FERRIMAGNETISM

Ferrimagnets are often associated with ferromagnets because their M(H) and M(T) behavior is nearly identical to that of ferromagnets. However, at the atomic level ferrimagnets are more similar to antiferromagnetics because the magnetic moments of the atoms in ferrimagnets are antiferromagnetically coupled; i.e., adjacent magnetic moments are locked in opposite directions. What makes ferrimagnets different from antiferromagnets is that the adjacent moments have different magnitudes. The larger of the two moments tends to align with the applied magnetic field while the smaller moment aligns opposite to the field direction (see Figure 16). The result is that the different moments add up to produce a large net moment aligned with the magnetic field. Some of the most useful materials for making permanent magnets are ferrimagnets. Many of these materials are non-electrically conducting ceramics.

UNITS

Antiferromagnets behave essentially like paramagnets. On the other hand, ferrimagnets behave essentially like ferromagnets, having the same types of irreversibility possible and the same parameters (Hc, Mrm, and Ms) used to describe their behavior.

E. SUPERCONDUCTIVITY

INTRODUCTION

Another very important type of magnetism is associated with superconductivity. The magnetic properties of superconductors are unique and very complex. Figure 17a is a plot of M(H) at a fixed temperature for a type-I superconductor in the superconducting state. Currents near the surface of a type-I superconductor completely screen the inside of the sample, from the applied magnetic field, up to a field called the critical field (denoted Hc). Screening of the field means that none of the applied magnetic field gets into the sample, and the superconductor acts like a magnetic mirror (with B = 0 inside the superconductor). Up to Hc, the M(H) curve is linear having the largest negative slope possible. This volume magnetic susceptibility is that of a perfect diamagnet (χ = -1/4π in cgs units), which is an enormous value compared to most other diamagnets.

An M(H) curve for an ideal type-II superconductor is shown in Figure 17b. Up to an applied field known as the lower critical field Hc1, a type-II superconductor behaves like a type-I superconductor. However, when the applied magnetic field H exceeds Hc1, the magnetization begins to decrease in magnitude due to the penetration of the magnetic field into the material in the form of flux vortices.
The magnetization will continue to decrease up to a magnetic field value called the *upper critical field* (denoted $H_{c2}$). At $H_{c2}$ and higher fields the superconductivity is suppressed and the system becomes normal (non-superconducting). The curve shown in Figure 17b is the ideal type-II superconductor $M(H)$ curve and this curve is reversible even though it is non-linear above $H_{c1}$. It is interesting to note that this ideal superconductor would be useless for most applications, and, in fact, no supercurrent could flow above $H_{c1}$ in such a superconductor. For it to be useful in practical applications we must modify the superconductor in ways such that the $M(H)$ curve of the superconductor becomes irreversible (hysteretic). This can be done by introducing defects into the material, usually through an appropriate choice of preparation and processing conditions. These defects serve to pin the magnetic field lines, thereby restricting their motion. It is the motion of the field lines that usually limits the current density above $H_{c1}$.

Introducing defects into an ideal superconductor changes the $M(H)$ curve from that of Figure 17b to one like that of Figure 18 which shows little evidence of $H_{c1}$; furthermore, the $M(H)$ curve is definitely neither linear nor reversible. Now it is possible for a supercurrent to flow above $H_{c1}$, and the amount of supercurrent that can flow can be determined from the value of the magnetization. An important quantity in such superconductors is the critical current density (denoted $J_c$), and it is a remarkable result that a magnetic measurement can be used to determine how much electrical supercurrent (a transport property) can be carried by the superconductor. The relation between the magnetization $M$ and $J_c$ is called the *Bean Critical State Model* and is given by

$$J_c = \frac{s M}{d},$$

where $d$ is the sample width or diameter and the constant $s$ is a shape dependent constant having a value $s = 10/\pi$ for an infinite rectangular slab sample and $s = 15/\pi$ for a cylindrical sample. (This equation is for units of $J_c$ in A/cm², $M$ in G, and $d$ in cm.)

Another important property of a superconductor is its superconducting transition temperature (usually denoted $T_c$ for critical temperature). This is the temperature at which the sample goes from the superconducting state to normal state upon warming. $T_c$ usually decreases as $H$ is increased. It is common to measure the *Meissner effect* in order to determine $T_c$. When an *ideal* superconductor is cooled through its superconducting transition with a very small field applied to the sample (field-cooled (FC) measurement), the magnetic field will be completely expelled from the inside of the superconductor at $T_c$. The expulsion of the field at $T_c$ is the Meissner effect and it is possible to determine $T_c$ by measuring $M(T)$ as the point at
which there is a drop in \( M \) (remembering that \( M \) is negative). A plot of \( M(T) \) for a high temperature superconductor is shown in Figure 19.

