# INDUCTANCE ENHANCEMENT OF A MEMS INDUCTOR WITH SELF-ALIGNED MAGNETIC NANOPARTICLES

*Jae-Shin Lee[1], Seung-Deok Ko[2], Chang-Hoon Han[3], Yong-Hoon Yoon[1], Min-Ho Seo[1], and Jun-Bo Yoon[1]*
[1]School of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, KOREA
[2]Departmet of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA
[3]SK Hynix Inc., Icheon, Gyeonggi-do, KOREA

## ABSTRACT

This paper reports a novel method of integrating magnetic nanoparticles (MNPs) with a MEMS inductor. The proposed method is based on the self-alignment of MNPs in response to a magnetic field generated by the integrated MEMS inductor itself. Because it is the natural tendency of MNPs to gravitate towards spots of maximum magnetic flux density, the alignment process results in an MNP distribution that is optimal for maximizing inductance. This new method of increasing the inductance of a MEMS inductor has been first suggested and demonstrated here. With only a 1wt% MNP mixture and a simple planar spiral inductor structure, the proposed method yielded a significant inductance gain of over 50%, which is comparable to the state of the art inductance gain achieved with MNPs by any method. In previous reports, this much gain was obtained with a 50wt% MNP mixture.

## INTRODUCTION

Recently, as the size of electronic devices has become smaller, it has become increasingly necessary to reduce the size of electronic components. One of those components is the inductor, an essential passive element in electronics. Unfortunately, there is a proportional relation between the size of an inductor and its performance, and this limits the ability to reduce its size, earning it a negative reputation as the most space-consuming component.

Among many forms of inductors, the MEMS inductor is an attractive candidate for resolving this size problem, because it not only features low resistance and a high Q factor, but can also be integrated into ICs. However, its low inductance density (inductance value per unit area, ~100nH/cm$^2$) keeps it from being widely applied.

Based on the remarkable progress in microfabrication techniques, some major improvements have been made with respect to inductor structures, such as air-suspended multi-turn MEMS inductors, and MEMS solenoid inductors [1-2]. These works have reported inductors with greatly enhanced performances, but their inductance density values were still not sufficiently high. Thus, along with structural advances, a variety of techniques have been developed to enhance the magnetic permeability of the space near the target inductors, by applying magnetic materials [3], since higher magnetic permeability leads directly to higher inductance density.

In this regard, magnetic nanoparticles (MNPs) have recently attracted attention as a means of enhancing inductance density [4-8]. Due to their small unit size, it is easy to fill the space near the target inductors with MNPs regardless of the inductor structure. Moreover, MNPs exhibit small magnetic losses because of their superparamagnetic characteristic, and are immune to skin depth effect. Furthermore, a network of MNPs have omnidirectional and frequent discontinuity, leading to higher resistance to eddy current loss. The most commonly applied form of MNPs is as a fluidic mixture. Generally, to realize high magnetic permeability, an extremely large amount of MNPs are mixed with an electrically insulating liquid medium (typically 1:1 mass ratio = 50wt%), and then the mixture is applied by dropping it around the target inductors, followed by solidification without any other treatment. The resulting medium has a dense and random distribution of MNPs. The highest reported inductance gain achieved by this method ($\triangle L/L_0$) was 56%.

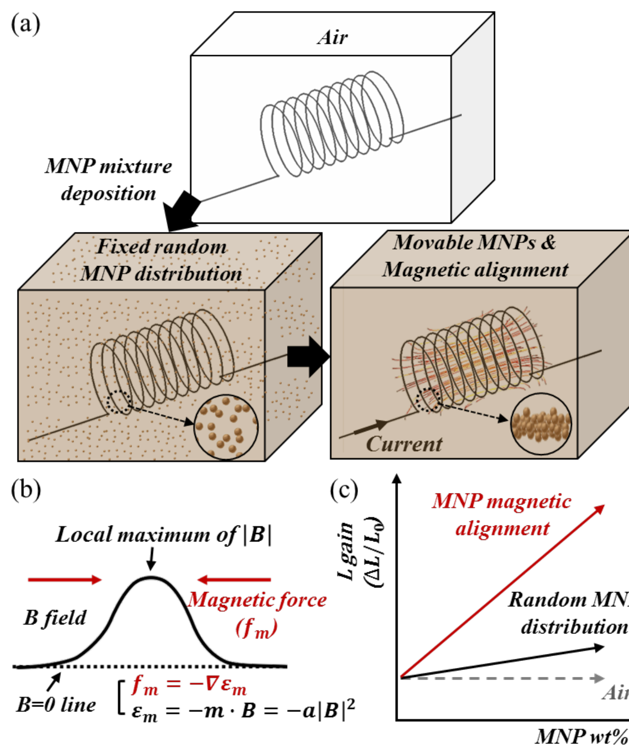


*Figure 1: (a) Schematic illustration of the proposed method. (b) Direction of magnetic force on MNPs according to B field distribution. (c) Comparison of inductance gains between conventional and the proposed method.*

