Magnetic Materials for EAS Sensors

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An overview is given of the new technology of electronic article surveillance (EAS). The focus is on the magnetic materials used principally as sensors in EAS. The principal characteristics of these materials that make them suitable as tags are highly nonlinear *B-H* characteristics or strong magnetomechanical coupling with low acoustic loss. Specific materials characteristics are described for various EAS systems.

Keywords
electronic article surveillance, magnetic materials, sensors, systems analysis

1. Introduction

ELECTRONIC article surveillance (EAS) is a 25-year-old industry with a rapidly expanding world market currently in excess of $600 million per year. This article examines the magnetic characteristics of the major classes of materials that are key to the success of EAS. The magnetic materials used in this business amount to several tens of millions of dollars annually. Growth in this industry exceeds 20% per year.

Electronic article surveillance systems are currently used in libraries, grocery stores, clothing, video and other merchandise outlets, as well as to monitor everything from equipment traffic in factories to infant location in hospital nurseries.

What is needed for operation of EAS is to set up an interrogation zone (usually defined by a magnetic dipole antenna pair) near the entrance or exit to an area to be secured (Fig. 1a). When the magnetic field in the interrogation zone is perturbed by a suitable object (a tag, marker, or label), the system is alerted. The tags of interest here are magnetic. The perturbation signal must be of a nature that it can be resolved from the signal produced by the drive antenna and distinguished from the noise caused by other equipment and magnetic objects in and around the interrogation zone.

Magnetic markers could cause small perturbations in the spatial distribution of the fields inside the interrogation zone. This method of detection is not used because of the irregularity of such perturbations. Magnetic markers could also change the characteristics of the excitation field in frequency or in time. Frequency shifting of the excitation field is a consequence of harmonic generation or, in some cases, periodic multiplication. Such tags are called harmonic tags (Fig. 1b). When a harmonic tag causes part of a primary signal at a frequency ω_1 to appear at a frequency $n\,\omega_1$, the perturbed signal then has a distinguishing characteristic that allows it to be resolved from the primary signal, provided the fraction of the intensity shifted to $n\,\omega_1$ is not too small. Temporal perturbation of the excitation field can be effected by a tag that returns a delayed signal, echo, or response after the excitation field is turned off. Such tags are called resonant or magnetoelastic tags (Fig. 1c). When a magnetoelastic tag is excited by a primary signal for a period of time, it stores magnetic energy in an elastic mode, much like a tuning fork stores acoustic energy in an elastic mechanical system. Once the excitation is turned off, the magnetoelastic tag "rings down" in a characteristic way that allows its signal to be separated in time from the primary signal and distinguished from the signals of most other possible magnetic objects passing through the interrogation zone.

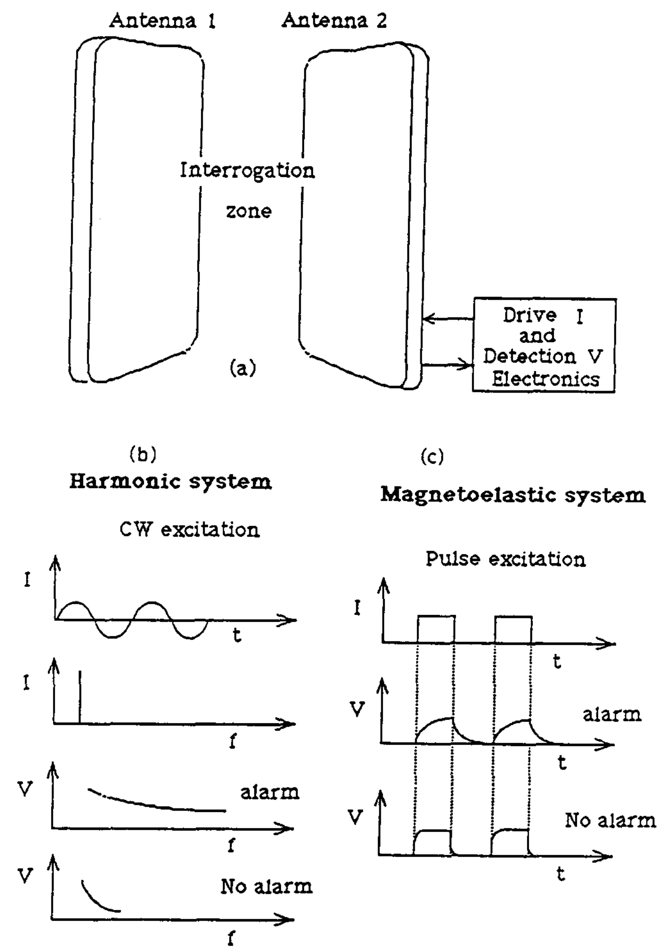

Fig. 1 (a) Schematic of EAS system showing antennas and the drive and detection electronics. (b) Harmonic system: drive current versus time and its spectral intensity as well as voltage picked up for active tag present or none present. (c) Magnetoelastic system: drive current as well as picked up voltage for active tag present or none present.

