tal of the square wave that represents the recording signal. In the central plane of the medium, the demagnetization factor at high densities approaches the limiting value $N = 1$, and the demagnetizing field approaches the value $H_d = -M_0$, where M_0 is the demagnetized value of the magnetization between transitions, or the peak value if the magnetization is sinusoidal. At the surface of the medium, however, the demagnetization factor approaches the limiting value $N = 0.5$, and the demagnetizing field approaches the value $H_d = -0.5M_0$, one-half the field limit in the central plane (Wallace, 1951; Westmijze, 1953*b*). In Sec. 1.2.5 on reproduction it is shown that, as the recording density increases, the useful flux supplied to the reproducing head comes from a progressively shallower layer immediately beneath the surface. It can therefore be argued that the demagnetization conditions at the surface of a medium of appreciable thickness are of dominant importance compared with those in the center.

1.2.4 Perpendicular recording

The corresponding situation for a medium with perpendicular anisotropy is illustrated in Fig. 1.8. In the central plane of the medium the demagnetization conditions are the reverse of what they were for longitudinal recording. At the low density shown in Fig. 1.8*a*, the demagnetization factor in the perpendicular direction approaches the maximum value $N = 1$, corresponding to $H_d = -M_0$. At a high density, shown in Fig. 1.8*b*, the demagnetization factor and the demagnetizing field approach zero. From this central-plane analysis it would appear that perpendicular recording should be the ideal mode to use for high-density recording (Iwasaki and Nakamura, 1977). If, however, the demagnetization factor is evaluated at the surface rather than at the center, the limiting value is $N = 0.5$, corresponding to a demagnetizing field of $H_d = -0.5M_0$, exactly the same as for longitudinal recording (Wallace, 1951; Westmijze, 1953*b*). Therefore, at densities so high that conditions near the surface rather than in the central plane are of paramount importance, the effects of demagnetization in perpendicular recording should be little different from those in longitudinal recording (Westmijze, 1953*b*; Mallinson and Bertram, 1984).

Such arguments are on too limited a basis to warrant arriving at definitive conclusions concerning the relative merits of the longitudinal and perpendicular modes of recording. More complete analyses need to take into account a variety of complex macromagnetic and micromagnetic considerations. Important macromagnetic factors include the finite head-field gradients and demagnetization effects during the recording process; the keeping effect of heads (particularly large-pole ring heads) in modifying demagnetization fields; the enhancement of perpendicular recording media made possible by the use of a high-permeability underlayer; and, perhaps most difficult of all, the nonlinear nature and directional properties of the hysteresis loops of the media. The more important micromagnetic factors include the precise structure of the magnetic boundary defining a transition, and the way in which a relatively thick perpendicular medium is magnetically "switched" throughout its depth.

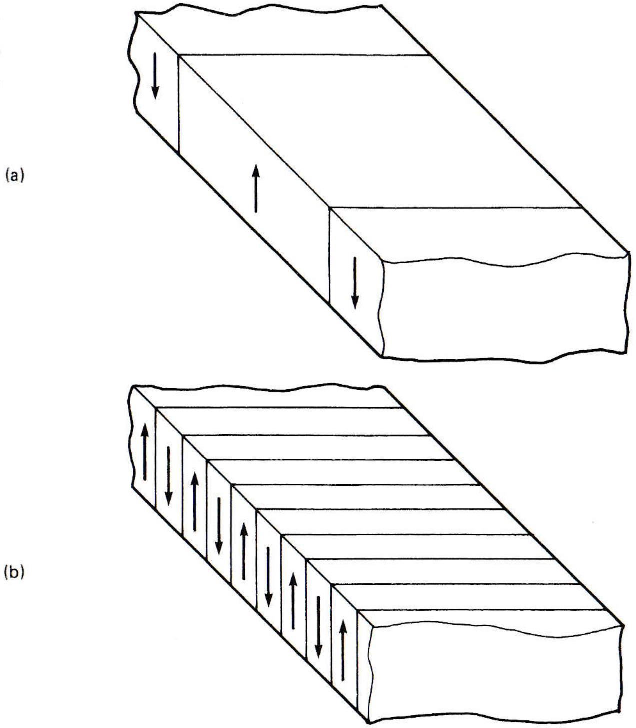

Figure 1.8 Perpendicularly recorded magnetization at (*a*) a low and (*b*) a high density.

