NOVEL MEMS-BASED FABRICATION TECHNOLOGY OF MICRO SOLENOID-TYPE INDUCTOR FOR MICRO ENERGY APPLICATION

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Abstract: Solenoid configuration is preferred for micro inductor because of high quality factor and low loss but it is difficult to be realized using conventional MEMS process. In this work, we present a novel MEMS-based fabrication technology of micro solenoid-type inductor using cylindrical projection lithography. Micro inductor prototypes were successfully prepared. The minimum feature sizes including average line width and pitch were reduced to about 18.3 μm and 39.4 μm, respectively. Electroplating process of copper layer was also successfully established for tiny capillary substrates. 4.7 and 5.6 μm thick copper layers were electroplated on 1 mm-diameter capillary and the measured resistance per windings was about 0.56 Ω and lower. The prepared prototypes show attractive potentials in application of micro energy technology such as electric current sensing.

Keywords: MEMS, micro solenoid-type inductor, cylindrical projection lithography.

INTRODUCTION

Solenoid-type inductor is one of the most commonly used electronic components and there have been being strong interests into its miniaturization technology. Solenoid-type micro inductor is particularly interesting for micro energy applications such as electric current sensing, because it has higher inductance and lower loss than other types of inductor [1]. As a matter of fact, the solenoid-type micro inductor is difficult to be prepared using conventional MEMS processes, which are mainly for planar substrates. As a result, most reported MEMS-based micro inductors are still of planar configurations, and so they have limited performance and high loss.

Very recently, K. Kratt et al. [2-3] have successfully prepared solenoid-type micro coils using an automatic wire bonder. One micro coil with 4 windings and a diameter of 690 μm can be fabricated in 200 ms. Although, their method is very attractive for practical applications, V. Demas et al had found that the lithographic coils showed better performance than wire wound coils when the pitch was shorter than 50.8 μm [4]. Therefore, there are still many efforts on developing photolithography-based fabrication technology for micro solenoid-type inductor [4]. Using laser irradiation, T. Kikuchi et al. also successfully fabricated a platinum grid-shaped microstructure, a microspring, and a cylindrical network microstructure with 50–100 μm line width [5]. Matsumoto et al. [6] developed a three-dimensional X-ray lithography method using X-rays from a synchrotron radiation facility as a light source for lithographic exposure and an X-ray mask for patterning cylindrical microcoil structures with a high aspect ratio. However, these methods are involved of expensive equipments or limited resolutions. New photolithography method should be developed for the fabrication and integration of micro solenoid-type inductor onto a common substrate on which other MEMS components and circuits can be easily fabricated. In this work, we would present a new cylindrical photolithography method for fabrication of solenoid-type inductor on a 1 mm-diameter capillary. Fig. 1 is schematic of the micro inductor to be prepared.

CYLINDRICAL PROJECTION LITHOGRAPHY SYSTEM

Fig. 2 is illustration of the cylindrical projection lithography system that was mainly involved of the movement of cylindrical substrate at the programmed speed and displacement. In this system, light source is
an Hg–Xe lamp (LC8, Hamamatsu photonics), which has a wavelength range of 250-600 nm.

This broad wavelength of incident light results in chromatic aberration in the focal plane. To remove this chromatic aberration, a bandpass interference filter with a central wavelength of 436 ± 10 nm was inserted between the light source and the shutter. The mask pattern was projected on to the cylindrical substrate with the reduction ratio of 1:2 by passing through the all optical elements. The He-Ne laser beam was utilized as a reference to setup and align all optical elements. The cylindrical substrate could be moved in X and θ-direction. The mask could be moved in X, Z, θ-direction. Therefore, the whole system has five degree-of-freedom so that various patterns could be prepared. Fig. 3 shows the fabrication sequences of micro solenoid-type inductor on 1 mm-in-diameter quartz capillary. Metal seed layers were deposited on the quartz capillary using sputtering method. Photoresist films on 1 mm-in-
diameter capillary were deposited using direct spray coating. In this work, Shipley S1830 positive photosresist (Shipley Co. LLC) was used. In addition, AZ5200 thinner (AZ Electronic Materials) was used as thinner solvents. AZ5200 thinner mainly consists of propylene glycol monomethyl ether acetate (PGMEA).

