Meissner-levitated micro-systems

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Abstract. Advanced silicon processing techniques developed for the Very Large Scale Integration (VLSI) industry have been exploited in recent years to enable the production of micro-fabricated moving mechanical systems known as Micro Electro Mechanical Systems (MEMS). These devices offer advantages in terms of cost, scalability and robustness over their preceding equivalents. Cambridge University have worked for many years on the investigation of high temperature superconductors (HTS) in flywheel energy storage applications. This experience is now being used to research into superconducting Micro-Bearings for MEMS, whereby circular permanent magnet arrays are levitated and spun above a superconductor to produce bearings suitable for motors and other micron scale devices. The novelty in the device lies in the fact that the rotor is levitated into position by Meissner flux exclusion, whilst stability is provided by flux pinned within the body of the superconductor. This work includes: the investigation of the properties of various magnetic materials, their fabrication processes and their suitability for MEMS; finite element analysis to analyse the interaction between the magnetic materials and YBCO to determine the stiffness and height of levitation. Finally a micro-motor with the above principles is currently being fabricated within the group.

1. Introduction
Very Large Scale Integration (VLSI) techniques developed for the manufacture of semiconductors can also be used to create extremely small scale mechanical devices commonly known as MEMS. A great deal of research has been carried out in this area and this paper concentrates on one aspect. That aspect is the problem of creating a small rotating device. Progress in this area has been severely limited by the problem of wear. Silicon is a very poor bearing material and even though VLSI can be applied to substrates other than silicon and coatings can be used bearing surfaces at this scale will always have short lifetimes because the rate of wear increases as the size of the device reduces [1].

A solution is to make a non-contact bearing such as a magnetic bearing. This could possibly be an Active Magnetic Bearing in which the device was self-sensing by detecting, for example, the change in capacitance as a rotor moves above the ground plane. Even though this could be done planar coils are extremely difficult to construct and are not particularly efficient. In general and in this geometry higher flux densities are available from permanent magnet materials. A bearing using permanent magnet materials can be stabilized using a superconductor[2]. In addition at this scale the Meissner effect can be used to lift the rotor into position. Thus we have a self-stabilising, self-positioning suspension system. This paper describes elements from this system.
2. Theory
The device is shown schematically in figure 1. The rotor is patterned into 4 poles superimposed onto magnetic rings. Two sections of superconductor are used; the top (closest to the rotor) level is granular and gives a strong Meissner effect thereby providing lift. The level below is melt-textured with strong pinning and provides stability.

Ordinarily a planar magnetic disc magnetized through thickness would have a very high demagnetization factor and therefore a low average flux density. This can be ameliorated by patterning the disc into pillars or rings so that locally the orientation of the magnetisation is parallel to the long access. Section 2.1 presents the results of a model which demonstrates how the average levitation force varies as the mark-space ratio of the rings or pillars changes.

The rotor is patterned using a mould constructed from an elastomer commonly used in MEMS processing known as PolyDiMethylSiloxane (PDMS) and the magnet is formed from NdFeB powder. The powder has an average particle size of 10 μm and is made by sieving powder created by ball milling NdFeB magnets.

There are many competing models for flux pinning [3-5] however the Meissner effect although well understood has rarely been modelled for a granular superconductor. We propose in section 2.3 a new model based on an equivalent $\mu_r$ derived from the M-H curve for a superconductor. This produces excellent agreement with both experimental results and with a supplementary model which calculates the levitation height from the change in magnetic energy as the flux is expelled.

2.1. Magnetic Modelling
A model has been created in Femlab™ to study the effect of patterning magnetic arrays. In this model the magnet is modelled as shown in figure 3. Each of the faces corresponds to a plane of symmetry so the whole model corresponds to a quarter of a unit cell of the magnetic array. Using the model it is possible to vary the mark space ratio and observe the effect on overall magnetic moment, magnetic flux density and crucially, for the purpose of this line of research levitation force developed between this magnet and a superconductor. Also shown in figure 3 is a contour plot showing that the peak levitation force is obtained when the gap (g) between the magnets and the width (w) of the individual magnets is of the same order. The precise ratio is dependent on the permeability of the magnetic material. Hard magnetic materials such as NdFeB and SmCo which have a relative permeability $\mu_r$ of 1 or close to 1 peak at a ratio of 2:1 material to gap, softer materials which are more easily demagnetised have a ratio of slightly less than 1:1 material to gap.

