STRETCHABLE WIRELESS POWER TRANSFER WITH A LIQUID ALLOY COIL

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ABSTRACT

An integrated stretchable wireless power transfer device was demonstrated by packaging rigid electronic chips onto a liquid alloy coil patterned on a half-cured polydimethylsiloxane (PDMS) surface. To obtain low enough resistance, the long liquid alloy coil with a large cross section was made with a tape transfer masking followed by spray deposition of the liquid alloy. The measured results indicated the wireless power transfer efficiency reached 10% at 140 kHz and good performance under 25% overall strain. Different sizes of liquid alloy coils and a soft magnetic composite core were tested to improve the efficiency of the system.

INTRODUCTION

Stretchable electronics provides advanced integrated circuits by combining thin film technology and transfer processes, which already demonstrated great potential in conformably wearable and implantable devices [1]. To maximize the user experience, a monolithic integrated energy source is necessary for such a stretchable system. However, energy sources require an area or a volume for energy storage or energy harvesting. A wireless solution with antennas might be a feasible candidate as such a smart power source.

Several small scale antennas for a wireless power transfer (WPT) system for emerging electronic applications have been reported with a metal wire coil [2-4] as well as a stretchable thin metal film coil [5]. A gallium-based liquid alloy [6] can provide a highly stretchable functionality as a high performance conducting material. This liquid alloy has low resistivity and allows for a large cross section when stretched, which provides high electrical conductivity, compliance and reliability at high strain, and the gliding contact between a rigid device and the liquid alloy conductor does not fracture when strained [7,8]. In our previous work [7], metal stencil printing requires that all parts of the mask are connected and robust, otherwise they will easily deform. A new approach for liquid alloy patterning was proposed with a tape transfer mask [8], which allows the use of isolated parts with fragile and fine structures, and liquid alloy spraying for wireless power transfer coil fabrication. A stretchable wireless transfer coil was integrated with rigid circuits and successfully demonstrated with strain. A magnetic composite [9] as a core of the liquid alloy coil was tested, and different sizes of the liquid alloy coils were tested for a higher efficiency system. A stretchable WPT system with a liquid alloy coil may enable implantable or wearable electronic devices to be free from a bulky battery or wiring to an external power source.

DESIGN OF SOFT LIQUID ALLOY COIL

A liquid alloy, Galinstan (Geratherm Medical AG), coil was designed to be used as an electromagnetically resonant coil by inductive coupling for a wireless power transfer system. The coil has a non-equilateral octagon shape [3,4] and sized with outer dimensions of 30 × 30 mm and inner dimensions of 13.5 × 13.5 mm, which was based on the transmitting coil size. A smaller size of the liquid alloy coil, which was half sized in the all dimensions that was the line width of 250 µm and the distance of 175 µm between coil turns, was used for comparison of the efficiency with the large one.

The transmitting coil from a commercial product (Würth elektronik) was prepared with a simple transformer circuit. Impedance matching of the coils and circuits with resistance and capacitance at the given inductance of the liquid alloy coil (4µH) and the resonant frequency of 140 kHz was achieved by a parametric study of resistance, capacitance and frequency in the designed circuits. The bottom layer of PDMS (Wacker Chemie) packaging of the liquid alloy coil was made with thin layer (100 µm) to minimize electromagnetic coupling loss in the packaging layer.

DEVICE FABRICATION

The stretchable WPT device, Figure 1, was fabricated with a liquid alloy coil and a circuit with five chips including a rectifier, capacitors, a resistor and an LED integrated in a PDMS package. The planar liquid alloy coil was 82 cm long, 550 µm wide and 120 µm thick.

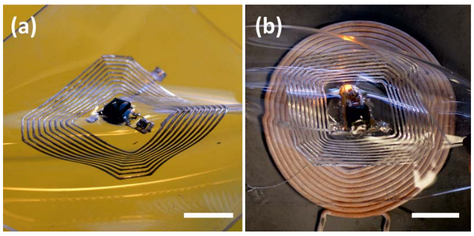

Figure 1: Photographs of a stretchable wireless power transfer coil fabricated with a liquid alloy patterning and chip integration in PDMS packaging (a) a stretched, free standing, integrated liquid alloy coil device and (b) a stretchable wireless power transfer device working with LED lightening. (Scale bars indicate 10 mm).

The liquid alloy coil was fabricated by spraying a liquid alloy through a tape transfer masking technique [8] as described in Figure 2. A tape mask was used for patterning of a liquid alloy, which was prepared with a cutting plotter, and a transfer tape was employed to transfer the cut mask onto a semi-cured PDMS substrate. After peeling off the tape mask, chips were placed on liquid alloy pads of the circuit and multilayer fabrication was done to connect the coil with the integrated circuit. Finally, the uncured PDMS was poured over to encapsulate and create an elastic package. An LED was integrated in the circuit to visualize the device working.