It is not uncommon to see a different measurement, often called magnetic shielding or screening, mistakenly called the Meissner effect. Magnetic shielding is measured by first cooling the sample to a low temperature below \( T_c \), then turning on a magnetic field (which is also called a zero-field-cooled (ZFC) measurement). The changing magnetic field induces currents that flow as long as the sample is superconducting. The Meissner measurement and the shielding measurement both are often mistakenly used as a measure of the amount (quantity) of superconducting material in a sample. A 100% Meissner fraction, which corresponds to a \( \chi = -1/4\pi \) susceptibility value, can be used as a legitimate measure of a completely superconducting sample. However, any value of the Meissner fraction less than 100% could simply mean that there is flux pinning in the sample. The shielding measurement has other potential problems. For example, if a sample has only a thin superconducting skin and a non-superconducting center, it could conceivably produce a \( \chi = -1/4\pi \) susceptibility value, since the skin could screen the whole interior of the sample to compensate the applied field \( H \) (\( B = 0 \) inside the sample).

UNITS

It is important to realize that the superconducting shielding results from the screening of a volume. The magnetization value will depend on the size of the applied field; therefore, it is the volume susceptibility \( \chi \) which is important. In cgs units, perfect diamagnetism, or complete screening, has a value of \( \chi = (-1/4\pi) \) cm³/cm³. Another way of viewing this is to realize that \( B = 0 \) in Eq. (1), requires that \( -\chi M = H \), and therefore \( M/H = -1/4\pi \). In SI units, \( \chi = -1 \).

The critical current density \( (J_c) \) is a current per unit cross sectional area. The cgs units are A/cm² and the SI units are A/m².

EXAMPLES AND ADVANCED TOPICS

Irreversibility Line

The region in the phase diagram between \( H_{c1} \) and \( H_{c2} \) in a type II superconductor is called either the Abrikosov or the flux-vortex phase. As discussed above, at a fixed temperature and for \( H > H_{c1} \), the magnitude of \( M \) decreases as \( H \) increases. The decrease in \( M \) is due to the fact that for \( H > H_{c1} \), \( B \neq 0 \) inside the sample, and some of the magnetic field actually penetrates into the superconductor. However, the magnetic field inside the superconductor is not distributed uniformly as it would be in most other types of material. The field that penetrates into a superconductor is quantized into single quanta of magnetic flux. A single quantum of magnetic flux
(denoted $\Phi_0$) has a value $\Phi_0 = 2.07 \times 10^{-7}$ G-cm$^2$ in cgs units. There is a supercurrent loop associated with each magnetic flux quantum and together this comprises an entity called a flux vortex.

Flux vortices can be thought of as discrete lines of B. When an electrical transport current is applied to a superconductor containing flux vortices, the vortices experience a force, called the Lorentz force, which acts perpendicular to the current. If the vortices are moved by the Lorentz force, however, they generate a voltage parallel to the current that in turn produces resistive losses. To keep a supercurrent flowing requires zero resistance, therefore the flux vortices must be kept from moving. Defects in the sample can pin the vortices and thereby allow large supercurrents (large $J_c$ values) to flow.

It was a surprise to many when it was observed that for high temperature superconductors the magnetic phase diagram between $H_{c1}$ and $H_{c2}$ was split into two regions and separated by a new phase boundary that is commonly referred to as the irreversibility line (IRL). On the upper side of the IRL below $H_{c2}$ there is no pinning, the magnetic behavior is reversible, and no bulk supercurrents can flow. For temperatures and fields below the IRL, the magnetic behavior is irreversible and bulk supercurrents can flow. One way of measuring the IRL is to use the zero-field-cooled/field-cooled (ZFC/FC) method described in the section on ferromagnets. Below the IRL, the irreversibility results in two different curves for ZFC and FC, while above the IRL there is only one value of M at a given H and T, and thus the ZFC and FC curves are superimposed as shown in Figure 19. The IRL is an important property that sets the limits on the range where a superconductor can be used in most applications. A plot showing the relationship between the IRL and the critical fields is presented in Figure 20.

**Minor Loops**

When trying to measure irreversible magnetic properties in a sample, it is important to be able to control the sample’s field history. Determining $J_c$ using a magnetic measurement requires that the critical state be established in the sample. To establish the critical state the field should be changed monotonically and then should not change at all during the measurement scan.

If the length of an MPMS measuring scan is too long, the sample will experience a significant change in the value of the magnetic field during the scan. This occurs because the field in a superconducting solenoid changes with position. Over a long scan length, the sample experiences non-monotonic field variations, and, in fact, the field at the sample oscillates as the sample moves up and down. The result is that the critical state in the sample is reduced or destroyed (the sample is effectively