PIEZOMAGNETIC CONTROL OF MACHINES

M R J Gibbs

Modern magnetic materials, particularly in thin film or multilayer form, offer piezomagnetic properties that have the potential to compete with piezoelectric materials in devices. This paper offers an overview of these new materials and their properties, gives a discussion of the potential benefits to be derived from using them, and gives an illustrative example of application in a device.

Modern piezomagnetic materials

For application of such materials in devices a number of basic criteria must be considered. For actuation using magnetostriction (the dimensional change on application of a magnetic field), a material with a low anisotropy constant, K, must be chosen in order to achieve a useful differential response; that is to achieve substantial strain for a small change in applied field. Further to this, account must be taken of the intrinsic, zero-field, domain structure in the magnetic material. It is important to ensure that the magnetisation process is dominated by moment rotation, and that the rotation angle over the range of activating fields is as close to 90° as possible.
By way of illustration we consider the deflection of a simple cantilever coated with piezomagnetic material. It has been shown [1] that for a magnetostrictive film of thickness t_f deposited on a cantilever of thickness t_s, the deflection d a distance l along the cantilever caused by a strain λ in a magnetic field is given by

$$d = 3l^2 \lambda \frac{t_f E_f (1+\nu_f)}{t_s^2 E_s (1+\nu_s)} \qquad (1)$$

for $t_f \ll t_s$, where the E_i are Young's moduli and ν_i are the Poisson's ratios. A typical maximum value for λ would be 60 ppm, and for a 100x5x1μm silicon cantilever, there could be a deflection of 1.5μm at the free end. Such simple deflection of a cantilever has been demonstrated [2], but the fields required were in excess of 1T due to the high anisotropy of the rare earth based films used.
A corollary to magnetostrictive strain is the field dependence of Young's modulus, the so called ΔE effect. Because the magnetisation is coupled to an applied strain via the magnetostriction, there is more strain for a given load in an applied field, than in zero field. An important application of this phenomenon for microelectromechanical systems, is the possibility of tuneable resonators. Any beam has a natural mode of vibration which is at a frequency related to its Young's modulus. The ΔE effect allows the construction of beams with a field dependent resonance. An application of this is shown below.
A natural choice of material would be an amorphous ferromagnetic thin film based on the transition metals. The non-crystalline structure quenches the macroscopic magnetocrystalline anisotropy, and the homogeneous and isotropic structure gives low coercivity, H_c, and high permeability, μ. Typical values would be $K=100\,Jm^{-3}$, $H_c=10\,Am^{-1}$ and $\mu=10000$ at low frequencies. Such films have been successfully grown on a range of technically significant substrates including GaAs(001), Si(001), Si_xN_y, glass and polyimide. A great deal is known about these materials in ribbon form [3] and similar properties are being observed in thin film form [4]. They can be successfully patterned using lift-off techniques [5], and are entirely compatible with micromechanical systems. Figs.1 and 2 show some typical magnetic data, and Fig.3 an atomic force microscope image of etched wires.
A more recent development in the materials area are piezomagnetic materials based on magnetic multilayer systems. Here the goal is to use the properties inherent to a layered structure to achieve higher magnetostriction than in bulk materials, whilst maintaining the magnetic softness.

M.R.J.Gibbs is with the University of Sheffield Centre for Advanced Magnetic Materials and Devices.

Fig.4 shows how the saturation magnetostriction constant and coercivity of an FeCo/Ag multilayer system varies with the thickness of the FeCo layer [5]. The Ag layer thickness was held constant at 2nm. The multilayers were grown using rf magnetron sputtering, and again have been produced on a wide range of substrates. Although these materials are polycrystalline, the grain size is very small, and the crystallographic nature such that again the macroscopic magnetocrystalline anisotropy is small. Material of this form was used in the demonstration device described below.

Potential advantages from the use of piezomagnetic materials

Piezomagnetic films are expected to achieve the goal of higher device integrity through enhancing reliability and providing diagnostics with the inclusion of self-test mechanisms. For example in accelerometers one method of self-test is thermal actuation. A magnetostrictively actuated device would have the very important operational advantage in that the actuation mechanism has DC stability. Piezomagnetic materials could overcome demanding packaging requirements, particularly for pressure transducers which are being required to operate at extremely high pressures (>1000 bar). Current pressure sensors require electrical connections to the diaphragm which must be lead out through the material of the pressure cell. The ability to sense diaphragm stress in a non-contacting manner would represent a major breakthrough. Another area of advantage could be in allowing the sensing of magnetic fields through a method of robust optical interrogation. This would find application in, for example, gear tooth sensing for aero engine systems.

Demonstrator device

By way of a demonstration project, and in close collaboration with the Lucas Advanced Engineering Centre, we have coated a Si microbridge with the FeCo/Ag multilayer described above. This microbridge formed part of a pressure sensor head. In the demonstrator the bridge was driven in to resonant vibration with pulsed laser light. The frequency of vibration was detected optically. As a magnetic field was applied to the device, the resonant frequency of the bridge could be tuned. The form of the response (see Fig.5) was that of a classic ΔE effect. Whilst the effect was not large, it must be remembered that nothing was done to try to optimise the performance. The importance of this result is two fold. It shows that piezomagnetic films can be integrated in to device structures, and also that the response can be controlled according to known physical principles.

Acknowledgements

The author is indebted to Prof.C.R.Whitehouse and Mr.R.B.Yates from the University of Sheffield Microelectromechanical Systems Unit, and Prof.S.J.Prosser and Mr.J.Dancaster of Lucas Advanced Engineering Centre, Solihull for discussions. The piezomagnetic film development has been supported by the British Technology Group and the Engineering and Physical Sciences Research Council.