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2. Magnetic Materials for Harmonic Tags

The *B-H* loop is an intrinsically nonlinear response function (Fig. 2). For magnetization in the hard direction below saturation, the loop is characterized by constant permeability. However, in general, and especially for fields applied in the easy direction of magnetization, permeability is a strong function of *B* or *H*:

$$B = \mu(H)H \qquad [1]$$

where the relative permeability can be expressed in even powers of *B* or *H*:

$$\mu_r = \mu_0 + \mu_2 H^2 + \mu_4 H^4 \ldots . \qquad [2]$$

Note that the response function μ_r is even in *H* so that *B* is odd in *H*, as demanded by symmetry, specifically, by time reversal invariance. The more square a loop, the greater the high harmonic content in the response function spectrum (Fig. 2).

Harmonic content in high-frequency response of a magnetic material is detected as high-frequency pickup in the windings or receive antenna that measure flux density $\beta = \phi/A$. Combining Eq 1 and 2 with Faraday's law yields:

$$V \propto \frac{\partial \varphi}{\partial t} = A\frac{\partial B}{\partial t} = A\frac{\partial}{\partial t}\left[\mu_0 H(t) + \mu_2 H^3(t) + \mu_4 H^5(t) \ldots .\right.$$

where

$$H(t) = H_0 e^{i\omega t}$$

Hence

$$\frac{\partial}{\partial t}(H(t))^n = (ni\omega)[H(t)]^{n-1}$$

and the pickup voltage becomes:

$$V(t) = A[\underbrace{\mu_0(i\omega)H_0 e^{i\omega t}}_{\text{fundamental}} + \underbrace{\mu_2(3i\omega)H_0^3 e^{3i\omega t}}_{\text{first odd harmonic}} + \underbrace{\mu_4(5i\omega)H_0^5 e^{5\omega t}}_{\text{second odd harmonic}} \qquad [3]$$

If a dc field is present, *H* in Eq 1-3 must be replaced by $H_0 + H_{dc}$. The expansions in Eq 2 and 3 will then contain both even and odd powers of H_0.

It is the amount of signal, or spectral weight, in high harmonic channels that characterizes the squareness of a magnetic material. The detection system is tuned to measure a specific harmonic or the ratio of specific harmonics. If the signal meets the selection criterion for the tag, an alarm is sounded.

Drive frequencies in the range 50 Hz to several kHz are commonly used, and harmonics up to the 15th to 19th can be detected if the permeability is peaked sharply enough.

Typically, soft (low anisotropy, low magnetostriction) magnetic materials, magnetized along a preferred axis, exhibit very square loops. Thus, Permalloy* and amorphous metallic alloys have served widely as harmonic EAS tags. A number of techniques can be used to enhance the squareness of the *B-H* loop of a magnetic material. The tag shape can be such as to minimize loop shearing and roundness. Thus, thin, narrow ribbons and sometimes wires are used. Also, the material can be annealed in a longitudinal field to increase loop squareness.

Unfortunately, high permeability is a property of magnetic materials that is extremely sensitive to processing and handling. This is particularly true in Permalloys where magnetic response can be degraded readily by plastic deformation. Permalloy has a yield strength on the order of 10^8 N/m^2. Permalloys generally are used in EAS tags that can be securely packaged and protected from handling stresses.

Amorphous alloys, such as Metglas** 2705 M ($Co_{69}Fe_4Ni_1B_{12}Si_{12}$) or 2826 MB ($Fe_{40}Ni_{38}Mo_4B_{18}$), although susceptible to degradation of magnetic response by plastic deformation, have yield strengths on the order of 7 ×

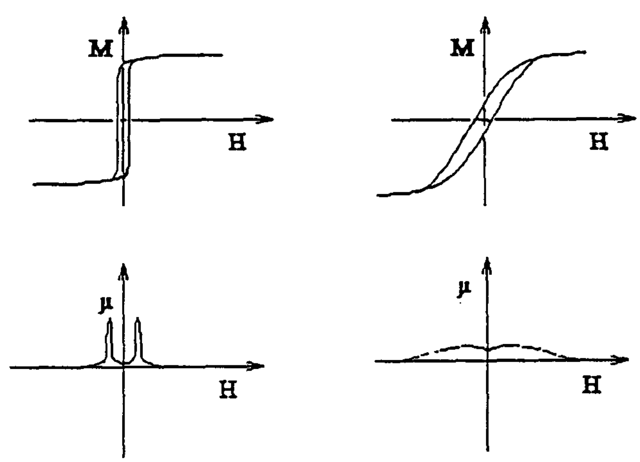

Fig. 2 Schematic of square loop and rounded or sheared loop, above. Below, field dependence of the permeability for the two cases. Permeability is highly nonlinear at left and nearly constant at right.

*Permalloy® is a registered trade mark of Western Electric.
**Metglas® is a registered trademark of Allied Signal Corp.

