FLEXIBLE PARYLENE-BASED MEMS INDUCTOR WITH $NI_{80}FE_{20}$ MAGNETIC CORE FOR MAGNETIC ENERGY COUPLING SYSTEM

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Abstract: Integrated flexible parylene-based inductors were successfully designed, fabricated and analyzed. Using parylene as the substrate, the inductors have good flexibility and biocompatibility. With the $Ni_{80}Fe_{20}$ core, the inductance was enhanced by 235% maximally and the quality factor was also improved significantly. The square spiral inductor showed the inductance of 800nH at 55MHz. The coil coupling power transmission system based on these inductors was set up and tested. The minimum attenuation was -21dB at 36MHz. The integrated fabrication process of the coils was fully IC compatible, which could be utilized in many implantable devices.

Keywords: MEMS inductor, $Ni_{80}Fe_{20}$, soft magnets, electrodeposition

INTRODUCTION

Nowadays, the emergency of implantable medical devices based on micro-electro-mechanical systems (MEMS) technology has been a milestone in the development of medicine. For example, a high efficiency MEMS actuator which could realize precise drug delivery application was reported in [1].

However, the problems in seeking a proper power source greatly limit the applications of MEMS implantable devices. Although the battery is always the first choice, it is really not suitable for implantable applications due to the limited lifespan and bad bio-compatibility. Compared with batteries, inductively magnetic coupled system has been a promising power source because of its long lifetime, small volume and good biocompatibility [2, 3]. Ref. [2] reported a wireless power recharging system design for implantable bladder pressure chronic monitoring application. In [3], a battery-free compact neuro-stimulator was successfully powered by an inductively coupled system.

But the research for realizing high efficiency system is still in progress. The poor performance and biocompatibility problems of inductors always limit the overall performance of the system [4]. Although the handmade coils could provide high inductance and quality factor (Q-factor), the biocompatibility problems will limit its applications in implantable devices. By contrast, MEMS inductors exhibit considerable advantages, such as small volume, IC-compatible fabrication and good biocompatibility, but the poor performance is the critical problem. In [3], using MEMS inductors, the device was more than 50 times smaller than traditional devices, but the energy transmission distance was only 1mm which was too short for many other applications.

Therefore, in recent years, many researches focus on how to enhance the inductance and Q-factor of MEMS inductors, such as the 3D structure in [5] and the folding method in [6]. But as using complicated structures, the complexity of fabrication increased.

In this paper, based on electrodeposition technique, on the parylene substrate, we tried to integrate MEMS coil with $Ni_{80}Fe_{20}$ soft magnetic core. Thus, the Permalloy can enhance the inductance and Q-factor of the coil. Meanwhile, the parylene layer can provide good flexibility and biocompatibility.

DESIGN OF MEMS PLANAR INDUCTORS

In this study, in order to improve the inductance and Q-factor, the planar flexible parylene-based inductor with $Ni_{80}Fe_{20}$ soft magnetic core are designed and fabricated.

Fig. 1 illustrated the structures of the inductors, which consists of copper coils, $Ni_{80}Fe_{20}$ soft magnetic core and parylene substrate.

The high permeability of soft magnets can increase the magnetic flux in the center so that enhance the performance of the inductors. Several soft magnetic materials, such as NiFe, CoNbZr and FeHfN, were introduced in previous research [7]. In this study, $Ni_{80}Fe_{20}$ was chosen to be the soft magnetic core. Compared with other materials, $Ni_{80}Fe_{20}$ alloy has a high relative permeability which can lead to a large inductance enhancement. And the lower resistivity of $Ni_{80}Fe_{20}$ can reduce the additional energy losses in the core so that the Q-factor of the coils can be improved. Furthermore, $Ni_{80}Fe_{20}$ can be fabricated by electrodeposition technique, which has lots of advantages such as simple setup, low cost, precise pattern control and IC-compatibility.

