Analysis of Quality Factor of the Quartz Crystal Resonator with N-M Asymmetric Electrodes

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***Abstract*—Recently, the quartz crystal microbalance (QCM) with N-M asymmetric electrodes has been reported to improve significantly its sensitivity. As a main part of QCM, the performance of quartz crystal resonator is directly related to QCM sensor. Therefore, it is necessary to develop a high performance of quartz crystal resonator. Considering that the quality (Q) factor is one of the most important parameters to the quartz crystal resonator. However, there is few studies to report the Q-factor of QCM resonator with N-M asymmetric electrodes. Herein, we investigate the Q-factor of QCM resonator with N-M asymmetric electrodes. The experimental results show that their Q-factors are larger than 15000, and all half bandwidths are less than 650 Hz. These performance parameters show that the QCM with N-M asymmetric electrodes have excellent stability and they can be reliably applied in many fields.**

Keywords—Quartz crystal resonator, quality factor, N-M asymmetric electrode, resonance frequency

I. INTRODUCTION

In the past serval decades, the quartz crystal microbalance (QCM) sensor has been used widely due to its excellent performance such as ultra-high sensitivity, low cost and real-time detection [1-3]. The common structure of QCM is two metal electrodes plated on quartz crystal surface like sandwich structure, and it is developed based on piezoelectric effect of quartz crystal. As a kind of micro-mass sensor, the QCM sensor is able to detect the small mass of nanogram scale. Therefore, it almost can be used in any field related to processes of small mass change. Sauerbrey proposed and verified that the relationship between the change of resonance frequency of QCM resonator and the mass change on the electrode [4].

Recently, the quartz crystal microbalance (QCM) sensor with asymmetric electrodes has been become a important direction to improve its sensitivity [5,6]. For example, citing the papers in asymmetric electrodes. It is well known that the QCM is consisted of quartz crystal resonator and oscillation circuit. Thus, the performance of quartz crystal resonator is closely related to QCM performance. Considering the frequency stability is one of the most important parameter for quartz crystal resonator, therefore, the frequency stability is also crucial to QCM sensor. As a parameter characterizing the stability of resonance frequency of resonator, quality factor (Q-factor) is a key parameter for QCM sensors. However, few studies report the Q-factor of quartz crystal resonator with N-M asymmetric electrodes structure. It is necessary to study the Q-factor of quartz crystal resonator with N-M asymmetric electrodes structure.

Comparing with traditional symmetric electrode QCM sensor, the QCM sensor with N-M asymmetric electrodes structure has higher sensitivity [6,7]. It means that the N-M asymmetric electrodes structure can improve significantly sensitivity. Thus, it will become more and more attractive in applications. However, the Q-factor of quartz crystal resonator with N-M asymmetric electrodes has been few reported up to now. In this study, we investigate detailly the Q-factor of quartz crystal resonator with N-M asymmetric electrodes structure. The Q factors of all QCM resonators with N-M asymmetric electrodes are larger than 15000, and all half bandwidths are less than 650 Hz. Additionally, the minimum detectable fractional frequency deviation is not greater than 6.5×10^{-5}Hz, it indicates that these QCM resonators have extremely high frequency resolution in theory. These performance parameters show that the QCM resonators with N-M asymmetric electrodes have excellent stability and they can be reliably applied in many fields.

II. QUALITY FACTOR ANALYSIS

A. Quartz Crystal Resonator withN-M asymmetric Electrodes

Currently, in order to meet the urgent needs for high sensitivity, the N-M asymmetric electrode QCM sensor has been reported [6]. In this paper, we designed two kinds of QCM sensors with N-M asymmetric electrodes. Fig. 1 shows that the two sizes of the AT-cut 10 MHz quartz crystal resonators with N-M asymmetric electrodes we have designed. The diameter and thickness of the quartz wafer are 8.7 mm and 0.167 mm. It should be noted that the N electrode (800 Å thickness) and M electrode (800 Å thickness) present up electrode and bottom electrode, respectively. For first type of N-M electrode quartz crystal resonator, the N electrode and M electrode are 5.1 mm and 4.1 mm, respectively. For second type of N-M electrode quartz crystal resonator, the N electrode and M electrode are 5.1 mm and 3.1 mm, respectively.

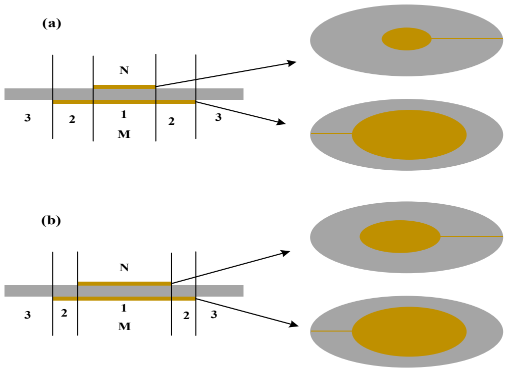

Fig. 1. Quartz crystal resonator with N-M asymmetric electrode structure. "1", "2" and "3" present the full electrode area, part electrode area and non-electrode area. (a) "3.1-5.1" type; the diameters of up and bottom electrodes are 3.1 mm and 5.1 mm. (b) "4.1-5.1" type; the diameters of up and bottom electrodes are 4.1 mm and 5.1 mm.

B. *Quality Factor of Quartz Crystal Resonator withN-M asymmetric Electrodes*

The Q-factor is a crucial parameter for quartz crystal resonator. According to definition of the Q factor, it describes the resonance frequency sharpness of quartz crystal resonator. In addition, it is related closely to the minimum detectable frequency change [8]. The Q-factor can be calculated by the following equation [9].

$$Q=\frac{f_0}{2\Gamma} \tag{1}$$

where f_0 is the resonance frequency of quartz crystal resonator; 2Γ is half-bandwidth of quartz crystal resonator. This equation means that the Q-factor is equal to the ration of resonance frequency and half-bandwidth. In general, when f_0 is constant, the Q-factor value increases with the decrease of half-bandwidth.

