Ink-jet printing enables maskless electroplating mould patterning for rapid MRI coil fabrication

Markus V. Meissner[1], Nils Spengler[1], Dario Mager[1], Jens Höfflin[1], Peter T. While[1], and Jan G. Korvink[1]
[1]*Department of Microsystems Engineering - IMTEK, University of Freiburg, Freiburg, BW, Germany*

We introduce a new rapid fabrication method to define high-aspect-ratio MRI field coils using inkjet printing, maskless lithography, and copper electroplating. Silver-nano-particle ink is deposited by ink-jet printing to structure conductive silver tracks directly on a transparent polymer substrate. This instant, droplet-based, deposition technique demands minimal material consumption and processing effort [1]. In the process presented here, electroplating is used to increase the electrical conductivity of the printed tracks. To perform anisotropic copper plating, an electroplating mould is formed by backside lithography into a permanent negative resist. Lithographic shadow masks are not required because the printed silver tracks also act as the mask, with the additional advantage of placing the silver seed layer at the bottom of the electroplating mould. We have fabricated a planar micro-coil for 1H spin excitation and reception, and tested it in a magnetic resonance microscopy experiment.

Fabrication: (i) Ordyl SY317 (Elga Europe, 17 µm thick) dry film resist is laminated on a bare glass substrate. Ordyl is flood exposed and baked on a hotplate (2 min 70 °C) to improve the silver wetting behaviour. (ii) Silver ink (U5603, Sun Chemical) is deposited using a Dimatix material printer (DMP-2831, FUJIFILM-Dimatix, USA, see Figure 1) (iii) The printed silver structures are sintered at 180 °C for 20 min. (iv) A dual layer of Ordyl SY355 (total resist height of 100 µm) is laminated on top of the silver tracks. (v) As illustrated in Figure 1, Ordyl SY355 is exposed from the backside by a collimated light source to structure electroplating moulds. In essence, the printed silver tracks act as the lithographic mask. (vi) After wet development of the Ordyl, the electroplating moulds remain self-aligned with respect to the printed seed layer. (vii) Further, the electroplating moulds are filled up by copper plating. During electroplating, the printed silver tracks act as the electroplating seed layer and remain in strong adhesion to the Ordyl SY317 polymer. For electroplating, a customized plating bath was constructed.

Multi-turn planar coils require an inside-to-outside interconnection, in order to electrically connect the inner winding to the feed tracks. This is structured on an additional layer. The process was extended to also structure vias and via-to-via interconnections, again, entirely by inkjet printing. Optically opaque marker ink combined with front side lithography is used to embed vias into unstructured Ordyl resist. Subsequently, an interconnection is printed using silver ink, and electroplating is again performed to increase the electrical conductivity further (see Figure 2).

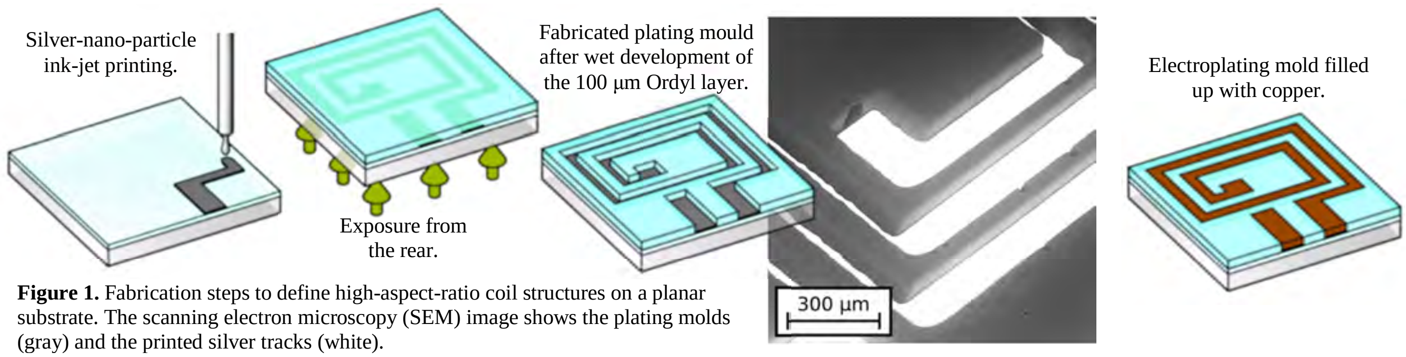

Figure 1. Fabrication steps to define high-aspect-ratio coil structures on a planar substrate. The scanning electron microscopy (SEM) image shows the plating molds (gray) and the printed silver tracks (white).

