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SOI-based radial-contour-mode micromechanical disk resonator

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Abstract: This paper reports a radial-contour-mode micromechanical disk resonator for radio frequency applications. This disk resonator with a gold plated layer as the electrodes, was prepared on a silicon-on-insulator wafer, which is supported by an anchor on another silicon wafer through Au–Au thermo-compression bonding. The gap between the disk and the surrounding gold electrodes is 100 nm. The radius of the disk is 20 μm and the thickness is 4.5 μm. In results, the resonator shows a resonant frequency of 143 MHz and a quality factor of 5600 in vacuum.

Key words: RF-MEMS; micromechanical disk resonator; SOI; thermo-compression bonding

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1. Introduction

Recently, micro-electro-mechanical systems (MEMSs) have been developing rapidly. With developments in communication, it is very important to investigate radio frequency (RF) MEMS. The RF MEMS resonator is a key device and is small in size, light in weight, can be mass produced and can be integrated with other circuit elements to form a RF front-end module[1,2].

Various kinds of RF MEMS resonators have been reported. The contour-mode disk resonator is a promising candidate for resonating a frequency range from 10 MHz to GHz[3]. The radial-contour-mode disk resonator is an important kind of resonator. In 1999, the first radial-contour-mode disk resonator was fabricated at the University of Michigan and the diameter of that resonator was 34 μm. Its frequency was 156 MHz and its Q value reached 9400[4]. Later, the frequency increased to 1.14 GHz[5] and then 1.51 GHz[6], and the material used to fabricate these resonators was polysilicon. Now, the frequency has reached 1.9 GHz through the use of diamonds[7]. Surface processing technology was used for all of these structures.

Surface processing technology has some mechanical design limitations. First, the vertical size of the device is limited because the film thickness is constrained by processing technology; second, the horizontal size of the device is affected by the mechanical properties, especially by stress. Single-crystal silicon has good electrical properties and excellent mechanical properties. By using single-crystal silicon and bonding technology, a large vertical size three-dimensional structure can be fabricated. Au–Au thermo-compression bonding is a kind of low temperature bonding technology and can be used to fabricate three-dimensional devices.

In this paper, as a new approach, a radial-contour-mode disk resonator is fabricated by using SOI wafer and Au–Au thermo-compression bonding technology.

2. Resonator design

The radial-contour mode disk resonator has a high resonant frequency and high quality factor, which can meet the communication requirements. The device is composed of a resonator disk supported by an anchor in its center and two electrodes surrounding the disk. The working process of the resonator includes the conversion of electronic and mechanical signals. Through signal transfer, the device can be divided into three parts. The first part is the input transducer, which is the capacitance of the input electrode and the disk resonator. This capacitance converts the electronic signal into a mechanical signal. The second part is the mechanical resonator, which selects the frequency by its resonance frequency. The third part is the output transducer, which is the capacitance of the output electrode and the disk resonator. This capacitance converts the mechanical signal into an electronic signal. Figure 1 shows a schematic picture of the disk resonator.

The dimensions and materials of the structure define the characteristics of the device—the resonant frequency, the qual-

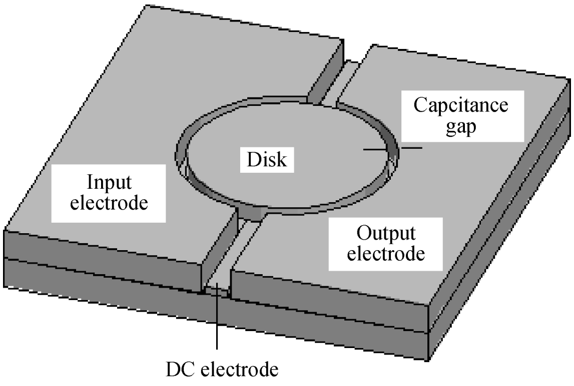

Fig. 1. Schematic picture of the disk resonator.

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ity factor and the output power.

