveal a pronounced spatial modulation of the differential conductance above the Co island. The spatial modulation is ascribed to electron confinement within the Co nanostructure. The modulation pattern can be understood as an electron interference pattern, resulting from electron scattering at the boundary of the Co island.

However, the most striking result of this study is, that the patterns of Fig. 2 A and B differ. To quantify this difference we compute from images A and B in image C the asymmetry map as $\text{map}_C = (\text{map}_A - \text{map}_B)/(\text{map}_A + \text{map}_B)$. This asymmetry map of Fig. 2 C reflects the spin-polarization of the Co island [1]. The asymmetry map reveals a spatially modulated positive signal above the inner part of the island, whereas the island rim shows a negative asymmetry signal. Thus, our study reveals that the spin-polarization of a Co nanostructure is spatially modulated on a sub-nm scale.

We performed state-of-the-art calculations of the spin-resolved electronic local density of states above the Co island [5] to identify the electronic origin of the experimental results presented in Fig. 2. The calculations reveal that the spatial modulation presented in Fig. 2 A and B is mainly due to majority electrons, whereas the minority electrons contribute a nonmodulated signal. The opposite spin-polarization of the rim is ascribed to the special electronic structure near the rim, which deviates from the inner part of the island. This is caused by structural relaxation and electron spill-out near the island rim.

We conclude that electron confinement within the Co nanostructure is a spin-dependent phenomenon which affects mainly majority electrons. This interpretation of the results is further corroborated by energy-dependent measurements. We find a conclusive explanation for the observed energy dependence of the modulation of the $dI/dV$ signal by considering the relative magnitudes of the modulated majority and the nonmodulated minority density of states [1].

Our combined experimental and theoretical study identifies a new venue to tune spin-polarization in nanostructures by exploiting spin-dependent electron confinement [5].

References