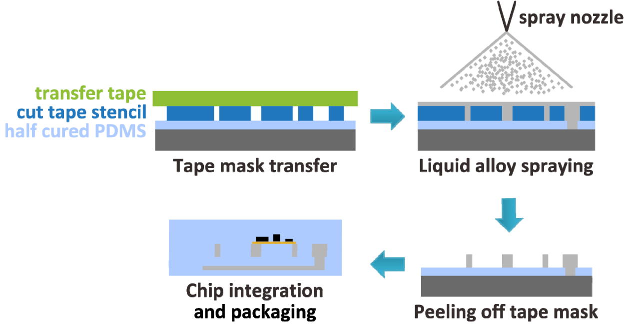

Figure 2: Fabrication process of the stretchable liquid alloy coil device with tape transfer mask, spraying, chip integration and packaging.

A magnetic powder, cobalt iron oxide (Sigma-Aldrich), was mechanically mixed with PDMS as 50 wt% and cured at 70°C for one day to make a core material. The cured magnetic composite was soft and elastic. The magnetic composite core was structured from a metal mold with the diameter of 13 mm and the height of 2 mm. A reference PDMS core with the same dimension as the magnetic composite core was prepared, which was used to make the same gap between the transmitting and receiving coil in case of no magnetic core under the liquid alloy coil for the magnetic core effect comparison.

RESULTS AND DISCUSSION

Stretchability of the Integrated Wireless Power Transfer Device

The fabricated liquid alloy WPT coil was tested as a receiving (R_x) part coupled with a transmitting (T_x) part by changing strains and distances between the T_x and R_x coil. The stretchable WPT device which had a liquid alloy coil and integrated chips showed an efficiency of 10% and worked with 25% strain, Figure 3.

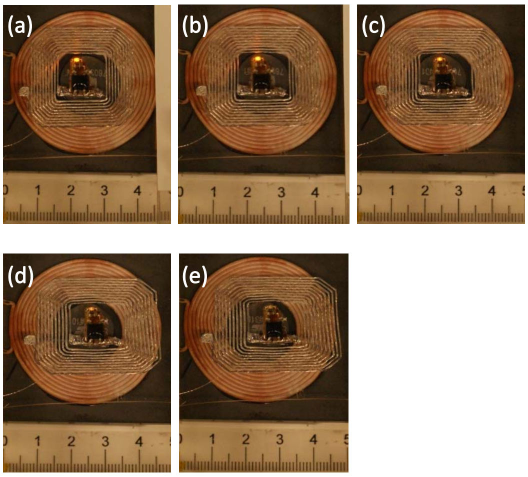

Figure 3: Stretchability test of the fabricated liquid alloy coil integrated with chips in PDMS packaging during wireless power transfer operation with various strains from (a) 0% to (e) 25%.

Strain and Positioning Effect

Without chip integration in the package but with copper wires inserted through a PDMS package for measurements, stretching of the liquid alloy coil up to 50% caused changes of the resistance and the power efficiency of the device as shown in Figure 4. The transferred power efficiency was calculated from the measured voltages and currents as

$$\eta(\%) = \frac{Power(R_x)}{Power(T_x)} \times 100 \qquad (1)$$

and the inductively induced voltage and current to the liquid alloy coil in the receiving part was measured after rectification.

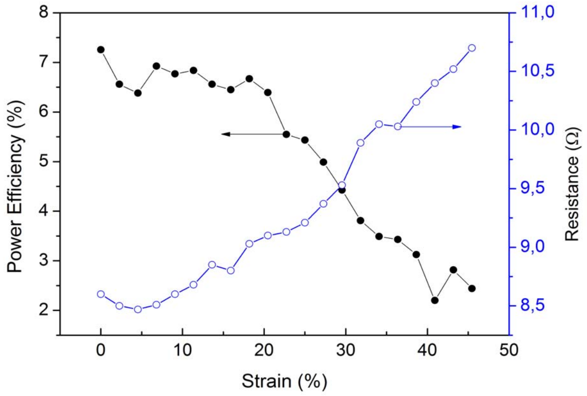

Figure 4: Strain effect of the stretchable liquid alloy coil on power transfer efficiency and resistance.

By increasing the strain up to 50% of the initial length of the soft liquid alloy coil, the resistance of the coil was increased to 26.5% of its initial resistance, and the power efficiency was reduced by 71.4% of the initial efficiency. The reduction of the power efficiency was caused by the resistance increase of the liquid alloy coil by strain, by the change of the coil area which is connected to the *Q* factor and the coupling factor, and by the misalignment of the coaxial position between the T_x and R_x coil. Whereas, when the coaxial alignment of two coils was maintained, the power efficiency was sustained with small changes, which can be originated from a manually controlled setup for alignment and stretching, as shown in Figure 5.

