FREQUENCY TRIMMING OF SILICON RESONATORS AFTER PACKAGE WITH INTEGRATED MICRO-EVAPORATORS

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ABSTRACT

This paper presents for the first time a novel method to trim the resonant frequency of a silicon bulk acoustic resonator after package with an integrated micro-evaporator. The micro-evaporator is bonded to the silicon resonator face to face. During trimming, an electric power is applied to heat the micro-evaporator locally to evaporate the top aluminum layer. The resonant frequency of MEMS resonator is trimmed permanently by the deposition of Al. The trimming rate is sensitive to the electric power and can be adjusted from -0.3 ppm/min to -12.2 ppm/min. The method can be used for both the coarse and the fine trimming.

INTRODUCTION

Absolute single-digit ppm frequency accuracy is a "must" for oscillators, while on the other hand the absolute frequency accuracies of MEMS resonators are about several hundred ppm even with the design for manufacturing due to the fabrication tolerance [1]. The resonant frequency may be adjusted electrically by fractional-N phase lock loops (PLL). However the powers of PLLs are relatively high, which limits the applications of MEMS oscillators. Permanent passive trimming techniques are desirable.

It is well known that the frequency of crystal resonators can be shifted downwards by deposition of a mass-loading layer. However, it is really a challenge to trim the MEMS resonators with the mass-loading effect because the MEMS resonators must be vacuum packaged before measurements and have to be trimmed after package. Laser trimming method was presented in MEMS resonators which were packaged with transparent caps [2][3]. The diffusion of deposited metals by local heating was also presented for post fabrication frequency trimming [4], though the Si-metal alloy formed by local heating may deteriorate the quality factors and the temperature coefficients of resonant frequency.

This paper reports a post-packaging permanent trimming method. The frequency of the resonator is trimmed by local evaporation of Al with integrated micro-evaporators. The experiments show that the deterioration of the Q factor after trimming is negligible.

PRINCIPLE

The structure of the resonator integrated with the micro-evaporator is schematically shown in Figure 1. The micro-evaporator chip is bonded to the silicon resonator face to face. Two micro-evaporators are included in the micro-evaporator chip to deposit Al to the two far ends of the resonator. Because the far ends of the resonators are less stressed, the local evaporation trimming features very mild influence on the Q factors. Each micro-evaporator is formed by a silicon evaporator boat supported by two silicon beams, with a low stress silicon nitride layer and an aluminum layer on top. The aluminum layer serves as the source material of evaporation, while the SiN_x layer serves as the barrier layer. To trim the resonator, electric power is applied to the micro-evaporator to heat the evaporator boats locally to evaporate the top Al layer. Owing to their small volumes, the evaporator boats may be heated to high temperature by a relatively small power. It is obtained by simulation that the temperature of the evaporator boat may reach 1117.8°C when 430 mW electric power is applied, without considering the heat of fusion and evaporation, as shown in Figure 2.

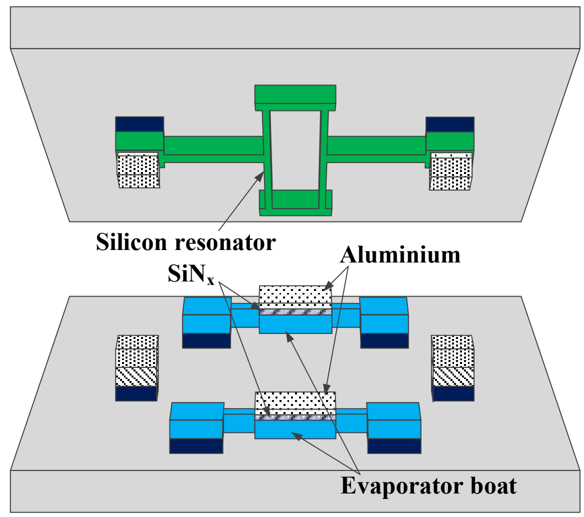


Figure 1: The schematic view of the micro-evaporator, which is bonded to the MEMS resonator face to face.

The evaporation rate of Al is formulated as

$$E = \alpha p \sqrt{\frac{M}{2\pi RT}} \tag{1}$$

where p is the saturation vapor pressure of Al at the temperature T. It is obtained from literature that p=10^{-6} Torr at 821 °C and p=10^{-4} Torr at 1010°C.

