Proceedings of the 3rd IEEE Int. Conf. on
Nano/Micro Engineered and Molecular Systems
January 6-9, 2008, Sanya, China

Q-Enhanced Fold-and-Bond MEMS Inductors

Po-Jui Chen[1,*], Wen-Cheng Kuo[1,2], Wen Li[1], Yao-Joe Yang[2], and Yu-Chong Tai[1]

[1]*Department of Electrical Engineering, California Institute of Technology, Pasadena, CA, USA*
[2]*Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan*

***Abstract*—This work presents a novel coil fabrication technology to enhance quality factor (Q factor) of microfabricated inductors for implanted medical wireless sensing and data/power transfer applications. Using parylene as a flexible thin-film device substrate, a post-microfabrication substrate folding-and-bonding method is developed to effectively increase the metal thickness of the surface-micromachined inductors, resulting in their lower self-resistance so their higher quality factor. One-fold-and-bond coils are successfully demonstrated as an example to verify the feasibility of the fabrication technology with measurement results in good agreements with device simulation. Depending on target specifications, multiple substrate folding-and-bonding can be extensively implemented to facilitate further improved electrical characteristics of the coils from single fabrication batch. Such Q-enhanced inductors can be broadly utilized with great potentials in flexible integrated wireless devices/systems for intraocular prostheses and other biomedical implants.**

Keywords - bonding; flexible; inductor; parylene; quality factor

I. INTRODUCTION

Polymer MEMS (microelectromechanical systems) has attracted many researchers' attentions in recent years with many successful demonstrations of being sensing/actuating/structuring elements in a wide range of applications, including physical transduction, biological/chemical analysis, and medical care [1]. Their ease of fabrication at low temperature along with exclusive mechanical flexibility naturally make polymeric devices/systems a promising alternative to silicon-based paradigms. Among various polymer materials, parylene (poly-para-xylylene) has desirable features as it can be deposited as a pinhole-free conformal coating through room-temperature CVD (chemical vapor deposition) process, and can be dry-etched using oxygen plasma [2]. These features enable parylene process to have high compatibility with conventional microfabrication techniques. Parylene MEMS technology have been developed for almost ten years. It has a great contribution on flexible "skin" applications initially for aerodynamic flow controls accomplished by using parylene as a flexible and robust thin-film substrate [3,4].

Given by the fact that one of its derivative, parylene C, is well known as a FDA approved USP Class VI grade biocompatible polymeric material, microfabricated medical devices made out of parylene have bright potentials for biomimetic and implantable applications. One example is to exploit parylene as the platform material for integrated intraocular retinal prostheses [5]. In such application thin-film metals are preferred for electrical components such as flexible electrodes and coils to guarantee their best material quality. Electroplated and sputtered metals can be thick alternatives but their qualities are typically not as good as evaporation-deposited metals. This concern becomes more crucial especially when the devices/systems are eventually implanted inside harsh biological environments interacting with live tissues and biofluids. On the other hand, even with better material qualities, evaporation-deposited metals are usually limited in their film thickness due to process cost. This fact unfavorably constraints the quality factor (Q factor) that is needed for remotely powering or sensing coils in which the coupling is created wirelessly with external circuits [6]. Therefore, this paper reports a straightforward fold-and-bond method as a post-fabrication technique to mitigate the evaporated metal thickness limit thus produce Q-enhanced inductors. These Q-enhanced coils are valuable not only for retinal prosthesis but also other ophthalmic implants such as sensing coils in telemetric intraocular pressure sensors [7].

II. DESIGN

The Q factor of an inductor on an insulating substrate can be defined as follows [8]:

$$Q = 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}} = \frac{\omega L}{R}\left[1-\left(\frac{\omega}{\omega_r}\right)^2\right] \quad (1)$$