However, this dense and random distribution of MNPs is not an optimized nor efficient form. An extremely dense network of MNPs can increase its own electrical conductance, and higher electrical conductance may cause a degradation of the inductor performance. In addition, the use of an extremely large amount of MNPs is not cost efficient. Hence, a new method of applying MNPs in an optimized and efficient way to enhance the inductance density is required.

In this paper, we propose a new method for realizing an optimum and efficient distribution of MNPs in an automatic way. By combining a MEMS inductor and a microfluidic system, it was possible to induce a spontaneous alignment of the MNPs in relation to the inductor's magnetic field. The contribution of such distribution to inductance gain was investigated.

## CONCEPT

Magnetic materials located in a non-uniform magnetic field acquire different amounts of magnetic potential energy ($\varepsilon_m$) depending on their positions. Non-uniform magnetic potential energy gives rise to a magnetic force ($f_m$) acting on the magnetic materials (Figure 1(b)). The natural tendency of the force is to head towards a minimum point of magnetic potential energy, to maintain a minimized energy state. Because of the inverted sign relation between magnetic flux density ($B$) and $\varepsilon_m$, the direction of the force is towards the point where the magnetic flux density is maximum. Consequently, the magnetic materials are dragged into the local maximum points of $B$ (Figure 1(b)), naturally. Therefore, if the MNPs can move freely, they will spontaneously form a distribution concentrated on the maximum $B$ points. This distribution can selectively maximize magnetic permeability at the point where $B$ is high, and maintain a relatively low density of MNPs at small $B$.

Thus, based on this distribution, the effective magnetic permeability of the MNP network can be maximized while keeping its electrical conductance low, and therefore the distribution is very efficient.

MEMS inductors have a structure that locally concentrates magnetic flux, and thus the distribution of the $B$ in MEMS inductors is generally non-uniform. Therefore, when MNPs are employed in a MEMS inductor, the effective magnetic permeability experienced by the inductor can be increased more efficiently if the MNPs are aligned in accordance with the $B$ distribution of the inductor, rather than simply random and dense MNP distribution. Since the forces that make up this distribution occur naturally along the $B$ formed by the inductor, the MNPs will spontaneously form this efficient alignment if they can move freely around the inductor (Figure 1(a)). To sum up, by simply introducing a spontaneous alignment of the MNPs, a higher inductance gain can be obtained than by applying MNPs in a random manner (Figure 1(c)).

## DESIGN AND FABRICATION

To verify the concept, we designed a MEMS inductor integrated microfluidic system (Figure 2(a)). A planar spiral inductor structure was chosen because of its fabrication simplicity, high magnetic field gradient, and ease of dissipating the heat generated by the Joule heating during the MNP alignment. The planar spiral inductor was made by Cu electroplating, and features a 100 µm inner diameter, 25 µm line width, 20 µm line thickness, with 15 µm spacing between lines. As can be seen in Figure 2(b), the $B$ distribution exhibits a local maximum $B$ very near the inductor line and a global maximum $B$ near the center of the spiral, due to $B$ superposition. The distribution of the MNPs can be expected to be similar to the $B$ distribution, if the MNPs are aligned by the magnetic forces. The simulated maximum $B$ value was over 20 mT at 1 A of current flow, which is sufficient for MNPs with ~ hundreds nm of diameter to overcome the viscosity of the liquid medium (Oleic acid). Since it was necessary to flow a large amount of current to form a sufficiently strong magnetic force, a 300 nm SiN film was formed on a Si substrate as an insulating layer with high electrical resistivity as well as high thermal conductivity.

A 1wt% MNP mixture was prepared by mixing magnetic nanoparticles (NiZnFe2O4 nanoparticles, d<100 nm, Sigma Aldrich) into an electrically insulating and chemically inert liquid (Oleic acid) (Figure 2(a) left inset). Since the mixture should only affect the immediate vicinity of the inductor, a microfluidic structure was introduced to guide and confine the mixture around the inductor. The microfluidic structure was designed to have a large 4x4 mm injection part, which is connected to a smaller part around the inductor to facilitate manual injection of the mixture. The microfluidic structure was formed by photolithography with 100 µm SU-8 (Figure 3(a)). As can be seen in Figure 3(b), the fluidic mixture was successfully guided and confined around the target inductor.

