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MEMS Inductor Consisting of Suspended Thick Crystalline Silicon Spiral with Copper Surface Coating*

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Abstract: A novel MEMS inductor consisting of a planar single crystalline silicon spiral with a copper surface coating as the conductor is presented. Using a silicon-glass anodic bonding and deep etching formation-and-release process, a 40μm-thick silicon spiral is formed, which is suspended on a glass substrate to eliminate substrate loss. The surfaces of the silicon spiral are coated with highly conformal copper by electroless plating to reduce the resistive loss in the conductor, with thin nickel film plated on the surface of the copper layer for final surface passivation. The fabricated inductor exhibits a self-resonance frequency higher than 15GHz, with a quality factor of about 40 and an inductance of over 5nH at 11.3GHz. Simulations based on a compact equivalent circuit model of the inductor and parameter extraction using a characteristic-function approach are carried out, and good agreement with measurements is obtained.

Key words: MEMS inductor; suspended spiral; copper coating; quality factor; modeling and parameter extraction; radio frequency
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1 Introduction

There has always been great interest in pursuing inductors with a high quality factor (Q), large inductance (L), and high self-resonant frequency (SRF). Inductors play a key role in wireless radio frequency (RF) front-end circuitry, particularly in resonators for low phase-noise voltage controlled oscillators. They are also used as filter components and reactive impedance matching elements.

In recent years, many loss reduction techniques based on MEMS (micro-electromechanical systems) technology have been adopted to improve the performances of RF inductors. To reduce substrate loss and parasitic capacitances, suspended structures achieved using deep etching[1,2] or three-dimensional lithography[3] are adopted. To reduce series resistance and thus resistive loss, thick metal electroplating or electroless plating have been used to form a thick metal wire or a coating layer as a conductor[2,3]. To obtain a large L value, solenoid coil constructions have been fabricated[4,5]. MEMS inductors with a Q of several tens, L of several nH, and SRF of 10 to 20GHz have been reported[2,3].

We propose a novel MEMS inductor with a Cu-coated thick crystalline silicon spiral suspended on glass substrate. The silicon spiral is fabricated in bulk crystalline silicon substrate bonded to a glass substrate through silicon anchors using bulk-silicon micromachining, with a thickness of several tens of micrometers, as the 40μm-thick sample presented here. A highly conformal Cu-coating layer is then formed on every side of the spiral by electroless plating. Due to the reduction of resistive loss and the elimination of parasitic capacitances and substrate loss, the fabricated inductor exhibits excellent characteristics at high frequencies. The Q of the inductor reaches about 40 and L over 5nH at 11.3GHz, with an SRF higher than 15GHz. Furthermore, the suspended single crystal silicon spiral

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with a thickness exceeding several tens of micrometers may exhibit better mechanical properties, such as a higher rigidity, than suspended metal or deposited polysilicon spirals with thicknesses of only a few micrometers, which makes the structure insensitive to mechanical vibrations, and may effectively suppress the phase noise due to frequency jitter induced by random structural vibrations in certain applications.

2 Fabrication

Together with electroless plating technology, a silicon-glass anodic bonding and deep etching formation-and-release process[6] was used to manufacture the inductor. Figure 1 schematically depicts the main steps of the fabrication process. The bottom electrodes, consisting of sputtered Au/Pt/Ti (130/50/30nm), were formed on the areas of the glass substrate from which 130nm were etched away. Bulk crystalline silicon substrate was first etched by inductively coupled plasma (ICP) to form silicon anchors with a depth of 10μm. The etched silicon substrate was then attached to the glass substrate by anodic bonding through the anchors. The bonded silicon substrate was thinned by KOH wet etching and then milled by ICP deep dry etching from the back to form a 40μm-thick single crystalline silicon spiral. The anchors also serve as electrical joints between the suspended silicon spiral and the bottom electrodes on the glass substrate. Finally, electroless plating was carried out to form a highly conformal Cu coating layer on the silicon spiral surfaces, with nickel (Ni) thin film plated on the surface of the Cu layer for final surface passivation. The suspended structure enabled the metals to be plated on every side of the silicon spiral. During the electroless plating, Cu and Ni were selectively deposited on the silicon and metal surfaces but not on the glass surface. In the fabrication process, only three photolithography masks were needed. This process has been demonstrated to be controllable and reproducible. With this process, MEMS variable comb capacitors can also be produced, and monolithic inductor-capacitor circuits can be formed in combination with the inductors.

