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A comparison of two multilayer microcoil fabrication techniques

A. C. Hartley, R. E. Miles, J. Corda
School of Electronic and Electrical Engineering
University of Leeds, Leeds. UK. LS2 9JT

ABSTRACT

The use of magnetic actuators at the microscale has so far been limited when compared with the alternative electrostatic approach. This is mainly due to the fabrication difficulties encountered when producing magnetic components at the microscale. However, the force available from a magnetic actuator far exceeds that of its electrostatic counterpart for a given footprint area, as the magnetic devices have a greater potential to be fabricated into the third dimension. The ability to create multiple layer microcoils, easily and reproducibly, would greatly exploit this fact, enabling devices to be constructed that can produce actuation forces/distances far in excess of any other currently available microtechnology. To this end, the fabrication of two types of multiple layer coil has been investigated, both based around the ultra-thick negative photoresist, SU-8. Single, double and quadruple layer coils have been fabricated in electroplated copper and a commercially available silver colloidal paint. The fabrication times and processing steps have been assessed for each, together with the respective conductivities and the maximum current densities, before burnout of the conductors. The thermal implications of stacked multi layered coils have also been assessed. The coils fabricated have a diameter of 0.93mm.

Keywords: Multiple layer, microcoils, SU-8, silver colloid, electroplated copper

1. INTRODUCTION

Since the emergence of MEMS as a viable technology for the production of small, inexpensive and fast actuators and sensors, there have been many different technologies and techniques that have led to what is increasingly becoming a commercially exploitable field. As with all technologies however, there are some ideas that are more favoured and suitable than others, based upon their particular merits. In the world of microactuation two technologies tend to stand clear of the rest – electrostatic and electromagnetic. The former is traditionally preferred owing to its simplicity of fabrication and design though there are many well documented problems such as high operating voltages, low actuation forces and stiction. In contrast, electromagnetic actuation tends to be more difficult to design and fabricate, but for a given footprint area, can produce a larger actuation force because, unlike electrostatic devices, they readily lend themselves to three dimensional geometries.

A typical electromagnetic actuator consists of a stator which will be a flux generator in the form of a coil or hard magnetic material and a moving element that can be another flux generator or a soft magnetic material. Soft magnetic materials can be coupled to the stator and used to capture and guide the magnetic flux to a desired space such as an air gap. All of these elements have volumetric qualities that affect the device performance. Fig 1a demonstrates the concept of a typical single coil magnetic actuator placed on a soft ferromagnetic substrate with the mover, in this case being a soft ferromagnetic material.

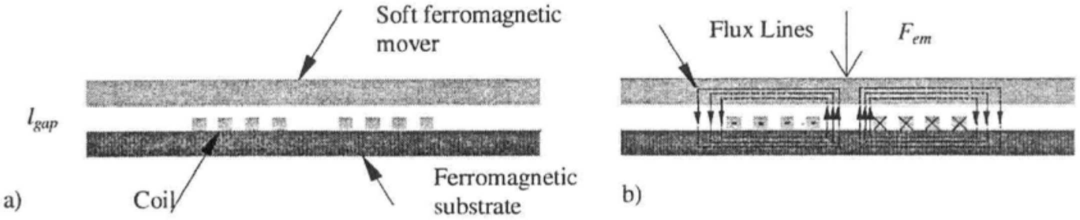

Fig 1. a) A cross section of a simple electromagnetic microactuator, b) the same actuator energised

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If we assume for simplicity that the mover is a soft ferromagnetic material, when the coil is energised the flux lines will pass through it as shown in Fig 1b. It will then be pulled towards the stator of the device and closing the air gap between the two. Assuming that there is no loss of magneto motive force, mmf, in the magnetic substrate and ignoring any fringing effects of flux in and around the device, the force on the mover generated by the field can be expressed approximately by simple electromagnetic theory as:

$$F_{em} = \frac{\mu_0}{8 l_{gap}^{2}} A (NI)^2 \qquad 1.1$$

Where N is the number turns in the coil, I is the current passing through each turn, A the pole face area associated with the flux and l_{gap} is the length of the air gap.

