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Magnetic Material Structures, Devices And Methods

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention is directed to magnetic material structures, methods for making magnetic material structures and devices made from magnetic material structures.

2. Description of the Prior Art

As the home, office, transportation system, business place and factory become more automated and electronically connected, and as electronic devices and appliances such as computers, communication devices, wireless communication devices, electronic games, entertainment systems, personal data assistants, transportation vehicles, manufacturing tools, shop tools, and home appliances become more sophisticated there is, and will be, an ever-increasing demand for higher performance and low cost electronic circuits, sensors, transducers, data storage systems and other magnetic devices which employ magnetic thin film materials. In order for these devices to remain competitive in the market place each product generation must be higher performing, unobtrusive and, usually, less expensive than the previous. Hence there are ever increasing demands for technical improvements in the materials and structure of these devices.

For all of these applications the magnetic material has an improved performance if the magnetic properties can be better controlled during the construction. Two familiar properties, which are sometimes considered to be intrinsic magnetic properties, are the saturation magnetization, Ms, and the magnetocrystalline anisotropy energy density constants (usually denoted by a subscripted K symbol). The meaning of magnetic anisotropy energy is that the magnetization would have a preferred direction, or directions, of orientation. That is, the energy of the system is minimal when the magnetization vector points along certain directions. These directions are referred to as the magnetic easy axes while the magnetic hard axes coincide with magnetic orientations where the energy is maximized. However, it should be noted that the magnetic anisotropy is not actually an intrinsic property in the sense that the materials are commonly not made perfectly. Nevertheless, good performance in device applications is almost always dependent upon there being a single preferred magnetic orientation or anisotropy direction and so in the manufacturing process one strives to achieve a desired uniaxial anisotropy. An objective of the present invention is to provide new mechanisms for controlling the magnetocrystalline anisotropy of thin magnetic films. By doing so the performance of almost all magnetic devices are envisioned to be improved.

In general the anisotropy energy is a function of the orientation of the magnetization vector with respect to a given physical axis. Here, we define a "uniaxial" anisotropy to exist if the anisotropy energy density function only contains a single maximum and a single minimum as the magnetization angle, θ, is rotated by 180 degrees from a physical axis. Likewise we define an "ideal uniaxial" anisotropy energy to exist if the energy equation has only a $\sin^2(\theta)$ or $\cos^2(\theta)$ dependence. Materials and device processing to achieve a desired orientation or anisotropy is commonly difficult and sometimes impossible, perhaps because heretofore the mechanism for achieving anisotropic orientation has not been well understood. Furthermore, uniform control of the orientation of the magnetic anisotropy is often difficult to achieve and maintain in a manufacturing process where many different desired material properties must be obtained simultaneously.