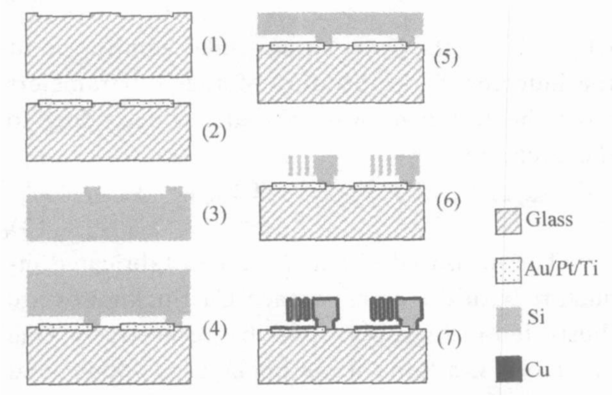

Fig. 1 Sequence of the main steps of the silicon-glass anodic bonding and deep etching formation-and-release process combined with electroless plating for fabricating the inductor

During the formation of high quality thick Cu coating on the surfaces of the silicon spiral through electroless plating, surface pretreatment and activation are critical. The surface pretreatment consisted of $H_2SO_4 + H_2O_2$ immersion for cleaning followed by isotropic oxygen plasma bombardment for further cleaning and surface roughing for better adhesion between the plated Cu and the silicon surfaces[7].

After the pretreatment, surface activation was carried out with $HF + PdCl_2$ (150ml/L + 0.2g/L), using palladium chloride as a catalyst. During the activation, the native oxide layer was first stripped from the silicon surfaces with hydrofluoric acid, and then palladium particulates were deposited as catalytic centers. The oxide and glass surfaces, however, are immune from the palladium particulate deposition. Based on experimental investigation, the optimal activation time is found to be between 30s and 1min.

The recipe for the Cu electroless plating solution we adopted is as follows: Cu(Ⅱ) sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$, 7g/L) as oxidation agent, formaldehyde (HCHO, 5ml/L) as reduction agent, 2,2′-dipyridyl (25ml/L) as brightener, ethylenediaminetetraacetic acid (EDTA, 15g/L) as complexing agent, and RE-610 (2.4mg/L) as surfactant. Potassium hydroxide (KOH, 18g/L) was used to adjust the pH value of the plating solution. The plating temperature was about 60℃. Figure 2 shows a cross-sectional scanning electron microscope (SEM) image of the conductor, which consists of Cu-coated thick silicon. It can be seen that a highly conformal Cu coating layer with thickness up to 900nm can be achieved on the silicon spiral surfaces through a 10min plating process.

Our Ni electroless plating process was similar

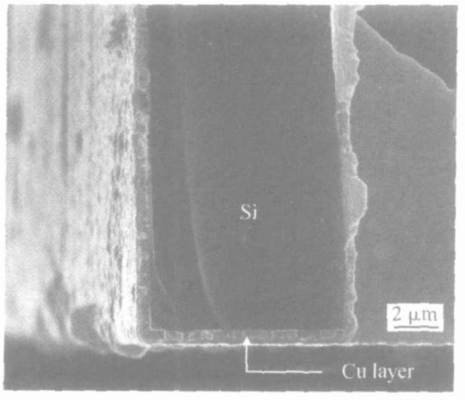

Fig. 2 SEM cross-sectional image of the conductor, which consists of Cu-coated thick crystalline silicon

to that for Cu electroless plating. The recipe for Ni electroless plating we adopted is as follows: Ni sulfate hexahydrate ($NiSO_4 \cdot 6H_2O$, 19g/L) as oxidation agent, sodium hypophosphite ($NaH_2PO_2 \cdot H_2O$, 20g/L) as reduction agent, and trisodium citrate dihydrate ($C_6H_5Na_3O_7 \cdot 2H_2O$, 20g/L) as complexing agent. Ammonia solution was used to adjust the pH value of the plating solution. The plating temperature was also about 60 ℃. The duration of the Ni plating and the corresponding surface pre-activation was 1min.

Figure 3 is an SEM view of one of the fabricated inductors with 3.5 turns. The conductor consisting of a 40μm-thick single crystal silicon spiral with Cu surface coating is suspended on glass substrate. The spacing and width of the silicon spiral are about 20 and 10μm, respectively. The use of insulating glass substrate eliminates substrate loss, and the Cu coating on the silicon spiral reduces the series resistance.