2.1. Resonance frequency

For a radial-contour-mode disk resonator, the vibration frequency can be obtained by the one-dimensional vibration theory. Its diameter is far larger than its thickness and only longitudinal vibration is taken into account. The resonance frequency is obtained by solving the vibration equation[8]:

$$kRJ_0(kR) - (1-v)J_1(kR) = 0, \tag{1}$$

where $k = \omega/\sqrt{E/\rho(1-v^2)}$, E is the Young's modulus, ρ is density of the material and v is the Possion ratio. $J_n(y)$ is the Bessel function of the first kind of order n. Equation (1) has multiple solutions, if the solution is $R(n)$ we will get the frequency of this mode through Eq. (2):

$$f_n = \frac{R(n)}{2\pi R}\sqrt{\frac{E}{\rho(1-v^2)}}. \tag{2}$$

When the material characteristics and the diameter are defined, the resonance frequency is also defined.

2.2. Anchor

The anchor is closely related to energy loss. For a vibrating body, there is no displacement at the vibration nodes and also no energy loss at these points. One vibration node of a radial-contour-mode disk resonator is the center point. In order to decrease energy loss, the anchor should be in the center of the disk and should be small. However, a small anchor adds difficulty to the fabrication process. In order to achieve enough bond strength to support the disk, the bonded area must be big enough, however, the area should not be too big due to the limitation of energy loss.

2.3. Capacitance gap

The capacitance between the disk and the surrounding electrodes convert the mechanical signal and electronic signal. When the resonator is actuated by electronic signals, the electrostatic force transferred to the disk is given by

$$F = \frac{1}{2}\frac{\varepsilon_0 s}{d^2}(V_\mathrm{p} - v_\mathrm{i})^2, \tag{3}$$

where ε_0 is permittivity, d is the space between the electrode and disk, s is the overlap area between the input electrode and the disk, and v_i is the AC signal applied to input electrode. The disk has displacement at this force, if the displacement is Δd, the capacitance change ΔC is given by

$$\Delta C = \frac{\varepsilon_0 s}{d} - \frac{\varepsilon_0 s}{d - \Delta d}. \tag{4}$$

The output current is given by

$$i_o = V_\mathrm{p}\frac{\Delta C}{\Delta t}. \tag{5}$$

When the frequency of the AC signal is coincided with the resonant frequency of the disk, the output current achieves a maximum.

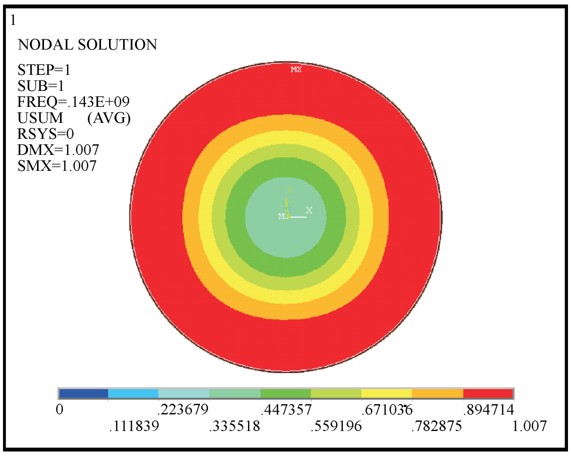


Fig. 2. Model simulation.

Through the analysis of Eqs. (3)–(5) we can find that the capacitance gap influences the displacement of the disk and finally influences the output power.