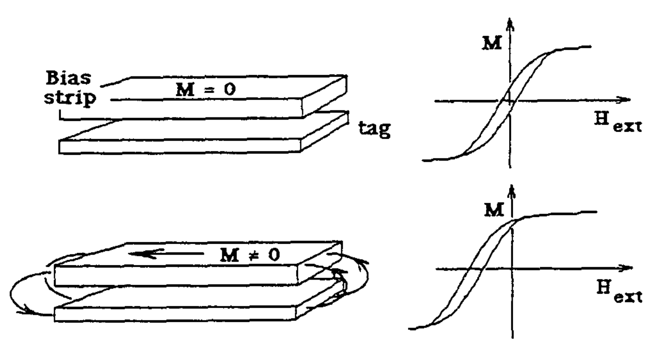

Fig. 3 Schematic of bias strip used in some tags. Right: *M-H* loops of tag with bias material demagnetized or in its remanent state.

10^8 N/m^2. Hence, amorphous alloys are less susceptible than Permalloy to loss of permeability by plastic deformation. Thus, amorphous alloys may be used in a greater variety of EAS situations, including soft goods surveillance.

As described so far, these tags are always "on" or responsive to ac excitation fields unless they are physically damaged (e.g., by plastic deformation), or unless they are magnetically biased beyond saturation. Often, a piece of semihard magnetic alloy such as Vicalloy*, Arnokrome**, or Crovac*** having a coercivity on the order of 50 to 100 Oe can serve as a switch. It may be placed adjacent to the soft magnetic material (Fig. 3). As long as the semihard alloy is demagnetized, it applies no net field to the soft, active member of the tag; the tag is "on," i.e., it responds to $H(t)$ with a rich, characteristic harmonic content. If the semihard magnet is exposed to a high magnetic field and left in a remanent state, its remanent field of a few Oe closes through the adjacent soft material, saturating it and rendering it inactive or "off." In this case, $\mu(H)$ is driven beyond its sharp peak toward its saturation value of unity, and very little signal is detected at high frequencies. Thus, the soft material is the active part of the tag, the sensor. The semihard material is the switch that can turn the sensor off or on.

* Vicalloy® is a registered trademark of Telecon Metals Ltd.
** Arnokrome® is a registered trademark of Arnold Engineering.
*** Crovac® is a registered trademark of Vacuumschmelze GmbH.

3. Pinned Wall Tags

Another family of harmonic tags has grown around a phenomenon first described by Bozorth[1] as a "wasp-waisted" or Perminvar† loop (Fig. 4a). When certain soft magnetic alloys are annealed below T_c in a demagnetized state (i.e., any magnetic field present has a strength less than that needed to saturate the material), the domain walls induce their own local anisotropy (governed by the direction of magnetization at each point across the wall). This local anisotropy tends to stabilize the positions of the walls. The locally induced anisotropy is said to pin the existing domain walls. These "pinned walls" resist motion under application of weak fields until a "depinning threshold" field, H_p, is reached (Fig. 4b). For $H \geq H_p$, the walls may move abruptly from their pinning potential wells, giving rise to a sharp flux jump with rich harmonic content (Fig. 4c). The pinning field should be greater than the earth's field, but not so great that the tag is hard to switch. Values of H_p from 0.4 to 1.0 Oe are common.

†Perminvar® is a registered trademark of Kanthal Corp.

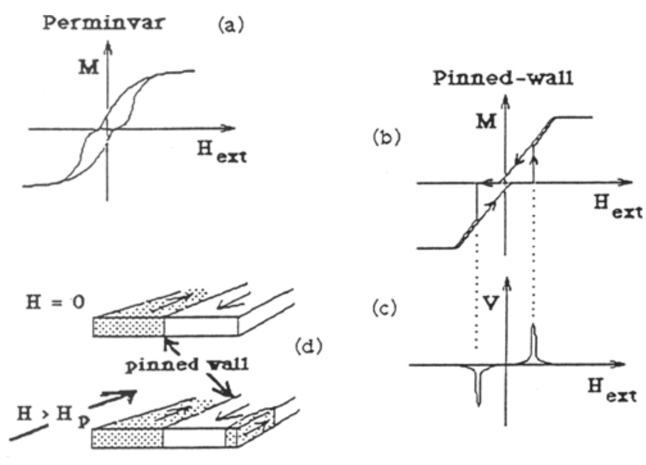

Fig. 4 (a) Typical Perminvar loop. (b) Pinned-wall loop. (c) Voltage pulse it produces. (d) Schematic of pinned-wall tag in demagnetized state and after nucleation of a mobile wall due to $H > H_p$.

