

Fabrication and Characterization of a Concentric Cylindrical Microtransformer

Rebecca J. Jackman, John A. Rogers, and George M. Whitesides, *Member, IEEE*

Abstract—This paper describes the use of a nonphotolithographic technique—microcontact printing—to fabricate a concentric cylindrical microtransformer having an outer diameter of $\sim 350\ \mu\text{m}$. For frequencies of up to 20 kHz, this microtransformer has a high coupling coefficient (>0.9). At higher frequencies, properties of the ferromagnetic material used in the construction of the microtransformer limit performance.

Index Terms—Fabrication, magnetic materials/devices, transformer.

I. INTRODUCTION

MINIATURIZATION of electrical components has created a need for inductors and transformers with micron-sized features. The requirement for a large number of turns per-unit length, however, makes their fabrication challenging. Planar microtransformers can be constructed by the step-wise addition and/or removal of materials using conventional techniques [1]–[12]. Although nonplanar or three-dimensional (3-D) structures have several advantages over planar designs (e.g., they occupy less area), methods to construct such devices involve elaborate fabrication schemes [13], [14]. In this paper, we show a simple route to the fabrication of a 3-D concentric cylindrical microtransformer that has a coupling coefficient that is presently limited by the ferromagnetic material used in the device.

Our fabrication procedure relies on microcontact printing to generate conducting coils with micron-scale features on a cylindrical support. Microcontact printing (μCP) uses an elastomeric stamp, cast from a master made by photolithography or other means, to print an “ink” [15]–[17]. This ink can either prevent removal [18] or initiate deposition [19] of material. Because the stamp used to deliver ink to the substrate is elastomeric, it is possible to print on curved substrates with almost no distortion of features and no problems with depth-of-focus [20].

II. EXPERIMENTAL PROCEDURES

The procedure used for the fabrication of the microtransformer is described below and is illustrated schematically

Manuscript received September 8, 1996; revised December 19, 1996. This work was supported in part by the National Science Foundation under Grants PHY-9312572 and DMR-9400396, by the Advanced Research Projects Agency and the Office of Naval Research, and by the William F. Milton Fund of the Harvard Medical School. The work of R. J. Jackman was supported by Natural Sciences and Engineering Research Council of Canada. The work of J. A. Rogers was supported by the Harvard University Society of Fellows.

The authors are with the Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA 02138 USA.

Publisher Item Identifier S 0018-9464(97)04162-9.

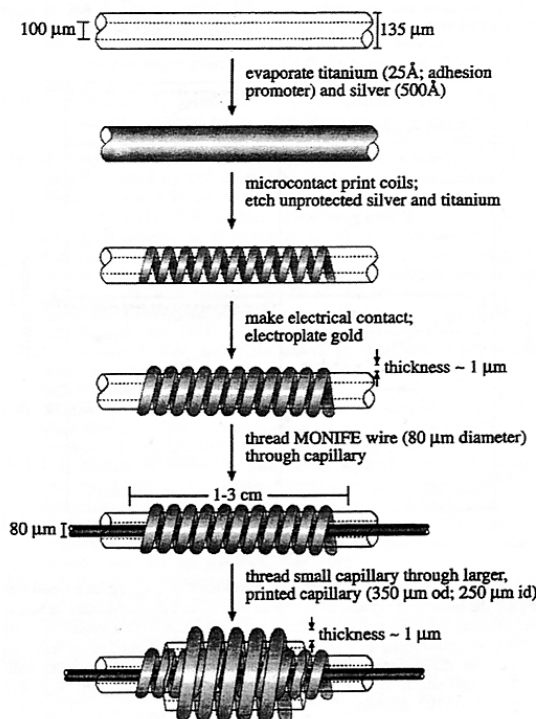


Fig. 1. Procedure for the fabrication of concentrically wound cylindrical microtransformers using microcontact printing and electroplating.

(Fig. 1). Stripping the polyimide coating from glass capillaries (PolyMicro Technologies Inc., Phoenix, AZ) using a heated nichrome wire produced capillaries with an outer diameter of $134.5 \pm 0.5\ \mu\text{m}$ and an inner diameter of $95.6 \pm 0.5\ \mu\text{m}$. We coated these capillaries with titanium ($\sim 25\ \text{\AA}$, as adhesion promoter) and silver ($\sim 500\ \text{\AA}$) using an e-beam evaporator. Mounting the samples on a stage that was rotated about two orthogonal axes during the evaporation allowed metal to be deposited on all sides of the capillaries in a single evaporation [21].

