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A Solenoid-Type Inductor Fabricated by MEMS Technique *

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Abstract: A solenoid-type inductor for high frequency application is realized using a micro-electro-mechanical systems (MEMS) technique. In order to achieve a high inductance value and *Q*-factor, UV-LIGA, dry etching technique, fine polishing and electroplating technique are adopted. The dimensions of the inductor are 1500μm ×900μm ×70μm, having 41 turns with a coil width of 20μm separated by 20μm spaces and a high aspect ratio of 3.5 :1. The maximum measured inductance of the inductor is 6.17nH with a *Q*-factor of about 6.

Key words: inductance value; microelectromechanical systems; quality factor

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1 Introduction

It is well known that a wireless communication system is becoming more and more important in daily life. For this great demand, portable and high quality electronic products are absolutely necessary in the future. The inductor plays a very important role among passive devices. It affects the quality of the sub-circuit, such as the band pass filter, LNA (low noise amplifier), and VCO (voltage controlled oscillator). The miniaturization of the inductor and the integration of the inductor with electronic circuit are the key to realizing electronic products with high performance, small size, light weight, high saturation current, high efficiency, and low product lost[1~5]. However, most of the conventional geometries for microinductors are meander-types or spiral-types, whereas most of the macro-scale inductors are solenoid-types. The main reason for not using the solenoid-type geometry inductors is that the fabrication of a microinductor with high inductance value and high quality factor (*Q*-factor) at high frequency is an extremely difficult task using the conventional semiconductor technology at present. In recent years, with the development of the MEMS technique, particularly the non-silicon fabrication technology of UV-LIGA (UV-Lithografie, Galvanoformung, Abformung) has become one of the most advanced technologies in fabricating the three-dimensional structures and RF MEMS (RF micro-electro-mechanical systems)[6,7]. It is reported Al is used as a conductor to fabricate solenoidal inductor, which creases resistance larger than that Cu[8]. In this work, an inductor for high frequency application based on solenoid-type geometry is designed and fabricated using the MEMS technique.

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2 Design

For a solenoid-type inductor whose geometry is composed of multilevel metal conductors (Fig. 1), neglecting the effect of the substrate and fringing, the inductance L can be represented by

$$L = \frac{\mu A_c N^2}{l_c} \tag{1}$$

where μ is the permeability of the core, A_c is the cross-sectional area of the core, l_c is the total length of the core, and N is the number of coil turns.

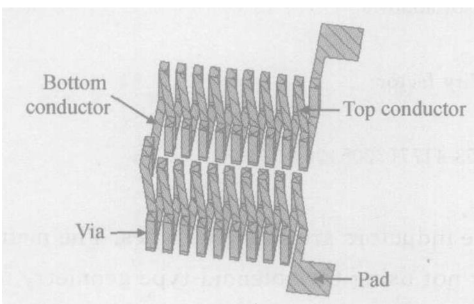

Fig. 1 Schematic diagram of a solenoid-type inductor

The quality factor can be defined by

$$Q = \frac{\omega L}{R} = \frac{\omega \mu N A_c A_w}{2(w + l)\rho l_c} \tag{2}$$

where A_w is the cross-sectional area of the conductor, ω is the radian frequency, $2(w + l)$ is the length of one coil turn, and ρ is the resistivity of the conductor material.

From Eqs. (1) and (2), it is seen that the inductance value and Q-factor are linearly proportional to μ and A_c in the microinductors. However, unlike the conventional inductors, the inductance value is not proportional to the square of the number of coil turns in the microinductor, since, due to the fabrication constraints on the micromachined inductor, a larger number of coil turns requires a longer core length. In a given dimensional area, the area of the core can be increased, which requires a tall via structure. Therefore, a high aspect ratio of 3.5 : 1 is used to achieve high inductance and Q-factor for a given total inductor area in this experiment.

3 Fabrication process

Figure 2 shows a brief fabrication process for the complete inductor. First, the double-side alignment symbols were formed on the clean glass substrate (Fig. 2 (a)), which is very important for double-side mask alignment photolithography. The chromium/copper layers were sputtered as a seed layer for electroplating and then covered by 10μm thick photoresist. The patterns of the bottom conductor traces were transferred photolithographically, followed by selective electroplating of the bottom conductor lines. Then 50μm thick via hole patterns were formed photolithographically and Cu vias were electroplated through those via holes. After that, the photoresist and chromium/copper seed layer were removed with dry etching, avoiding the erosion of bottom conductor lines by wet drying.