This simple expression demonstrates the increase in force that can be gained by increasing N, I and A. For a fixed footprint area there is an optimum ratio of pole face area and coil area to achieve the maximum force meaning that the volume filled by the copper is fixed. Because of the permissible temperature the NI product cannot be increased within this volume and we need to fabricate further layers of coil on top of the first, or increase the thickness of the coil to allow for a greater current to pass without unwanted temperature build up. The force, F_{em}, rises as the square of NI so multiple layers would result in a significant increase. In practice the increase may not be ideal due to a reduction in the surface to volume ratio and thus a lower thermal efficiency. However, if the thermal conditions can be controlled, then the resulting increases should be considerable. For example, if the same current could be passed through a four layer coil as that for a single layer coil, the increase in force would be a factor of 16. Equally, considering the same example the switching distance could be increased by a factor of four while retaining the same force.

Research in to the fabrication geometries of microcoils has been quite inventive over recent years to avoid using the third dimension. Ref[1,2] gives good examples. There are however examples of three dimensional coils e.g. Ref[3] is an example of a true spiral inductor though the potential seems limited due by the complex fabrication requirements. Ref[4] demonstrates another innovative 3d coil though this would have limited use as an actuator. The coils discussed in Ref[1 - 4] are electroplated in copper. This tends to be a reliable method but costly in terms of time and processing tolerances. Ref[6] provides details of several different types of coil including a double layer coil used as a transformer though due to its design being quite planar it would not be ideal for use as an actuator.

One aim of the work described here is to investigate the stacking of single layer electroplated coils and suggest an alternative that is easier, quicker and more reliable to fabricate, not only to facilitate exploitation of the third dimension, but also as a quick and easy way to produce inexpensive coils for use in a wide range of applications. Furthermore, these coils could be used for the testing of prototype magnetic elements where a realistically determined flux is needed to obtain accurate information for a ferromagnetic microbeam or micromagnet. Alternative methods for this purpose exist as demonstrated in Ref[5] where a surface mounted inductor was adapted to provide the flux and although this has limited success, the flux generated is not as realistic as would be produced in an actual microactuator.

An alternative conductive medium is proposed in this investigation and is a solvent based silver colloidal material that can be deposited in a mould, as opposed to electroplating a conducting material into the mould. The two methods of fabrication proposed are similar and based around an SU-8 former. (SU-8 is a photoplastic which is finding increased popularity amongst microfabricators seeking to make high aspect ratio microcomponents and electroplating moulds for LIGA style fabrication.) Both approaches are explained together with a discussion of the chosen coil design and its implication, not only to the fabrication methodology, but also to the possible consequences on the device's operating characteristics. Single, double and quadruple layer coils have been fabricated in both technologies and compared for ease of fabrication, processing time and number of steps. The conductivity and maximum possible current density before burnout have also been measured.

2. COIL DESIGN

The general concept for the fabrication of the coils is best described as stacked fabrication whereby a layer of coil is fabricated, followed by an insulating layer and then a second coil placed on top with the two connected by a via. This is described in Section 3 (Fabrication).

As for the design of the individual layers of coil the specifics are not of great importance in terms of shape (i.e. round or square) as this will not really change the 'stackability' of the layers. Size is an important factor however, as this will affect the fabrication criteria. If the coil's diameter is reduced excessively then there could be unnecessary complications in the fabrication caused by lithography issues and the channel filling ability of the electroplating solution or of the colloidal material. Conversely, if the coils are made excessively large, then the use as a rapid prototyping tool or test bed for magnetic micro components, would not be viable.

For these reasons it was decided to make circular coils (given that they are more efficient in terms of space) with a diameter of 0.93mm with a central pole diameter of 250μm. Fig. 2 shows a schematic for two individual layers of coil. The first and second layers in the coil are drawn so as to keep the current flow in the same direction through the layers.