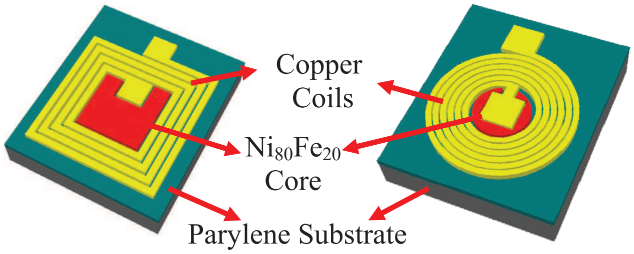


Fig. 1: 3D schematic of inductors with magnetic core

Parylene layer is used as the substrate to provide good flexibility and biocompatibility. According to [8], parylene can well protect the device as long as 60 years at body temperature. Thus, parylene is perfect for MEMS implantable applications. In this paper, the metal electrodeposition on soft parylene layer was optimized and realized.

In order to analyze the effects of $Ni_{80}Fe_{20}$ core, as is shown in Fig. 1, we designed both the square and circular spiral coils. To make comparison between coils with air core and FeNi core, several inductors were designed as listed in Table 1.

Table 1: Design of different inductors

No.	I1	I2_Air Core	I2_FeNi Core
Type	Square	Circular	
Coil (μm)	*w*=300, *d*=100	*w*=200, *d*=50	
Core (μm)	3000×3000	Air Core	*Radius*=1000

FABRICATION PROCESS

In this paper, based on our previous research for electrodeposition of magnetic materials [9], a simple integrated fabrication process is suggested in Fig. 2. The detailed process is as follows:

- 10μm parylene layer was deposited on silicon wafer and Ti/Cu layer was sputtered on the substrate as the seed layer for electrodeposition;
- The mold for Cu coil was built by the 1st thick photoresist lithography and 10μm copper was electroplated;
- By the 2nd photolithography, we got the mold for magnetic core;
- 10μm $Ni_{80}Fe_{20}$ was electroplated on the wafer;
- The seed layer was removed and the parylene substrate was peeled off from the silicon wafer.

During the fabrication process above, the electrodeposition of $Ni_{80}Fe_{20}$ is the key step. Table 2 illustrated the main compositions of the electroplating bath. The bath mainly contains nickel sulphate salts, nickel chloride salts, iron sulphate salts and other additives. The saccharin can decrease the residual stress and improve the surface morphology. The boric acid is used to keep a constant pH environment.

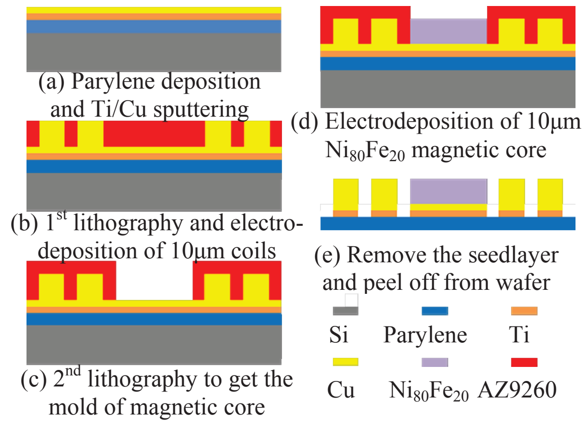


Fig. 2: Schematic illustration of fabrication process

Table 2: Parameters of $Ni_{80}Fe_{20}$ electrodeposition

Composition	g/L	Composition	g/L
$NiSO_4 \cdot 6H_2O$	317.4	$FeSO_4 \cdot 7H_2O$	117.1
$NiCl_2 \cdot 6H_2O$	91.6	NaCl	20.0
H_3BO_3	40.0	$NaC_{12}H_{25}SO_4$	0.2
Saccharin	3.5	H_3PO_4	5.0
Current Density=4ASD, duty cycle: 50%, 60℃			

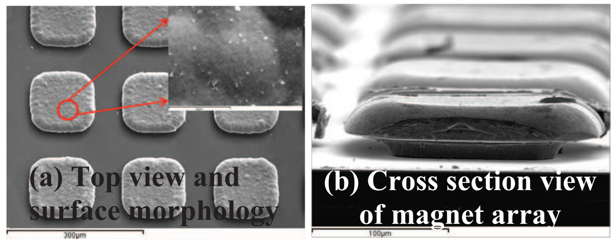
When doing electrodeposition, the nickel foil was used as the anode to provide nickel cation for the bath. An air agitator was used to ensure uniform ion transportation in the bath so that we could get the smooth surface. The AC current was introduced to improve the surface quality and the temperature of the bath stayed at 60℃.