Work is proceeding along these lines using a variety of analytical, computer-modeling, and experimental techniques (e.g., Iwasaki, 1984; Middleton and Wright, 1982; Beardsley, 1982*a*, 1982*b*; Bromley, 1983; Weilinga, 1983; Tong et al., 1984). The results are described and discussed extensively in Chap. 2, and specific aspects related to media, heads, recording limitations, and measurements are covered in Chaps. 3 to 6.

1.2.5 Reproduction

Reproduction with a magnetic head is insensitive to the direction of the recorded magnetization. The head reacts to the flux emerging from the surface of the medium, but the vectorial nature of the magnetization that created this flux cannot be deduced from the head response. Thus, for example, a ring head is just as adept at reproducing a perpendicular recording as a longitudinal one. Another simplifying fact is that, unlike the recording process, the reproducing process is linear. Therefore it is possible to deduce the response to complex waveforms from considering sine waves.

For the present purpose, attention is confined to an inductive ring head. If an efficient head of this type makes perfect contact with the medium, and all the available flux ϕ is collected, the voltage induced in a coil of N turns is

$$e = -N\frac{d\phi}{dt} = -NV\frac{d\phi}{dx} \tag{1.5}$$

where the x direction is down the track. If the flux (or a Fourier component of it) is sinusoidal and written as $\phi \cos(2\pi x/\lambda)$, the peak voltage in the coil becomes

$$E = -\frac{2\pi NV\phi}{\lambda} = -2\pi N\phi f \tag{1.6}$$

and is proportional to frequency.

Further information concerning the response of the head can be obtained from a knowledge of the field distribution of the head when energized, by applying the principle of reciprocity (Westmijze, 1953*a*). One of the key results—and it applies to any type of reproducing head—is that the head output falls off exponentially with the spacing that exists accidentally, or purposely, between the active surfaces of the head and the medium. Thus

$$\frac{e_d}{e_0} = \exp\left(-\frac{2\pi d}{\lambda}\right) \tag{1.7}$$

where the subscripts denote a spacing of d and a spacing of zero. The severity of this spacing loss increases rapidly with decreasing wavelength, and can be conveniently calculated by expressing the loss as $54.6d/\lambda$ in decibels (Wallace, 1951). The spacing loss is always of critical significance in magnetic recording, and often is the dominant cause of loss at high densities.

A further aspect of the spacing loss is that it applies also to the spacing between the head and elementary layers positioned beneath the surface of the medium. As an elementary layer becomes deeper, it becomes less capable of contributing significantly to the short-wavelength, or high-density, output. Consequently, at very high densities, virtually all the output comes from a thin layer near the surface, when the medium has a thickness which is an appreciable fraction of the wavelength (Wallace, 1951).

So far, it has been assumed that the head gap length is infinitesimal. When it is finite, it is the source of another, aperture-type of loss, the gap loss, that produces a null in the reproducing response as the wavelength approaches the gap length (Lübeck, 1937; Westmijze, 1953*a*). In practice, gap loss is one of the easier losses to control, except when the same head has to be used for recording and reproducing. A similar (usually larger) loss is associated with the finite thickness of the pole in a single-pole head when it is used for reproducing.

1.3 Practical Constraints

1.3.1 Noise and interference

All magnetic recorders produce unwanted signals in the form of noise and interference, and these impose limitations on the achievable performance. The subject is covered extensively in Chap. 5 and receives only brief mention here. Essentially, there are two major sources of noise: the medium and the reproducing head (electronics noise is usually negligible). Medium noise arises from the fact that no medium is magnetically homogeneous. Particulate media are obviously discontinuous, and create noise in accordance with the number, density, size, and spatial distribution of the particles (Mann, 1957; Mallinson, 1969; Daniel, 1972). Deposited-film media are inhomogeneous because they possess a grain structure, or because irregular domains are formed to minimize the energy at transition boundaries (Baugh et al., 1983; Belk et al., 1985). The major head noise arises from the fact that any head possesses an impedance, and the real part of this impedance gives rise to noise of thermal origin. Other forms of head noise are associated with magnetic domain changes (Barkhausen noise) or magnetostriction effects ("rubbing" noise).

