ON-CHIP, MEMS-SCALE, HIGH-PERFORMANCE, 3D-SOLENOIDAL TRANSFORMERS

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Abstract: We present the fabrication of micro-scale, true solenoidal 3D transformers, using an industrial type wirebonding machine. Photolithography is used to define cylindrical SU-8 posts on a Pyrex substrate, which act as support structures during winding and as transformer cores during operation. An automatic wirebonder is employed to wind insulated Gold wire in a helical manner around the posts. A fabricated transformer with a post diameter of 1.5 mm yields a primary inductance of 372 nH, a secondary inductance of 339 nH, and a coupling-factor of 92%. The transformer's efficiency at 50 Ω load was measured to be 50%. Compared to previous devices our transformer obtains equivalent, or even better results at a dramatically reduced fabrication effort and consuming less substrate area.

Keywords: micro-transformer, 3D-inductor, wirebonder.

INTRODUCTION

Micro-Transformers are an essential part of power-convertors and isolator circuits. They have been fabricated and studied for more than two decades. Miniaturization and integration, while keeping high performances, are the key challenges in the production of micro-transformers. The integration of a magnetic core to enhance the performance, while reducing the size, is one way to overcome these challenges, but besides additional complexities in material processing, material losses limit the magnetic core performance in and above the MHz region [1]. Increasing the switching frequency in the convertor is another way which enables further reduction in size of the inductors [2], but, on the other hand, introduces additional HF-related parasitic effects, such as the skin- or proximity effect [3].

Many studies have been done on the fabrication of inductive structures for transformer coils, including planar spiral coils [4], 3D solenoids [5] or toroidal shaped coils [6]. Planar-spiral shaped inductors in micro-transformers are fabricated by electroplating the conductors with thicknesses of several microns on top of an insulating substrate. An advantage of flat transformers is their relatively straight forward, MEMS compatible fabrication process. This, however, is paid by relatively low inductances and medium quality factors [7]. Meanwhile, the 2D geometry of these transformers consumes a lot of substrate area and limits the integration of magnetic cores.

Reports on 3D solenoidal structures based on electroplating of multilevel metal layers were published, e.g., in [5], which ease the integration of a magnetic core, but makes the fabrication time consuming due to the several plating steps.

In this paper, the fabrication of SU-8-core, micro-scale, true solenoidal 3D transformers, using an industrial type automatic wirebonding machine is presented. Using standard UV-lithography for the batch-fabrication of the cores, combined with the fast winding process provided by the wirebonder, enables high throughput fabrication of high-performance, on-chip MEMS-scale transformers.

Wirebonding is an established, state-of-the-art CMOS-compatible assembly and packaging technology. Although it is a serial process, it provides high throughput and is therefore widely spread in industrial applications. Wirebonders allow the highly precise shaping of micron sized wires at high speed. It is capable to make true 3D inductors with various shaped cross sections, such as circles or rectangles around supporting posts or magnetic cores. Compared to the successive electroplating of metal, it is much less time consuming, and is therefore cheaper and faster. This fabrication can easily be implemented in existing fabrication chains, allowing direct on-chip integration into a given circuit. It is highly suitable for numerous applications as wires of diverse materials, such as Copper, Gold, Aluminum or Platinum are offered in a diameter range from 18 to 75 µm. Recently, also coated wires providing electrical insulation are available [8] which allow extended design flexibility. Compact coils, with up to 10 layers of windings, each having up to 20 turns are feasible.

Research on on-chip bondwire inductors was first reported by Craninckx et al. [9]. In [10] Shen et al. presented an on-chip bondwire inductor and transformer, coated with a Ferrite-Epoxy layer. Although it was a fast process which yielded a high quality-factor, the total device was larger than a one cent coin.

The fabrication of 3D micro coils using an automatic wirebonder has been reported initially by Kratt et al. [11]. In [12] Raimann et al. applied this technique to produce transformers on cast magnetic cores, which were manually assembled onto a PCB. We have now improved the technology towards a CMOS compatible, slim batch fabrication. We use SU-8 polymer cores thus completely avoiding magnetic material without any compromises in performance compared to [12].