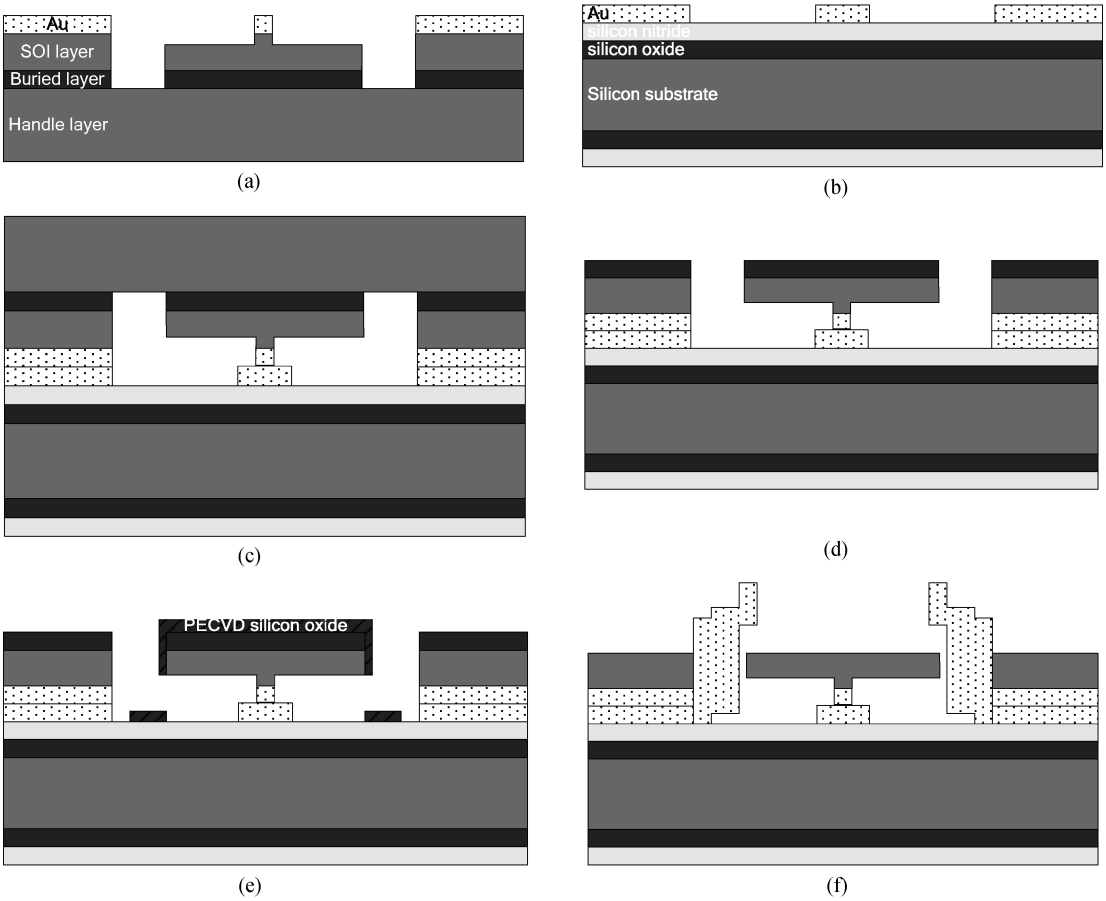
Figure 2 shows a simulation of a radial-contour-mode disk resonator by finite element analysis (FEA) package "ANSYS". The material parameter of the resonator is as follows: Young's modulus (170 GPa), density (2330 kg/m^3), Poisson ratio (0.278). The radius of the disk is 20 μm and the thickness is 4.5 μm. Through mode analysis, the resonance is 143.33 MHz. It is low compared with the frequency from Eq. (1), –148.59 MHz. The analysis is that the thickness cannot be ignored and the coupling vibration decreases the frequency.

3. Fabrication

According to the analysis and processing conditions, we have fabricated a radial-contour-mode disk resonator using a new approach. In this fabrication process, four inches of SOI wafer is used to define the disk. The SOI layer is 5 μm, the buried layer is 0.6 μm and the handle layer is 400 μm. The DC electrode is fabricated on a high impedance wafer. The two wafers are bonded together through Au–Au thermo-compression bonding technology. The input and output electrodes are fabricated by Au plating. The disk and surrounding electrodes are spaced by a narrow gap, which is defined by a SiO_2 sacrificial layer. The process flow diagram is shown in Fig. 3. The radius and the thickness of the disk are 20 μm and 4.5 μm, respectively. The capacitance gap is 100 nm and the diameter of the anchor is 3 μm and 0.6 μm high.