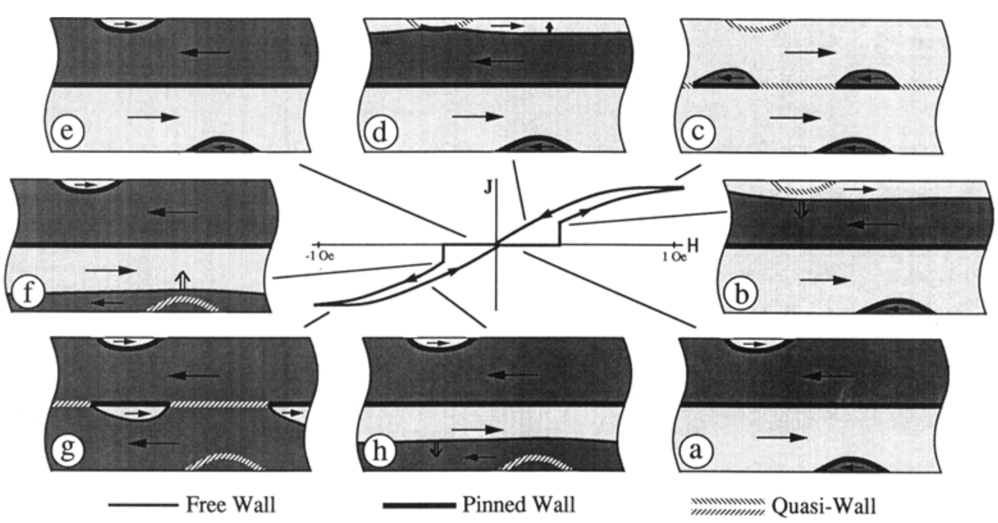

Fig. 5 Schematics of the domain configurations in a ribbon with a pinned-wall loop for various points on the magnetization curve. (a) Demagnetized state. (b) Immediately after field exceeds wall-pinning field. (c) Near saturation. (d) Field decreasing toward demagnetized state. (e) Demagnetized state. (f) Negative re-entrant reversal. (g) Negative saturation. (h) Approaching demagnetized state from negative saturation.

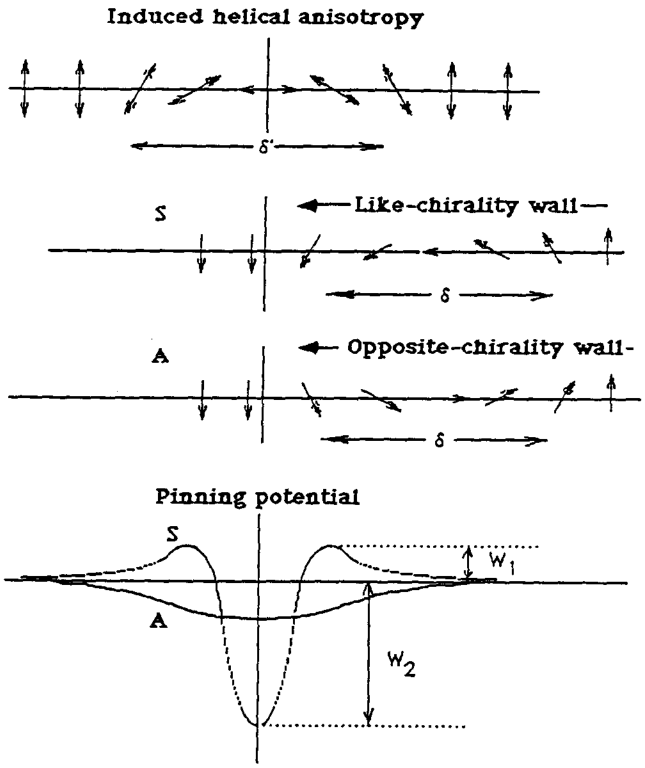

Fig. 6 Schematic representation of an induced helical anisotropy (IHA) of width δ′ and two domain walls of opposite chirality (*S* for symmetric and *A* for antisymmetric) and width δ approaching from the right. At bottom is the pinning potential seen by each wall as it approaches and interacts with the IHA as calculated by Aroca et al.[4] Their results give $W_2 \approx 0.1$ erg/cm^2. The simple, shallow well is for the unlike-chirality, *A*, wall, the deeper potential with the initial barrier is for the like-chirality, *S*, wall.

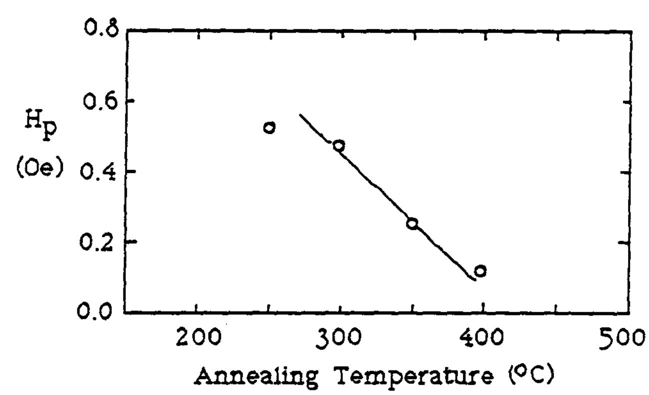

Fig. 7 Temperature dependence of field-induced pinning anisotropy field, H_p, in amorphous $Co_{72}Fe_6B_{15}Si_5Mo_2$.[5]