By microcontact printing using a stamp with parallel lines ($25\ \mu\text{m}$ wide) with a period of $50\ \mu\text{m}$, oriented at an appropriate angle to the capillary (6.8° for a capillary with $134.5\ \mu\text{m}$ diameter), we generated a continuous coil ($n = 2 \times 10^4$ turns/m) of a hexadecanethiolate (HDT) monolayer around the silver-coated capillary [21]. Selective wet chemical etching ($0.001\ \text{M}\ \text{K}_4\text{Fe}(\text{CN})_6$, $0.01\ \text{M}\ \text{K}_3\text{Fe}(\text{CN})_6$, and $0.1\ \text{M}$

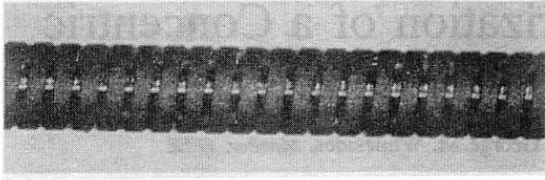


Fig. 2. Optical micrograph of microtransformer fabricated as described in the text and illustrated schematically in Fig. 1. The outer coil has an outer diameter of 350 μm . The inner coil has an outer diameter of 135 μm .

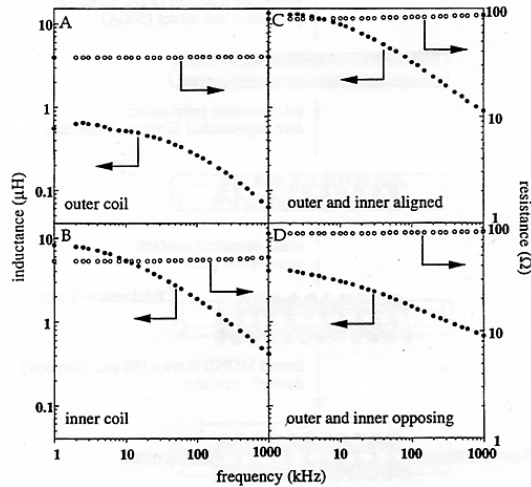


Fig. 3. Data showing inductances and resistances of (A) the outer coil (o) and (B) the inner coil (i) and of the inner and outer coils connected in series with helicities (C) aligned ($i + o$) and with helicities (D) opposed ($i - o$) for the microtransformer as a function of frequency. The applied current was 10 mA. The dimensions of the microtransformer were for the inner coil: $\ell = 14.5$ mm and $n = 2 \times 10^4$ turns/m; and for the outer coil: $\ell = 3.1$ mm and $n = 10^4$ turns/m.

$\text{Na}_2\text{S}_2\text{O}_3$) removed silver not derivatized by μCP [22]. Subsequent immersion of the capillary in 1% HF solution for ~ 10 s removed exposed titanium and left an electrically isolated microcoil. After making electrical contact to the coil using silver paint and gold wire, we electroplated gold (Orotemp 24, Technic Inc., Providence, RI) for ~ 4 min at a current density of ~ 5 mA/cm 2 to reduce the resistance of the coils. The final thickness of the gold was ~ 1 μm . Ferromagnetic wire (80 μm diameter, MONIFE 479; California Fine Wire, Grover Beach, CA) was threaded through the bore of the glass capillary.

To assemble the concentric cylindrical microtransformer, we inserted this small capillary (135 μm outer diameter (o.d.), $n = 2 \times 10^4$ turns/m; $\ell = 14.5$ mm) into the bore of a larger capillary (350 μm o.d., 250 μm inner diameter (i.d.)), that itself was patterned with a coil (linewidth 50 μm ; 10^4 turns/m; $\ell = 3.1$ mm). Both inner and outer coils were then contacted electrically using gold wire and silver paint.