First, an SOI wafer (5 μm/0.6 μm/400 μm) is selected to fabricate the disk resonator. Thin layers of Cr, Pt and Au (150 Å, 300 Å and 500 Å) are spluttered on the SOI wafer and then the metal is patterned through metal lift-off technology. The patterned wafer is etched 5000 Å with RIE and the anchor of disk is defined. After this process, the retained SOI layer is etched by high-density inductively couples plasma (ICP) to form the resonator disk. The buried layer is retained to avoid contact between the surrounding electrode and the disk, and this layer is etched to the handle layer via dry etching. Figure 3(a) shows the cross section of the disk resonator.

Next, other high resistance silicon wafers are selected. A 600 nm-thick oxide layer is grown and then 250 nm silicon



(a) (b) (c) (d) (e) (f)

Fig. 3. Process flow for radial-contour mode micromechanical disk resonator.

nitride is deposited. The oxide layer and silicon nitride layer are used to protect the silicon when the handle layer of SOI is etched. Cr, Pt and Au (150 Å, 300 Å and 2000 Å) are splutterred on the wafer, this layer metal is used to define the DC electrode through metal lift-off technology. This is shown in Fig. 3(b).

After the two wafers are prepared, the two wafers bond together through a Au–Au thermo-compression bonding technique, as shown in Fig. 3(c). In order to obtain a good bonding result, two points should be considered: the surface treatment before bonding, and the temperature and press of the bonding process. The wafer is placed in a plasma atmosphere for 5 min to improve the surface activation energy and then exposed to UV light for 5 min. Short-wave UV light in the ultraviolet can penetrate into the tiny surface. Photosensitized oxidation occurs and generates volatile gas. This process can make the surface clean thoroughly. After surface treatment, the two wafers bond with SUSS's MA6/BA6 at 400 ℃. At this temperature, Cr diffuses to the Au surface and the resistivity of the metal film will abnormally increase[9]. Pt film can prevent this phenomenon.

Next, the handle layer is removed. The handle layer is etched via a combination of wet and dry etching. Under the influence of stress, in wet conditions, if the handle layer is too thin, cracks appear and liquid etches the structure, to avoid this, 70 μm Si is retained after wet etching and this thin layer Si is cleared away by high selective dry etching. The disk is released as shown in Fig. 3(d).

1200 Å PECVD silicon oxide is deposited to define the capacitance gap. The silicon oxide thickness is deposited on the surface and the sidewalls are different. 1000 Å is deposited on the sidewall. This layer is patterned and etched down to the silicon nitride layer, so Au electrodes fabricated on silicon nitride and can avoid falling down when the capacitance gap is released. This process is shown in Fig. 3(e).

Last, Au is plated to form the input electrode and output electrode. Finally the structure is released. Hydrofluoric acid solution (HF : H_2O (1 : 5) @ 40 ℃) is used for the sacrificial layer etching. Figure 3(f) shows this process.

Figure 4 shows the SEM image of the disk resonator and the capacitance gap.

4. Testing and results

An Agilent 8722ES network analyzer is used to attain the resonator frequency spectrum. The resonator is vacuous encapsulated and placed on a testing system. A metal box with printed circuit support and electrical feedthroughs allowing coaxial and DC connections to external instrumentation is used to test the resonator. Capacitances, inductances and the packaged resonator are placed in the printed circuit, the characteristic of the inductance and capacitance is defined by the resonance frequency. The printed circuit is placed in the metal box and connected to the coaxial through this box. All the fabricated resonators were tested and the resonance frequency of the resonators achieved a good consistency. The Q values are slightly different, ranging from 3000 to 5600. When the DC

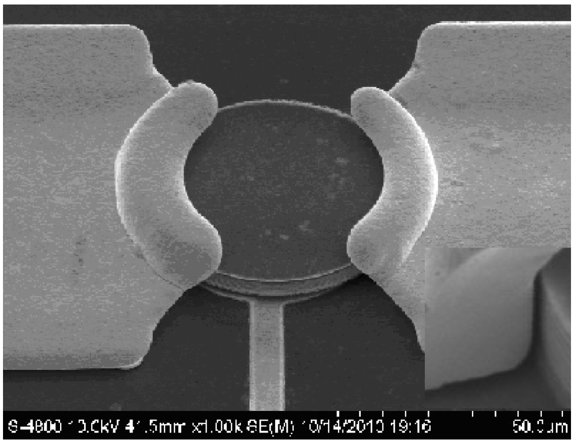


Fig. 4. SME image of the fabricated disk resonator.

