Magnetic anisotropy.

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Without magnetic anisotropy the compass would not work: the magnetization of the compass needle would always be aligned with the local (earth's) magnetic field, but no mechanical torque would be exerted on the needle and, as a consequence, the orientation of the needle would be unaffected by any homogeneous magnetic field. (Of course, an inhomogeneous magnetic field always produces a force acting on a magnetic object). It is the magnetic anisotropy which creates the link between the magnetization and the body of a ferromagnet and can result in a measurable torque.

For the same reason many electric motors, permanent magnets, magnetic data storage devices etc, rely on the existence of magnetic anisotropy which must thus be considered as a technically most relevant property of magnetic materials.

Conceptually, magnetic anisotropy is described as the dependence of the total energy of a magnetic body on the magnetization direction relative to some axes fixed to the crystalline lattice or the macroscopic shape. This must not be confused with an anisotropy of the magnetization itself, i.e. with a variation of the saturation magnetization with its orientation relative to the crystalline lattice which is, however, a small effect (appr. 10^{-4} – 10^{-3}) and difficult to observe.

Without an external magnetic field the magnetization of a ferromagnetic object is preferentially oriented along certain axes which correspond to an *energy minimum* and are called 'easy axes' of magnetization. The directions of the respective *energy maxima* are called 'hard axes' or 'hard directions'. The strength of the anisotropy is expressed by anisotropy constants, K_i ; it can be measured by the external field required to rotate the magnetization from an easy direction to a hard one. Materials with small/large anisotropy constants are called *magnetically soft/hard.*

Magnetic anisotropy (MA) is intimately related to symmetry — both to the symmetry of the crystal lattice and the shape of a given specimen. In particular, a spherical sample of a cubic material will have the weakest magnetic anisotropy which would be totally absent for a polycrystalline structure with a random orientation of the individual grains. Each symmetry breaking step will create an additional and potentially stronger MA. This is demonstrated by considering the cubic ferromagnet bcc-Fe upon reduction of the spatial symmetry from bulk material to thin films, surfaces, atomic steps and chains on the one hand and by imposing an anisotropic strain to the crystal lattice on the other hand. In particular, in monocrystalline Fe films a perpendicular anisotropy develops with decreasing thickness while the cubic anisotropy decreases and even changes sign at a critical thickness. Another example is the uniaxial magnetic anisotropy observed in a polycrystalline random $Ni_{81}Fe_{19}$ alloy ("Permalloy") which can be caused by a directional order of atomic pairs as a symmetry breaking effect. Two fundamental interactions are

responsible for magnetic anisotropies: *dipolar interactions* between atomics moments are directly connected with the shape of a given ferromagnetic body (“shape anisotropy”), while *spin-orbit coupling* (SOC) is the origin of all other anisotropies: magneto-crystalline, magneto-elastic, surface/interface anisotropies, which are intimately related to the local symmetry of the atomic configuration.

To experimentally evaluate magnetic anisotropies different methods are available which are based either on measuring magnetization loops via electric induction (vibrating sample magnetometer – VSM, SQUID etc.), the force on a magnetic dipole in an inhomogeneous magnetic field (Faraday balance, alternating gradient magnetometer – AGM), the torque exerted on a magnetic dipole in a homogeneous magnetic field (torque magnetometer, cantilever magnetometer, ferromagnetic resonance – FMR), magneto-optic effects like the magneto-optic Kerr effect – MOKE, or quantities which indirectly depend on the magnetization direction like magneto-resistance effects or the anomalous Hall effect – AHE. The respective strengths and shortcomings of these methods will be discussed.

For the theoretical description of magnetic anisotropy the most logic approach is to calculate the total energy of a magnetic specimen *ab initio* , e.g. by applying density functional theory (DFT) and taking into account all the details of the atomic structure and macroscopic shape. This, however, because of very small energies involved (down to 1-10 μeV/atom) is an extremely demanding task and has only been possible in special cases which will be discussed. Besides, in general the two fundamental interactions responsible for MA, i.e. dipolar interactions and SOC are considered in a phenomenological approach. Usually, the anisotropy energy is expanded in power series which must reflect the intrinsic symmetry operations of the respective crystal lattice (cubic, hexagonal, tetragonal etc.). The pair energy model introduced by L. Néel will be discussed which is exclusively based on symmetry arguments and has been very successful in predicting relations between elastic properties and magnetic anisotropies of ferromagnetic materials and, in particular, the existence of magnetic surface anisotropies long before they were experimentally observed.

Finally, methods will be discussed which allow to tailor magnetic anisotropies for specific applications by virtue of different control parameters like substrate, thickness and strain in epitaxial thin films, interfacial exchange coupling in heterostructures or by electric fields.