Background for Oriented Soft Magnetic Films

In magnetic devices, for example, such as sensors, transducers, transformers, inductors, signal mixers, flux concentrators, recording media keepers, data recording and playback transducers it is common that the magnetic response to a driving field possess high sensitivity and at the same time, low coercivity (Hc). Or stated simply, the material possesses essentially non-hysteretic behavior. For this type of behavior the device is constructed so that the applied field is directed along the hard magnetic axis of a uniaxial magnetic material. This results in the minimization of coercivity and hysteric effects, which are many times associated with magnetic domain wall motion of materialsthat are multi-axial. For example, a material, which has bi-axial anisotropy, will have two easy and two hard magnetic axes and will exhibit hysteresis and losses. In many of these applications a linear, or near linear response is also advantageous, while in other applications, such as signal mixers, a controlled non-linear response is desire. To obtain a linear magnetic response, requires both applying a field along the magnetic hard axis and that the anisotropy energy density function not only be uniaxial, but that it also have simple $\sin^2(\theta)$ or negative $\cos^2(\theta)$ dependence, where, θ, is the angle measured between the magnetization vector direction and the physically determined magnetic easy axis. Since there is the mathematical identity, $\sin^2(\theta) = 1 - \cos^2(\theta)$, and since the origin in the energy function is arbitrarily defined the use of $\sin^2(\theta)$ or $-\cos^2(\theta)$ yield equivalent physical behavior. Item [1] of Figure 1 illustrates the squared sinusoidal anisotropy energy density curve shape versus the angle of the magnetization vector with respect to the easy axis located at zero degrees. Figure 2 illustrates the response of the components of the magnetization, M_x and M_y, as a function of applied field, $H_x = H_a$, along the hard magnetic axis direction, x. The linear curve kinks only at the point [2] where the magnetization becomes saturated, or fully aligned with the applied field. For this special uniaxial anisotropy this occurs at the applied field value of H_k along the x direction, which is known as the anisotropy field. These response curves are sometimes referred to as hysteresis loops even though they exhibit no hysteresis. It is the shape of the $\sin^2(\theta)$ energy function that causes the response, M_x, along the hard axis to be linear and to be fully reversible. M_y is the response in the y direction to an applied field in the x direction. The curve shape shown is quadratic for applied field magnitudes less than H_k, where M_y is zero for larger magnitude fields. The quadratic behavior is necessary for linear M_x since $M_s^2 = M_x^2+M_y^2$, where M_s is the total, constant, saturation magnetization vector magnitude. If the anisotropy energy is uniaxial, but is not governed by the, ideal, $\sin^2(\theta)$ functional form then the magnetic response is not linear. However, heretofore, the applicant knows of no real material examples exhibiting both a uniaxial energy curve and a non-linear M_x versus H_x behavior.

Materials exhibiting the $\sin^2(\theta)$ energy density functional form are often referred to as having Stoner-Wohlfarth behavior after the famous ideal uniaxial single domain magnetization theory. However, thin films are commonly multi-domain even though they might exhibit the $\sin^2(\theta)$ functional energy form on a localized basis. Unless the hard axis direction is the same at all points in a sample and the applied driving field is exactly parallel to the hard axis then domain wall motion can commonly be observed. This motion results in coercivity mechanisms and hysteretic energy losses. The lossless behavior of samples represented by Figure 2 is due to the magnetization rotating in response to the applied field rather than a response via domain wall motion. Multi-axis anisotropy materials always switch via wall motion and so suffer losses.

It is also well known that, for soft uniaxial thin films, by first applying a field along the easy axis, and then by keeping a constant bias field in this direction, to eliminate 180 degree domain walls, one can force all of the material to appear to be single domain as the hard axis is then driven. Hence, because of this bias field, $H_b = H_y$, in the easy axis direction the application of any finite H_x field along the hard axis can never quite drive the magnetization vector completely to the energy maximum [3] and the response will always be reversible and so lossless. This is not the case for materials with multiple anisotropy axes. For uniaxial materials the rotational response is key to many sensor devices and it is common in various forms of magnetoresistive sensors to provide a bias field along the easy axis by either applying a small field or by exchange coupling the magnetic sensor material to a hard magnetic material that has been so oriented to provide an effective bias field.

For some sensor applications, such as anti-theft devices, and special electronic mixing circuit devices, soft, low loss, magnetic properties are desired simultaneously with a specific non-linear response. In these applications, the driving field has historically, and most commonly, been directed along an easy axis or in the direction of the lowest magnetic anisotropy energy. In this direction magnetic domain wall motion is usually significant. This domain wall motion commonly results in a highly non-linear response or even in strong hysteretic behavior.

Certain anti-theft, article surveillance, article identification or inventory control devices rely upon detecting harmonic signals, which are generated by this non-linear behavior or upon materials being driven in to saturation. One of many examples, of this type of surveillance system and tag is described in U.S. Patent No. 3,747,086. This type of tag response has also been disclosed as enabling multiple bits of information to identify objects in U. S. Patent No. 5,538,803 Other article tag devices are based upon the magnetoelastic effect and mechanical resonance, where coupling exist between the magnetization and the mechanical strain in the material. An example, of this type of tag is disclosed in U.S. Patent No. 4,510,489. In these later devices it is desirable to drive the magnetization towards a hard axis so

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