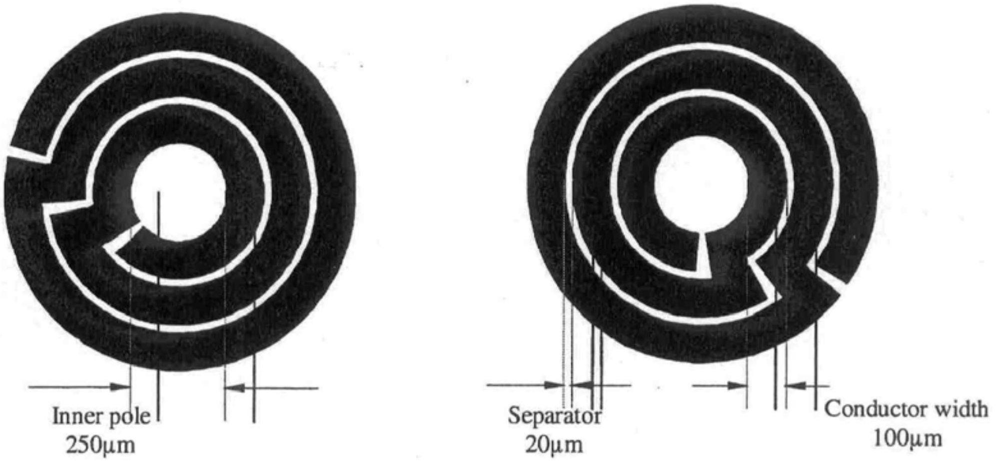

Fig 2 Configuration of individual layers of coil: a) 1st layer and b) 2nd layer

When deciding on the number of turns and conductor thicknesses several things were considered. First is the separation of the conductor turns. It is not only important to consider the mechanical strength of the barrier, but also its use as an electrical isolation. There will be a potential difference created between turns of the coil due to its resistance and if the SU-8 mould wall is not thick enough the turns could short out. If the conductors are too thick or too many in number then valuable footprint area could be lost unnecessarily to the photoplastic instead of being filled with copper. The calculations for these factors are not shown here as they are rudimentary in nature. In short, it was decided that the dividers would be 20μm wide and the conductors 100 μm wide.

The thickness of each individual layer is another factor that requires attention. If the thickness is too great then there will be unwanted complications in the fabrication of both the paint and the electroplated copper coils. Likewise if the layers are too thin then there will be unnecessary fabrication or a reduction in *NI* for the amount of layers made. After several trial experiments with the silver colloid it was decided that 50μm was an ideal thickness which also suited the electroplating. These experiments are described later.

3. FABRICATION

The fabrications processes for both sets of coils were similar to allow for an accurate comparison of data. 1mm thick glass microscope slides were used as the substrate for both cases.

3.1. Electroplated multilayer coils

It was decided that the best conductive material deposition method to use for our purposes was an acid based copper plating, as it is easy and safe to implement and commercially available. The copper plating solution used was CuBath 482 which is made by Enthone-EMI and is typically used for IC fabrication. The manufacturers processing recipe was used and no attempt was made to optimise it for speed of deposition, surface quality or conductivity. (Another recipe was taken from Ref [7] and though this proved to have a slightly higher conductivity, its deposition was poor and unreliable.) The only variance made to the CuBath 482 was the addition of a small amount of methanol to lower the surface tension of the solution, preventing any bubbles getting trapped in the mould at the start of the plating creating discontinuities in the conductors. Anodes with a phosphorous content, believed to be 4%, were used along with air agitation and a current density of 25mA/cm^2.

The fabrication of the coils is of a LIGA style utilising the ultra thick negative photoresist (photoplastic) SU-8. This photoresist is finding increasing usage in the MEMS community for various purposes and relevant data is readily available in the literature and from the manufacturers, MicroChem Corp [8]. For this reason only the processing steps used here will be briefly described. All the SU-8 used in this work is part of the SU-8 2000 series.

The surfaces of the glass substrates were roughened slightly (to improve adhesion) and then cleaned with organic solvents and dried at 200°C for 10mins. To further improve the adhesion of the coil structures, a 10μm thick layer of SU-8 is spun, prebaked, given a long blanket exposure and postbaked at 120°C to ensure a good cross link in the SU-8 and maximum adhesion. To retain this property it is preferable to avoid thermal shocking of the samples and so they should not be heated or cooled at a rate greater than 4°/min when temperatures exceed 50°C. Though this may seem extreme it proves necessary given that in a four layer coil there could be as many as eight layers of SU-8 coupled with several lapping stages all of which can lead to a catastrophic failure of adhesion.

