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Phase transitions and anisotropies in ultra thin magnetic films

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Phase Transitions and Anisotropies in Ultra Thin Magnetic Films

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Abstract

In this thesis different aspects of ultra thin epitaxial layers have been studied. The magnetic information is obtained using three different methods: the magneto-optic Kerr effect, spin polarised low energy electron diffraction, and a scanning electron microscope with polarisation analysis.

The weakly uniaxial ferromagnet Fe/W(110) has been investigated in the monolayer thickness regime in view of its behaviour at the phase transition point. This two dimensional magnet exhibits static susceptibilities which are enhanced by four orders of magnitude with respect to bulk samples.

By measuring three critical exponents $\beta = 0.13 \pm 0.02$, $\gamma = 1.5 \pm 0.8$, and $\delta = 14 \pm 5$ independently, the system Fe/W(110) could be established into the two dimensional Ising class. For this symmetry class the equation of state $M(T,H)$ can be computed theoretically. The measured equation of state follows the predicted theoretical curve: The data obtained for the ultra thin epitaxial magnet can be understood as an unambiguous test of the scaling hypothesis in two dimensions. This is the first experimental verification of this model calculation.

Epitaxial films of fcc Fe have been grown on top of a Co(100) substrate covered with a Cu spacer. These films show only a small thickness interval where their Curie temperature lies above room temperature. A reorientation of the magnetisation direction from out-of-plane to in-plane is observed with decreasing Cu spacer thickness. In the region of paramagnetic Fe and at fixed Cu spacer thickness the induced magnetisation of the top layers of the Fe overlayer changes direction with increasing Fe layer thickness. This can be understood as the paramagnetic Fe following the oscillatory exchange field emanating from the Co layer.

For Co films grown on top of stepped Cu(100) substrates unusual effects are observed upon adsorption of different materials. Upon coverage with submonolayers of the different adsorbates Cu, Fe, Ag, and O the magnetisation direction of rather thick films changes from being parallel to being perpendicular to the preferential step direction. The magnetic properties of the Co films seem to be particularly sensitive to Cu overlayers: by increasing the Cu overlayer thickness further switching of the magnetisation direction can be observed.

Zusammenfassung

In dieser Arbeit werden verschiedene Eigenschaften von ultra dünnen epitaktischen Schichten beleuchtet. Die magnetischen Informationen werden durch die Verwendung von drei verschiedenen Methoden erreicht: mit dem magnetooptischen Kerr Effekt, mit spinpolarisierter niederenergetischer Elektronenbeugung und mit einem Rasterelektronenmikroskop mit Polarisationsanalyse.

Der schwach uniaxiale Ferromagnet Fe/W(110) wurde im Dickenbereich der Monolage auf sein Verhalten am ferromagnetischen Phasenübergang untersucht. Dieser zweidimensionale Magnet zeichnet sich am Phasenübergang durch eine statische Suszeptibilität aus, die gegenüber dem ferromagnetischen Festkörper um vier Grössenordnungen erhöht ist.

Das System Fe/W(110) konnte durch die unabhängige Messung von drei kritischen Exponenten $\beta = 0.13 \pm 0.02$, $\gamma = 1.5 \pm 0.8$, und $\delta = 14 \pm 5$ der Symmetrieklasse des zweidimensionalen Ising Modells zugeordnet werden. Für diese wichtige Symmetrieklasse kann die Zustandsgleichung $M(T,H)$ theoretisch berechnet werden, wenn die Gültigkeit der Skalenhypothese vorausgesetzt wird. Aus diesem Grunde dienen unsere Daten, die der theoretischen Kurve folgen als Test der Skalenhypothese in zwei Dimensionen.

Epitaktische Filme von fcc Fe wurden auf ein Co(100) Substrat gewachsen, das mit einer Cu-Schicht bedeckt war. Diese Filme besitzen nur einen schmalen Dickenbereich, in dem die Curie Temperatur oberhalb Raumtemperatur liegt. Eine Reorientierung der Magnetisierungsrichtung von senkrecht zur Filmebene in die Filmebene mit abnehmender Cu Schichtdicke wurde beobachtet. In der Dickenregion des paramagnetischen Fe wechselt die durch den Co Film induzierte Magnetisierung ihre Richtung mit wachsender Fe Dicke. Die Magnetisierungsrichtung oszilliert im Austauschfeld des Co Films.

Bei Co Filmen, die auf leicht verschnittene Cu(100) Substrate aufgebracht wurden konnte nach Adsorption der Materialien Cu, Fe, Ag, und O ungewöhnliches Verhalten festgestellt werden. Durch Adsorption von Submonolagen dieser Materialien wechselt die Magnetisierungsrichtung von parallel zu senkrecht zu der vom Substrat vorgegebenen Stufenrichtung. Die Co Filme reagieren besonders empfindlich auf das Adsorbat Cu: Bei grösseren Bedeckungen wurde ein weiterer Magnetisierungsrichtungswechsel beobachtet.