where L is the inductance, R is the resistance, $\omega = 2\pi f$ is the operation frequency, and $\omega_r = 2\pi f_r$ is the resonant frequency of the inductor. Eq. (1) clearly shows that the inductor must be operated below its self-resonance to avoid minimizing Q due to lossy self-resonance factor. Moreover, regardless of operation frequency, Q can be increased by either increasing the capacity index of stored magnetic energy L or decreasing the capacity index of dissipative electric energy R. Because the inductance is generally determined in priority based on designed frequency spectrum of an integrated system, efforts including this work are made on reducing the ohmic loss of an inductor. In the fond-and-bond concept as shown in Fig. 1, two or more symmetric thin-film planar spiral coils produced from the same fabrication batch can be seamlessly connected in parallel to each other by folding and bonding the flexible device substrate. The inductance and resistance of a planar spiral coil can be written as follows [9]:

$$L \approx \frac{\mu_0 N^2 d_{avg} c_1}{2}\left[\ln\left(\frac{c_2}{\rho}\right) + c_3\rho + c_4\rho^2\right] \quad (2)$$

$$R \approx R_{DC} + \cancel{R_{AC}} \quad \text{(at low frequency)} \quad (3)$$

This work was supported in part by the Engineering Research Centers Program of the National Science Foundation under NSF Award Number EEC-0310723.

**Contact author: Po-Jui (PJ) Chen, California Institute of Technology, Electrical Engineering, M/C 136-93, Pasadena, CA 91125, USA. Tel: +1-626-395-2254, Fax: +1-626-584-9104, E-mail: pjchen@mems.caltech.edu*

where μ_0 is the magnetic constant, N is the number of spiral turns, d_{avg} is the arithmetic mean of the inner and outer diameters of the coil, c's are the coefficients corresponding to the spiral shape, and ρ is the fill factor of the coil winding. Note that within an appropriate frequency range, the DC series resistance is dominant over the AC resistance generated by insignificant high-frequency effects including skin effect, proximity effect, and eddy current. Accordingly, a new coil can be formed by stacking a number of $2n$ single coils after n times folding to have identical inductance but $2n$ times thicker equivalent metal thickness, resulting in $2n$ times lower series resistance and $2n$ times Q-factor enhancement. Two coils are used in this work to demonstrate doubled Q factor after one substrate folding and bonding, while it can definitely be extended to multiple-fold-and-bond process in order to further improve the inductors with higher Q factor. Parylene C is selected as the substrate material to fulfill the concept because of its mechanical flexibility (Young's modulus ~4 GPa), its robustness (yield strength ~55 MPa), and its electrically insulating behavior in addition to the reasons stated above.

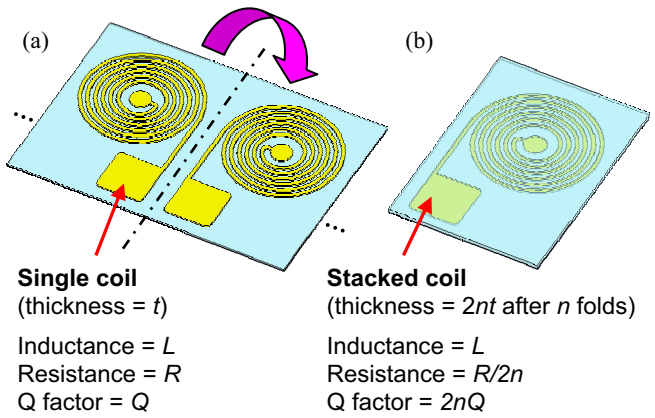

Figure 1. Concept of flexible inductors with enhanced Q-factor by thin-film substrate folding-and-bonding: (a) Unfolded device; (b) Folded device. One-folding coils are drawn in (a) for representation.

III. Fabrication

The microfabrication process of one-fold-and-bond thin-film coil unit is illustrated in Fig. 2 using silicon wafer as the carrier substrate. A 5-µm-thick sacrificial photoresist layer was optionally spin-coated on the wafer for ease of final device release. A 5-µm-thick parylene C layer was coated for device substrate, followed by depositing 200 Å/0.5 µm chromium/gold for metal lines of the inductor. Chromium was involved for adhesion promotion purpose between parylene and gold layers. Metals were patterned by using wet etchants accompanied by parylene patterning using oxygen plasma, both with photoresist as etch masks. In the end, the devices were free-released by stripping the photoresist in acetone. They were collected after alcohol cleaning for device-level fold-and-bond process. Fig. 3 shows a pair of symmetric microfabricated 10-turn planar spiral coils with 4.2 mm outer diameter (O.D.) and 1.4 mm inner diameter (I.D.) on a 9.7 mm x 6.5 mm parylene film before folding and bonding. Through holes with 320 µm O.D. were also created on corners of the parylene film for accurate device alignment during substrate folding.

