# Solenoidal out-of-plane micro coils for MR analysis manufactured with a wire bonder

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## Introduction

Three dimensional micro coils are needed in medical technology for high-resolution magnetic resonance imaging (MRI) or for nuclear magnetic resonance (NMR) spectroscopy. The coil sensitivity, and therefore the desired signal, is maximized when the size of the coil matches that of the sample [1, 2]. For small samples or for single cell imaging, micro coils are used advantageously. Solenoids have greater magnetic field homogeneity and a higher filling factor compared to planar coils. It is difficult to miniaturize the manufacturing process of 3-D objects and there exist only few publications on manufacturing 3-D micro coils. Some authors use a hand-winding technique to produce their micro coils, e.g. [3]. A more complex process is described by Rogers et al. [4] who use microcontact printing with a rolling process. Dohi et al. [5] use surface micromachining with a folding process to produce a standing micro coil. One thing all described methods have in common is the low reproducibility and the lack of suitability for mass production.

When manufacturing micro coils with a wire bonder, we are able to produce solenoids with their axis perpendicular to the substrate and which are cheap and producible in a mass production sense. Wire bonding is a well-established technology in microelectronics where high accuracy and high manufacturing speed is achieved.

## Coil manufacturing

The normal wire bond process can roughly be divided into four phases: ball forming, welding the ball to the substrate (first contact), loop forming and terminating the loop with a wedge bond (second contact). During the loop process, the shape of the wire is formed, e.g. with respect to loop height or kinks. Modern wire bonders allow the user to define three dimensional coordinates, to which the bondhead moves consecutively. Therefore, almost arbitrary loop shapes are possible. Our method for solenoidal coils is the following: locate the ball and wedge position next to a post, move circularly around the post in such a manner that the wire plastically deforms to the post's shape and remains as a solenoid. We have tested four different coil diameters (300 µm, 600 µm, 690 µm, and 1000 µm) with two different posts (metal pole and glass capillary with a sample volume in the picoliter range) on two different substrates. A modified wire bonder heater plate served as a proof of principle substrate and a custom made printed circuit board (PCB) served for characterization of the coils, but also to show the ability of mass production, as an 2-D array of micro coils was realized using this substrate. We used insulated wire with a diameter of 29 µm including 2 µm of insulation. Clearly, on chip manufacture is possible.

Figures 1–3 show manufactured micro coils. The regularity of the windings is clearly seen in figure 1. In figure 2, the coil remains in the wound shape after core removal. Figure 3 shows an array of coils directly manufactured on a PCB.

## Coil performance

We have characterized the coils with an *Agilent E5071B* network analyzer. Table 1 shows our measured data in comparison with a simulation (done with *FastHenry*, a 3-D inductance extraction program [6]) and with calculations (formulae from [2]). The measured inductance values at 300 MHz lie between 12.1 nH and 13.2 nH leading to an average of 12.7 nH with a standard deviation of 0.3 nH. The average resistance at 300 MHz is 580 mΩ. Consequently, the coils have an average quality factor of 41. Figure 4 show these values vs. frequency after calculating them from the measured complex impedance.

## Conclusion

By using an automatic wire bonder, we have demonstrated the feasibility of producing 2-D arrays of 3-D micro coils in a manner compatible with mass production for highly parallel bio-analysis. The coil axes are perpendicular to the substrate with air or glass capillary as core, they have excellent RF properties suitable for MR applications, and each coil takes about 200 ms to fabricate in a batch process.

## References

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*Tab. 1: Electrical properties for a coil with 4 windings and a diameter of 690 µm at 300 MHz.*

| | $L$ (nH) | $R_L$ (mΩ) | $Q$ | $f_{\mathrm{res}}$ (GHz) |
|---|---|---|---|---|
| Our Work | 12.7 | 580 | 41 | 6.1 |
| Calculation [4] | 17.6 | 523 | 63 | 5.9 |
| Simulation (*FastHenry* [7]) | 16.5 | 948 | 33 | - |

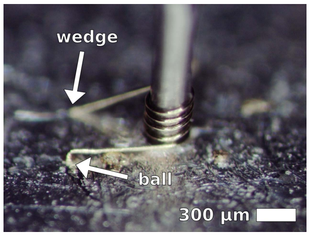

*Fig. 1: Five Windings, metal core.*

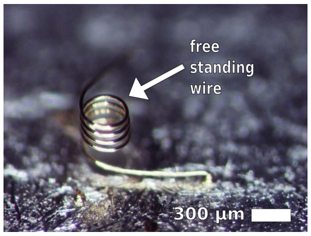

*Fig. 2: Air coil after core removal.*

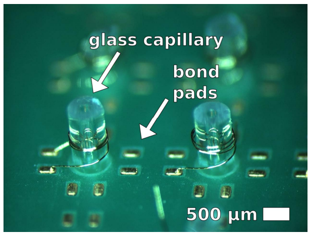

*Fig. 3: Two coils of an array, glass capillaries as core.*

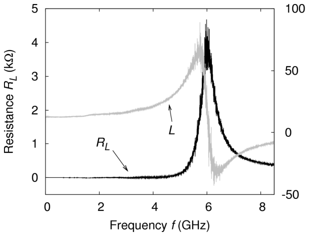

*Fig. 4: Resistance and inductance of a coil with 4 windings and a diameter of 690 µm.*