For a large sample, several walls may be present in the demagnetized state. After annealing, they are pinned with a distribution of values of H_p. Thus, a rounded Perminvar-like loop (Fig. 4a), may result. For a narrow amorphous ribbon, it is often

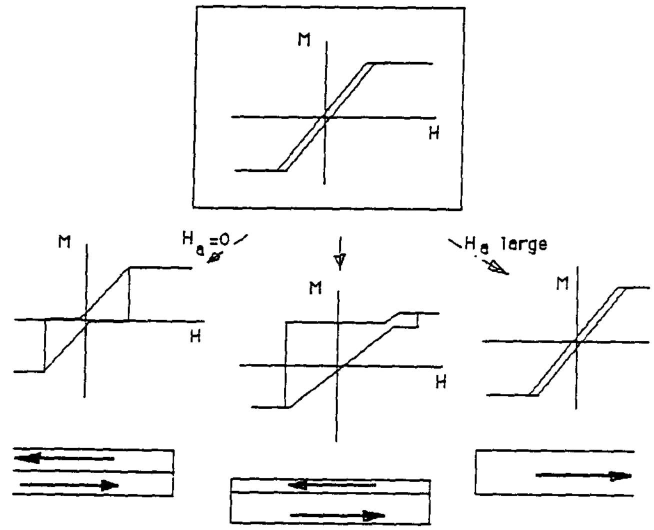

Fig. 8 Schematic of *M-H* loop for a sample with longitudinal anisotropy. Below are depicted the loops that would result for annealing in zero field, a weak but nonsaturating field, and a saturating field.

the case that a single wall is present. In this case, a single, sharp flux jump results for $H > H_p$ (Fig. 4b and c).

Although it is generally believed that above H_p the existing walls are de-pinned, there is direct evidence[2] that, in certain amorphous pinned wall materials, the flux jump event is associated with the nucleation of a new wall at the ribbon edge, whereas the pinned walls remain fixed (Fig. 4d).

These "pinned wall" *M-H* loops are sometimes called "regenerative" or "re-entrant" loops because of the return of magnetization by abrupt wall motion process. Such pinned wall loops have been observed in amorphous materials annealed in weak or zero external fields.[3,4]

Schafer et al.[2] made a thorough study of the domain structure, wall motion, and pinning in such materials. The structure of the domain wall and its Bloch line and other defects are important to the pinning behavior. When the sample is in the state of magnetization that existed during annealing ($M = 0$ in the present case, panels a and e in Fig. 5), the domain walls are pinned. Field excursions over a range $|H| < |H_p|$ result in no wall motion and no change in magnetization, $\chi = 0$. When H exceeds H_p, a new domain is nucleated (Fig. 5b) and moves abruptly to its equilibrium position. Increasing H further (Fig. 5c) causes the sample to approach saturation. Even if saturation is reached, the induced pinned-wall anisotropy still exerts a local torque on the magnetization. It is said that a quasi-wall is present, marking the position and chirality of the pinning site. As h is decreased from saturation, the torque at the quasi-wall promotes formation of a reversal domain (Fig. 5d). At $H = 0$, the starting configuration with a pinned wall (e) is reproduced. Increasing H in the negative direction results in a new nucleation event from the opposite side once $-H > -H_p$.

The shape and strength of the wall pinning potential created by low-field or zero-field annealing has been calculated by Aroca et al.[4] (Fig. 6). Their results show quantitatively that a wall of one chirality is strongly pinned in a well of its own mak-

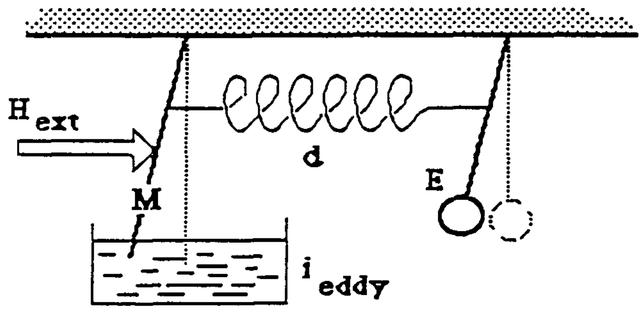

Fig. 9 Coupled pendulum analogy for a magnetoelastic oscillator. An external field drives the magnetic (M) oscillation, which is damped by eddy currents, i_{eddy}. The magnetic system is coupled to a mechanical or elastic (E) oscillator by the magnetostrictivity d.

ing (symmetric, S, Fig. 6), but less strongly pinned in a well made by a wall of opposite chirality (asymmetric, A, Fig. 6). The depth of the pinning potential for a like-chirality wall is calculated to be on the order of $W_2 \approx 0.1$ erg/cm^2. This is 10% of a typical domain wall energy. For a wall width of 1000 Å, this value W_2 corresponds to a pinning field on the order of 0.2 Oe.