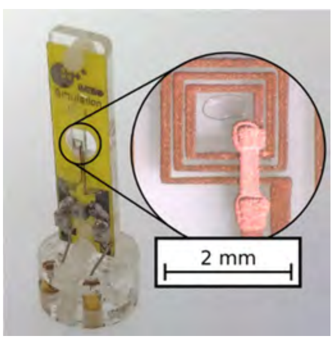

Figure 2. Coil holder fabricated out of polymethyl methacrylate (PMMA). The microscope image shows the printed micro-coil. The size of the coil is approximately 2 x 2 mm. The coil holder includes a printed circuit board with tuning and matching capacitors and is attached to a Micro 5 imaging probe head (Bruker) for measurement.

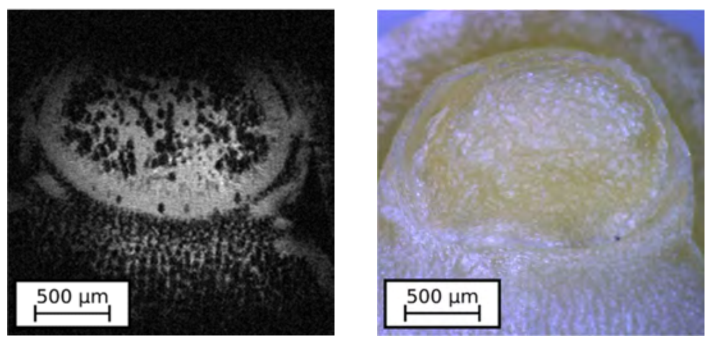

Figure 3. MRI image (left) and microscope image (right) of a piece of spring onion. The MRI image was captured with an in-plane resolution of 10 µm x 10 µm and a slice thickness of 40 µm. The image was taken in 9 h (T_a) by capturing 256 signal averages by a Flash sequence. The repetition time (T_R) was 500 ms.

Results: The printing process allows the formation of feature sizes down to 50 µm. The fabricated coil of Figure 2 was electrically characterized and has a self-resonance frequency in the range of 950 MHz. Magnetic resonance imaging was performed inside an 11.7 T Avance NMR wide-bore magnet (Bruker). A standard tuning network as shown on the coil holder in Figure 2 was used to adjust the resonance frequency to 500 MHz. To perform MR imaging, the micro-coil was surrounded by a commercial 2 T/m gradient system (Micro5, Bruker). Images of a piece of spring onion were acquired with an in-plane resolution of 10 µm x 10 µm, as illustrated in Figure 3. A signal-to-noise ratio of 15 was extracted from the image data.

Conclusion: The described process is particularly suitable for the rapid fabrication and prototyping of planar patch antennas, shim and gradient coils. Depending on the requirements, substrates sizes can be scaled and printed structures can be stacked to define multi-layer coils. The utilized materials possess a magnetic susceptibility close to water [2]. Ordyl SY resist shows biocompatibility, suitable for medical applications. The fabricated coil performs comparably to other micro imaging coils [3].

Acknowledgment: The authors gratefully acknowledge funding through the European Research Council (ERC), contact no. 290586, and the Humboldt Foundation.

References: [1] Kawahara, Y., Hodges, S., Cook, B. S., Zhang, C., & Abowd, G. D., 2013, Proceedings UbiComp ´13, doi:10.1145/2493432.2493486
[2] Wapler, M. C., Leupold, J., Dragonu, I., von Elverfeld, D., Zaitsev, M., & Wallrabe, U., 2014, JMR, 242, 233–42. doi:10.1016/j.jmr.2014.02.005
[3] Badilita, V., Meier, R. C., Spengler, N., Wallrabe, U., Utz, M., & Korvink, J. G., 2012, Soft Matter, 8(41), 10583. doi:10.1039/c2sm26065d