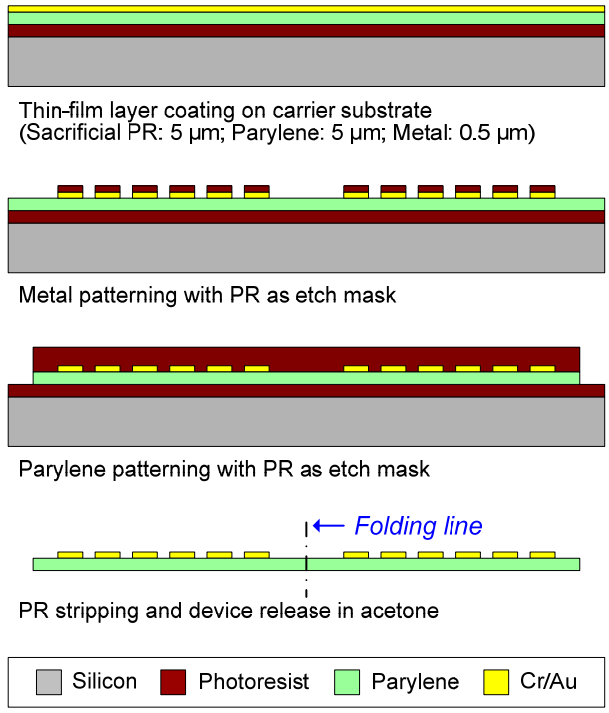

Figure 2. Fabrication process flow.

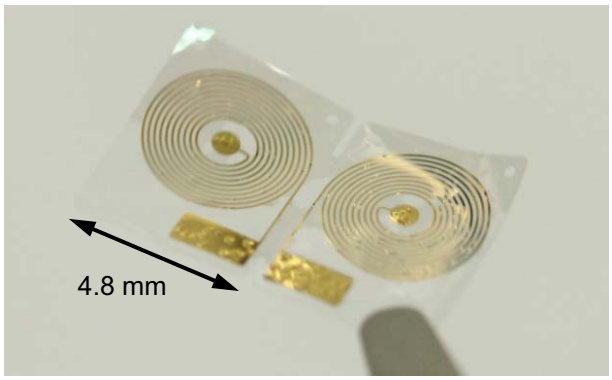

Figure 3. Microfabricated thin-film inductor before substrate folding. Device curvature due to residual stress gradient can be amended through thermally compressed parylene/parylene annealing/bonding.

After manually folded along the predetermined folding line as shown in Fig. 2, the parylene film was experienced a thermal bonding treatment to ensure good metal contact between top and bottom coils as well as device reliability. The folded film was heated to 250°C for 24 hours with weighing compression in vacuum to facilitate low-temperature parylene/parylene annealing/bonding [10]. Fig. 4 shows the completed flexible fond-and-bond coil after post-fabrication process. The misalignment between single coils was able to be controlled to approximately 10-20 µm, which minimally affects the mutual coupling between parallel coils in practice. No broken metal lines or ruptured film segment was observed after bending the film as shown in Fig. 5, confirming the remained mechanical flexibility of the bonded parylene film and ductility of the metal wires after the thermal treatment. Processing conditions of parylene/parylene bonding can be further optimized.

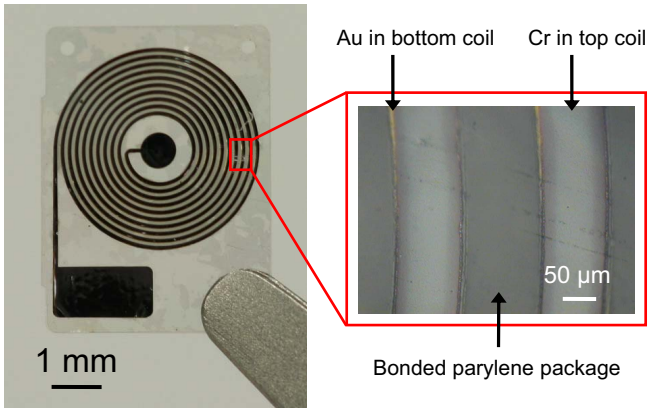

Figure 4. Fabricated one-fold-and-bond MEMS inductor (left) with its cut-off micrograph (right) showing controlled minimal misalignment between top and bottom single coils.