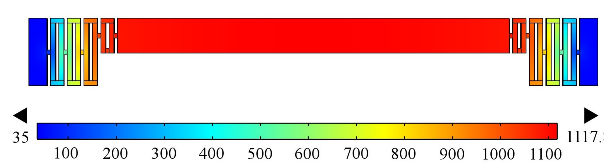


*Figure 2: The temperature of the evaporator boat is simulated to be 1117.8 ℃ when 430 mW electric power is applied. The coefficient of thermal conductivity of the rare air is assumed to be 0.029W/m*K.*

When aluminum is deposited to the resonator, the resonant frequency is trimmed down and Δf_0 is determined by the equation:

$$\frac{\Delta f_0}{f_0} = -\frac{\Delta m}{2m_{eff}} \approx -\frac{\rho_{Al} h_{Al}}{2\rho_{Si} h_{Si}} \tag{2}$$

where m_{eff} is the effective mass of the resonator, Δm is the mass of the deposited aluminum, ρ_{Si} and ρ_{Al} are the densities of silicon and aluminum respectively, h_{Si} and h_{Al} are the thicknesses of the resonator and the aluminum evaporated respectively . When the thickness of the resonator is small, trace amounts of aluminum may trim the frequency obviously. For example, when the thickness of the resonator is 5μm, a layer of 1nm thick aluminum trims down the resonant frequency about 116ppm. Theoretically, it takes less than 10 mins to trim down the resonant frequency about 1000ppm when the saturation vapor pressure of Al reaches 10^{-6} Torr. When the saturation vapor pressure of Al reaches 10^{-4} Torr, it takes just several seconds to trim down 1000ppm.

FABRICATION OF THE RESONATOR AND MICRO-EVAPORATOR

An LE mode MEMS resonator and a micro-evaporator chip is designed and fabricated to validate the method.

The micro-evaporator and MEMS resonator are fabricated with SOI MEMS processes separately and bonded together with flip-chip machine, as shown in Figure 3. The SOI layers are 5 μm thick and heavily boron doped to 0.01~0.02 Ω•cm.

The processes of the micro-evaporators are described as follows:

(a) A layer of 300 nm low stress silicon nitride is deposited by LPCVD and a layer of 600 nm aluminum is sputtered. Both layers are patterned. The aluminum layer serves as the source material of evaporation and the low stress silicon nitride serves as the barrier layer.

(b) After deposition and patterning of the Cr/Pt/Au electrode, the structures of the micro-evaporators are patterned by DRIE and released by HF vapor etching.

The processes of the silicon resonators are almost the same except that no low stress silicon nitride and aluminum layers are deposited.

After the Au stud bumps are fabricated on the micro-evaporator chips with wire bonding machine, the micro-evaporator chips and the silicon resonators are bonded face to face by thermal compression bonding with the flip-chip machine.

The SEMs of the samples are shown in Figure 4.

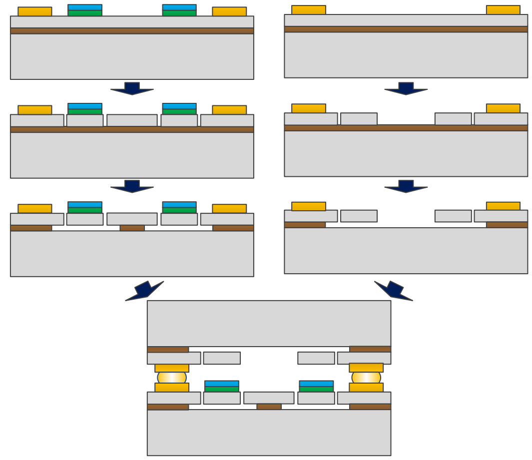
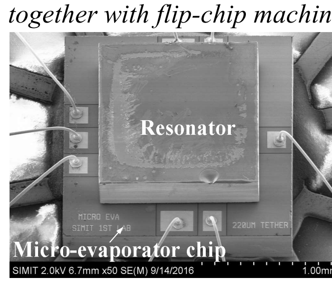
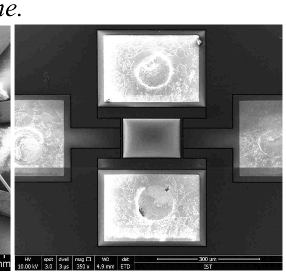
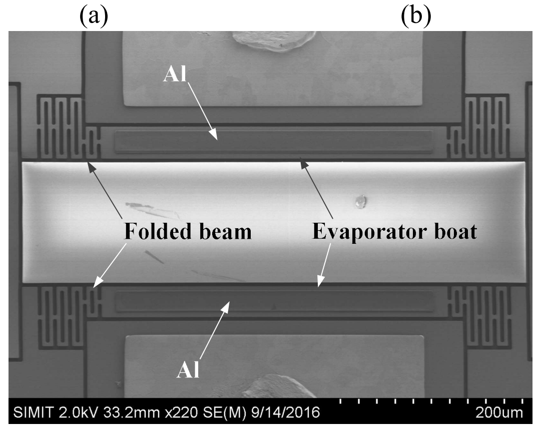


Figure 3 : The micro-evaporator and MEMS resonator are fabricated with SOI MEMS processes separately and bonded together with flip-chip machine.