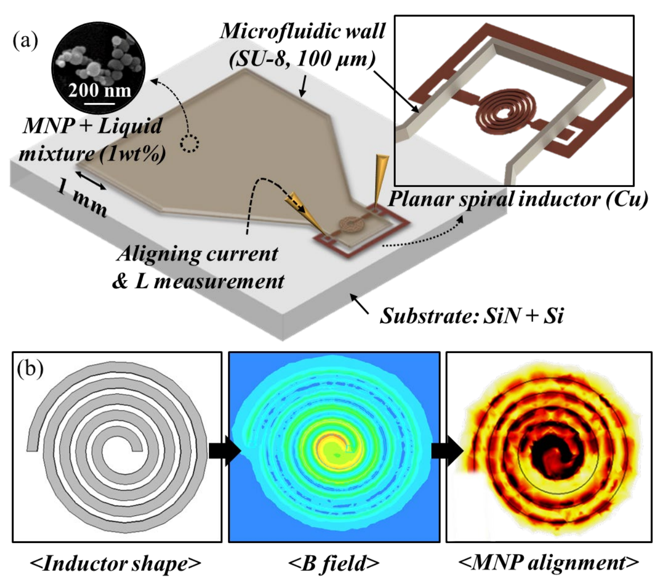


*Figure 2: (a) The inductor-integrated microfluidic system. (b) Prediction of B field distribution and corresponding MNP alignment (Darker color - higher MNP concentration).*

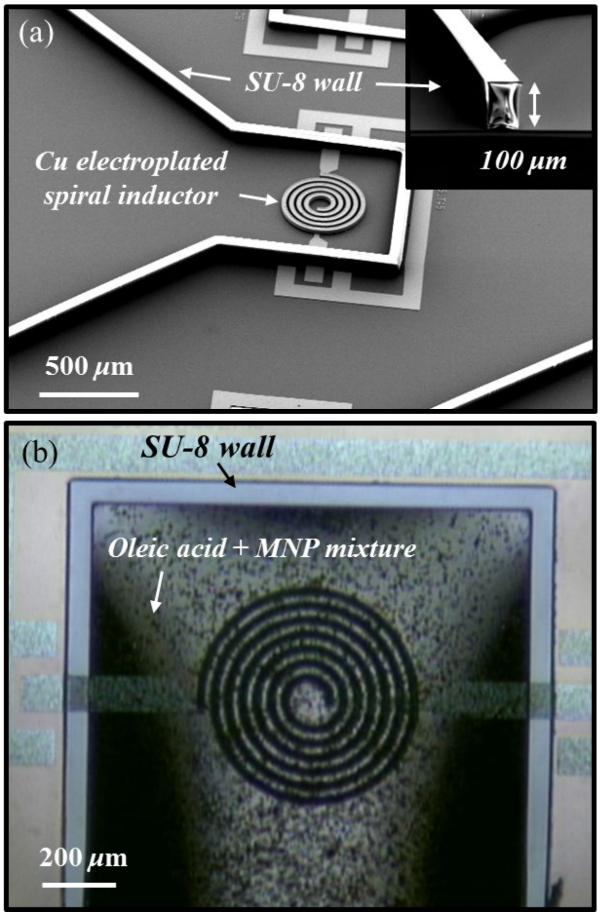


*Figure 3: (a) SEM image of a fabricated inductor integrated microfluidic system (inset: cross section of the SU-8 wall). (b) Optical microscope image after MNP mixture injection.*

## RESULTS AND DISCUSSIONS

The measurement scheme was divided into 3 steps: (1) Injection of the MNP mixture, (2)Alignment of the MNPs under high current, (3)Measurement of the inductance. The MNP mixture was manually injected using a pipette.

As the spontaneous MNP alignment process proceeded, it was observed that MNPs gathered near the inductor lines (Figure 4). The MNP movement slowed down after ~120s regardless of the amount of aligning current. The stabilized distribution of MNPs was similar to the simulated *B* distribution of the inductor. Since the MNPs converge to the local maximum point rather than the global maximum of the magnetic field, they were not more highly concentrated in the center of the inductor, which had the highest magnetic flux density. This is slightly different from the distribution obtained in the magnetic field simulation. It can be improved by increasing the mixing ratio of the MNP mixture, or by modifying the microfluidic structure so that the MNP supply to the center of the inductor is more efficient.