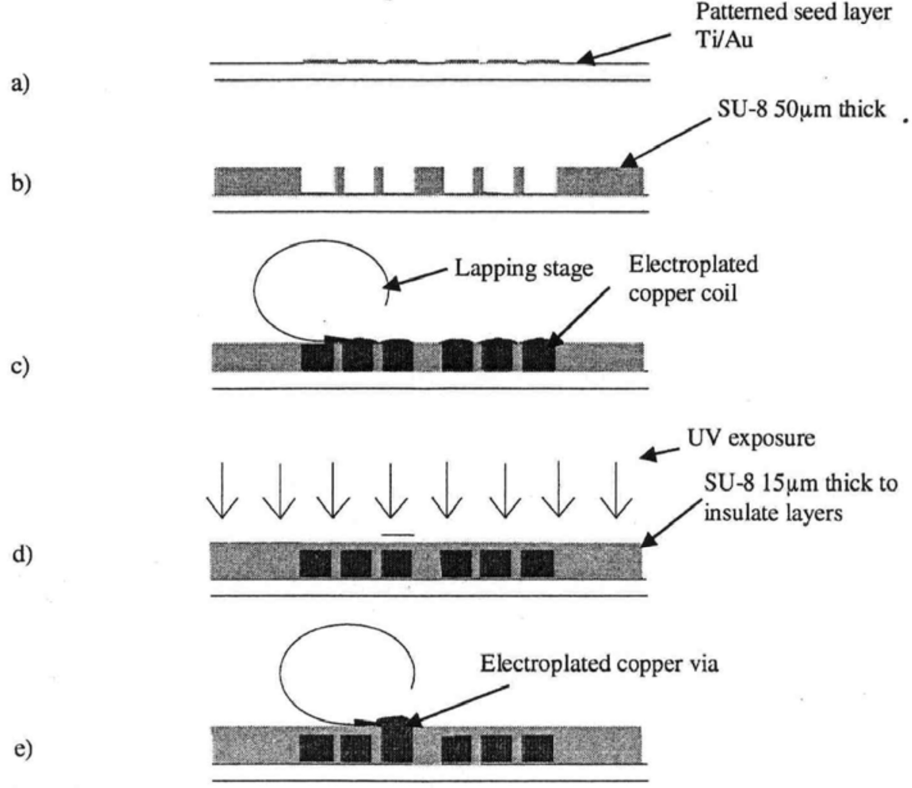

Fig.3 shows the fabrication steps described above

The following fabrication steps, illustrated in Fig 3, describe the main points for the multilayered electroplated coils. The SU-8 adhesion layer is not shown in the diagram. A layer of Ti/Au is evaporated on to the adhesion layer and patterned using a standard lift-off technique to produce a coil shaped seed layer for the electroplating, Fig 3(a). A 50µm layer of SU-8 is processed, exposed and developed on top of the seed layer to provide a coil mould to correspond with the seed layer, Fig 3(b). The SU-8 can then be plated for eighty minutes until the mould is filled and the sample lapped until a suitable surface is achieved as it is unlikely that after a 50µm plate the surface finish will be flat enough for further plating, Fig 3 (c). The next layer of SU-8 at a thickness of 15µm is to provide electrical insulation between the layers, Fig 3(d). A via hole is patterned in this layer and plated into until it is filled, Fig 3(e). Another lapping stage may be performed here if required. From here steps a) through e) can be repeated as many times as required to provide a stacked coil. Obviously, the last coil does not need a via as the connection can be taken from the edge of the coil (this presumes the layers are made in multiples of two).

3.2. Silver colloid multilayer coils

The silver colloid is a solvent based 'paint' supplied by RS in the UK Ref[9]. This particular colloid was chosen above others due to its availability and cost effectiveness.

The fabrication of the silver colloidal coils is similar to that of the electroplated device but with the electroplated copper replaced by the silver paint. To ascertain the optimum fabrication of the coils in terms of conductivity, speed and reliability of the deposition steps the thickness of the mould and bake times were adjusted by trial and error to find an optimum. Several thicknesses of SU-8 mould were tried to minimise the trapping of air bubbles during the spreading and also to allow the solvent to escape during the bake. Moulds ranging from 20µm to 100µm in depth were tested at widths of 50µm and 100µm. Both the widths worked well although the latter had better results in terms of conduction. It is presumed that the surface tension between the paint and the mould sides did not allow the silver particles to settle and compact properly. Of the thicknesses tried there was a rapid fall off in success after 50µm with air pockets forming in the conductive path in over 60% of the samples of 100µm deep and 100µm wide. This is compared to around 20% at 50µm thickness and 100µm wide. This is partly due to the spreading action trapping bubbles and partly due to the initial thickness of the paint (400µm) creating evaporation problems for the lower levels. The reduction in height of the paint after spreading is dependant on its solvent content which in turn is dependant on the age of the paint, though shrinkage of 75% would be a good general estimate.