Two type of electroplating processes were developed for copper windings. In the Process 01, copper is used as metal seed layers. Moreover, seed layers are removed after copper electroplating (Fig. 3 (f) & (g)). On the other hand, in the process 02, gold is used as seed layers, and after removal of seed layers, inductor patterns are directly electroplated (Fig. 3 (h) & (i)).

EXPERIMENTS
Fig. 3 shows the fabrication sequences of micro solenoid-type inductor on 1 mm-in-diameter quartz capillary. Metal seed layers were deposited by using sputtering with rotation of substrates. Photosresist films on 1 mm-in-diameter capillary were deposited by using direct spray coating. In this work, Shipley S1830 positive photosresist (Shipley Co. LLC) was used. In addition, AZ5200 (AZ Electronic Materials) was used as thinner solvents. AZ5200 thinner is mainly based on propylene glycol monomethyl ether acetate (PGMEA).

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RESULTS & DISCUSSION
Fig. 4 shows the fabricated micro inductor prototype with the pitch of 40 µm and the turns of 20. The averaged feature sizes including line width, pitch, and thickness along the longitudinal direction were 18.3 µm, 39.4 µm, 4.7 µm, respectively and the measured value of resistance was 0.56 Ω/turns. Solenoid-type micro inductors with the same pitch of 40 µm but more coils turns (20-100 turns) were also successfully prepared on the 1 mm-in-diameter capillary. However, the copper windings were damaged during the etching process of the seed layers, as shown in Fig. 4 (b). In addition, it is difficult to fabricate a thicker inductor because it is difficult to achieve fine patterns in resist films thicker than 10 µm using the current cylindrical photolithography system.

In order to solve this problem, instead of conventional process (Fig. 3 (f) & (g)), a directly electroplating process is also developed (Fig. 3 (h) & (i)). Fig. 5 (b) shows the fabricated micro inductor prototype using the direct electroplating process. The prepared inductor was of the pitch of about 40 µm. Its line width was about 30.3 µm. The inductor thickness was about 5.6 µm. Although the growth rate of copper layer along the sidewall of windings is almost as the same as that normal to the substrate, fine patterns were still achieved. Better results could be expected

| Table 1: Average feature sizes of prepared solenoid structure including line width, pitch and thickness. |
|---|---|---|
| width | pitch | thickness |
| designed values [µm] | 20.0 | 40.0 | 6.0 |
| measured values (Process 01) [µm] | 18.3 | 39.4 | 4.7 |
| measured values (Process 02) [µm] | 30.3 | 43.3 | 5.6 |
through optimization of mask pattern. Because gold seed layer exhibited better compatibility to the whole fabrication process, more effort would be concentrated on Process 02 and the latest results would be presented on the conference.

CONCLUSION

One novel MEMS-based fabrication technology of micro solenoid-type inductor was presented in this work using the cylindrical projection photolithography method. Micro inductor prototypes were successfully prepared and minimum feature sizes had been reduced down to 20 μm. Two type of fabrication process have been developed. In the process 01, a solenoid structure with the averaged feature sizes including line width, pitch, and thickness along the longitudinal direction were 18.3 μm, 39.4 μm, 4.7 μm, respectively and the measured value of resistance was 0.56 Ω/windings. In the process 02, a solenoid structure with the averaged feature sizes including line width, pitch, and thickness along the longitudinal direction were 30.3 μm, 43.3 μm, 5.6 μm, respectively. The inductor prototypes were of solenoid configuration so that high inductance and low loss could be expected, and thus they would be attractive for micro energy applications.

REFERENCES


