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## Preface

Magnetic domains are the elements of the *microstructure* of magnetic materials that link the basic physical properties of a material with its macroscopic properties and applications. The analysis of magnetization curves requires an understanding of the underlying domains. In recent years there has been a rising interest in domain analysis, probably due to the increasing perfection of materials and miniaturization of devices. In small samples, measurable domain effects can arise, which tend to average out in larger samples. This book is intended to serve as a reference for all those who are confronted with the fascinating world of magnetic domains. Naturally, domain pictures form an important part of this book.

After a historical introduction (Chap. 1) emphasis is laid on a thorough discussion of domain observation techniques (Chap. 2) and on domain theory (Chap. 3). No domain analysis is possible without knowledge of the relevant material parameters. Their measurement is reviewed in Chap. 4. The detailed discussion of the physical mechanisms and the behaviour of the main types of observed domain patterns in Chap. 5 is subdivided according to the crystal symmetry of the samples, according to the relative strength of induced or crystal anisotropies, and according to the sample dimensions. The last chapter deals with the technical relevance of magnetic domains, which is different for the different fields in which magnetic materials are applied. The discussion reaches from soft magnetic materials forming the core of electrical machines that would not work without the hidden action of magnetic domains, to magnetic sensor elements used in magnetic recording systems, which may suffer from domain-related noise effects.

We emphasize in this book (in Chaps. 5, 6) the analysis of actual magnetization processes, in particular of those that lead to discontinuities and irreversibilities in the magnetization curve. This approach is adequate for several important application areas, such as magnetic sensors and transformer materials. In other areas, such as those of bulk polycrystalline soft-magnetic materials, the link between observed elementary processes and possible technical descriptions of the hysteresis phenomena is difficult to establish. Formal de-

scriptions of hysteresis phenomena—shortly introduced by reference to actual textbooks in the last section of Chap. 6—use abstract concepts of magnetic domains in their justification. Whether the discrepancy between the simplified assumptions of hysteresis theories and the complexities of actual domain behaviour is technically relevant remains an interesting open question.

Previous books and reviews touching on the subject of magnetic domains and magnetization processes are listed separately in alphabetic order at the end of the reference list. The few recent works among these cover important, but on the whole rather specialized aspects. One of the aims of this book is to collect the knowledge available from the investigations of many magnetic materials. Although the technical areas of electrical steels, of high frequency cores, of permanent magnets, or of computer storage media have little in common, the magnetic microstructures in most of these materials obey the same rules and differ only in quantitative, not in qualitative aspects.

Despite the preference of many magneticians for the old Gaussian system of units, standard SI units are used throughout. A reference to the old system is made only occasionally. But we prefer to reduce equations to dimensionless units anyway in all practical examples, so that results get a broader range of applicability, and at the same time the mathematical expressions become independent of the unit system.

We take one liberty, however. The magnetic dipole density of a material is given by the vector field  $\mathbf{J}(\mathbf{r})$  (measured in Tesla or  $\text{Vs}/\text{m}^2$ ). Its official name is *magnetic polarization*, but very often and also in this book, it is called simply *magnetization*, although in the strict SI system this name is reserved to a quantity  $\mathbf{M}(\mathbf{r})$  that is measured in  $\text{A}/\text{m}$  and related to  $\mathbf{J}$  by  $\mathbf{M} = \mathbf{J}/\mu_0$ . We will never use the latter quantity, so no confusion is possible. Our choice agrees with the recommendation from *P.C. Scholten*<sup>1</sup>, except that he would prefer to use the abbreviation  $\mathbf{M}$  instead of  $\mathbf{J}$ , which we think might lead to confusion<sup>2</sup>. Anyway, in most cases we use the reduced unit vector of magnetization direction only, and we abbreviate this vector field by  $\mathbf{m}(\mathbf{r})$ .

The careful reader will discover quite a few original contributions in this book, not published elsewhere. They are intended to improve the grasp of otherwise abstract concepts and check their applicability. They also help to fill gaps in the published material. Such gaps may be too small or unimportant to justify an independent scientific publication, but they may form a serious obstacle for newcomers in their attempt to enter the field.