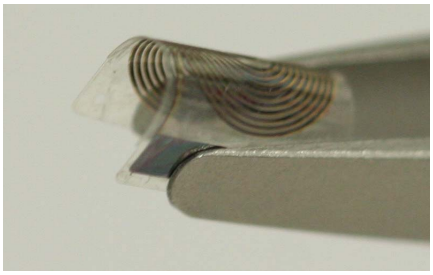

Figure 5. Flexibility demonstration of the fold-and-bond coil.

IV. Results and Discussion

The inductors were first simulated in electromagnetic FEM (finite-element-method) analysis using built-in package in CoventorWare (Coventor Inc., Cary, NC) to estimate their electrical characteristics. As expected, the increase of metal line thickness by ideal coil stacking did not cause substantial inductance change as shown in Fig. 6 but proportional reduction of overall self-resistance as shown in Fig. 7. The simulated lumped-model parameters were in good agreement with the calculated values using equations (2) and (3). In addition, both the inductance and the resistance were fairly independent on exciting frequency up to 1 GHz, at which 1%-2% of inductance change and 1%-9% resistance change were estimated. These simulation results of frequency response validate the feasibility of using such thin-film inductors in a moderate frequency range.

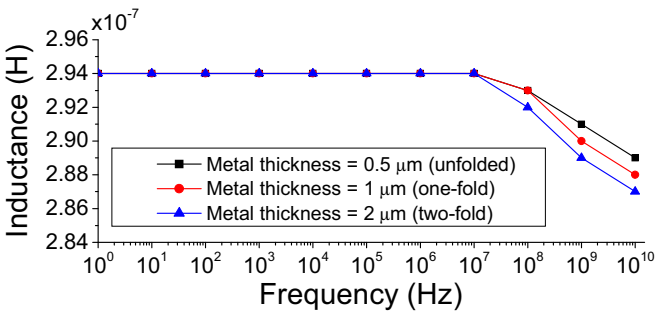

Figure 6. Simulation result on electrical inductance of ideally stacked coil.

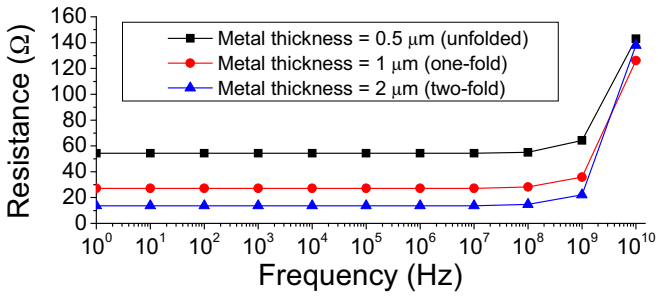

Figure 7. Simulation result on electrical resistance of ideally stacked coil.

Actual device characterization was conducted using Agilent 34401A multimeter and HP 4195A network/spectrum analyzer (HP/Agilent Technologies Inc., Santa Clara, CA) for electrical measurements with single coil (unfolded) and one-fold-and-bond coil (after one folding) for comparison. Probe tip scratch or oxygen plasma etch was selectively performed on the fold-and-bond coil in order to create access to the metal pads embedded under total parylene encapsulation for necessary electrical connection. The DC resistance was measured using the multimeter and inductance as well as self-capacitance of the inductor were measured using the network analyzer.

Testing results summarized in Table I successfully show effective improvement on electrical characteristics of the inductor after substrate folding and bonding, in good agreement with simulation results as shown in Fig. 6 and Fig. 7. The discrepancy of inductance and resistance change factor after folding was about 2% and 4% respectively, leading to overall 6% discrepancy of Q-factor enhancement from ideal value (2x). The parasitic self-capacitance obtained from both the single and the stacked coils was about 0.56 pF so the resultant self-resonant frequency was approximately 400 MHz, which guarantees the availability of the inductors operated in a frequency range of interest (1-300 MHz) for most biotelemetry and wireless medical implant applications.