60μm thick polyimide was spun on the top of the conductors and vias through multiple coating.

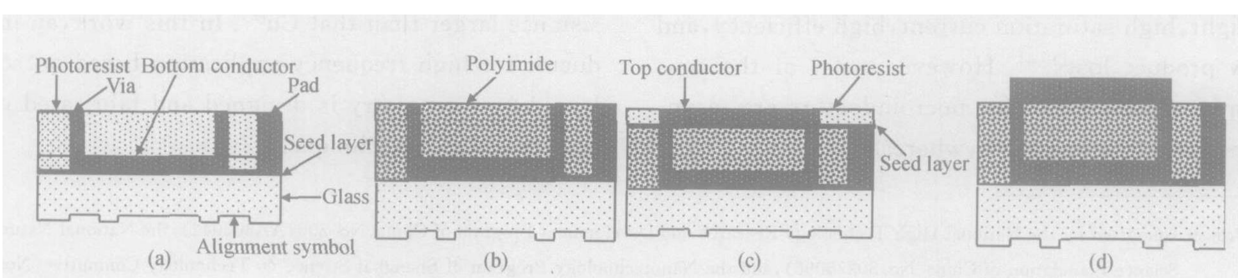

Fig. 2 Fabrication process for a complete inductor (a) Fabrication of alignment symbol, electroplating bottom conductor, via, and pad; (b) Spinning and curing polyinmide, and polishing polyimide until the vias were exposed; (c) Electroplating of top conductor; (d) Removal of seed layer

After coating, polyimide was cured at 60～250 ℃ for 2h and last at 250 ℃ for 2h. Then polyimide was fine polished until the vias were exposed. In this fabrication, polyimide, as a good passivation organic material for an integrated circuit, was used as the insulator and the structure holder because it has good insulating properties as well as good planarization and mechanical properties. Relative permittivity of polyimide is approximately 3.0, which is very similar to that of silicon oxide.

To fabricate the top conductor lines, the same process that was used to fabricate the bottom traces was used. In order to test the samples on the wafer, 2μm gold was plated. Figure 3 shows a SEM photographs of the fabricated microinductor, which consists of the electroplated multilevel copper conductor lines and polyimide as an insulation material.

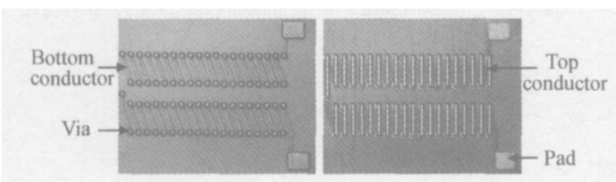

Fig. 3　SEM photos of the inductor　(a) After electroplating bottom conductor, via, and pad; (b) A complete inductor

4　Results and discussion

According to Eq. (1), there are three ways to improve inductance value: (1) increasing the permeability value (μ is a constant of 1 in the experiment); (2) increasing the cross-sectional area of the core through adding highness of the vias; (3) increasing coil turns, which means decreasing the coil width and space between the adjacent coils for a certain value of surface area. In this paper, a microinductor which has ultra-low profiles of 1500μm ×900μm, 41 turns, coils width of 20μm separated by 20μm spaces and a high aspect ratio of 3.5 ∶1, is fabricated by the MEMS technique. At last it is measured in the frequency range of 1MHz to 3GHz by the Agilent E4991A RF impedance/material analyzer, which connects to a probe station provided by a Cascade Microtech manufacturer. The Cascade Microtech ACP40-GS Series are also used as the probe head. After the instrument of open/short/load calibration, the measurement is performed. Figure 4 shows the inductance and Q-factor as functions of frequencies. The maximal inductance value of 6.17nH with the Q-factor of about 6 is achieved. According to Eq. (1), the calculated inductance value L is equal to 6.3nH, where $N = 41$, $\mu = 4\pi \times 10^{-7}$, A_c = 50μm ×170μm, l_c = 2840μm, which is approximatly the experiment value. For a low given dimensional inductor area (1500μm × 900μm), it is difficult to achieve such a high inductance value. For the same inductance value, a spiral inductor needs a larger size than a solenoidal inductor[4]. Though the solenoid-type inductor has a drawback of increasing fabrication complexity, the inductor has very good magnetic property such as a high inductance value. Since the main electromagnetic flux is parallel to the surface, it can be used as a microactuator.