A few hints to the reader: Up to five text organization levels are used. Three of them (chapter, section, subsection) are systematically numbered in a decimal classification. The sections appear in the right-hand page headers to facilitate orientation. A further subdivision is often needed. It is marked and referred to within the same subsection by “(A), (B) etc.”. In references from

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<sup>1</sup> P.C. Scholten: “Which SI?”, *J. Magn. Magn. Mat.* **149**, 57–59 (1995).

<sup>2</sup> The fundamental material equation is thus expressed in this book in the form  $\mathbf{B} = \mu_0 \mathbf{H} + \mathbf{J}$ .

other subsections a small capital letter (like in “Sect. 3.4.1A”) is appended. Where needed, an informal fifth level, marked “(i), (ii) etc.”, is added. Parenthesis with numbers like “(3.1)” always refer to equations, while brackets like “[212]” indicate citations. Parenthesis with lower case letters like “(a)” refer to parts of a figure mentioned in the same paragraph.

Some passages in Chap. 3 on domain theory are addressed more to the interested specialist than to the general reader. They are marked by smaller print. All references are collected in the order of occurrence after the text part. Orientation within the references section is supported by an author index that comprises all authors and coauthors of all cited references (explicit text references are listed first). In addition to the regular, numbered and captioned figures we offer numbered “sketches”, that are intended to facilitate reading, but which need no further explanation (thanks to John Chapman for suggesting this tool). The few tables are numbered and treated as if they were figures, which makes it easier to find them.

Erlangen, Dresden,  
July 1998

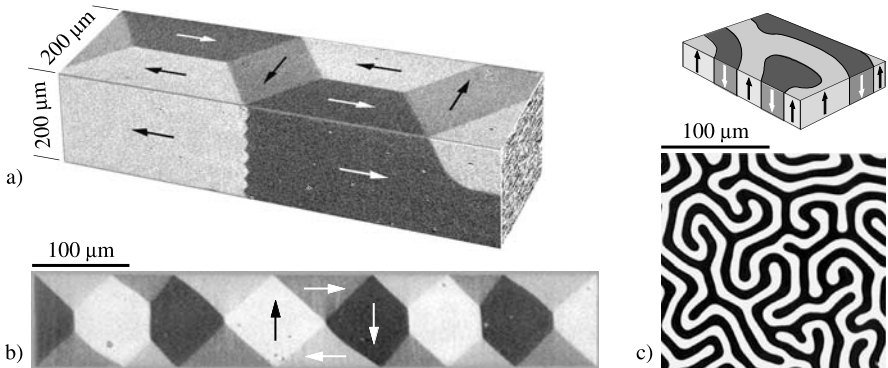
*Alex Hubert*  
*Rudolf Schäfer*

## Introduction

After a brief empirical definition of magnetic domains in this chapter the historical development of the knowledge of magnetic microstructure is outlined. This discussion is used to introduce the basic facts about domains.

### 1.1 What are Magnetic Domains?

Today it is easy to answer this question by reference to direct observation. Figure 1.1 shows the magnetic microstructure in the field-free state of different magnetic samples made visible with the help of polarization optics. In all cases, uniformly magnetized regions, so-called domains, are observed to appear spontaneously within otherwise unstructured samples.



**Fig. 1.1.** Domains observed with magneto-optical methods on homogeneous magnetic samples. (a) Images from two sides of an iron whisker, combined in a computer to simulate a perspective view (sample courtesy *R.J. Celotta*, NIST). (b) Thin film NiFe element (thickness 130 nm) with a weak transverse anisotropy (sample courtesy *M. Freitag*, Bosch). (c) Faraday effect picture of domains in a single-crystal garnet film with perpendicular anisotropy, together with a schematic of the magnetization

The directions of magnetization in the domains of Fig. 1.1, which can be determined by additional experiments in an external field, are indicated by arrows. Example (a) shows two sides of an iron whisker (the two images were mounted together to create a three-dimensional appearance). Example (b) displays a polycrystalline thin film in which the domains are determined by a weak transverse uniaxial anisotropy. A transparent single-crystal magnetic film with a uniaxial anisotropy perpendicular to the film plane is shown in (c). The black and white areas are magnetized into and out of the image plane, as indicated schematically. Looking at such clear pictures, we can have no doubt about the reality of domains. In the microscope the situation becomes even more convincing when domains are seen moving in a magnetic field. In the beginning, when domains were first conceived, no pictures of them were available—they were discovered by theory! The development of modern understanding of domains, starting from this first theoretical postulate, is outlined in the following section.