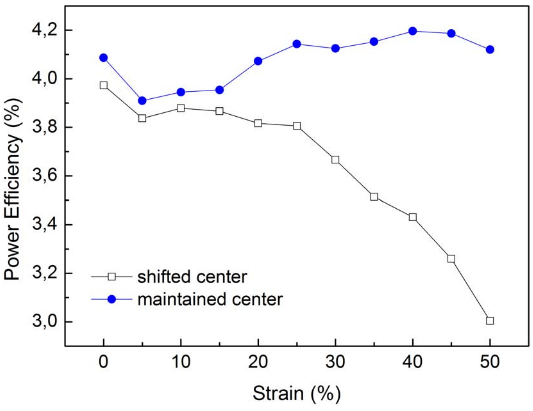

Figure 5: Alignment effect of coaxial positioning of the T_x coil and the R_x coil on the efficiency when the liquid alloy coil is stretched.

Figure 6 shows the efficiency change of the soft liquid alloy device in the wireless power transfer system with the distance changes of the T_x and R_x coil in the different directions, which are the distance of the two coils' axis and the distance of the two coils' planar surfaces. Both of the cases shows power efficiency reduction by the distance increase with the similar behaviors.

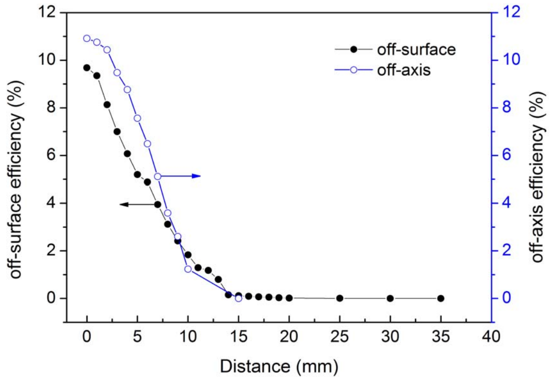

Figure 6: Wireless power transfer efficiency changes according to the positions of the liquid alloy coil relative to the transmitting coil.

Coil Size Effect

Different sizes of the liquid alloy coils were fabricated to compare their efficiencies. A smaller size of a liquid alloy coil compared to the original one was fabricated with half dimensions of the original one. The resistance of the large coil and the small coil was 11 and 9.8 , respectively. During the tests of the two coils, the air gaps between T_x coil and R_x coil were the same. The efficiencies of the two liquid alloy coils were tested with the same transmitting coil and the same circuits at 140 kHz as shown in Table 1.

Table 1: Transferred power efficiency of two different size coils of a liquid alloy.

Coil size	**Tx Power** (W)	**Rx Power** (mW)	**Efficiency** (%)
Large size	4.96	489	9.86
Small size	2.90	269	2.97

Figure 7 shows the efficiency changes of the two different size coils by strain changes. The smaller coil showed lower efficiency when the strain was increased. The power efficiency loss was calculated with the equation (1) as

$$\eta_{loss}(\%) = \frac{\eta_i - \eta_s}{\eta_i} \times 100 \qquad (2)$$

where η_i is the power efficiency of the system without strain in the liquid alloy coil and η_s is the power efficiency with strain in the liquid alloy coil.

An optimal design of a receiving coil size corresponding to a transmitting coil size will give higher efficiency with a higher Q factor in its RLC circuit and a higher coupling factor from its electromagnetic field interaction. A further study of the optimal design of the coil for a specific application in the future will be required.

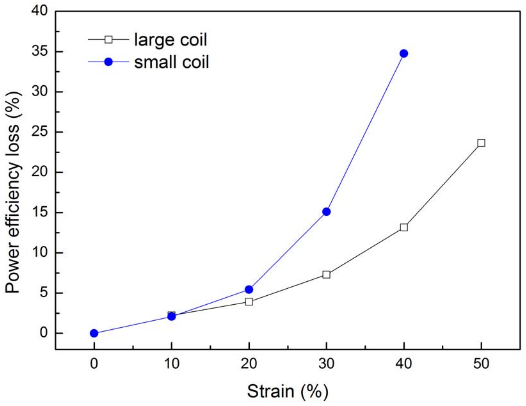

Figure 7: Coil size effect under strain conditions on wireless power transfer efficiency with the liquid alloy coils of two different sizes.

Magnetic Core Effect

To study a magnetic core effect, a magnetic composite core was applied under the large size coil of the liquid alloy to enhance the electromagnetic coupling between the T_x coil and the liquid alloy R_x coil. Figure 8 shows the composite core of cobalt iron oxide increased the wireless power transfer efficiency less than 1.5%, compared to the liquid alloy coil with a reference PDMS core, when the coaxial alignment of the T_x coil and the liquid alloy R_x coil was shifted with different distances between the axis of the two coils. The magnetic core effect on the efficiency was relatively higher at the larger shifted distance between the axis of the T_x and R_x coil.