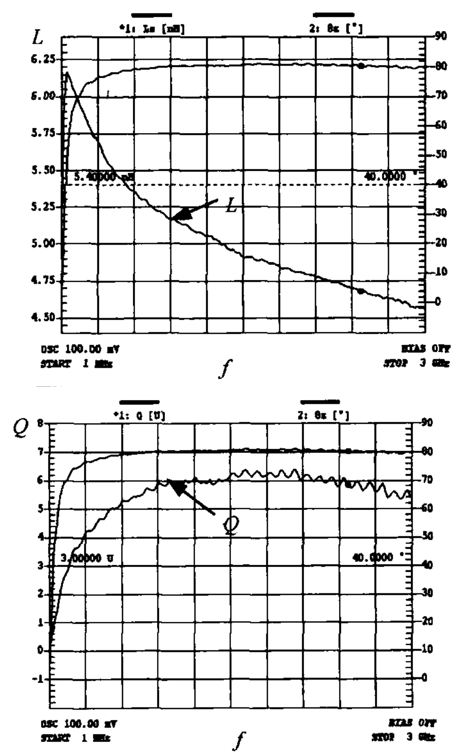

Fig. 4　Measured inductor parameter as a function of frequency　(a) Inductance versus frequency; (b) Q-factor versus frequency

5 Conclusion

A solenoid-type microinductor with ultra-low profiles is fabricated by the MEMS technique. The total inductor dimensions are 1500μm ×900μm × 70μm, having 41 turns, with coils width 20μm separated by 20μm spaces and a high aspect ratio of 3.5 ∶1. The inductance value of 6.17nH, which is approximate to the designed value, with *Q*-factor of about 6 is achieved. The devices fabricated in this experiment are compatible with IC technology, which have a good application future.

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References

[1] Liang S Y, Tsai S H, Lee C H, et al. Modeling and comparison of different micromachined three dimensional inductors. IEEE Radio and Wireless Conference, 2002: 277

[2] Chi Baoyong, Shi Bingxue. A 2.4GHz CMOS quadrature voltage-controlled oscillator based on symmetrical spiral inductors and differential diodes. Chinese Journal of Semiconductors, 2002, 23(2): 131

[3] Korenivski V. GHz magnetic film inductors. J Magn Magn Mater, 2000, 215/216: 800

[4] Kim Y J, Allen M G. Integrated solenoid-type inductors for high frequency applications and their characteristics. Electronic Components and Technology Conference, 1998: 1247

[5] Reyes A C, El Ghazaly S M, Dorn S J, et al. Coplanar waveguides and microwave inductors on silicon substrates. IEEE Trans Microw Theory Tech, 1995, 43(9): 2016

[6] Bryzekj. Impact to MEMS technology on society. Sensors and Actuators A: Physical, 1996, 56: 1

[7] Laurent D, Olivier G, De Rooij N F. Microsystems for diverse applications using recently developed microfabrication techniques. Proc SPIE, 2000, 4176: 16

[8] Liu C, Chen X L, Yan J L, et al. A novel lateral solenoidal on-chip integrated inductor implemented in conventional Si process. Chinese Journal of Semiconductors, 2002, 23(4): 352

采用 MEMS 技术制作的螺线管电感*

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摘要: 采用微机电系统技术制作了螺线管电感. 为了获得高电感量和 *Q* 值, 采用 UV-LIGA、干法刻蚀、抛光和电镀技术, 研制的电感大小为 1500μm ×900μm ×70μm, 线圈匝数为 41 匝, 宽度为 20μm, 线圈之间的间隙为 20μm, 高深宽比为 3.5 ∶1. 测试结果表明电感量最大值为 6.17nH, *Q* 值约为 6.

关键词: 电感量; 微机电系统; 品质因子

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