## 1.2 History of the Domain Concept

### 1.2.1 The Domain Idea

At the beginning of the nineteenth century scientists began to realize that magnetic matter consists of *elementary magnets* in a similar sense as matter in general consists of atoms and molecules. *Ampère's* hypothesis of elementary molecular currents (see [1]) is the best known example of such a theory. The concept of elementary magnets explains two well-known experimental facts: the impossibility of isolating magnetic south and north poles, and the phenomenon of magnetic saturation in which all elementary magnets are oriented in the same direction. In spite of the validity of this hypothesis, no progress in the understanding of magnetic behaviour was achieved until 1905 when *Langevin* [2] developed a theory of paramagnetism by using the methods of statistical thermodynamics. He showed that independent molecular magnets at room temperature lead to weak magnetic phenomena only, and he concluded that *strong* magnetism must be due to some interaction among the elementary magnets. Only two years later *Weiss* [3] elaborated this idea, following *van der Waals'* treatment [4] of the condensation of gases (which is caused by an attractive interaction among the molecules of the gas). In analogy to the “internal pressure” of *van der Waals'* theory, *Weiss* introduced a *molecular field* to model the average effect of the magnetic interaction in a tractable way. *Weiss'* famous theory succeeded in deriving the general shape of the temperature dependence of magnetic saturation. Adjusting the strength of the interaction so that the experimentally observed Curie temperature is reproduced, *Weiss* formally obtained a very large “molecular field”. Only much later *Heisenberg* [5] identified the nature of this field in the quantum-mechanical *exchange* effect.

The Weiss theory also predicted that the state of magnetic *saturation* is the thermodynamic equilibrium state at all temperatures sufficiently below the Curie point. This is true because the value of the molecular field is much larger than the internal or external magnetic fields occurring in practice. External magnetic fields have almost no influence on the value of the saturation magnetization in the Weiss theory. However, since the Weiss molecular field always follows the direction of the average magnetization, the magnetization vector is fixed only in its *magnitude*, while its *direction* remains arbitrary. This feature of the Weiss theory explains the fact that a piece of iron can appear non-magnetic at room temperature, far below the Curie point: the magnetization vectors in different parts of the sample only have to cancel each other. Of course, there are infinitely many possibilities for such a macroscopically non-magnetic state. In his original work Weiss just mentioned the possibility that part of a crystal is magnetized in one direction, and part in the opposite direction. He did not introduce a name for the magnetic substructure in this article. The now almost universally adopted term *domain* structure for the subdivision into uniformly magnetized regions inside a crystal was introduced later [6 (p. 162f.)]. It still reflects the initial uncertainty about its nature, meaning something that is known only vaguely [7 (p. 120)].

### 1.2.2 Towards an Understanding of Domains

It was still a long way from the domain idea to a theory of magnetic hysteresis and the very high permeabilities found in ferromagnets (a piece of soft magnetic iron can have a one million times higher permeability than vacuum!). Some hints from experiment were necessary before the theory could proceed. A first confirmation of the domain concept was found by *Barkhausen* [8]. He discovered that the magnetization process is often discontinuous, giving rise to a characteristic noise when made audible by an amplifier. Originally, Barkhausen jumps had been interpreted as domain *switching*. Although this interpretation is not considered valid today, the further pursuit of the Barkhausen phenomenon led to a decisive discovery. Experimentalists had tried to find specimens in which, instead of the complicated Barkhausen noise, some simpler process took place during magnetization reversal. Certain stressed wires showed in fact only one giant jump leading immediately from one saturated state to the opposite one [9, 10]. The analysis of the dynamics of this process led *Langmuir* (see [11]) to the conclusion that such jumps could occur only by a spatially inhomogeneous process, namely by the propagation of a *boundary* between domains of opposite magnetization. This hypothesis was soon confirmed by the famous experiments of *Sixtus* and *Tonks* [11] who followed the propagation of the domain boundary in a stressed wire by electronic means. It inspired *Bloch* [12] to analyse theoretically the transition between domains, finding that the walls must have a width of several hundred lattice constants due to Heisenberg's exchange interaction that opposes an abrupt transition. Wide domain walls effectively average over local