Measurement of the inductance (L) and resistance (R) of the inner coil, outer coils, and of the inner and outer coils connected in series, both with their helicities aligned and then opposed, allowed characterization of the transformer. We made

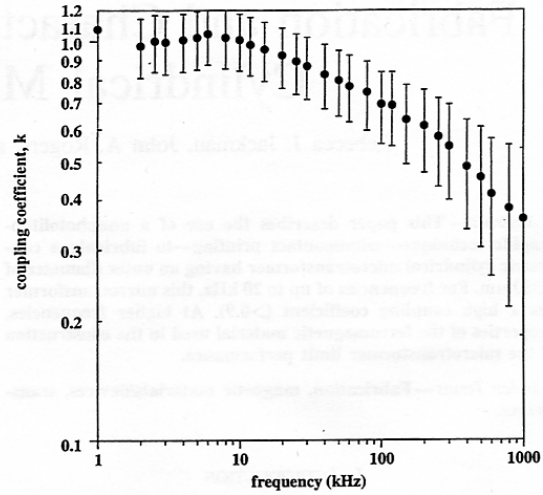


Fig. 4. Data showing the coupling coefficient, k , as a function of frequency for the concentric cylindrical microtransformer calculated using data presented in Fig. 3 and (1). The dimensions of the microtransformer were for the inner coil: $\ell = 14.5$ mm and $n = 2 \times 10^4$ turns/m; and for the outer coil: $\ell = 3.1$ mm and $n = 10^4$ turns/m.

all measurements using a Hewlett Packard LCR meter (HP 4284A, test fixture 16334 A SMD) in the frequency range from 1 kHz to 1 MHz and under a test current of 10 mA.

III. RESULTS AND DISCUSSION

A microtransformer fabricated using this procedure is illustrated in Fig. 2. Fig. 3 summarizes the inductance of the outer (L_o) and inner (L_i) coils and of the inner and outer coils connected in series with helicities aligned (L_{i+o}) and opposed (L_{i-o}). Qualitatively, in each case, the inductance decreases as a function of frequency (Fig. 3). We believe that this decrease is mainly caused by a dependence of the relative permeability of the core on frequency. Other groups have observed similar dependence on frequency for similar materials [13]. The large difference between L_{i+o} and L_{i-o} indicates that the coils are efficiently coupled.

From the inductances shown in Fig. 3, we calculated the no-load coupling coefficient, k , given by [23]

$$k = \frac{L_{i+o} - L_{i-o}}{4\sqrt{L_i L_o}}. \quad (1)$$

It is a measure of how well the magnetic fluxes of the coils overlap. For an ideal transformer, the flux generated in the primary coil is perfectly coupled to the secondary coil, and k is unity.

Fig. 4 shows the coupling coefficient calculated using data shown in Fig. 3 and (1). In the frequency range from 1 kHz to 20 kHz, the coupling coefficient is greater than 0.9; this value indicates nearly ideal behavior. We attribute the decrease in coupling at high frequency to the decrease of the permeability of the ferromagnetic material making up the core.

IV. CONCLUSIONS

In this letter, we described the fabrication and characterization of a microtransformer that has a large coupling coefficient ($k > 0.9$) at frequencies up to 20 kHz. Performance of the device was limited by the ferromagnetic material used in its construction. The relative permeability of the material that comprises the core decreases as a function of frequency. The precise dependence on frequency is determined by the nature of the material, the manner in which it was fabricated, and the section of wire used (due to inhomogeneities along its length). Future directions for this work include the exploration of different materials for the core and investigation of alternative designs for the transformer, e.g., a concentrically wound double coil on a single capillary.

ACKNOWLEDGMENT

The authors thank Prof. M. Prentiss for helpful discussions and Hewlett Packard for the use of the LCR meter.