The same glass substrates and adhesion layer was used as in the electroplated copper coils. SU-8 is processed 50µm thick and patterned in the shape of the coil to a form a mould for the paint, Fig 4 (a) and (b). The paint is then spread to a thickness of 200µm, Fig 4 (c). Before commencing any fabrication, it is necessary to agitate the paint for at least two minutes and leave it to settle for two hours. The spreading was done with a tool designed and ordinarily used for depositing thick layers of resist (as opposed to spinning)[1]. After spreading the desired thickness, the paint sample is baked on a hot plate to remove the solvent. The baking of the samples has quite a significant effect on the conducting properties of the colloid. Baking at high temperatures too soon in the curing process causes the formation of solvent pockets throughout the conductor's thickness and while baking too slowly extends the fabrication time which is undesirable. After trying several combinations of bakes it was decided that for a 50µm thick coil the sample should be moved immediately after deposition to a 30°C hotplate and the temperature ramped up to 120°C at 3°C/min followed by a further ramp up to 200°C at 6°C/min. After this the temperature can be reduced back down to 50°C before lapping the sample to remove the unwanted paint left on the substrate surface. The next step in the processing is to apply a second coat of SU-8 at 15µm thickness with a via hole exposed but not developed. A second layer at 50µm can then be deposited on top of this insulating layer and patterned for the next coil layer upon which the paint can be applied as above. This can be repeated as necessary to achieve a multilayer coil.

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[1] The spreading machine is a device that holds a substrate parallel to the path of travel of a blade. The height of the blade can be adjusted and manoeuvred to spread the desired thickness of a given substance onto the substrate with an accuracy of +/- 1µm at any given spot.

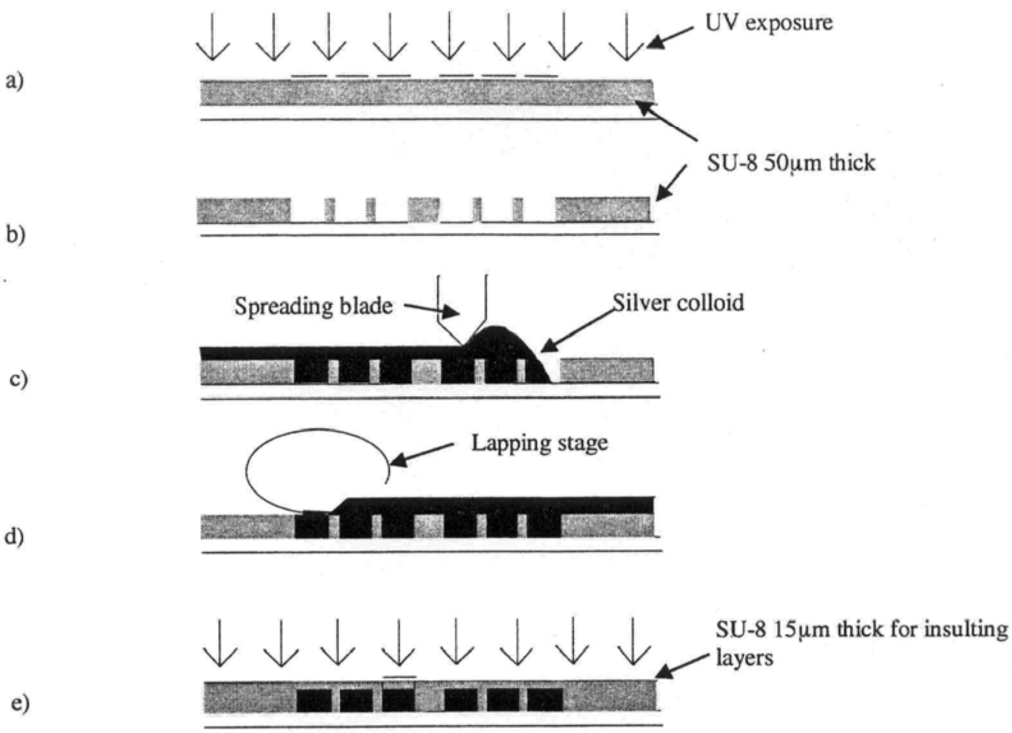


Fig. 4 Schematic diagram of fabrication for first layer of silver colloidal multiple layer coils. See text for stage explanation.