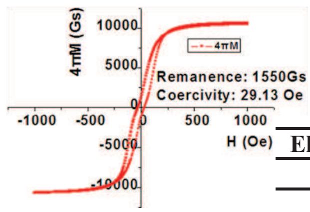
CHARACTERIZATION AND DISCUSSION

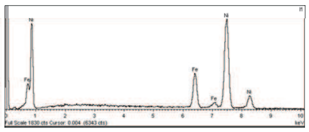
Characterization of $Ni_{80}Fe_{20}$ Magnetic Core

By thick photoresist lithography and electro-deposition technique, we successfully got the $Ni_{80}Fe_{20}$ soft magnets. Fig. 3 illustrates the typical results of electrodeposition experiments.

From the SEM photos in Fig. 3(a) and (b), it could be seen that the magnet array was well arranged and the surface was quite smooth. Fig. 3(c) exhibited the demagnetization loop. The small coercivity verified its soft magnetic property. The slope of the loop showed its high permeability which can enhance the performance of the coils. Fig. 3(d) verified that the proper material composition of the alloy.







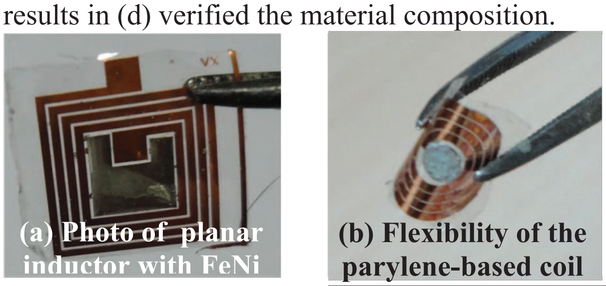
Element	Weight%	Atomic%
Fe	17.40	18.13
Ni	82.60	81.87

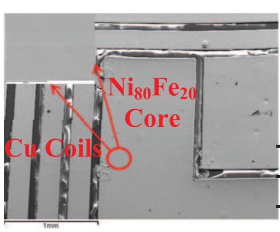
(c) Magnetic properties of FeNi magnets (d) Material composition analyzed by EDS

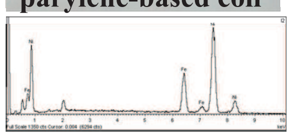
Fig. 3: Fabrication results of $Ni_{80}Fe_{20}$ soft magnets

Characterization of Planar Inductors

In this paper, by electrodeposition, the coils and magnets were achieved on parylene layer. After peeled off from silicon substrate, the inductors became flexible. In Fig. 4(a), both the coils and core were well arranged on the transparent parylene substrate. Fig. 4(b) showed the good flexibility which is helpful in implantable applications. The SEM photos in (c) showed the smooth surface and the EDS results in (d) verified the material composition.







Element	Weight%	Atomic%
Fe	20.07	20.89
Ni	79.93	79.11

(c) SEM photo and surface of $Ni_{80}Fe_{20}$ (d) Material composition analyzed by EDS

Fig. 4: Fabrication results of planar inductors

The performance of the planar inductors was tested by network analyzer. From Fig.5, it could be observed that I1 exhibited the maximum Q-factor of 3.93 at 29MHz and a high inductance of 800nH at 55MHz.

By comparison in Fig.6, due to the high permeability of $Ni_{80}Fe_{20}$, the inductance was enhanced by 24% at 5MHz and up to 235% at 51MHz. Meanwhile, in the range of 7MHz to 31MHz, the Q-factor also had a 5% to 25% increment. When the frequency was even higher, the resistance loss in $Ni_{80}Fe_{20}$ core became significant, which could cause the decrease of the Q-factor.