MICROFABRICATION PROCESS

To enable coil winding with the wirebonder, we need two predefined microstructures on a substrate: supporting posts and metal pads.

For manufacturing the transformer cores (Fig. 1a-d) which act as support structures during the winding procedure, UV photolithography is used to define cylindrical, 700 µm high SU-8 posts on a 4 inch standard Pyrex substrate. SU-8 enables us to precisely pattern posts with a high range of diameters from 250 µm to 2000 µm, providing high aspect ratios.

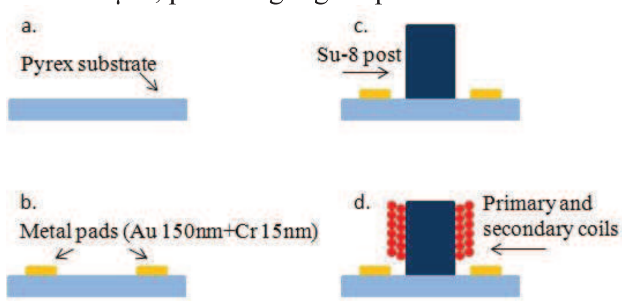

Fig. 1: Transformer fabrication procedures consist of metal patterning, thick SU-8 structure lithography and wirebonding.

Pyrex wafers were chosen to avoid the induction of eddy current in the substrate and hence to minimize substrate-related losses.

In order to define the bond position for the wires with respect to the position of the transformer cores, metal pads were defined on the substrate using a lift-off process. First, ma-N 1420 negative-tone photoresist is structured prior the deposition of a Chromium/Gold (15/150 nm) metal layer, which is then evaporated onto the substrate. After the lift-off, the SU-8 posts are structured subsequently.

Finally, the wirebonder is employed to wind 25 µm thick insulated Gold wire in a helical manner around the posts. Each coil, the primary and the secondary, consists of 12 turns and is wound in a tight manner, so that the secondary coil is accurately placed in the pits of the primary coil, as shown in Fig. 2 and 3. The winding time for each transformer is between 2 to 10 s depending on the number of turns and the post diameter. The required winding trajectories for both, the primary and the secondary coil, are defined in a homemade MATLAB code.

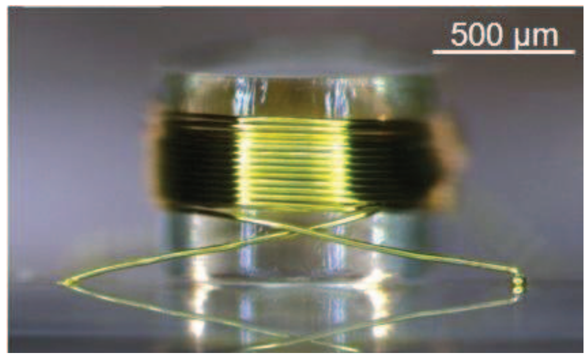

Fig. 2: Cross section view of a transformer with 1 mm diameter and 12 turns.

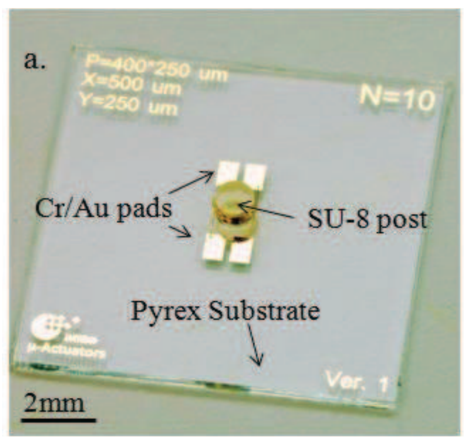

Fig. 3: Top view of a complete transformer chip on a Pyrex substrate.

MEASUREMENTS AND RESULTS

Two different transformers are presented here: sample 1 with a post diameter of 1.5 mm, and sample 2 with a post diameter of 1 mm. Both samples have 12 turns in the primary and in the secondary coil.

