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High aspect ratio PMMA posts and characterization method for micro coils manufactured with an automatic wire bonder

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ABSTRACT

We present the development of high aspect ratio PMMA posts manufactured in deep X-ray lithography technology. The posts serve as support structures for micro coil windings. The coils are wound around these cores by an automatic wire bonder, and they are fully compatible with MEMS processes. Posts with outer diameters down to 100 μm and minimal sidewall thicknesses of 20 μm have an aspect ratio of up 38, leading to single-layer coils with more than 20 windings. With a flexible software, the winding number is only limited by the post height. We introduce a specially designed structure to determine the forces caused by the winding process. These measured forces are confirmed by shear test data. Electrical measurements show a quality factor of over 50.

1. Introduction

The particular properties of 3-D coils – high inductance values and a very homogeneous magnetic field – are needed in applications like sensors or actuators. Especially for integrated devices micro coils are very useful. However, the MEMS compatible miniaturization is very difficult. Klein et al. [1] have reported coils with a rectangular cross section. Their process with reactive ion etching in borosilicate glass results after 40 single process steps in a coil with a diameter of about 200 μm. Rogge et al. [2] use deep X-ray lithography in PMMA to form straight coil sidewalls. The etched holes are electroplated to form the coils; a seed layer on top helps to form the bridge. A smart, but sophisticated technology uses out-of-plane folding to create coils with diameters down to 2 mm [3]. Micro coils with a circular cross-section have been made with a self-made coil winding machine around a glass tube [4]. Loose wire ends have to be soldered manually for further connection. The same holds for Rogers et al. [5] with their printed coils. Here, a cylinder is rolled over a stamp moistened with a non-specified, but presumably conductive ink. This starting layer now initiates the deposition of metal for the coil. Matsumoto et al. [6] use a 3-D LIGA process. An acrylic pipe is rotated and moved simultaneously during X-ray exposure. The cylinder is metalized by beam sputtering and electroplated to thicken the metal.

All coils in the mentioned publications either have their axis parallel to the substrate, what makes it difficult to access the inner volume of the coil providing the homogeneous field, or they are detached from the substrate, what makes it difficult to connect the coils. So far, no parallel full-wafer batch process has been published for coils with their axis perpendicular to the substrate.

Therefore we have started to develop a process using an automatic wire bonder to wind 3-D coils with, first, their axis perpendicular to the substrate, and second, with each wire end properly connected to a bond pad. The wire bonder winds wire around a core to form a solenoidal shape whilst the wire is plastically deformed. Kratt et al. [7] reported on a procedure for coils with 690 μm diameter on glass cores, which were still limited to five windings. A micro Helmholtz pair with two windings per coil on SU-8 posts was presented by Badilita et al. [8]. In this paper we present the MEMS compatible fabrication of vertical 3-D micro coils on high aspect ratio PMMA posts with more than 20 windings. The posts are made with deep X-ray lithography and serve as mechanical support structures. During the winding process the post have to withstand the winding forces. These forces are measured with a specially designed structure that let us deduce the minimal adhesive force of the PMMA to the substrate.

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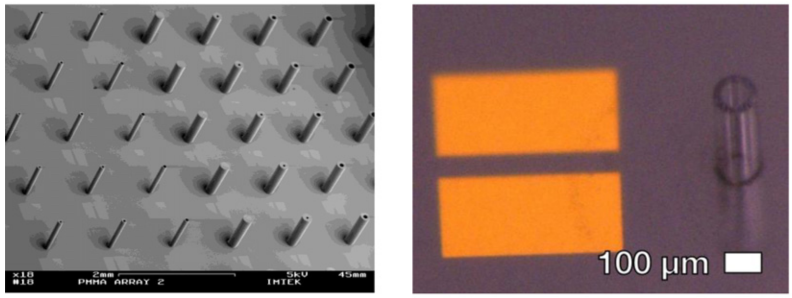

(a) Array of posts (b) 100 µm post, the sidewall thickness is 20 µm

Fig. 1. Posts made out of PMMA on a silicon substrate.

2. Methods

Coils are classically wound on a post. Even a self-supporting air-core coil is wound on a support, which may be removed after winding. Hence, before we start our coil winding procedure, we need microstructures as a pre-requisite that serve as supports. We decided to use poly(methyl methacrylate) (PMMA) as post material, as it can be patterned with deep X-ray lithography to achieve high aspect ratios. Silicon as well as Pyrex® serve as a substrate.