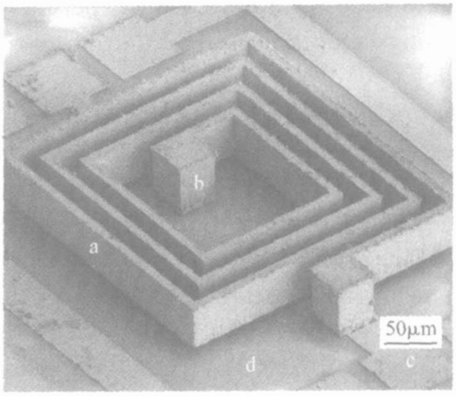

Fig. 3 SEM picture of the fabricated 3.5-turn inductor a: suspended conductor consisting of a thick silicon spiral with Cu-coating; b: Cu-coated silicon anchor; c: Cu-coated Au/Pt/Ti bottom electrode; d: glass substrate

3 Characterization

3.1 Measurement

On-wafer testing was performed with an HP 8510C network analyzer and Cascade 9000 ground-single-ground on-wafer probes, and two-port *S*-parameters were obtained. The two-port *Y*-parameters deduced from the *S*-parameters were then used to calculate *Q* and *L* of the inductor, which are defined as[8]

$$Q = \frac{\mathrm{Im}(1/Y_{11})}{\mathrm{Re}(1/Y_{11})} \tag{1}$$

$$L = \frac{\mathrm{Im}(1/Y_{11})}{\omega} \tag{2}$$

where Y_{11} is the short-circuit input admittance of the inductor. De-embedding of the *Y*-parameters from the test pads was carried out according to the equation[9]

$$Y_{\text{de-embedded}} = [(Y - Y_{\text{open}})^{-1} - (Y_{\text{short}} - Y_{\text{open}})^{-1}]^{-1} \tag{3}$$

The measured *Q* and *L* of two fabricated inductors with different surface Cu thicknesses are illustrated in Figs. 4(a) and (b), respectively. One inductor has a thin Cu coating layer of 400nm, and the other has a thick Cu coating layer of 900nm. It is apparent that the thick Cu-coated inductor exhibits a higher *Q* than the thin Cu-coated inductor, mainly due to the greater reduction in the series resistance of the conductor. As shown in Fig. 4(a), *Q* values as high as 38.7 and 10.1 at 11.3GHz are realized for the former and latter, respectively. From Fig. 4(b), the thick Cu-coated inductor shows a slightly lower *L* than the thin Cu-coated inductor, as predicted physically, and the *L* of the inductors reaches over 5nH at 11.3GHz. In addition, an SRF higher than 15GHz is achieved for the inductors, which is mainly due to the elimination of substrate capacitances by using glass substrate. The glass substrate also improves the inductor *Q* and *L* at high frequencies.

3.2 Modeling

Due to the elimination of substrate loss, the lumped element equivalent circuit for the present RF MEMS inductor can be simplified from the asymmetric single-π model to a series branch Y_s

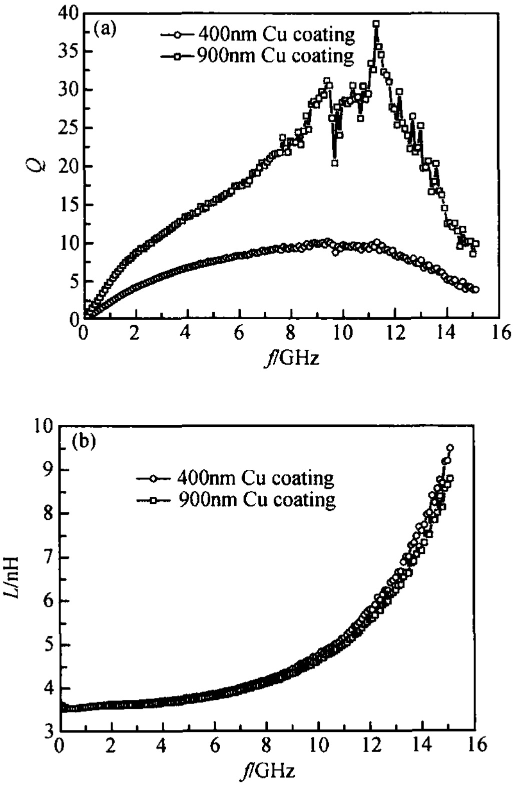

Fig. 4　Measured Q (a) and L (b) of the inductors with thick and thin Cu coatings

containing L_s, R_s, and C_s[10]. Using the de-embedded S-parameters and a characteristic-function approach[10], we carried out model parameter extraction based on the compact equivalent circuit. It can be verified that

$$Y_s = \frac{1 - \omega^2 L_s C_s + j\omega R_s C_s}{R_s + j\omega L_s} \qquad (4)$$

The real and imaginary parts of Eq. (4) can be written as

$$\frac{1}{\mathrm{Re}(Y_s)} = R_s + \omega^2 \frac{L_s^2}{R_s} \qquad (5)$$

$$\frac{\mathrm{Im}(Y_s)}{\omega} = C_s - \frac{L_s}{R_s}\mathrm{Re}(Y_s) \qquad (6)$$

Based on the measured S-parameters, the linear slope of $1/\mathrm{Re}(Y_s)$ as a function of ω^2 in Eq. (5) yields L_s^2/R_s. Similarly, the linear slope of $-\mathrm{Im}(Y_s)/\omega$ as a function of $\mathrm{Re}(Y_s)$ in Eq. (6) can be used to derive L_s/R_s, and in combination with L_s^2/R_s derived from Eq. (5), L_s and R_s can be obtained. Furthermore, C_s can be obtained from Eq. (6) if we know L_s and R_s. This method for extracting inductor model parameters takes into account the asymmetry of the inductor.