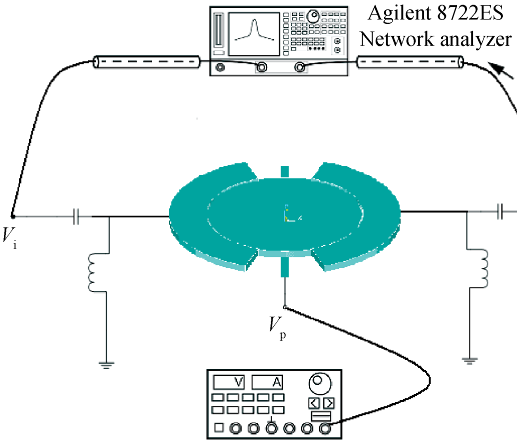


Fig. 5. Measurement scheme.

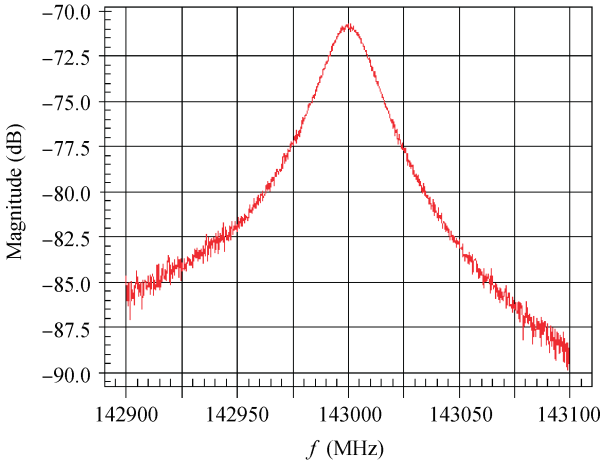


Fig. 6. Transmission spectrum for the disk resonator.

power is 12 V, the resonance frequency of the resonator is 143 MHz and the best Q is 5600. Figure 5 shows the testing system and Figure 6 shows the resonance characteristic. The resonance frequency coincides with the simulation but the Q value of this resonator is not high.

The quality factor (Q) of a resonator is:

$$Q = 2\pi \frac{W}{\Delta W}, \tag{6}$$

where ΔW denotes the energy dissipated per cycle of vibration and W denotes the maximum vibration stored per cycle. Many dissipation mechanisms exist in MEMS resonators, such as air damping, thermoelastic damping (TED), surface loss and support loss. All of these energy loss mechanisms affect the Q of a resonator[10]. Compared with the quality factor (approximately 10000) and the anchor size (diameter $\leqslant 2.0$ μm)[11], the Q value of the resonator we have fabricated is lower and the anchor is larger. Our analysis is as below: The anchor of the resonator is large and the energy loss through support via the anchor to substrate is more. The motion of a disk in its radial-contour mode is symmetric and purely radial for fundamental and higher modes. Its center corresponds to a motionless nodal point during vibration. Theoretically, the vibration node has no vibration displacement and no energy loss. The vibration node is infinitely small. The anchor supporting the disk has a certain size and there are consequent acoustic energy losses to the substrate through the anchor. In order to lower the energy loss through the anchor, the anchor should be reduced and the small area bonding technology should be improved. The other reason that lowers the Q value is related to the air damping. The vacuity of our vacuous encapsulated result is not high. Further work is in progress.

Q values have some differences, and the reason for this is as below. During fabrication, the anchor may not be at the center of the disk, so the energy loss through the support via the anchor to substrate is different, and the Q value is not the same.

5. Conclusions

A radial-contour-mode disk resonator is prepared using an SOI wafer and Au–Au thermo-compression bonding technology. The characteristic of the resonator is measured using a network analyzer. The DC power is 12 V, the characteristics of a resonator are achieved, the frequency is 143 MHz and the Q is 5600. As to the next work, the quality factor of the resonator will be improved by reducing the anchor area and realizing higher vacuum sealing.

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