2.1. Sample preparation

To define the metal pads for the connection of the wire ends of the micro coils, a chromium/gold layer of 50/500 nm thickness was evaporated on the substrate. AZ 1518 photoresist was UV-patterned and the chromium/gold metal was subsequently wet-etched to define the pads.

On top of the structured pads, a PMMA layer was glued on the pre-patterned substrate using a PMMA/MMA based adhesive which includes some adhesion promoter and which is radically polymerized. The thickness of the resulting glue layer is in the range of 10–15 µm, which guarantees a stable connection of the PMMA to the silicon. The superimposing of this layer was done automatically with an industry standard "gluing robot". Therefore we have a uniform distribution of the glue on the surface and as a consequence a maximal adhesive strength of the PMMA. The PMMA layer itself was put with the same machine on top of the glue. Assembly accuracy in this step is not critical as the radiated area is much smaller than the PMMA sheet size. A pressure of 400 kPa was applied for 8 h to ensure a stable compound. The prepared substrate was then radiated with synchrotron radiation at ANKA, the synchrotron light source at the *Forschungszentrum Karlsruhe* (FZK). The pre-patterned substrate is aligned with respect to the X-ray mask using an alignment system with a precision of about 3 µm. The X-ray mask consists of a titanium membrane (2.3 µm) and a gold absorber layer (ca. 25 µm). The used radiation dose at the bottom is 3.5 kJ/cm^3.

We have used three different thicknesses (350 µm, 580 µm, 760 µm) of the PMMA sheet in combination with a silicon substrate. Two different thicknesses have been utilized on Pyrex® (350 µm and 700 µm). In both cases, post diameters are 500 µm, 200 µm, and 100 µm. The inner diameters are varied down to 80% of the outer diameter for the larger posts and 60% for the 100 µm post. This results in a minimal sidewall thickness of 20 µm. In the case of the thickest sheet (760 µm), the sidewall thickness of 20 µm leads to an aspect ratio of 38:1. Fig. 1 shows an array of posts as well as a single 100 µm post. By employing X-ray lithography to define the supporting (hollow) posts for the subsequent micro coil winding, we open the perspective to further fill the inner volume of the coil with soft-magnetic materials.

2.2. Coil winding process

Modern wire bonders allow the user to define 3-D coordinates, to which the bondhead moves consecutively. Thus solenoidal coils are fabricated by locating the first contact ("ball") next to a post and moving circularly around the post in such a manner that the wire plastically deforms to the post's shape and remains as a solenoid (scheme in Fig. 2).

The trajectory then is terminated with the second ("wedge") bond. We are able to produce 3-D micro coils in a fast (single coil manufacturing time down to 200 ms), easy (single step process), precise (accuracy < 3 µm), and reproducible way (batch process compatible). Fig. 3 shows a coil with 20 windings made of an insulated gold wire (*X- Wire*™ from *Microbonds*) with a diameter of 25 µm wrapped around a PMMA post of 500 µm diameter.

3. Characterization

The adhesive force of the PMMA to the substrate has been measured in two ways. First, we used a shear tester, which directly was applied to the posts. Second, we measured the maximum possible winding height until the posts broke off the substrate. The pulling force of the wire during the winding procedure was measured by the help of specifically designed microstructures.

3.1. Shear measurements

For the shear measurements on the posts we used a *DELVOTEK 5600 Pull-Shear-Tester*. The chisel of the machine was placed in front of the post. After a touchdown to the substrate, the chisel moved to the desired shear height – 20 µm in our case. The machine now pushed with increasing force against the post until it broke and the force dropped to zero.

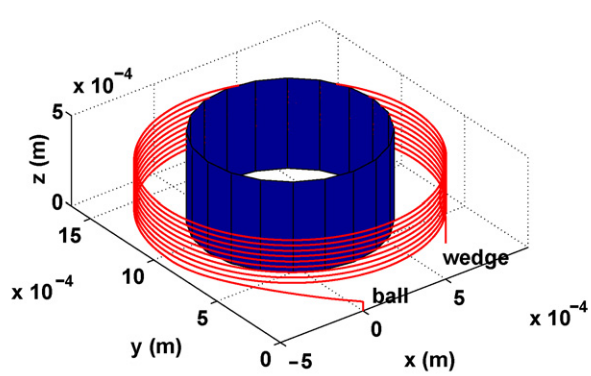

Fig. 2. Trajectory scheme for a coil made with an automatic wire bonder.