Table I. Experimental results of one-fold-and-bond coil testing.

	Single coil	**Stacked coil**	**Change factor after folding**
Inductance	289 nH	283 nH	0.98x
Resistance	53.42 Ω	27.69 Ω	0.52x

Projected Q-factor enhancement after one folding ~1.88x

Effects of coil misalignment were also studied with assistance of simulation to better understand the deviation from ideal projected Q-factor enhancement. Two stacked coils with one-axis misalignment as illustrated in Fig. 8 were used as a model to preliminarily analyze changes of inductance and resistance. The simulation results as shown in Fig. 9 indicate that the differences in inductance and in resistance were less than 1.4% and 3.7% within one pitch misalignment. This finding well matches the obtained experimental results as less than 20 μm coil misalignment was achieved in existing devices. It also provides an important reference for future coil design.

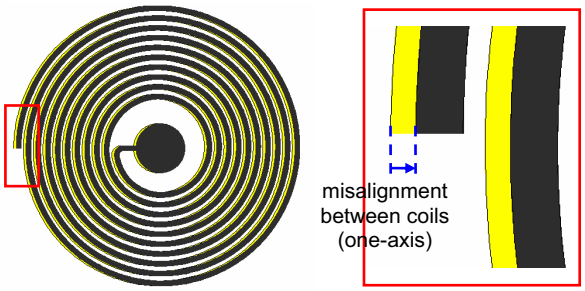

Figure 8. Illustrated model for coil misalignment simulation (yellow: bottom coil; dark gray: top coil).

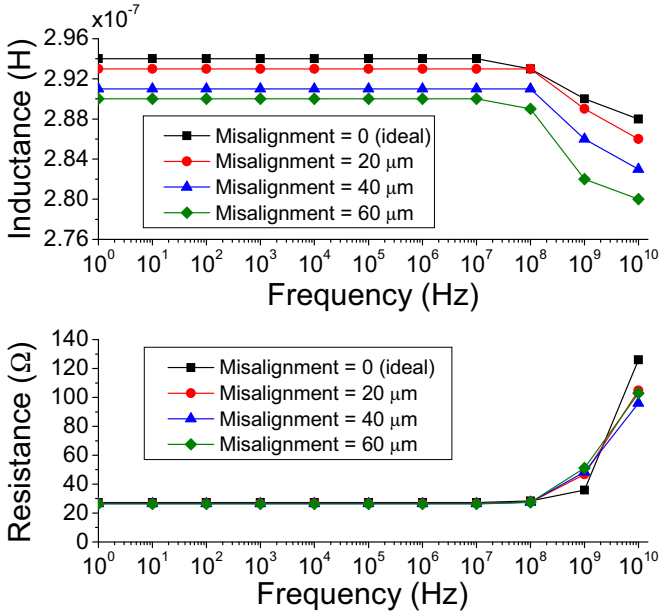

Figure 9. Simulation results on electrical characteristics of misaligned coils.

Multiple-folding-and-bonding process is currently under development for potentially higher Q-factor enhancement. The device as shown in Fig. 10 will be utilized to prove the two-fold-and-bond concept with the associated process flow as illustrated in Fig. 11. After one fold-and-bond process, the metals are believed to be exposed with controlled oxygen plasma etch to the parylene encapsulation for next film folding and bonding. This process can be repeated multiple times to stack more coils for further inductor improvement.

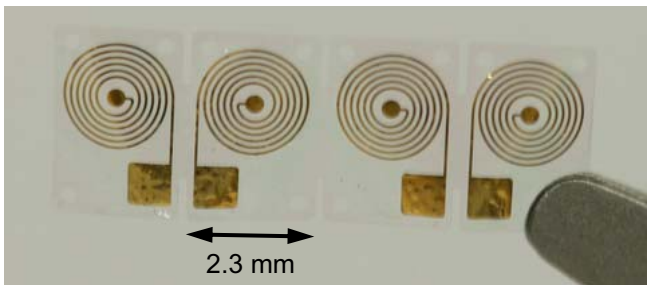

Figure 10. Flexible two-fold-and-bond inductor (before folding) and the proposed process flow.