References

1. Klokholm, E: "The measurement of magnetostriction in ferromagnetic thin films", IEEE Trans.Mag. Vol. 12 (1976) pp.819-821
2. Hayashi, Y. *et al*: "Dependence of magnetostriction of sputtered Tb-Fe films on preparation conditions", IEEE Trans.Mag. Vol. 29 (1993) pp.3129-3131
3. Thomas, A.P. and Gibbs M.R.J.: "Anisotropy and magnetostriction in metallic glasses", J.Magn.Magn.Mat. Vol. 103 (1992) pp.97-110
4. Mattingley, A.D., Shearwood, C. And Gibbs, M.R.J.: "Magnetic and magnetoelastic properties of amorphous Fe-Si-B-C films", IEEE Trans.Mag. Vol.30 (1994) pp.4806-4808
5. Lafford, T.A., Gibbs, M.R.J., Zuberek, R., and Shearwood, C.: "Magnetostriction and magnetic properties of iron-cobalt alloys multilayered with silver", J.Appl.Phys. Vol.76 (1994) pp.6534-6536

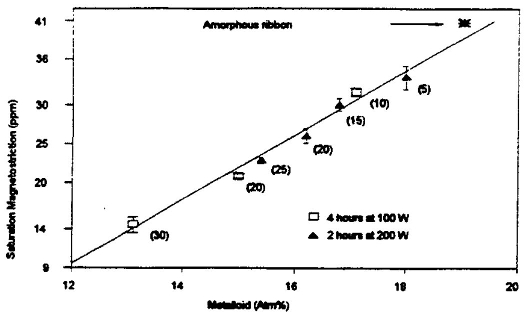

Fig.1 The variation of saturation magnetostriction with metalloid content in an FeSiBC amorphous thin film

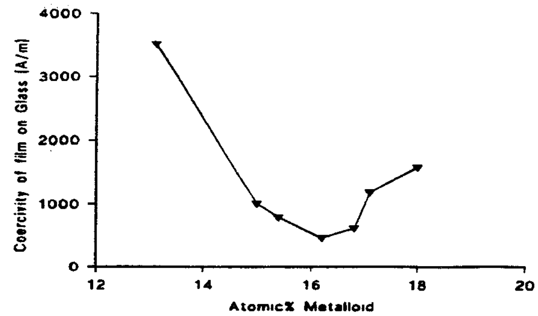

Fig.2 The variation of coercivity with metalloid content in an FeSiBC amorphous thin film

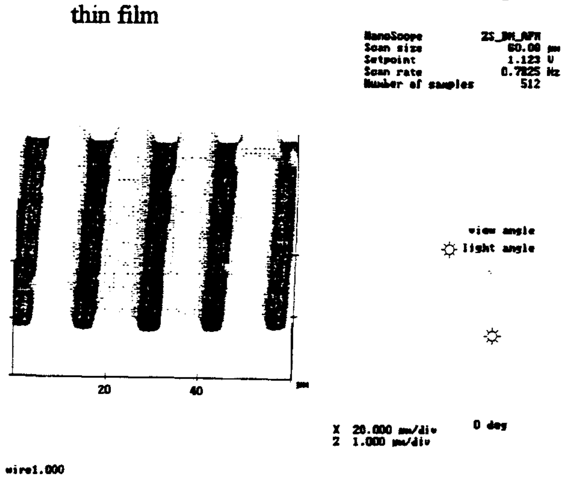

Fig.3 AFM image of patterned wires made from an amorphous ferromagnetic thin film

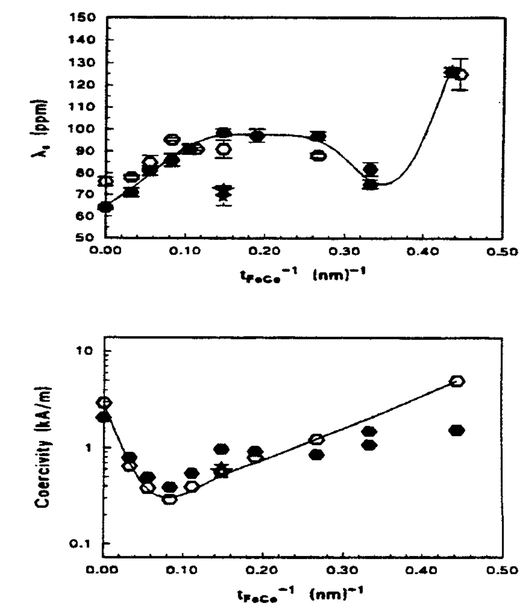

Fig.4 The variation of saturation magnetostriction and coercivity with FeCo layer thickness in an FeCo/Ag multilayer series

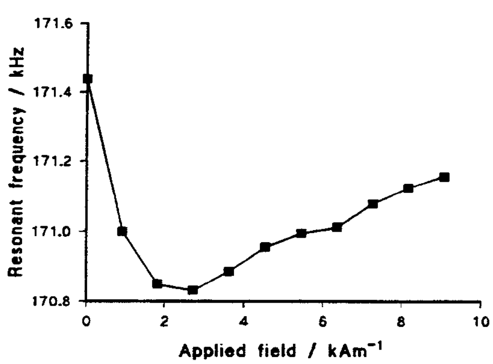

Fig.5 The variation of resonant frequency with applied field for a Si microbridge coated with an FeCo/Ag piezomagnetic film