REFERENCES

- [1] K. Yamasawa, K. Maruyama, I. Hirohama, and P. P. Biringer, "High-frequency operation of a planar-type microtransformer and its applications to multilayered switching regulators," *IEEE Trans. Magn.*, vol. 26, pp. 1204–1209, May 1990.
- [2] Y. Kobayashi, S. Ishibashi, K. Shirakawa, J. Torii, H. Matsuki, and K. Murakami, "New type of cloth-inductor and transformer with thin amorphous wires and multi-thin coils," *IEEE Trans. Magn.*, vol. 328, pp. 3012–3014, Sept. 1992.
- [3] M. Mino, T. Yachi, A. Tago, K. Yanagisawa, and K. Sakakibara, "A new planar microtransformer for use in microswitching converters," *IEEE Trans. Magn.*, vol. 28, pp. 1969–1973, July 1992.
- [4] K. Yamaguchi, S. Ohnuma, T. Imagawa, J. Torii, H. Matsuki, and K. Murakami, "Characteristics of a thin film microtransformer with circular spiral coils," *IEEE Trans. Magn.*, vol. 29, pp. 2232–2237, Sept. 1993.
- [5] H. Kurata, K. Shirakawa, O. Nakazima, and K. Murakami, "Study of thin film micro transformer with high operating frequency and coupling coefficient," *IEEE Trans. Magn.*, vol. 29, pp. 3204–3206, Nov. 1993.
- [6] K. Yamasawa, "A DC-DC converter using a microtransformer," *IEEE Translation J. Mag. Jpn.*, vol. 9, pp. 120–126, July/Aug. 1994.
- [7] H. Kurata, K. Shirakawa, O. Nakazima, and K. Murakami, "Solenoid-type thin-film micro-transformer," *IEEE Trans. J. Magn. Jap.*, vol. 9, pp. 90–94, May/June 1994.
- [8] I. Marinova, Y. Midorikawa, S. Hayano, and Y. Saito, "Thin-film transformer and its analysis by integral equation method," *IEEE Trans. Magn.*, vol. 31, pp. 2432–2434, July 1995.
- [9] J. W. Lu, F. P. Dawson, and S. Yamada, "Analysis of high frequency planar sandwich transformers for switching converters," *IEEE Trans. Magn.*, vol. 31, pp. 4235–4237, Nov. 1995.
- [10] H. Tsujimoto, and O. Ieyasu, "High frequency transmission characteristic of co-planar film transformer fabricated on flexible polyimide film," *IEEE Trans. Magn.*, vol. 31, pp. 4232–4234, Nov. 1995.
- [11] Y. Sakamoto, M. Natsusaka, M. Ohta, and K. Murakami, "A planar transformer utilizing a parametric oscillation," *IEEE Trans. Magn.*, vol. 31, pp. 4238–4240, Nov. 1995.
- [12] M. Mino, T. Yachi, A. Tago, K. Yanagisawa, and K. Sakakibara, "Planar microtransformer with monolithically integrated rectifier diodes for use in microswitching converters," *IEEE Trans. Magn.*, vol. 32, pp. 291–296, Mar. 1996.
- [13] S. Kawahito, Y. Sasaki, H. Sato, T. Nakamura, and Y. Tadokoro, "A fluxgate magnetic sensor with micro-solenoids and electroplated permalloy cores," *Sens. Actuators*, vol. 43, pp. 128–134, May 1994.
- [14] B. Löchel, A. Maciossek, M. Rothe, and W. Windbracke, "Micro-coils fabricated by UV depth lithography and galvanoplatin," *Sens. Actuators*, vol. A54, pp. 663–668, June 1996.
- [15] A. Kumar and G. M. Whitesides, "Features of gold having micrometer to centimeter dimensions can be formed through a combination of stamping with an elastomeric stamp and an alkane thiol 'ink' followed by wet chemical etching," *Appl. Phys. Lett.*, vol. 63, pp. 2002–2004, Oct. 1993.
- [16] A. Kumar, H. A. Biebuyck, and G. M. Whitesides, "Patterning self-assembled monolayers: Applications in materials science," *Langmuir*, vol. 10, pp. 1498–1511, 1994.
- [17] J. L. Wilbur, A. Kumar, E. Kim, and G. M. Whitesides, "Microcontact printing: A new technique for fabrication," *Adv. Mater.*, vol. 6, pp. 600–604, 1994.
- [18] Y. Xia, E. Kim, and G. M. Whitesides, "Microcontact printing of alkanethiols on silver and its application in microfabrication," *J. Electrochem. Soc. (USA)*, vol. 143, pp. 1070–1079, 1996.
- [19] P. C. Hidber, W. Helbig, E. Kim, and G. M. Whitesides, "Microcontact printing of palladium colloids: Micron-scale patterning by electrodeless deposition of copper," *Langmuir*, vol. 12, pp. 1375–1380, 1996.
- [20] R. J. Jackman, J. L. Wilbur, and G. M. Whitesides, "Fabrication of submicron features on curved substrates by microcontact printing," *Science*, vol. 269, pp. 664–666, Aug. 1995.
- [21] J. A. Rogers, R. J. Jackman, and G. M. Whitesides, "Constructing single and double helical microcoils and characterizing their performance components of microinductors and microelectromagnets," *J. Microelect. Syst.*, to be published.
- [22] Y. Xia, X.-M. Zhao, E. Kim, and G. M. Whitesides, "A selective etching solution for use with patterned self-assembled monolayers of alkanethiols on gold, silver, and copper," *Chem. Mater.*, vol. 7, pp. 2332–2337, 1995.
- [23] D. A. Bell, *Fundamentals of Electric Circuits*, 3rd ed. Englewood Cliffs, NJ: Reston Publishing Co., 1984, pp. 675–714.