2.2. Patterning
Two techniques for creating magnetic arrays are being examined. The first is using electroplating to deposit CoMnNiP. A template is created using a copper seed layer with the desired pattern defined on it using the photoresist SU8 25 and conventional lithography. SU8 is used because it can be laid down in thick layers of up to 100 microns thick while still permitting a reasonably small feature size thus pillars with aspect ratios of the order of 3 can be created. The second technique also uses SU8 but in this case the SU8 is patterned from a PDMS mould. A PDMS mould is useful because it can be
reused and this cuts down the processing time. Having created the SU8 template the magnetic material used is NdFeB which has been ball-milled into an extremely fine powder and which is then pressed into the mould. This yields a material with a reasonable coercive strength with a M-H curve as shown in figure 2.

![Figure 3 – Magnetic Model Geometry and Results](image)

2.3. Meissner Effect Modelling

In order to produce a strong Meissner effect and achieve the levitation required it is necessary to use two sections of superconductor one melt-textured and the other granular. The granular material provides the Meissner effect but because of the granular nature it cannot be represented as a single Meissner layer. Typically an M-H loop is of the form shown by the solid line in figure 4. Since $H_{c2}$ is very large in comparison with $H_{c1}$ this can be represented mathematically by two straight lines (shown dashed).

$$M = -H; H < H_{c1} \quad M = -\lambda H_{c1} \left(1 - \frac{H}{H_{c2}}\right); H > H_{c1}$$

![Figure 4 – Typical M-H curve for HTS](image)

Values for $H_{c1}$ and $\lambda$ are obtained experimentally and the equation is then used to calculate the magnetisation and from that the levitation height for a magnet incident on the superconductor. This simple model has been checked against an equivalent calculation which assumes that the magnetic energy released is converted into kinetic energy and from there into potential energy. Figure 5 shows results obtained where the proximity of the magnet to the melt-textured YBCO and therefore the amount of pinning is varied by inserting copper spacers. Good agreement is obtained between model and measurement levitation height. Also shown is the calculated stiffness v. height in arbitrary units.
3. Conclusions
An ideal solution to the problem of wear in a rotating MEMS device is to use magnetic levitation. Using a superconductor enables this to be achieved without the need for active control. Flux pinning provides stability, the Meissner effect enables lift off. We are in the process of developing a MEMS motor which will be driven electrostatically and suspended magnetically. In this paper we have described some of the basic fabrication methods which are required and the modelling methods we have developed. We have achieved stable levitation in a planar device activated using the Meissner effect We are making magnetic arrays and are developing the additional patterning techniques required to implement the motor. Finally we have developed a novel method of analysis which combines modeling of the critical state with modeling of the Meissner phase.

References
[1] Williams J A, “Friction and wear of rotating pivots in MEMS and other small scale devices”, Wear 251 (2001) 965-972
[2] Coombs, T.A.; Samad, I.; Ruiz-Alonso, D.; Tadinada, K., “Superconducting micro-bearings”, IEEE Transactions on Applied Superconductivity, Volume 15, Issue 2, June 2005 Page(s):2312 – 2315
[3] C. P. Bean, “Magnetization of high-field superconductors,” Rev. Mod .Phys., vol. 36, pp. 31–38, Jan. 1964
[4] T. A. Coombs, A. M. Campbell, A. Murphy, and M. Emmens, “A fast algorithm for calculating the critical state in superconductors,” COMPEL—The Int. J. Computation Math. Elect. and Electron. Eng., vol. 20, no. 1, pp. 240–252, 2001.
[5] L. Prigozhin, “Analysis of critical-state problems in type-II superconductivity,” IEEE Trans. Appl. Superconduct., vol. 7, pp. 3866–3873, Dec. 1997.