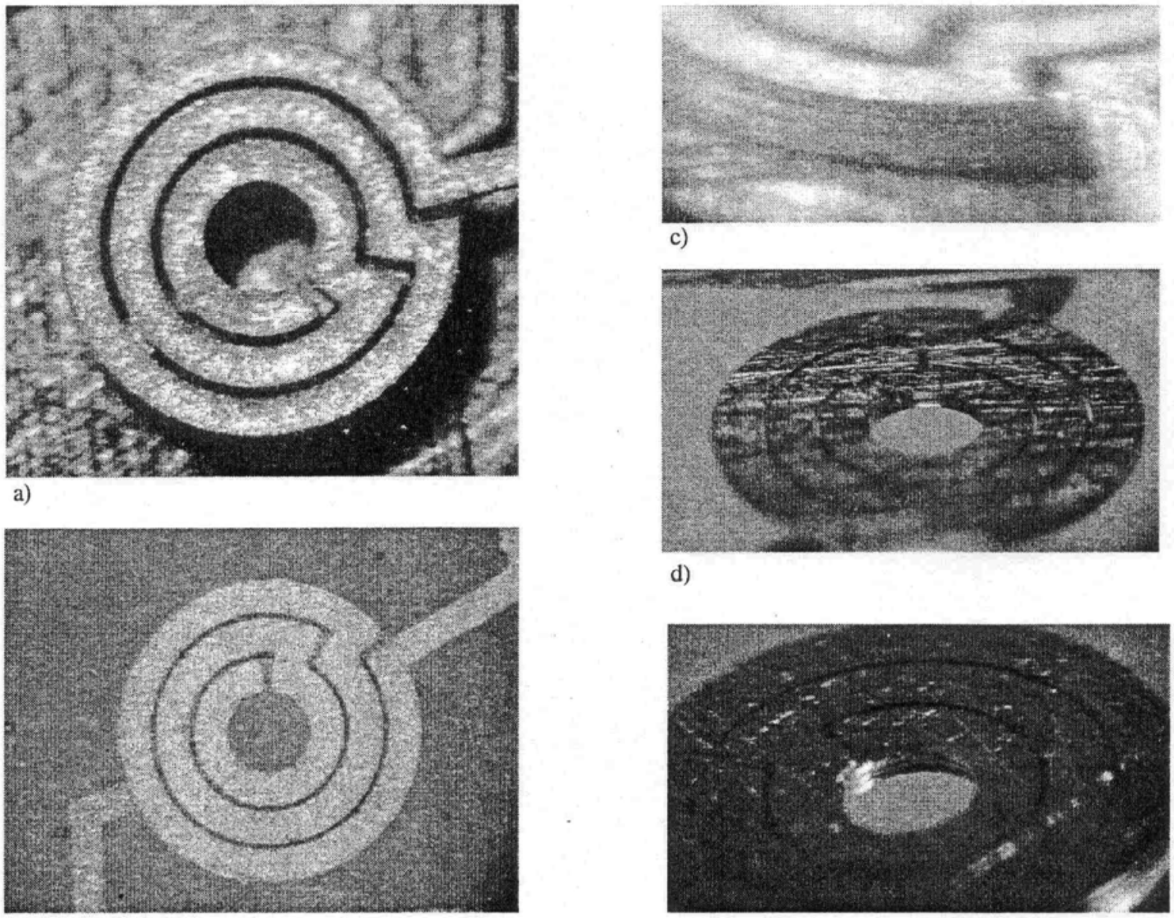
To increase the conductivity of the silver colloid it was found that the higher the bake temperature the better. Unfortunately, a degradation in the SU-8 is experienced at around 250°C. Also, if these coils are to be used in conjunction with other magnetic components as is likely, then the temperature needs to be kept below 200°C so as not to exceed any possible Curie temperatures. For this reason it is preferable to pass a current through the paint samples upon completion but before use to generate some intense local heat and achieve the maximum conductance possible. A regulated current supply was used to ramp the current through the coils up to 80% of the maximum value. During this time the voltage falls in accordance with the increase of conductivity which on average was found to be around a factor of six. No harm to the SU-8 mould was observed during this time.

4. RESULTS AND DISCUSSION

The two types of coils have been successfully built in single, double and quadruple layers, a selection of which are shown in Fig 5. The scratch marks on the copper coils were not polished out given the risk of adhesion failure.