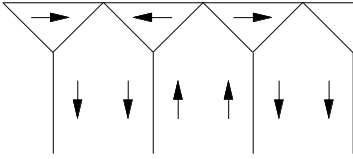
inhomogeneities, such as point defects; this result explains why domain walls can be so easily moved as shown in the Sixtus-Tonks experiment.

In a parallel development, the effects of anisotropies, magnetostriction and internal stresses on the magnetic microstructure were investigated by many prominent authors, such as *Akulov* [13], *Becker* [14] and *Honda* [15]. The textbook of *Becker* and *Döring* [16] summarizes this work. The most important results (as far as they apply to our subject) may be stated as follows:

- Crystal *anisotropy* (the preference of the magnetization vector to align with so-called easy crystal axes) and *magnetostriction* (the spontaneous deformation of the crystal related to the magnetization direction) are independent material properties that cannot be derived from the Weiss theory of ferromagnetism or from Heisenberg's exchange interaction. They are connected to spin-orbit coupling effects and can be determined by experiments on single crystals. Because of fundamental symmetry relations they do not distinguish between a magnetization direction and its opposite.
- As a consequence of anisotropy, the magnetic microstructure consists of domains that follow the easy axes of the anisotropy functional. A magnetization process can be either based on the displacement of domain walls, or on the rotation of the magnetization vectors inside the domains. The attempt to explain observed hysteresis curves of soft magnetic materials and in particular their high permeability by *rotation* processes alone fails, since the measured anisotropies are generally too large.
- If the cubic anisotropy of iron favours the  $\langle 100 \rangle$  directions, inhomogeneous stresses inside a piece of iron will induce domains magnetized along more than one of the easy axes, thus generating  $90^\circ$  walls (a  $90^\circ$  wall is a wall in which the magnetization rotates by  $90^\circ$  from domain to domain).

It is difficult, however, to reconcile the observed permeabilities with  $90^\circ$  wall motions alone, since their positions are bound to stress inhomogeneities. Also compatible with the anisotropy are  $180^\circ$  walls. If they are present, their position is not determined by stresses, and they will therefore be mobile, explaining the high permeabilities. From anisotropy and stress considerations alone, however, there is no reason why these  $180^\circ$  walls should exist, except occasionally for continuity reasons. We postpone a graphic representation of these arguments to Fig. 1.3 for reasons that will become immediately apparent.

One element of a complete theory of magnetization processes was missing at this point. Some authors (*Frenkel* and *Dorfman* [17], *Bloch* [12], *Heisenberg* [18]) had already perceived the missing link: the magnetic *dipole* interaction, also known as magnetostatic energy or stray field energy. For a long time this interaction had been more or less forgotten after Weiss had proved it to be much too weak to explain ferromagnetism as such. The dipolar interaction was used in a crude way to derive the macroscopic magnetization curve of a finite body from the hysteresis of an infinite or ring-shaped body, using the demagnetizing factor and the shearing transformation. It was well understood that



**Fig. 1.2.** The first realistic model of magnetic domains by *Landau* and *Lifshitz* [22]

a uniformly magnetized single crystal carries an excess energy—the demagnetizing energy—which can be large compared to the usual anisotropy energies. Heisenberg [18], for example, still assumed that to minimize this demagnetizing energy, tiny threadlike domains had to develop. Again the experiment had to give a hint to the solution. In 1931 *v. Hámos* and *Thiessen* [19] and independently *Bitter* [20, 21] showed the first pictures of magnetic micropatterns obtained with the help of an improved powder method. Even if none of the observed structures could be understood in detail at the time, the pictures demonstrated three important features: domains were static, they could be rather wide, and they frequently had a periodic and regular appearance.

