Electrodeposited Magnetic MEMS: From Structures to Actuators

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Conductive, electroplated NiFe alloys such as permalloy have been widely used for the fabrication of electromagnetic MEMS components. One example of their application has been as energy storage elements in switched-mode power converters. As switching frequencies increase, it is possible to reduce the values and overall dimensions of the magnetic components in these converters. However, as frequencies increase (e.g., into the low MHz region and beyond), core losses (e.g., due to eddy currents) in unlaminated conducting cores also increase, driving the use of low conductivity core materials such as ferrites. Since many ferrites have lower saturation flux densities than NiFe alloys the overall dimensions of the device resist further miniaturization. Thererfore, there is a need for processes to fabricate laminations in conducting, micromachined permalloy cores.

In macro-scale magnetic devices, low-loss laminated cores are typically achieved by stacking alternating layers of core material and insulating material (which blocks eddy current flow), and laminating the entire stack together. As permeabilities and desired operation frequencies increase, lamination thicknesses should be reduced to the micron range (i.e., on the order of the magnetic skin depth) while simultaneously maintaining total core thicknesses of tens to hundreds of microns to prevent saturation. These requirements dictate large numbers of thin, high-aspect-ratio laminations, which are best achieved using micromachining technology itself. A manufacturable approach allowing micron-scale (or smaller) laminations and large total core thickness without the need for interposing vacuum steps or sub-micron lithography is presented. The approach is based on *sequential electroplating* to form densely alternating stacks of magnetic and nonmagnetic material. Previous work in sequential electroplating has produced compositionally-modulated stacks, which have been proposed as fabrication aids (Leith and Schwartz, J. Micromech. Microeng., 9, 97-104 (1999)) or nanostructured materials with improved wear characteristics (Yang and Cheh, J. Electrochem. Soc., Vol. 142, no.9, p. 3034-39 (1995)) This approach can be exploited to create laminations as well. For example, consider an alternating, conformal sequential electroplating of layers of NiFe and Cu, followed by selective sacrificial etching of the Cu. Since the copper sacrificial interlayer is itself conducting, it can act as a plating base for the subsequent deposition of NiFe without the necessity of multiple vacuum steps, multiple coating of insulating layers, or multiple photolithography steps. Highly laminated structures can therefore be achieved merely by alternating plating baths during fabrication, followed by selective removal of the Cu layers to provide electrical insulation between the magnetic layers (Figure 1). Additional features are also incorporated in the fabrication sequence to ensure mechanical integrity of the lamination stack after removal of the sacrificial layer. Inductors with highly laminated cores fabricated using the sacrificial layer approach exhibit quality factors exceeding those of unlaminated core devices by a factor of 3-4 at a frequency of 1 MHz (Park, Cros, and Allen, Proc. MEMS 2002).

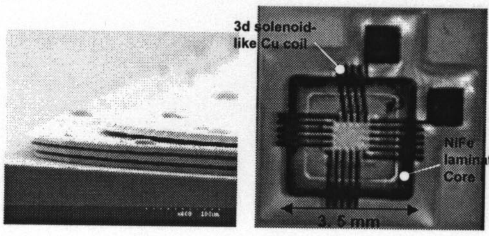

Figure 1: *Close view of surface micromachined, laminated permalloy core (left). Integrated inductor fabricated with laminated core (right).*

The approached described above can also be applied to electromagnetic actuators. Since these devices typically operate at relatively low frequency (even down to DC), laminations are typically not required. As an example, consider a micromachined switch utilizing magnetic actuation. Electromechanical relays remain widely used for a number of applications including automotive control circuitry, test equipment, and the switching of high frequency signals. Historically the manufacturing process of electromechanical relays has been serial, i.e., devices are built one at a time, which can result in production bottlenecks and make it difficult to produce large relay arrays. Solid state relays (SSRs) have been one solution to this production problem. SSRs allow for devices to be batch fabricated; however, in some cases they may also have higher offset voltage injection, lower maximum off-state resistance, and higher contact power dissipation than their electromagnetic counterparts. Micromachined relays (Taylor and Allen, Proc. Transducers '97) are produced by the application of batch fabrication techniques to electromechanical relays in an attempt to combine the best attributes of both electromechanical relays and SSRs. This particular device uses a single layer coil to actuate a movable upper magnetically responsive platform. The minimum current for actuation was 180 mA, resulting in an actuation power of 33 mW. Devices have been tested which can make and break 1.2 A of current through the relay contacts when the relay is electromagnetically switched. Operational lifetimes in excess of 300,000 operations have been observed. A normally closed relay has also been developed through the addition of permanent magnets to the microrelay. These devices have also been able to electromagnetically switch 1.2 A of current. Multi-pole devices, which contain more than one pair of contacts per coil have also been realized, and possess comparable performance characteristics to single-pole devices.

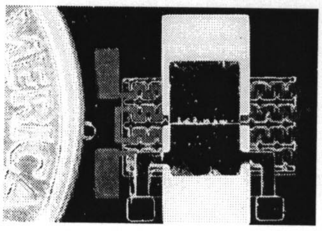

Figure 2: *Photomicrograph of a cantilever microrelay shown next to a dime. This type of relay has been able to switch 1.2A by means of electromagnetic actuation of the upper plate.*