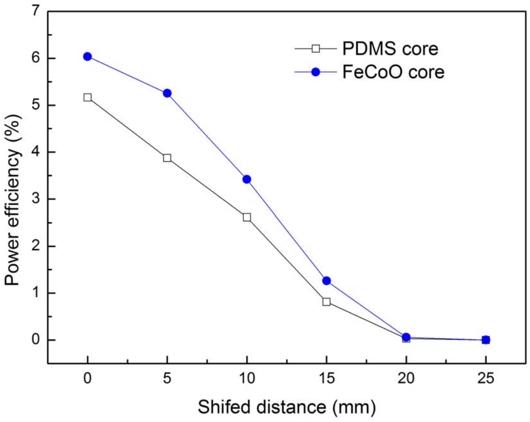

Figure 8: Magnetic composite core effect on power transfer efficiency with shifted coaxial distances of the Tx and Rx coil.

For a further application of the magnetic composite core to the resonant inductive coupling system, the characterization of magnetic properties, such as magnetic field strength, permeability and hysteresis, and the size of a magnetic composite core, will be needed in the future. Magnetic composite core integration with a stronger magnetic material in the elastomer package may help electromagnetic coupling in the WPT system.

CONCLUSIONS

A stretchable wireless power transfer coil with a liquid alloy and integration of rigid chips in PDMS packaging was demonstrated. The liquid alloy based wireless transfer coil showed 10% efficiency in the WPT system and strained up to 25% in stretch with chip integration. Different sizes of the liquid alloy coils and a magnetic composite core affected to the wireless power transfer efficiency under different test conditions. Optimization of the liquid alloy coil design and circuit impedance matching should be studied for a higher efficiency of the stretchable wireless power transfer system. The liquid alloy coil can be applied to soft electronic systems as a wireless power source for a smart package and this system can provide user convenience by a wireless energy transfer function without any wired connection through a package to the wearable electronics or biomedical systems.

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REFERENCES

[1] J. A. Rogers, T. Someya, Y. Huang, "Materials and Mechanics for Stretchable Electronics", *Science*, vol. 327, no. 5973, pp. 1603-1607, 2010.

[2] S. Kim, R. Harrison, F. Solzbacher, "Influence of system integration and packaging for a wireless neural interface on its wireless powering performance", *30th Annual International IEEE EMBS Conference,* Vancouver, August 20-24, 2008, pp. 3182-3185.

[3] R. Bosshard, J. Mühlethaler, J. W. Kolar, I. Stevanovic, "Optimized Magnetic Design for Inductive Power Transfer Coils", in *Proceedings of the 28th Applied Power Electronics Conference and Exposition (APEC 2013)*, Long Beach, California, March 17-21, 2013, pp. 1812-1819.

[4] D. Hendrickx, J. Pannier, T. Nobels, F. Petré, "Wireless power transfer for industrial applications through resonant magnetic induction", *International Workshop on Wireless Energy Transport and Harvesting*, Eindhoven, June 26-28, 2011, pp. 1-6.

[5] S. Xu, Y. Zhang, J. Cho, J. Lee, X. Huang, L. Jia, J. A. Fan, Y. Su, J. Su, H. Zhang, H. Cheng, B. Lu, C. Yu, C. Chuang, T. -I. Kim, T. Song, K. Shigeta, S. Kang, C. Dagdeviren, I. Petrov, "Stretchable batteries with self-similar serpentine interconnects and integrated wireless recharging systems", *Nature Communications*, vol. 4, no. 1543, 2013.

[6] R. C. Chiechi, E. A. Weiss, M. D. Dickey, G. M. Whitesides, "Eutectic Gallium–Indium (EGaIn): A Moldable Liquid Metal for Electrical Characterization of Self-Assembled Monolayers", *Angew. Chem. Int. Ed.*, vol. 47, pp. 142 –144, 2008.

[7] S. H. Jeong, A. Hagman, K. Hjort, M. Jobs, J. Sundqvist, Z. G. Wu, "Liquid alloy printing of microfluidic stretchable electronics", *Lab Chip,* vol. 12, pp. 4657-4664, 2012.

[8] S. H. Jeong, K. Hjort, Z. G. Wu, "Tape transfer printing of a liquid metal alloy for stretchable RF electronics", *Sensors*, vol. 14, no. 9, pp. 16311-16321, 2014.

[9] W. Wang, Z. Yao, J. C. Chen, J. Fang, "Composite elastic magnet films with hard magnetic feature", *J. Micromech. Microeng.*, vol. 14, pp. 1321-1327, 2004.

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