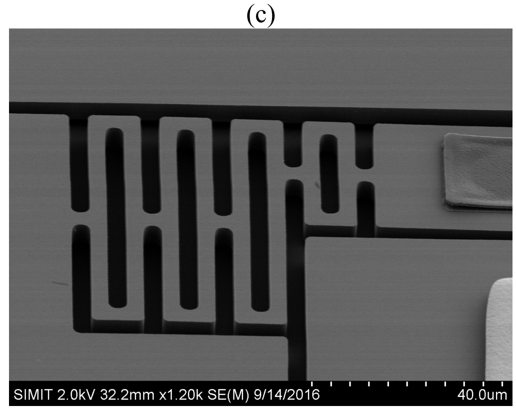




(a) (b)



(c)



(d)

Figure 4 : SEMs of the samples; (a) the micro-evaporator chip bonded to the resonator; (b) silicon resonator; (c) micro-evaporator; (d) the close-up of the folded beam.

FREQUENCY TRIMMING

The MEMS resonator was characterized and trimmed in a vacuum chamber, whose pressure was about 0.01Pa. The resonator employed electrostatic driving and piezoresistive sensing. The resonator itself was used as a piezoresistor and connected with a resistor to form a Wheatstone half-bridge. The resonant frequency and the Q factor was characterized with a network analyzer.

Before evaporation, the resonant frequency of the resonator was measured to be 3.705263MHz at 35°C, while Q factor was 162950, as shown in Figure 5. The excitation voltage of the Wheatstone half-bridge was as low as 0.5V to suppress the self heating.

The resonator was trimmed with the micro-evaporators three times. The two micro-evaporators were connected in parallel and an electric power of 286 mW was applied for 2 hours for the first trimming. After that the resonator was cooled and measured at 35 °C again. The resonant frequency was measured to be 3.70352MHz and the Q factor was 162020, as shown in Figure 5. The resonant frequency was trimmed down about 469.3 ppm. The average trimming rate was about -3.9 ppm/min. It was estimated that about 97pg Al was deposited at one end of the resonator.

Then an electric power of 210 mW was applied for 1 hours to trim the resonator again. The resonant frequency was trimmed down another 18.9 ppm. The Q factor was measured to be 162610, as shown in Figure 5. The average trimming rate was about -0.3 ppm/min. It was estimated that about 3.9pg Al was deposited at one end of the resonator.

An electric power of 320 mW was applied for 20 min to trim the resonator for the third time. The resonant frequency was measured to be 3.70255MHz and the Q factor was 161180 at 35 °C, as shown in Figure 5. The average trimming rate was about -12.2 ppm/min. It was estimated that about 50.4pg Al was deposited at one end of the resonator.

The parameters and measurement results of three time local evaporation trimming are summarized in Table 1. It can be obtained from Table 1 that the average trimming rate is sensitive to the electric power and can be adjusted from -0.3 ppm/min to -12.2 ppm/min. The method can be used for both the coarse and the fine trimming. The trimming deteriorated the Q factor slightly from 162960 to 161180.

Table 1: The parameters and measurement results of three time local evaporation trimming

	1	2	3
Heating Power (mW)	286	210	320
Evaporation time (min)	120	60	20
Δf/f (ppm)	-469.3	-18.9	-243.8
Mass of deposited Al (pg)	194	7.8	100.8
Trimming rate (ppm/min)	-3.9	-0.3	-12.2

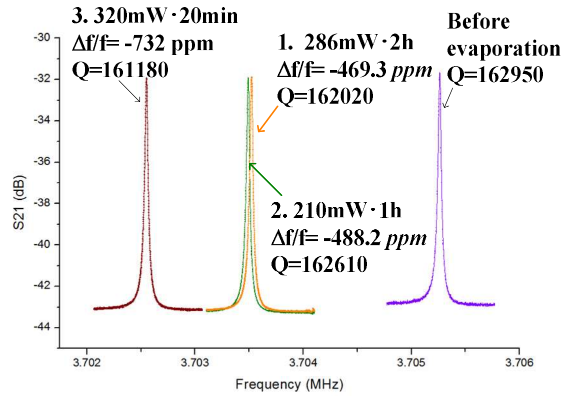


Figure 5 : The frequency responses of the MEMS resonator before and after the local evaporation trimming. The frequencies are measured at 35 ℃

CONCLUSIONS

A post-packaging permanent trimming method of the MEMS resonators is demonstrated in this paper. The resonant frequency of the resonator is trimmed down permanently by local evaporation of Al with integrated micro-evaporators. The resonant frequency of a LE mode silicon resonator was trimmed down about 732ppm, whose original resonant frequency was 3.7053MHz. The Q factor decreases mildly from 162950 to 161180 after trimming. The average trimming rate is sensitive to the electric power and can be adjusted from -0.3 ppm/min to -12.2 ppm/min. The method can be used for both the coarse and the fine trimming.

ACKNOWLEDGEMENTS

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