Summary

In the past 25 years exciting new effects have been discovered in the field of ferromagnetism in reduced dimensions [2.1-2.3]. But only the novel magnetic characterisation techniques of the past few years in combination with advanced techniques in metal epitaxy and thin film engineering has rendered the field of ultra thin film magnetism - with film thicknesses in the monolayer range - accessible to the scientist. Consequently new major discoveries, such as the discovery of exchange coupling oscillations [2.4], giant magneto resistance [2.5] have enriched this vast field.

In this thesis I address some of the current topics in ultra thin film magnetism. Three different techniques are employed to obtain magnetic information. Spin polarised low energy electron diffraction, a highly surface sensitive method, spin polarised scanning electron microscopy, which combines a surface sensitive tool with high spatial resolution, and the magneto-optic Kerr effect, which allows to work in externally applied magnetic fields.

The development of the theory of critical point behavior can roughly be divided in three periods. Beginning with Van der Waal's approach to the liquid-gas transition [2.6] the *mean field theory* was extended to numerous other phase transitions [2.7]. For some systems, such as superconductivity it was highly successful. However, with the increasing experimental accuracy and the progress in numerical calculations its incorrectness in the neighborhood of the critical point became more and more evident.

Around 1965 phenomenological approaches took these deviations into account resulting in the concept known as *scaling invariance* [2.8-2.11]. In the same period the idea of *universality* was introduced, which states, that apparently dissimilar systems may obey the same laws at the critical point [2.12, 2.13].

The next step in the theory of phase transitions were the calculations of K. Wilson and co-workers [2.14, 2.15]. They combined the concepts of scaling and universality and performed real calculations of critical point behavior. Wilson's *renormalisation group approach* was the major breakthrough in the understanding of critical phenomena.

In 1926 Weiss and Forrer investigated the properties of bulk Ni at the Curie point [2.16]. A later reanalysis in 1968 showed that their data explicitly obeys the scaling laws. Their data served as a test of the scaling hypothesis in

three dimensions. The experimental test of the scaling laws in two dimensions, and in particular using a system with Ising character is the topic of chapter 5. The Ising model is one of the few exactly solved problems in statistical physics [2.17]. Onsager's famous solution, however, is only valid in zero magnetic field. The knowledge of some zero field critical-point exponents implies that we know that a system behaves Ising like on some particular paths in the critical region. In particular: neither do we know anything about the behavior of the system in an applied magnetic field nor do we have information about the behavior of the system on an arbitrary path along the three dimensional surface representing the full equilibrium phase diagram. The missing part to our knowledge is the equation of state in the critical region. Gaunt and Domb [2.18] obtained *numerical* results for the 2D Ising model with magnetic field.

We succeeded to prepare ultra thin ferromagnetic films of Fe/W(110), which show Ising behavior at the phase transition. We measured the magnetisation of our Fe/W(110) films as a function of temperature and externally applied field over a wide temperature range. The measured equation of state explicitly displays scaling behavior and follows closely the calculations of Gaunt and Domb [2.18]. These experiments serve as an unambiguous test of the scaling hypothesis in two dimensions.

After the first observation of exchange coupling between ferromagnetic films across a non magnetic spacer film [2.19] many systems have been investigated [2.20]. The exact mechanism of the coupling phenomena is still unsolved. Bruno and Chappert applied the general theory of Rudermann-Kittel-Kasuya-Yosida (RKKY) to the problem of interlayer coupling [2.21]. They calculate the exchange coupling by application of the RKKY theory to the specific Fermi surface and crystallographic geometry of the system. Edwards and co-workers use a different approach [2.22]. They consider the possibility of confinement of d-holes within the non-magnetic spacer. In their model these spin polarised quantum well states are responsible for transmitting the exchange coupling. The key to the understanding in both models is the role of the Fermi surface of the non-magnetic spacer.

In chapter 6 the possibility of using a paramagnetic layer to study directly the exchange coupling from a ferromagnetic specimen across a standard non magnetic Cu spacer is introduced.

The direction of the magnetisation in ultra thin magnetic films depends on a subtle balance between the different energy terms, such as the exchange

energy, bulk magneto-crystalline anisotropies, and anisotropies which are introduced by artificial defects. The most prominent artificial defect of course is the surface of a film [2.23]. Steps can easily be introduced by varying the miscut angle of a sample [2.24] and can serve to model another anisotropy term. The ultimate goal for technological applications would be the controlled engineering of these anisotropy terms resulting in the modifications of the direction of the magnetisation vector.

In chapter 7 the possibility of manipulating magnetic properties of rather thick Co films on top of slightly miscut Cu(100) substrates will be demonstrated. We succeed in changing the magnetisation direction by adsorption of submonolayers of different adsorbates.