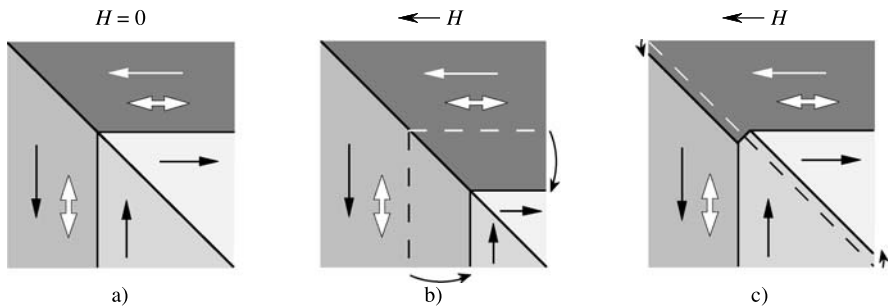
Probably stimulated by such observations and by their first theoretical analysis by Bloch (see the footnote at [12 (p. 321)]), *Landau* and *Lifshitz* [22] presented the solution in 1935: domains are formed to minimize the total energy, an important part of which is the stray field energy. And the stray field energy can be avoided by *flux-closure* type domains as shown in Fig. 1.2. (The basic idea of such closed flux patterns had been put forward already by *Zwicky* [23].) If the magnetization follows a closed flux path everywhere, the stray field energy is zero and therefore even smaller than in the hypothetical thread domains. Landau and Lifshitz proved for the first time that a domain model like that of Fig. 1.2 has a lower energy than the uniformly magnetized state.

The stray-field-free model structure of Fig. 1.3 is thought to represent a part of an extended domain pattern. It contains both  $90^\circ$  and  $180^\circ$  walls and demonstrates that both wall systems can be displaced without violating the constraint of flux-closure. Note, however, that the motion of the  $180^\circ$  wall system (b) is compatible with the grown-in stress pattern (which is thought to favour different axes on both sides of the diagonal), in contrast to a displacement of the  $90^\circ$  wall system (c).

Landau and Lifshitz also gave the answers to a number of questions that were still debated at that time:

- The exchange interaction tends to align the neighbouring dipoles and causes them to act together. In most cases the correspondence principle therefore permits treating the average magnetization as a classical *vector* field rather than as a quantum-mechanical spinor field.
- Thermal agitation plays a role only in small particles or at temperatures close to the Curie point. Under normal circumstances the equilibrium magnetic microstructure must be considered *athermal*.





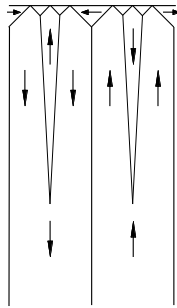
**Fig. 1.3.** The different behaviour of  $90^\circ$  walls and  $180^\circ$  walls in an external field  $H$  for a crystal subject to an inhomogeneous stress pattern (double arrows). A  $180^\circ$  wall motion (b) would be compatible with the stress pattern, but the independently possible  $90^\circ$  wall motion (c) would generate a conflict with the intrinsic stresses

- Macroscopically, the effect of exchange interaction can be expressed to a sufficient accuracy by a *stiffness* term, a quadratic form of the first spatial derivatives of the magnetization vector. This stiffness energy favours uniform magnetization, particularly on a microscopic scale.
- Even inside domain walls the Weiss postulate of a constant value of magnetization should be valid (in contrast to Bloch's treatment who still assumed a ferromagnet to become paramagnetic in the middle of the walls). The magnetization *rotates* in passing through the wall.
- Domain structures are a consequence of the finite dimensions of magnetic bodies. The domain size increases with the specimen size. A uniform infinite or toroidal body may have *no* domain structure in equilibrium.

