# Analysis Of The Effect Of Electrode Structure On The Uniformization Of Mass Sensitivity Distribution

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***Abstract*—To uniformize the mass sensitivity distribution of QCM, the mass sensitivity distributions of circular and ring electrode QCM were analyzed theoretically and verified by the Comsol Multiphysics software (based on finite element method). The results of circular and ring electrode inspired us to propose the dot double-ring electrode structure, and the corresponding simulation results show that an almost uniform distribution can be obtained. This is because more division of the electrode region makes the distribution of the vibration energy dispersed. This research provides a new direction to uniformize the mass sensitivity distribution.**

***Keywords*—dot double-ring electrode; mass sensitivity distribution; Quartz Crystal Microbalance (QCM)***

## I. Introduction

Quartz crystal microbalance (QCM) originated from the Sauerbrey equation [1] derived by Sauerbrey in 1959, the equation is as follows.

$$\Delta f = -\frac{2f_0^2}{A\left(\rho_q \mu_q\right)^{1/2}} \Delta m \quad (1)$$

$\mu_q$ and $\rho_q$ are shear modulus and density of quartz crystal, respectively. $A$ is the active area of the QCM surface, on which a rigid film is adsorbed. $\Delta m$ is the mass change of the rigid film, and $\Delta f$ is the corresponding frequency shift. The equation shows the linear relationship between the mass change of rigid film and frequency shift, which opens the door to QCM. In 1998, Josse et al. [2] pointed out that the mass sensitivity of the QCM surface is not fixed, but a Gaussian distribution. And the mass sensitivity distribution function was also given out. Gaussian distribution is an extremely uneven distribution; the maximum mass sensitivity is located in the center of the electrode and then decays exponentially with the radial direction, which is not conducive to the practical application of QCM.

To uniformize the mass sensitivity distribution, a lot of research has been done. The ring electrode was proposed by Josse in 1998 [2]. Its sensitivity distribution is bimodal, which overcomes the non-uniformity of the mass sensitivity distribution to a certain extent, but the non-uniformity is still obvious. In 2013, Xianhe Huang [3-6] proposed dot-ring and double-ring electrode inspired by the ring electrode. The corresponding sensitivity distributions have three peaks and four peaks, respectively. Compared with the single-ring electrode, the non-uniformity of the mass sensitivity distribution of the double-ring electrode has been greatly improved. Zhenghua Qian [7] and Haifeng Jiang [8] continued to study single-ring and double-ring electrodes in order to achieve a thorough uniformity of sensitivity distribution. Their research further improved the uniformity of the mass sensitivity distribution.

Inspired by the course of the ring to dot-ring and double-ring electrode, we believe that changing electrode structure is a better way to achieve uniform sensitivity distribution. In essence, change in electrode structure brings about change in vibration energy strength and vibration energy distribution. Therefore, in this paper, we continue to research the effect of the change of electrode structure on the mass sensitivity distribution, to further improve the uniformity of the mass sensitivity distribution.

## II. Theory

The mass sensitivity function [2, 9] is:

$$S_f(r) = \frac{|A(r)|^2}{2\pi \int_0^\infty r|A(r)|^2 dr} \cdot C_f, \quad (1)$$

$C_f$ is the Sauerbrey's sensitivity constant with a value of $1.78\times10^{11}$ Hz · cm$^2$/kg, $A(r)$ is the particle displacement amplitude function and $r$ is the distance from the electrode center. $A(r)$ is the solution of the following Bessel equation [2].

$$r^2 \frac{\partial^2 A}{\partial r^2} + r\frac{\partial A}{\partial r} + \frac{k_i^2 r^2}{N} A = 0, \quad (2)$$

where $N$ depends on the material constants of the quartz crystal, and $k_i^2 = (\omega^2 - \omega_i^2)/c^2$, where $i$ =*E, U, P* (*E, U,* and *P* represent the full electrode region, non-electrode region and partial electrode region, respectively), $c = \sqrt{c_{66}/\rho_q}$ is the acoustic wave velocity in the crystal (where $c_{66}$ is the elastic stiffness constant, $\rho_q$ is the density of the quartz), $\omega_i$ is cut-off frequency of full electrode region ($\omega_E$), non-electrode region ($\omega_U$) and partial electrode region ($\omega_P$), respectively.

Energy trapping effect [10, 11] refers to that when the frequency of the wave is higher than the cut-off frequency, the wave can propagate freely, otherwise, the wave will decay exponentially around the wave source. Due to the effect of electrode, the order of cut-off frequency is $\omega_U > \omega_P > \omega_E$. The operating frequency of the QCM is higher than $\omega_E$ and

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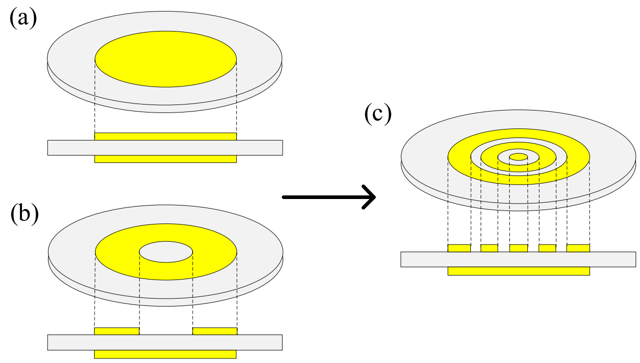