Interference—the appearance of signals other than those intended—arises in many ways, such as cross-talk between different elements in a multitrack head; incomplete erasure of a previously recorded signal; track misregistration when a head scans a track on successive occasions; and print-through, the magnetic transfer of signals between the layers in a stored reel of tape. Which effect is the most serious depends on the type of recorder and the application. In most analog recorders, medium noise is dominant, but reproducing head noise will become more significant as signal frequencies go up and track widths diminish. Medium noise is also the dominant form of noise in digital disk drives, but, currently, interference due to track misregistration constitutes a more serious limitation than noise. Print-through is of consequence only in the analog recording of audio signals.

1.3.2 Head-medium interface

Magnetic recording involves mechanical motion between the media and heads, and, as intimated above, the spacing between these components must be made critically small. This combination imposes stringent demands upon the surface characteristics of media and heads: their flatness, smoothness, freedom from asperities, frictional properties, and mutual capability to resist wear.

In the great majority of recorders using flexible media, the heads and media are run nominally in contact in order to reduce spacing losses to the values required for high-density performance at practical head-media speeds. The head material, profile, and surface integrity are critical properties in achieving adequate head life and avoiding undue wear of the medium. The corresponding properties of the medium are, if anything, more critical, because they must be maintained over an enormously larger surface area. Particulate media have the advantage that the magnetic and tribological properties can be controlled independently, through the choice of particle and the choice of plastic binder and additives.

In rigid-disk drives the problem is approached differently. The head is mounted on a slider which flies above the rotating disk, and provides an air bearing which, in principle, avoids wear entirely (Gross et al., 1980). Early air bearings were formed by designing the slider to create hydrodynamic pressure and weighting the head to achieve a flying height of about 20 μm. Modern bearings are designed to be self-adjusting and to fly at a height of 0.5 μm or less. In practice, wear is not entirely eliminated by the use of a flying head. Durability to occasional head-medium contacts at full velocity is required in addition to the slower-speed contact which occurs when the head takes off or lands during starting and stopping the disk rotation. Because of these requirements, the disk magnetic layers are protected by lubricant or protective overcoat layers. Such layers are typically required when metal-film media are used, but their thickness must be small with respect to the flying height in order to avoid excessive spacing loss.

A detailed discussion of the head-medium interface, with particular emphasis on the rigid-disk interface, is given in Chap. 7.

1.4 Recording Technology Emphasis

1.4.1 Areal density

Magnetic recording research and development efforts will continue to be aimed toward achieving higher areal density by a combination of increases in linear and track densities (Mallinson, 1985). Increases in linear density will require improvements in materials and recording techniques, and controlled miniaturization of the key recording components. Increases in track density will require advances in media properties, narrow-track head design, and head-positioning technology. Some of the areas that are expected to receive emphasis are outlined below.

1.4.2 Head and media developments

Sophisticated methods of head fabrication will continue to be developed for ferrite, metal, and composite head structures. In particular, the use of deposition techniques, similar to those used in the semiconductor industry, is an attractive means to achieving some of the miniaturization goals, and applications of film heads can be expected to broaden. This technology has also spurred renewed interest in flux-sensing read heads, particularly those relying upon the use of a thin magnetoresistance element. Such heads give larger reproduce signals than inductive heads, particularly at lower head-to-medium speeds. This higher sensitivity can be used to offset the lower signal flux available when track density is increased.

Media developments cover a broad range of materials and processes. Iron oxide remains the dominant magnetic ingredient of particulate media, but the higher magnetization of metal particles makes them advantageous for certain high-areal-density applications. Deposited-metal-film media have even higher magnetization potential, and a high-output amplitude can be obtained from a very thin layer, which is favorable at high linear and track densities. Metal-film media are receiving rapidly growing attention, and progress is being made in solving some of the problems associated with durability, corrosion, and other defects that inhibited their use in the past.

The dimensions of head magnetic elements and the recorded transitions in media have decreased to the point where micromagnetic structure and switching mechanisms can no longer be ignored. Grain size in ferrite-head poles, domain effects in film-head poles, and micromagnetic irregularities in recorded transition boundaries are becoming of critical concern. Further advances in head and media materials and design will be assisted by a better understanding of, and ability to control, domain-level phenomena.

1.4.3 Recording modes

The dominant mode of recording has been to magnetize the medium predominantly in the longitudinal direction. Early attempts to record in the perpendicular direction failed because the media used would not readily support such magnetization (Hoagland, 1958). The situation was changed in the mid-1970s by the introduction of a cobalt-chromium medium which possesses the requisite properties favoring magnetization in the perpen-