The strength of the pinning field induced by zero-field annealing decreases toward zero as the annealing temperature approaches T_c (Fig. 7).[5] This behavior is typical for induced magnetic anisotropy. The smaller pinning field strength at lower temperatures reflects the slower annealing kinetics there.

If a weak but nonsaturating field, H_a, is present during annealing, the loop is simply a shifted pinned wall loop (Fig. 8). The pinning condition (zero susceptibility portion of M-H loop) occurs not for $M = 0$, but at a magnetization corresponding to that realized during annealing. Such asymmetric pinned wall loops also offer a characteristic signal with enhanced high-harmonic content.[6]

4. Magnetoelastic Resonant Tags

Resonant tags make use of the second technique for distinguishing the tag signal from the antenna signal; they exhibit a response that is delayed in time relative to the drive signal (Fig. 1c). The ring-down of a resonant tag is detected after the drive antenna is switched off. Magnetoelastic tags are best thought of using the analogy of coupled harmonic oscillators (Fig. 9). When a magnetic material has a coupling between its magnetic and elastic properties, changing the direction of magnetization produces a strain called magnetostriction. Conversely, a stress on the material causes a change in the preferred direction of magnetization. Figure 9 represents the magnetic and elastic degrees of freedom of such a material by pendulums M and E, respectively. The coupling between these modes is provided by a thermodynamically defined parameter, the magnetostrictivity:

$$d = \partial M/\partial\sigma = \partial e/\partial H \quad [4]$$

These relations follow from the dependence of magnetization response, $M = \chi^{\sigma}H + d\sigma$, and strain response, $e = S^{H}\sigma + dH$, where $s^{H} = 1/E^{H}$, on applied stress, σ, and field, H.

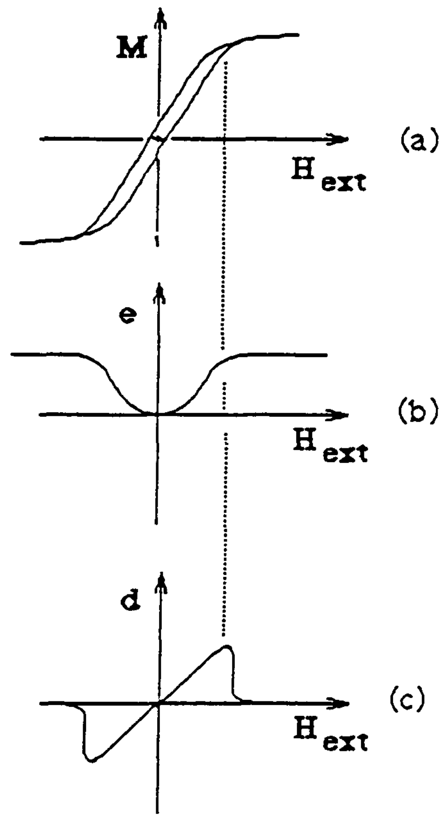

Fig. 10 (a) M-H loop for a magnetostrictive material. (b) Field dependence of magnetostrictive strain corresponding to (a). (c) Magnetostrictivity, $d = de/dH$, as a function of field for loop in (a).

Application of an ac magnetic field from a transmitting antenna drives M into oscillation, and depending on the strength of d, some of this energy is transferred into the elastic mode, E. That is, a standing acoustic wave is set up. The frequency of the acoustic wave is given approximately by:

$$f = \frac{1}{2\pi l}\sqrt{\frac{Y}{\rho}} \quad [5]$$

where l is the sample length; Y is Young's modulus; and ρ is the mass density. This is the frequency of a standing longitudinal wave of wavelength $2l$ in a length of material. The atomic displacements are zero near the center of the strip and maximum at the free ends. At audio drive frequencies, there is a speaker. Conversely, driving the system acoustically causes a change in magnetization that can be detected by a pickup coil or antenna. This is the principle of a microphone, or sonar receiver. Typical magnetoelastic tags measure a few centimeters in length and have resonance frequencies from 30 to 100 kHz. While the drive antenna is on, the system finds on optimal resonant response that includes both magnetic and mechanical oscillations. When the magnetic drive is turned off, the magnetic system would stop oscillating in a matter of nanoseconds if $d = 0$, because of the absence of an inertial mass in the magnetic system. However, the energy stored in E now leaks back through the coupling channel, sustaining magnetization oscillations during a ring-down period. If the magnetic system is