Fig. 1. Electrode structures. (a) Circular, (b) ring, (c) dot double-ring

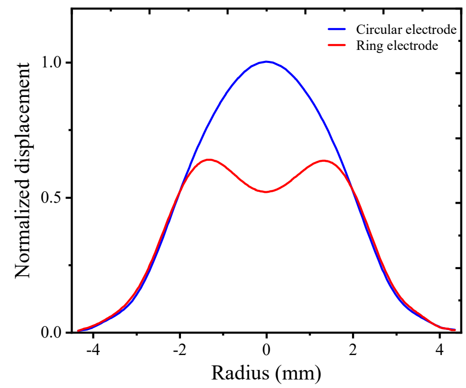


Fig. 2. Particle displacement amplitude distributions of circular and ring electrode

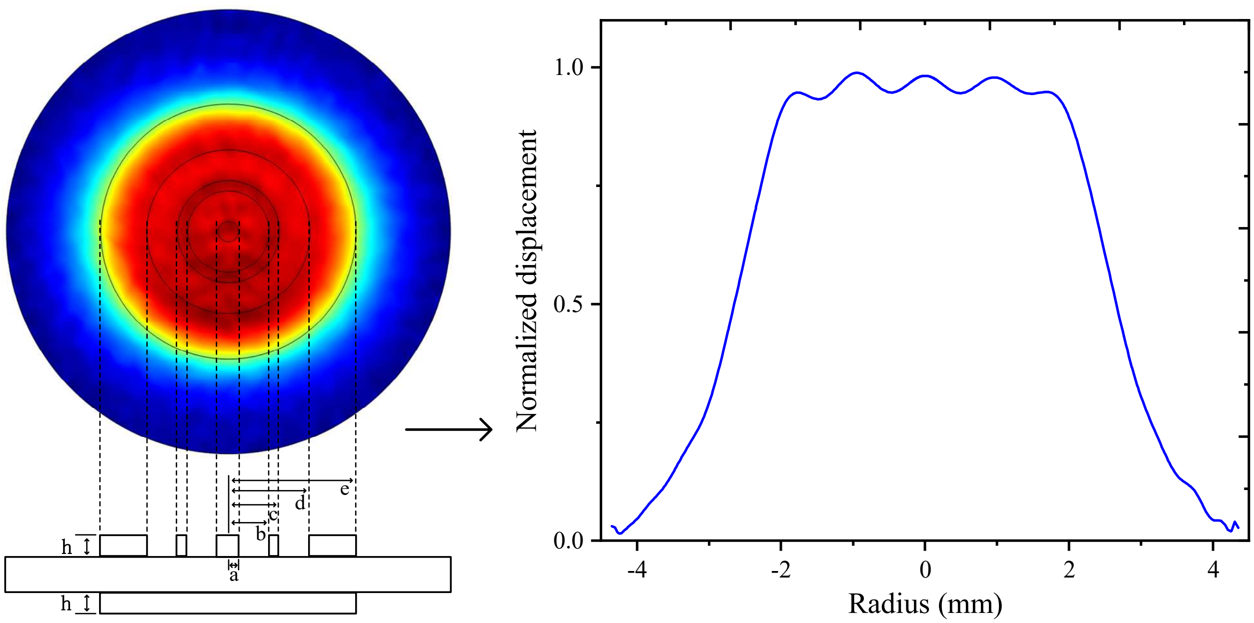


Fig. 3. Schematic of dot double-ring electrode and its distribution of particle displacement amplitude. h = 88 nm, a = 0.2 mm, b = 0.8 mm, c = 1 mm, d = 1.6 mm, e = 2.5 mm

lower than $\omega_U$ and $\omega_P$. Therefore, the wave will propagate freely in the full electrode region, but in the partial electrode region and non-electrode region, the propagation will be greatly hindered. This means that most of the vibration energy is confined to the full electrode region. We can adjust the distribution of vibration energy by adjusting the electrode structure to improve the uniformity of the mass sensitivity distribution.

## III. ANALYSIS AND VERIFICATION BASED ON SIMULATION

To verify the analysis above, we adopt Comsol Multiphysics software (based on finite element method) to simulate and analyze the mass sensitivity distribution of QCM, and an almost uniform sensitivity distribution is obtained. The thickness and diameter of the quartz wafer used are 166 um and 8.7 mm, respectively; the electrode material is gold; the corresponding frequency is about 9.9 MHz. In addition, to be more intuitive, the displacement distribution curve is normalized and fitted.

Fig 1 shows the electrode structures of the circular, ring, and dot double-ring electrode. And the simulation results of the circular electrode and ring electrode are shown in Fig. 2. For the circular electrode, we can see that the distribution is Gaussian; the maximum value is located in the center of the electrode. This is because the center area of the quartz wafer is full of the electrode, most of the vibration energy is concentrated in this area. Then we dig out the central part of one side circular electrode to form a ring, and the central area becomes the partial electrode area. At this time, the vibration energy is transferred from the central partial electrode area to the ring full electrode area. The lack of vibration energy in the central area makes the center of the distribution curve concave. Therefore, changing the full electrode region does change the distribution of vibration energy. Next, we designed a dot double-ring electrode to adjust the distribution of vibration energy. The electrode structure and simulation results are shown in Fig. 3. In the gradient map, the deeper the red, the greater the displacement amplitude of the particle. We can see that more division of the electrode region achieves an almost uniform distribution. The vibration energy in the dot electrode, inner ring electrode, and outer ring electrode is slightly stronger. There is still a slight depression between the dot electrode, the inner ring electrode, and the outer ring electrode, but we think this depression can be eliminated by adding more ring electrodes and adjusting the width and position of the dot electrode and the ring electrode.

## IV. CONCLUSION

The analysis and corresponding simulation results show that the mass sensitivity distribution is mainly affected by the electrode structure. The main reason for this is the energy trapping effect. More division of the electrode region makes the distribution of the vibration energy dispersed, so that the uniformity of the mass sensitivity distribution is improved. This provides a new direction for the uniformization of the mass sensitivity distribution.

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