One of the most significant aspects to consider with regard to the performance of the multilayer coils, or indeed any conductor, is that of its resistivity. To measure the resistivity of the two materials, ten strips of each was fabricated 10mm x 0.1mm x 0.05mm and the resistance measured in each. Good consistency was experienced by all the samples. The resistivities were calculated from measured resistance and are 10×10^{-8} Ωm and 3.1×10^{-8} Ωm for the silver colloid and copper respectively.

The maximum current density before burnout was also measured in the test strips to provide a base line for a similar measurement in the coils. This way any reduction in the current density could be reliably attributed to the thermal build up in the coil and give some grounds to the usefulness of the multilayers. A steady state test was performed whereby the current was increased in the test strips and left to reach steady state for 30s before incrementing the current by 0.2A. There was no attempt to remove the heat from the coils during this test and for this reason the figures listed below could be improved upon with the addition of heat sinks. The maximum current through the copper strips was 7A and through the paint 2.4A relating to a current density of 14×10^{8} Am^{-2} and 4.8×10^{8} Am^{-2} respectively. This represents a reduction by a factor of approximately 3 in the painted structure when compared to the copper, which is constant with the result obtained for resistivities.


a)

b)

c)

d)

e)

Fig 5. Optical photos showing the a) a plan view of the quadruple layer colloidal coil, b) a plan view of the double layer coil, c) an angled view of the quadruple layer colloidal coil, d) an angled view of the double layer copper coil and e) an angled view of the quadruple layer copper coil.

The maximum current density and resulting *NI* product for each coil is given in Table 1 below.

	Single Layer		Double Layer		Quadruple Layer	
	J 10^8 A/m^2	NI A	J 10^8 A/m^2	NI A	J 10^8 A/m^2	NI A
Paint	3.2	4.4	2.2	6	1.4	7.7
Copper	9	12.4	6.2	17	4	22

Table 1 The current densities and NI for the single, double and quadruple layer coils

There is a distinct reduction in the current density as the number of layers is increased owing to the temperature build-up in the coils as a result of a reduced surface to volume ratio. This factor will reduce the effective usefulness especially as the ability to conduct the heat away becomes increasingly more difficult as the layers are added. These figures could be improved upon by fabricating the coils on a thermally conductive substrate or by placing similar material around the coils. It is also unlikely that the coils would be driven in the steady state and would more likely be pulsed in some sort of switching signal of a given frequency and duty cycle. Given the variety of solutions this issue was not pursued further.

The main aim of the work was to develop a technology whereby coils – multilayer or single – could be fabricated with a minimum of fabrication steps and time. The issue of time is obviously related to the equipment being used. However, it would be fair to say that the silver colloid would take approximately 40% less time per layer of coil and via than that of copper with the number of processing steps experiencing a similar reduction.

The yield of the devices is difficult to quantify in doing prototype work such as this. It was found that the electroplating suffered very few faults once the recipe for the electroplating was refined. As for the silver colloid, much is dependant on the condition of the material at the time of fabrication. There is a good deal of parasitic evaporation of the solvent associated with the colloid and hence the parameters change somewhat depending on the age of the paint. The production of solvent pockets in the conductors is also of concern. However, if the paint is left to settle for long enough after agitation and before being deposited and the baking is kept to a slow ramp rate as suggested above, this problem can be reduced to a minimum.

If the quadruple layer copper coils as presented in this paper were used in an actuator under steady state conditions, then there could be an increase of force by a factor of 3.15 when compared to the single layer. If all the heat could be removed by either using a suitable duty cycles and/or heat removal methods then the figure could, in the ideal case, be as high as 16. This is unlikely in practice, but there is certainly a need for further investigation into how the removal of heat might best be achieved. Even with the figure presented here, the extra fabrication demands of such technologies are more than justified.

The colloidal coils have proved to be a fast and reliable method of fabrication ideal for use as proof of concept and testing fabrications. Although the conductivity is less than that of the copper versions, this should not matter greatly when used in systems where efficiency is of no great concern and the duty cycles can be such to allow the removal of heat.

5. CONCLUSIONS

The fabrication of two types of multiple layer coils – copper and silver colloid - has been considered and compared. The more traditional copper coils have a higher conductivity but take far longer to produce with more fabricating steps. The silver colloidal coils make ideal prototyping tools where realistic micro magnetic fields are needed to test other micro components. The thermal limits of the stacked coils have been briefly touched upon quantitatively to demonstrate the non proportional increase of NI product for every added layer. The increase in force gained from using such coils, even with poor thermal characteristics, it is still well worth the more demanding multilayer fabrication.

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