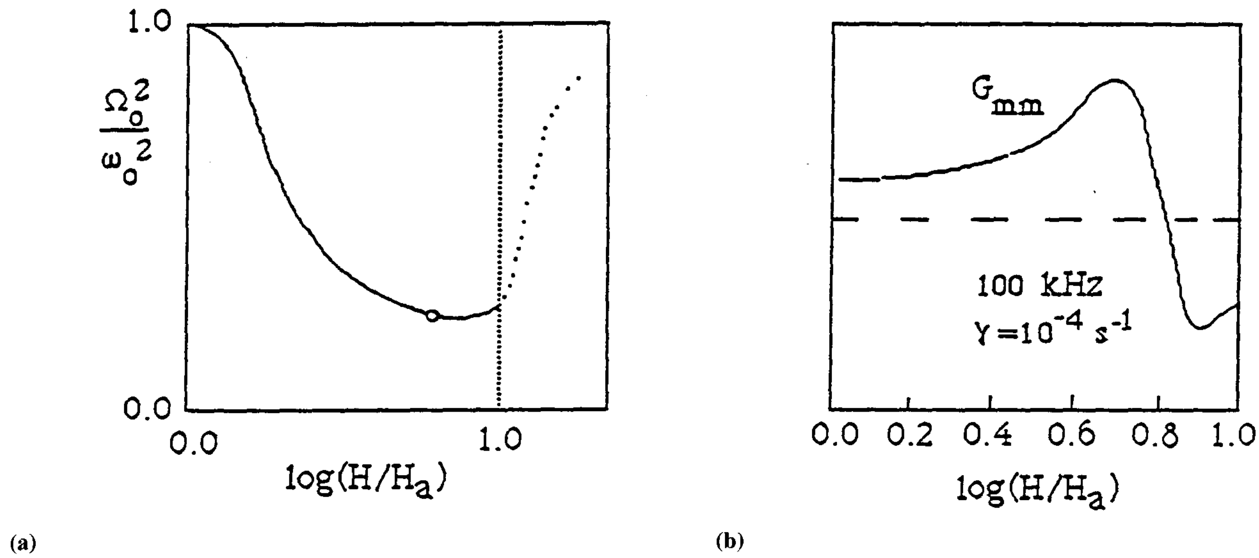

Fig. 11 (a) Bias field dependence of the square of the coupled *M-E* frequency, Ω_0, normalized to the drive frequency. Data point near minimum indicates point at which coupled susceptibility G_{mm} is plotted in (b). $\omega_0 = 10^5$ Hz and damping parameter, $\gamma = 10^{-4}$ s^{-1}.

metallic, it is damped by eddy currents. The acoustic loss in the elastic system, by comparison, is negligible in amorphous alloys.

The shape of a typical magnetoelastic tag sample and its low coercivity (due largely to its amorphous nature) lead to a *M-H* loop like that shown in Fig. 10(a). Such a loop is described below saturation approximately by the simple equation:

$$M(H)/M_s = \cos\theta = H/H_A \quad [6]$$

where H_A is the anisotropy field. H_A may be due largely to sample shape and generally amounts to a few Oe. For such a linear magnetization process, the magnetostrictive strain $e(H)$ is quadratic in H,[7] as shown schematically in Fig. 10(b):

$$\begin{aligned} e(H) &= (3/2)\lambda_s\,[\cos^2\theta - (1/3)] \\ &= (3/2)\lambda_s[(H/H_A)^2 - (1/3)] \end{aligned} \quad [7]$$

Finally, the magnetostrictivity (Eq 4) that couples elastic and magnetic modes

$$d = (3\lambda_s/H_A^2)H \quad [8]$$

increases linearly to a peak then vanishes at $H = H_K$ (Fig. 10c). Coupled magnetoelastic modes are strongest near the peak in d. The tag is made to operate near this point by placing a thin sheet of semihard magnetic material adjacent to the soft, resonating element, as was shown in Fig. 3 for the harmonic tag. A strip of Arnokrome®, Crovac®, or Vicalloy®, of dimensions comparable to those of the tag, can provide the bias field of a few Oe needed to hold the tag near its optimal *ME* coupling point near the knee of its *M-H* curve. If the semihard magnet ($H_c \approx 50$ to 100 Oe) is demagnetized, it no longer biases the *ME* element to its peak d value, and the sensor is deactivated.

As in any coupled oscillator, the frequencies of the coupled modes Ω_i are shifted from those of the uncoupled modes, ω_i. Figure 11(a) shows the bias field dependence (d dependence) of the square of the reduced coupled frequency, $\Omega_i(H)/\omega_i(0)$. It can be seen that the suppression of the resonance frequency has a shape that loosely reflects the field dependence of d in Fig. 10(c).

The coupled magnetoelastic susceptibility tensor has been derived by Spano et al.[8] and by Mermelstein:[9]

$$\begin{pmatrix} M \\ e \end{pmatrix} = \begin{pmatrix} G_{mm} & G_{me} \\ G_{em} & G_{ee} \end{pmatrix} \begin{pmatrix} H \\ \sigma \end{pmatrix} \quad [9]$$

Here, G_{mm} is not merely the magnetic susceptibility, dM/dH, but rather the magnetic response to a magnetic field for a coupled system. The calculated dependence of G_{mm} on the bias field is shown in Fig. 11(b).[10,11] The drive frequency, ω_o, is selected to be 100 kHz (open point, Fig. 11a) and the damping parameter is 10^{-4} s^{-1}. The desirable material properties for large amplitude response during excitation are large magnetization, large magnetostriction, and a transverse magnetic anisotropy that is not too strong.