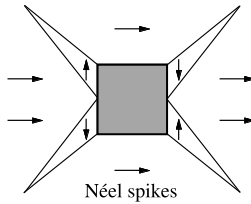
### 1.2.3 Refinements

The model of Landau and Lifshitz proved to be too simple to explain actual observations. Starting from their basic ideas, refinements and extensions were contributed in succeeding years. In the early articles the fundamental difference between the domains in uniaxial crystals, like cobalt, and in cubic crystals, like iron, was poorly understood.

For example, in an article presented by *Lifshitz* in 1944 [24] a theory of domain *branching* was introduced (see Sketch 1.1), a feature that was well known from experiments on uniaxial crystals [25]. *Lifshitz'* article was meant to apply to iron, a cubic material (it contained among other contributions also the first correct calculation of the  $180^\circ$  wall in iron). But *Lifshitz* failed to see the additional degrees of freedom of the domain structures of cubic crystals with their multiple easy directions. *Néel* [26, 27] in his independent work made full use of these possibilities, predicting a number of remarkable domain structures. A famous example among these, the *Néel spikes* (see Sketch 1.2), can be used to estimate the coercivity connected with large inclusions in iron crys-



Sketch 1.1.

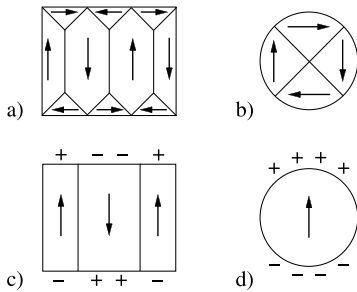


Sketch 1.2.

tals. When they were later observed experimentally [28], this was considered a striking success of domain theory.

Landau and Lifshitz as well as Néel had studied large crystals with weak anisotropies in which the assumption of completely flux-closed domain structures (“pole avoidance”) is well justified (Fig. 1.4a, b). Thus the explicit calculation of the stray field energy was not necessary. (Lifshitz [24] did, however, calculate the energy of the internal fields in his branched structures.) In small specimens or in uniaxial crystals with large anisotropy open structures as in Fig. 1.4c, d are expected; they were first calculated by *Kittel* [29, 30].

Meanwhile, experimental methods had improved considerably. Powder had been replaced by finer *colloids* [31]. Arbitrary samples were replaced by well oriented crystals, and after preparing an undamaged crystalline surface it became possible to obtain meaningful pictures. In the famous article by *Williams, Bozorth and Shockley* of 1949 [32] the identity between the domains of domain theory and the observed magnetic microstructure was convincingly



**Fig. 1.4.** The more or less flux-closed patterns of low-anisotropy cubic particles (a) and (b), compared to the open domain structures for high-anisotropy uniaxial particles (c) and (d)

demonstrated. In the same year Kittel [30] reviewed domain theory and experiments, and this review became the generally accepted reference for domain research. What followed can be called *application* of the established theory, stimulated by improved methods of domain observation, by the preparation of materials with surprising new magnetic structures, and by applications based on the properties of domains. This process is continuing and will be discussed in detail in this book.

### 1.3 Micromagnetics and Domain Theory

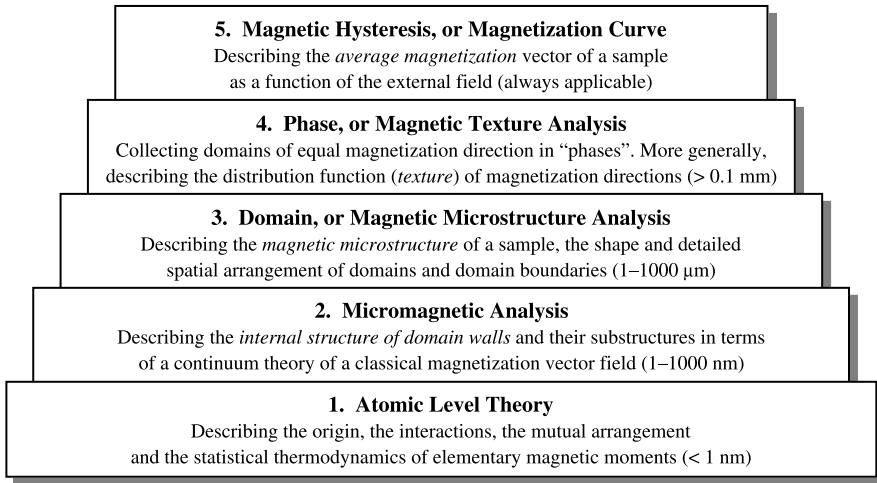
Micromagnetism is the continuum theory of magnetic moments, underlying the description of magnetic microstructure. The theory of Landau and Lifshitz is based on a variational principle: it searches for magnetization distributions with the smallest total energy. This variational principle leads to a set of differential equations, the *micromagnetic equations*. They were given in [22] for one dimension. Stimulated again by experimental work [25] and its analysis, *W.F. Brown* [33,34] extended the equations to three dimensions, including fully the stray field effects (see [35,36]).