After injecting the same concentration of MNP mixture, the inductance gains obtained by flowing different levels of aligning current for 3 minutes were compared (Figure 5).

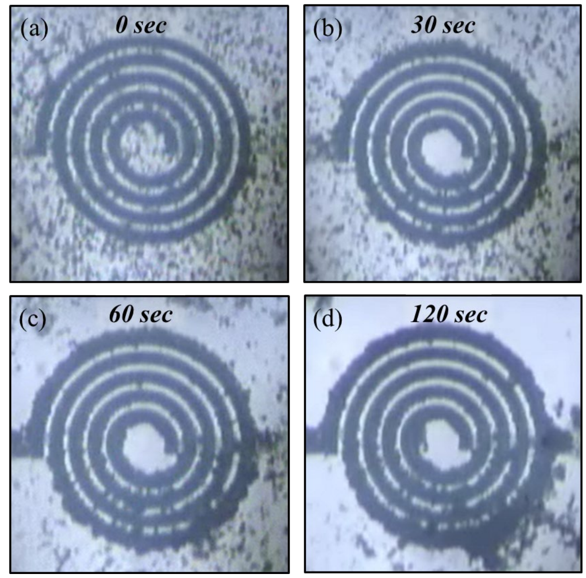


*Figure 4: Change of MNP distribution near the inductor at various alignment times. (aligning current: 1 A). (a) Initial state (0 s). (b) 30 s. (c) 60 s. (d) 120 s.*

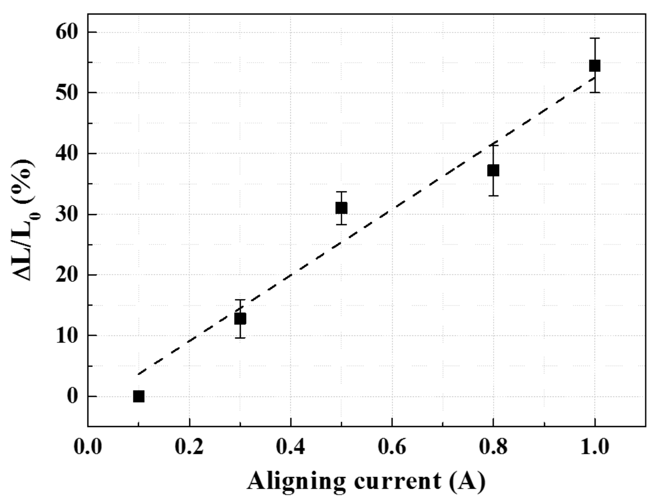


*Figure 5: Inductance (L) gain based on the magnitude of the aligning currents (after 3 min. alignment).*

We found that the inductance gain was linearly proportional to the amount of aligning current. This proportional relation implies that the degree of MNP alignment can be modulated by adjusting the amount of aligning current. The magnetic moment ($m$) of the MNPs and the magnitude of the magnetic field formed around the inductor increase in proportion to the current level. Therefore, as the current increases, the magnetic force applied to the MNP increases, overcoming the viscosity of the oleic acid and the repulsion between nanoparticles. Consequently, although the total amount of MNPs were identical in each case, the larger aligning current resulted in denser alignment of the MNPs where the local maximum points of the magnetic field formed around the inductor, thus achieving a more effective distribution of the MNPs.

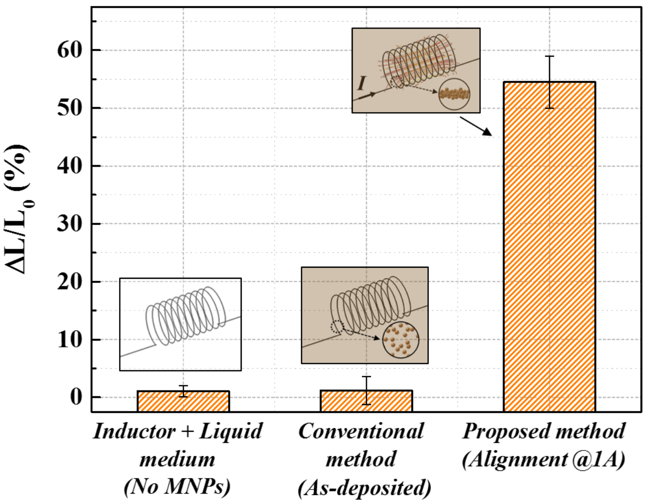


*Figure 6: Enhanced inductance gain achieved by the proposed method.*

To confirm the effectiveness of the MNP alignment, the changes in inductance produced by different treatments were compared (Figure 6). When only the liquid medium was applied, the inductance was hardly changed (~1%). When we added the MNPs (~1wt%) to the liquid medium, still no change was observed. In contrast, when we applied the aligning current, the MNP alignment resulted in an inductance gain of 54.5%, on average, which is comparable to the highest gain reported using an extremely dense (~50wt%) MNP mixture. This result confirms that the proposed spontaneous alignment of MNPs really works in an optimal and efficient way to increase the inductance of a MEMS inductor.