The actual signal picked up by the detection antenna in a magnetoelastic tag system reflects the ring up and ring down of the tag as the drive antenna is turned on then off (Fig. 1c). Butterworth and Smith[12] have laid out the equivalent circuit model for a magnetoelastic resonator and identified the physical correspondence of each circuit element. They begin with the mechanical equation of motion, with the atomic displacement given by x and its time derivative by x':

$$\alpha x'' + \beta x' + \gamma x = F \quad [10]$$

Here, α is the system mass; β is the mechanical damping parameter; and γ is the force constant proportional to the modulus of elasticity. In the equivalent circuit derived from this equation, the magnetic inductance is proportional to the permeability of the magnetic system and the mechanical inertia to the square of the magnetostrictivity, d. The capacitance is inversely proportional to the permeability. The circuit resistance is due to the electrical resistivity of the tag (eddy current damping). The authors have used measured material parameters to determine values for these circuit elements[11] to generate the characteristic behavior shown in Fig. 1(c). After the drive antenna is turned on, the amplitude of the resonance increases as $A_o(1 - e^{-t/\tau})$. After the drive antenna is turned off, the tag rings down with a decaying amplitude $A_o e^{-t/\tau}$. The relaxation time is proportional to the product of the permeability and resistivity.

The equivalent circuit model is useful in that it indicates which physical properties of the material control the various characteristics of the signal. The loss process is not as well understood. Eddy currents in the magnet are a source of dissipation, but more importantly d controls the rate at which elastic energy is fed back into the magnetic system. So there is a dilemma: a large value of d is needed for a strong coupled M-E response, but not so large that the energy transfer is too quick. Without a better theory of loss mechanisms, it is difficult to define a quality factor that indicates just what an optimal value of d would be.

5. Noise

We have mentioned the problems associated with noise entering the EAS system from outside or leaving the system and interfering with other equipment or personnel. Here we consider generated within the tag itself.

There are two major sources of noise from the tag material, Barkhausen noise and magneto-thermal noise. Barkhausen noise results from the irregular motion of domain walls. It is usually characterized by its noise power spectrum. These spectra generally show that Barkhausen noise drops with increasing frequency, like $f^{-1.6}$ for $f \geq 10$ Hz.[13] Barkhausen noise can be appreciable; a value of 10 mV per turn at 60 Hz, over a bandwidth of 10 Hz, is typical for 3% SiFe. It is important for reliable harmonic tag operation that the greatest amount of flux change occurs in a single jump. This is the noise that is characteristic of the tag. All other branches of the M-H loop should be free of flux jumps and other magnetic material present (e.g., bias magnet, shielding) also should be free of noisy domain wall motion processes.

Thermomagnetic noise results from thermal fluctuations of magnetization and the associated magnetostatic field fluctuations. Equating the thermal and magnetic energies for a tag of volume, V

$$k_B T/2 \approx \tfrac{1}{2} BHV$$

we get a magnetostatic field fluctuation in terms of the permeability,

$$H_{noise} \approx \sqrt{kt/\mu V}$$

This noise is on the order of 0.2 μOe for a typical tag. This is not a problem in present tags, but it may be for a thin film tag.

6. Shielding

The antennas used to excite and detect EAS tags are highly complex in their design and function. The transmit antenna must focus its energy into the interrogation zone, not in directions where it could interfere with other electronic equipment, such as cash registers, computers, scanners, or other EAS detection systems. The receive antenna must be sensitive to the weak response of a tag, which may fill only one part in 10^{10} of the interrogation zone. It must not trigger an alarm in response to electrical signals from the transmit antenna, or from other electrical equipment or magnetic objects.

Magnetic shielding is often used with these antennas to improve their efficiency. The shielding material should have none of the characteristics of the type of tag for which the system is designed. This is obvious, but it is not trivial to achieve because the shield is much closer to the antenna and has a volume 10^7 to 10^8 times greater than that of the tag.

Specifically, for harmonic tags, the shields must be very linear in their magnetic response and especially free of harmonics in the frequency range of the tags. For magnetoelastic resonant tags, the shields must not exhibit any magnetoelastic ringing in the frequency range at which the tags ring.

Nonoriented steels have been widely used for shielding in EAS systems. They exhibit a rounded M-H response with moderate remanence and a fairly flat $\mu(H)$. Furthermore, they should be characterized by low Barkhausen noise, which could have high-frequency content in the range of the tags of interest.

7. Outlook

As mentioned earlier, the EAS industry is growing rapidly. The materials challenges lie in developing new tag signatures that are reproducible, reliable, deactivatable, and reactivatable. In addition, only safe field levels should be required to trigger the tag. Opportunities exist at higher frequencies where smaller tags may be used. Thin films and magnetic multilayers may offer many new opportunities for novel magnetic signatures. In terms of improving present tags and extending present materials, it appears that the greatest opportunities exist in magnetic annealing to increase stability, signal-to-noise ratio, and possibly even develop new loop characteristics for new tags.

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