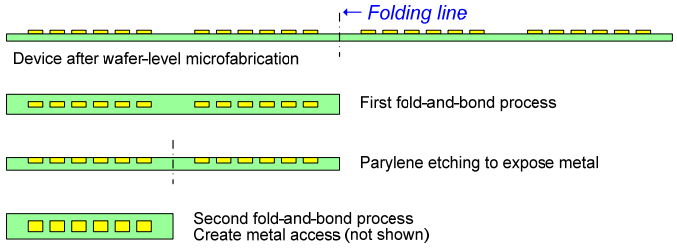

Figure 11. Proposed two-fold-and-bond process for device shown in Fig. 10.

V. Conclusion

A novel fold-and-bond coil fabrication technology has been successfully developed to enhance Q factor of microfabricated inductors. Using parylene C as a polymeric substrate material facilitates convenient folding of the flexible device film in order to stack the metal coils for better electrical characteristics. One-fold-and-bond process enabled by a low-temperature parylene/parylene thermal bonding technique was successfully demonstrated with stacking two symmetric planar spiral coils produced from the same fabrication batch. The coils were fully characterized by simulation and experimental measurements, in which good agreements were obtained with each other. The projected Q-factor enhancement of the one-fold-and-bond inductor was found to be approximately 1.88x. Preliminary coil misalignment study was also conducted. Current work is underway to demonstrate the applicability of the multiple-folding-and-bonding process for further Q-factor enhancement. This fabrication technology will be implemented in the near future to incorporate such Q-enhanced MEMS inductors as an integrating component in flexible biomedical implants.

References

[1] G.T.A. Kovacs, *Micromachined Transducers Sourcebook*, McGraw-Hill, Boston, 1998.

[2] E. Meng and Y.-C. Tai, "Parylene Etching Techniques for Microfluidics and BioMEMS," in *Proc. 18th IEEE Int. Conf. MEMS 2005*, Miami Beach, FL, USA, Jan. 30 - Feb. 3, 2005, pp. 568-571.

[3] Y. Xu, Y.-C. Tai, A. Huang, and C.-M. Ho, "IC-Integrated Flexible Shear-Stress Sensor Skin," *J. Microelectromech. S.*, vol. 12, pp. 740-747, 2003.

[4] S. Ho, H. Nassef, N. Pornsinsirirak, Y.-C. Tai, and C.-M. Ho, "Unsteady Aerodynamics and Flow Control for Flapping Wing Flyers," *Prog. Aerosp. Sci.*, vol. 39, pp. 635-681, 2003.

[5] D.C. Rodger, J.D. Weiland, M.S. Humayun, and Y.-C. Tai, "Scalable High Lead-Count Parylene Package for Retinal Prosthesis," *Sensors and Actuators B: Chemical*, vol. 117, pp. 107-114, 2006.

[6] W. Li, D.C. Rodger, E. Meng, J.D. Weiland, M.S. Humayun, and Y.-C. Tai, "Flexible Parylene Packaged Intraocular Coil for Retinal Prostheses," in *Proc. 4th IEEE-EMBS Int. Conf. MMB 2006*, Okinawa, Japan, May 9-12, 2006, pp. 105-108.

[7] L. Rosengren, P. Rangsten, Y. Bäcklund, B. Hök, B. Svedbergh, and G. Selén, "A system for passive implantable pressure sensors," *Sensor. Actuat. A: Phys.*, vol. 43, pp. 55-58, 1994.

[8] V.G. Welsby, *The Theory and Design of Inductance Coils*, John Wiley and Sons, Oxford, 1960.

[9] T.H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*, Second Edition, Cambridge University Press, New York, 2004.

[10] H.-S. Noh, Y. Huang, and P.J. Hesketh, "Parylene Micromolding, A Rapid and Low-Cost Fabrication Method for Parylene Microchannel," *Sensor. Actuat. B: Chem.*, vol. 102, pp. 78-85, 2004.