The extracted model parameters for the thick Cu-coated inductor are as follows: $L_s = 3.31\mathrm{nH}$, $C_s = 0.0214\mathrm{pF}$, and $R_s = 5.2\Omega$. As shown in Fig. 5 (a), the fit between measurement and simulation for L is within 1% root-mean-square (RMS) deviation over the broad frequency range of 0.1 ~ 15GHz, indicating high precision of the model parameters. The fit between measurement and simulation for Q is within 10% RMS deviation for frequency between 8 ~ 13GHz, where Q peaks, as shown in Fig. 5(b).

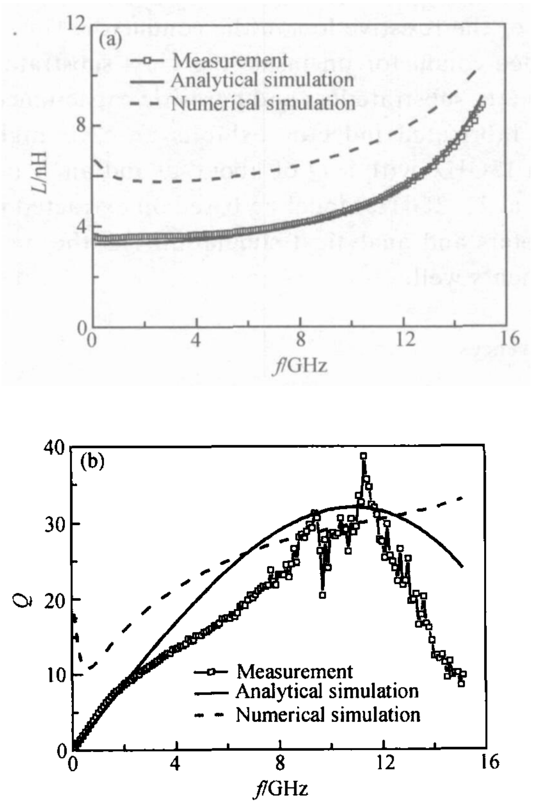

Fig. 5　Simulated L (a) and Q (b) of the inductor with thick Cu coating　The solid lines represent simulations based on parameter extraction with a compact equivalent circuit model, and the dashed lines are based on EM numerical simulations.

The inductor with a thick Cu coating layer was also simulated numerically by an electro-magnetic (EM) simulator, with the conductor approximated by a uniform Cu layer. The simulated L is about 50% over-estimated compared to the measurement, and the simulated Q at about 11.3GHz frequency at which Q reaches the maximum, is consistent with the measurement, as shown in Fig. 5.

4 Conclusion

A novel MEMS inductor with high Q and L at high frequencies has been fabricated and characterized. The fabrication involves a silicon-glass anodic bonding and deep etching formation-and-release process combined with Cu electroless plating to realize a Cu-coated thick crystalline silicon spiral suspended on glass substrate. The highly conformal and uniform Cu coating layer on every side of the silicon spiral leads to significant reduction of the resistive loss in the conductor. The suspended conductor on insulating glass substrate eliminates substrate loss and parasitic capacitances. The fabricated inductor exhibits an SRF higher than 15GHz, with a Q of about 40 and an L over 5nH at 11.3GHz. Modeling based on extracted parameters and analytical simulation fits the measurements well.

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表面镀铜悬浮厚单晶硅螺线MEMS电感*

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摘要: 报道了一种由悬浮在玻璃衬底上的表面镀铜平面单晶硅螺线构成的新型MEMS电感,可消除衬底损耗及减小电阻损耗. 采用一种硅玻璃键合-深刻蚀成型释放工艺并结合无电镀技术制作该电感,形成厚约40μm的硅螺线,在硅螺线表面镀有高保形厚铜镀层,在铜镀层表面镀有起钝化保护作用的薄镍镀层. 该电感的自谐振频率超过15GHz,在11.3GHz下,品质因子达到约40,电感值超过5nH. 基于该电感的简化等效电路模型,采用一种特征函数法进行了参数提取,模拟结果与测量结果符合得很好.

关键词: MEMS电感; 悬浮螺线; 表面镀铜; 品质因子; 建模与参数提取; 射频

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