In order to apply the proposed method to actual MEMS inductor products, a step to fix the fluidic MNP mixture into a solid state should be added. In this study, oleic acid, which is a transparent insulator, was used to visually observe the movement of the MNPs. In order to introduce the fixing process step, a low viscosity PR, thermosetting fluid, or UV curable resin, etc. can be utilized.

# CONCLUSION

This study first proposes a self-aligned MNP concept for enhancing a MEMS inductor's inductance density. When a magnetic material is subjected to a magnetic force in a non-uniform magnetic field, if the magnetic material can move freely, it forms a distribution spontaneously that increases the magnetic permeability of the medium. In this study, an integrated MEMS inductor and microfluidic system device was designed and successfully manufactured, that allows MNPs to be spontaneously aligned by an applied magnetic force. By simply passing an aligning current through the fabricated devices, MNPs could be arranged around the MEMS inductor along the magnetic field it formed. The alignment process was saturated after about 120 seconds. It was confirmed that the degree of alignment can be controlled in proportion to the magnitude of the alignment current. In this way, we obtained an inductance gain of 54.5% from a very dilute MNP mixture of 1 wt%, which is similar to the inductance gain obtained in previous studies using an extremely thick MNP mixture of 50 wt%.

# ACKNOWLEDGEMENTS

We would like to express our gratitude to Ye-Na Kim, a graduate student of Department of chemistry, KAIST who helped us to select MNP solvents.

# REFERENCES

[1] E. C. Park, Y. S. Choi, J. B. Yoon, S. Hong, and E. Yoon, "Fully integrated low phase-noise VCOs with on-chip MEMS inductors" *IEEE Transactions on Microwave Theory and Techniques*, 51(1), 289-296, 2003.

[2] J. B. Yoon, B. I. Kim, Y. S. Choi, and E. Yoon, "3-D lithography and metal surface micromachining for RF and microwave MEMS" in *2002 IEEE The 15th International Conference on Micro Electro Mechanical Systems (MEMS),* January, 2002, pp. 673-676.

[3] D. S. Gardner, G. Schrom, F. Paillet, B. Jamieson, T. Karnik, and S. Borkar, "Review of on-chip inductor structures with magnetic films" *IEEE Transactions on Magnetics*, 45(10), 4760-4766, 2009

[4] N. Marjanović, A. Chiolerio, M. Kus, F. Ozel, S. Tilki, N. Ivanović, Z. Rakočević, V. Andrić, T. Barudžija, and R. R. Baumann, "Magnetite nanoparticles: synthesis, thin film properties and inkjet printing of magnetic cores for inductor applications" *Thin Solid Films*, 570, 38-44, 2014.

[5] K.Zeng, W. N. Allen, M. Sinani, C. Martinez, and D. Peroulis, "Magnetic nanoparticle ink for RF integrated inductor applications" in *2014 IEEE MTT-S International Microwave Symposium (IMS2014),* June, 2014, pp. 1-4.

[6] K. Koh, J. Park, J. Park, X. Zhu, and L. Lin, "Core-shell magnetic nanoparticles for on-chip RF inductors" in *2013 IEEE 26th International Conference on Micro Electro Mechanical Systems (MEMS),* January, 2013, pp. 465-468.

[7] C. Yang, J. Zhan, X. Wang, Q. Fang, Z. Shi, Y. Yang, T.-L. Ren, A. Wang, Y. Cheng, and X. Li, "Stacked-spiral RF inductors with vertical nano-particle magnetic-medium" in *2012 IEEE 25th International Conference on Micro Electro Mechanical Systems (MEMS)* January, 2012, pp. 721-724.

[8] C. Yang, F. Liu, T. L. Ren, L. T. Liu, G. Chen, X. K. Guan, A. Wang, and Z. X. Yue, "Ferrite-partially-filled on-chip RF inductor fabricated using low-temperature nano-powder-mixed-photoresist filling technique for standard CMOS" in *2007 IEEE International Electron Devices Meeting*, December, 2007, pp. 1038-1040.

# CONTACT

*J.-S. Lee, tel: +82-42-350-5476;
jslee@3dmems.kaist.ac.kr