The DC resistances of the both samples were measured with four-point probes using an Agilent 34410A digital Multimeter. Scattering parameters of the transformers were measured using an Agilent E8361A Network Analyzer, which was connected to a Cascade Microtech 9000 probe station, equipped with two Cascade SG-500 microprobes having a pitch of 500 µm. Prior to the measurement, the setup was calibrated using a Cascade PN106-683 impedance standard substrate. By conversion of the scattering parameters into an impedance matrix, primary and secondary inductances as well as electrical resistance, quality-factor and mutual-coupling were determined, whereas the efficiency has been measured directly using the scattering parameters as described in [13]:

$$G = \frac{|S_{21}|^2}{1-|S_{11}|^2} \qquad (1)$$

Self-resonances for both samples were determined at around 50 MHz (Fig. 4). Below self-resonance, the inductances of the primary and secondary coils were measured to be L_{11}= 372 nH and L_{22}= 339 nH for sample 1, and L_{11}= 199 nH and L_{22}= 182 nH for sample 2, as shown in Fig. 4.

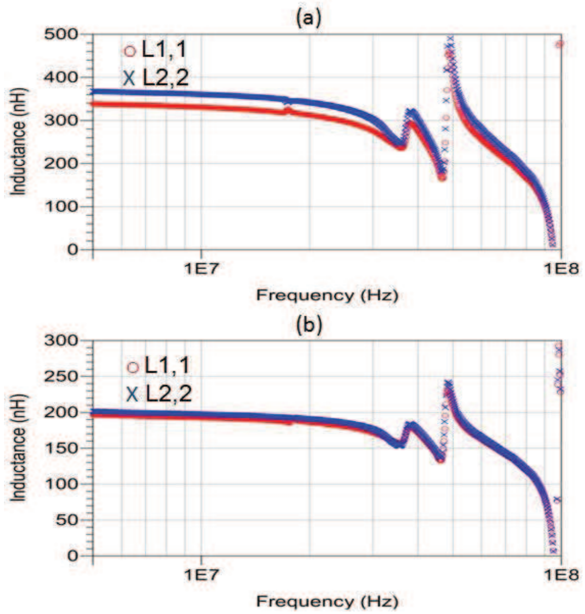

Fig. 4: Two ports inductance for (a) sample 1 (∅= 1.5 mm) and (b) sample 2 (∅= 1.0 mm).

Table 1: Transformers comparison

Parameter	Sample 1	Sample 2
Core ∅ (µm)	*1500*	*1000*
Turns	*12*	*12*
L_{11} *(nH)*	*372*	*199*
L_{22} *(nH)*	*339*	*182*
$R_{11\,dc}$ (Ω)	*3.93*	*2.81*
$R_{22\,dc}$ (Ω)	*3.90*	*2.58*
Q_{max}	*13*	*11*
Coupling	*92%*	*93%*
$Efficiency_{max}$	*50%*	*39%*

The DC resistances are part of table 1 that lists and compares all parameters. The difference of inductance and resistance between the primary and the secondary coils results from their slightly diverse wirebonding trajectories. They were necessary to enable the same start height of the windings above the substrate for both coils and wind them one on top of the other without reveling the wires.

The quality-factor of the transformers reached the maximum value of 13 in sample 1, respectively 11 for sample2 (Fig. 5).