The micromagnetic equations are complicated non-linear and non-local equations; they are therefore difficult to solve analytically, except in cases in which a linearization is possible. However, a number of problems in domain research needs micromagnetic methods for their adequate treatment:

- The investigation of the magnetic behaviour of small particles that are too small to accommodate a regular domain structure, but too large to be described as uniformly magnetized (Sect. 3.3.3A).
- The calculation of the internal structure of domain walls (Sect. 3.6).
- The investigation of finely divided surface magnetization patterns of samples, where the magnetization is subject to conflicting influences (Sect. 3.3.4).
- The description of rapid dynamic magnetization reactions (Sect. 3.6.6).
- The calculation of the magnetic stability limits (switching; Sect. 3.5).

To treat such problems, work on numerical solutions of the micromagnetic equations is increasingly pursued. It appears utopic, however, to apply micromagnetic methods to large-scale domain structures. The gap between the size of samples for which three-dimensional finite element calculations are possible (at most up to perhaps a micron cubed), and the scale of well defined domain patterns (often reaching millimetres and centimetres) is simply too large.

For most problems we have to rely on *domain theory*, a theory that combines discrete, uniformly magnetized domains with the results of micromagnetics for the connecting elements, the domain walls and their substructures. We will see that in many cases, reliable guidance in domain analysis can be obtained from domain theory.



**Fig. 1.5.** The hierarchy of descriptive levels of magnetically ordered materials. The values in parenthesis indicate the sample dimensions for which the different concepts are applicable

Repeating some arguments, we show in Fig. 1.5 how domain theory is embedded into more general descriptions of magnetic materials. Five levels [37] are distinguished, which are connected with characteristic scales.

Level three of the scheme representing the centre of interest of this book is analogous to classical metallography. The continuum theory of micromagnetics appearing in level two forms the basis of domain analysis. Both levels together represent a *mesoscopic* approach in the description of a magnet. Level four corresponds to the discussion of a material in terms of phase diagrams, and is an important limiting aspect of domain analysis. It ignores the detailed arrangement of domains and focuses on their volume distribution. Level five, the phenomenology of technical magnetization curves, is touched in so far as connections between hysteresis and domain phenomena can be established.

The atomic foundation (level one), the question how to explain the observed magnitudes of magnetic moments, crystal anisotropies, or magneto-elastic interactions, is completely excluded. Level one also deals with the spin structure of a magnetically ordered material, the arrangement of spins on the crystal lattice sites. From the mesoscopic viewpoint of micromagnetics and domain theory it does not matter whether a material is ferromagnetic or *ferrimagnetic*. In this book we consider ferrimagnets generally to be included in discussing ferromagnets for short. An interesting hybrid between atomic description and micromagnetics averages over the spins only along one or two dimensions, and retains the atomic description otherwise (see e.g. [38]).

It should be mentioned that the term "micromagnetic" is getting fashionable also outside the range of its original description. Almost every magnetic investigation that touches microscopical aspects is found to be called "micro-

magnetic” (some recent examples are [39–41]). We stick (in agreement with still the vast majority of authors) with the classical definition of *W.F. Brown* [34], restricting the term micromagnetics to the *continuum theory of magnetically ordered materials*, to the second level in Fig. 1.5.