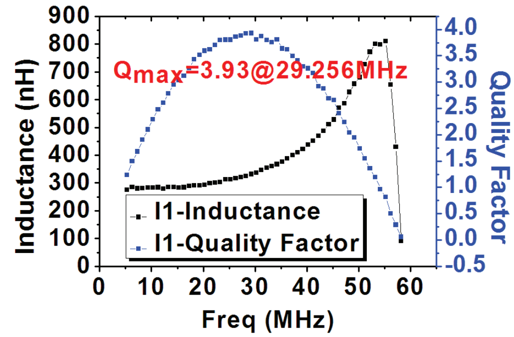


Fig. 5: Measured inductance and Q-factor of I1

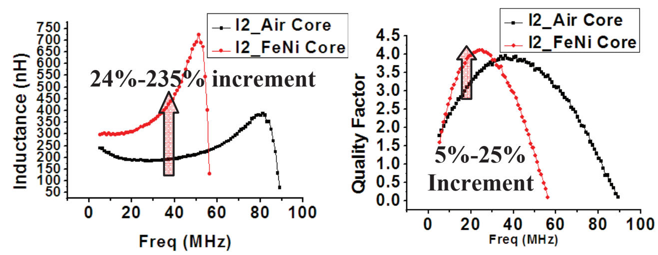


Fig. 6: Comparison of inductance and Q-factor between I2_Air Core and I2_FeNi Core

Compared with the solenoid inductor in [10], as is shown in Table 3, using $Ni_{80}Fe_{20}$ magnetic core, our planar inductor shows a higher inductance and a modest Q-factor with easier fabrication process. Meanwhile, with parylene substrate, our inductor has better flexibility and biocompatibility.

Table 3: Discussion and comparison between our work and previous research

Reference	[10]	Our Work
Coil Area	<1mm^2	20mm^2
Inductance	70nH	800nH
Q-Factor	>5	3.9
Fabrication Difficulty	3D solenoid, difficult	Planar coil, relatively easy
Bio-compatibility	modest, silicon substrate not flexible	Flexible, good compatibility due to parylene substrate

It could be seen that although the Q-factor was improved by integrating magnetic core, it is still not very high. Considering that the resistance of the testing line and contacts affected the Q-factor, it still needs further improvements.

APPLICATIONS IN WIRELESS SYSTEM

Since we got the MEMS coils, we tried to use these coils to build an inductively coupled wireless power transmission system. Based on previous research [11], the model was shown in Fig. 7. As the receiver coil, the MEMS inductor was placed in a cylinder container filled with simulated body fluid (SBF) solution, which was used to simulate the human body environment. The handmade copper transmitting coil was outside the container. The coupling efficiency was measured by network analyzer. As is shown in Fig.8, the minimum attenuation was -21dB at 36MHz, which could satisfy the signal and power supply of many implantable MEMS devices.

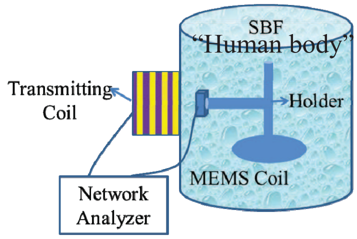


Fig. 7: 3D schematic of inductively coupled system

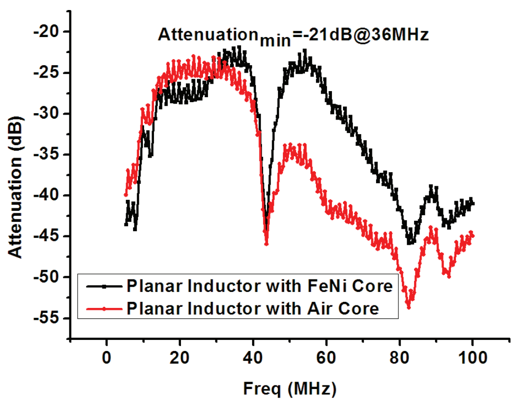


Fig. 8: Measured attenuation of wireless power transmission system based on MEMS planar inductors

CONCLUSIONS

In this paper, a flexible parylene-based planar inductor with $Ni_{80}Fe_{20}$ core was designed, fabricated and analyzed. Based on the electrodeposition technique, the thick metal deposition on soft parylene layer is realized and the whole fabrication process is IC-compatible. With magnetic core, the inductance of the MEMS coils was enhanced by 235% maximally and the Q-factor was also improved significantly. The square spiral inductor showed the inductance of 800nH at 55MHz. Meanwhile, with parylene substrate, the coils exhibit good flexibility and biocompatibility.

Based on these inductors, the inductively coupled system was set up and tested. The minimum attenuation was -21dB at 36MHz, which could satisfy the power supply of many implantable MEMS devices.

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