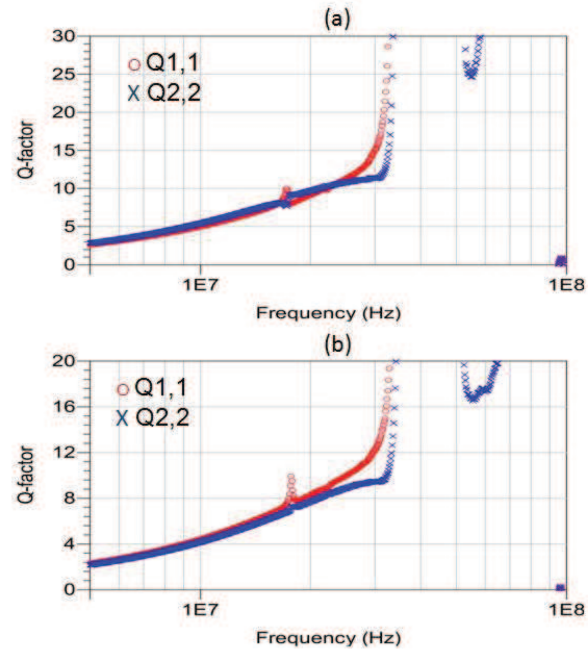

Fig. 5: Two ports quality-factor for (a) sample 1 and (2) sample 2.

The coupling-coefficients (Fig. 6) were both determined at a high value of 92%, resp. 93%, thanks to the compact 3D design of the transformers.

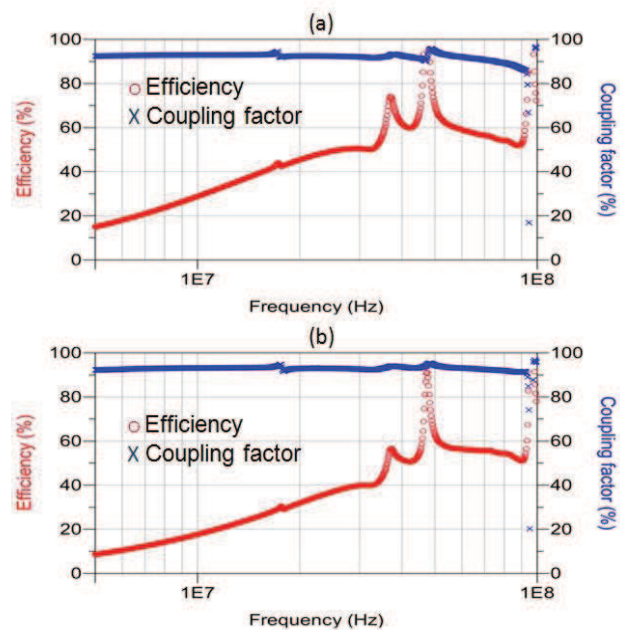

Fig. 6: Efficiency measured with 50 Ω load (red line) and coupling-factor (blue line) for (a) sample 1 and (b) sample 2.

Finally, sample 1 yielded a higher transformer maximum efficiency of 50% at 50 Ω load of the Network Analyzer, whereas sample 2 achieved 39% at the same load (Fig. 6).

CONCLUSION

We have demonstrated a very fast and flexible process for the fabrication of 3D, on-chip micro-transformers by using an automatic wirebonder. The fabricated samples yielded equivalent inductances and resistances, but higher coupling-factors and efficiencies than other previously published air core transformers. Table 2 compares our results to literature values, of which most included a magnetic core.

To improve the still moderate quality-factors of our transformers we will use Copper wire instead of Gold for its better conductivity, and we will enhance the thickness of the bond pads by electroplating depending on the frequency of interest and the skin depth at that frequency. Both, the post diameter and the number of turns are additional geometric factors to optimize the design towards maximum efficiency and quality-factor.

Table 2: Comparison of diverse transformers: white background with air-core, grey background with magnetic-core

Transformers	L_{max}(nH)	R_{DC}(Ω)	K(%)	F_{max}(MHz)
Sample 1	*372*	*3.93*	*92*	*40*
Sample 2	*199*	*2.81*	*93*	*40*
Ref. [4]	*500*	*~10*	*63*	*125*
Ref. [18](G2)	*35*	*23.7*	*87*	*60*
Ref. [12] (SR)	*370*	*2.6*	*86*	*100*
Ref. [14]	*400*	*0.48*	*93*	*20*
Ref. [5]	*100*	*1.2*	*90*	*0.5*
Ref. [15]	*800*	*1.1*	*90*	*11*
Ref. [16]	*800*	*7.7*	*93*	*40*
Ref. [17]	*100*	*<1*	*53*	*300*

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