On the other hand, in order to understand the relationship between Q-factor of quartz crystal resonator and the minimum detectable fractional frequency deviation, we can deal with it by the Allan deviation theory [10]. In time domain, the Allan deviation $\sigma_y(\tau)$ is defined by [11]

$$\frac{\Delta f(\tau)}{f_s}=\sigma_y(\tau) \tag{2}$$

where f_s is the resonance frequency; $\Delta f(\tau)$ is the minimum detectable fractional frequency deviation. Besides, the empirical relationship between the Q-factor of QCM resonator and $\sigma_y(\tau)$ can be expressed [12]:

$$\sigma_y(\tau)_{\min}=\frac{1.0\times10^{-7}}{Q} \tag{3}$$

III. RESULTS

In order to better evaluate the quality of QCM resonators, we measured three samples for each type of resonators. The resonance frequency and half-bandwidth can be obtained by measurement device. Then the Q-factor and the minimum detectable fractional frequency deviation of QCM resonators with N-M asymmetric electrodes were calculated by the equation (1), (2) and (3), and the Q-factor values were shown as in Table I. Q-factor of 3.1-5.1 type QCM resonators are 16034, 25636 and 16568, respectively. Q-factor of 4.1-5.1 type QCM resonators are 15464, 22221 and 18783, respectively. The Q-factor of all QCM resonators with N-M asymmetric electrodes is greater than 15000, which indicates that they have excellent performance. Also, these results show that they can be used reliability in many research areas. In addition, the minimum detectable fractional frequency deviation is less than 6.5×10^{-5}Hz, it also indicates that these QCM resonators with N-M asymmetric electrodes have extremely high frequency resolution.

TABLE I. Q FACTOR OF QCM WITH N-M ELECTRODES

Sample ID	QCM-1	QCM-2 (3.1-5.1 type)	QCM-3	QCM-1	QCM-2 (4.1-5.1 type)	QCM-3
f_0 (Hz)	10,021,458	10,023,819	10,023,910	10,020,991	10,021,694	10,011,354
2Γ(Hz)	625	391	605	648	451	533
Q	16,034	25,636	16,568	15,464	22,221	18,783
$\sigma_y(\tau)_{min}$	6.24×10^{-12}	3.90×10^{-12}	6.04×10^{-12}	6.47×10^{-12}	4.50×10^{-12}	5.32×10^{-12}
$\Delta f(\tau)$(Hz)	6.25×10^{-5}	3.91×10^{-5}	6.05×10^{-5}	6.48×10^{-5}	4.51×10^{-5}	5.33×10^{-5}

IV. CONCLUSIONS

In this work, on one hand, we designed the QCM resonators with N-M asymmetric electrodes. On the other hand, we calculated and analyzed the Q factor and the frequency resolution of QCM resonators with N-M asymmetric electrodes. High Q factor for QCM resonator means that the high stability of output frequency. The experimental results show that Q factors of all QCM resonators with N-M asymmetric electrodes are larger than 15000, and all half bandwidths are less than 650 Hz. Additionally, their minimum detectable fractional frequency deviations are less than 6.5×10^{-5}Hz, it indicates that these QCM resonators with N-M asymmetric electrodes have extremely high frequency resolution in theory. These performance parameters show that the QCM resonators with N-M asymmetric electrodes have excellent stability and they will greatly attract attention of many researchers.

REFERENCES

[1] D. Y. Shim, S. M. Chang, J. M. Kim, "Development of Fast Resettable Gravimetric Aromatic Gas Sensors Using Quartz Crystal Microbalance." Sens. Act. B: Chem., vol. 329, 129143, 2021.

[2] Z. L. Xu, Y. Luo, "Immunoglobulin-Immobilized Quartz Crystal Microbalance for Staphylococcus Aureus Real-Time Detection," IEEE Sens. J., vol. 22, pp.11594-11601, 2022.

[3] F. Dirri, E. Palomba, A. Longobardo, E. Zampetti, B. Saggin, D. Scaccabarozzi, "A Review of Quartz Crystal Microbalances for Space Applications," Sens. Actuators A Phys., vol. 287, pp. 48-75, 2019.

[4] G. Sauerbrey, "Verwendung von Schwingquarzen zur Wägung dünner Schichten und zur Mikrowägung," Z. Phys, vol.155, pp. 206-222, 1959.

[5] X. Huang, Q. Bai, W. Pan, J. Hu, " Quartz crystal microbalance with approximately uniform sensitivity distribution," Anal. Chem., vol. 90, pp. 6367-6370, 2018.

[6] Y. Yao, X. Huang, B. Zhang, Z. Zhang, D. Hou, Z. Zhou, "Facile Fabrication of High Sensitivity Cellulose Nanocrystals Based QCM Humidity Sensors with Asymmetric Electrode Structure," Sens. Actuators B Chem., vol. 302, 127192, 2020.

[7] F. Josse, Y. L., S. J. Martin, R. W. Cernosek., "Analysis of the Radial Dependence of Mass Sensitivity for Modified-Electrode Quartz Crystal Resonators," Anal. Chem., vol. 70, pp. 237-247, 1998.

[8] T. Kartanas, V. Ostanin, P. K. Challa, R. Daly, J. Charmet, T. P. J. Knowles, "Enhanced quality factor lable-free biosensing with micro-cantilevers integrated into microfluidic systems," Anal. Chem., vol. 89, pp. 11929-11936, 2017.

[9] D. Johannsmann, The quartz crystal microbalance in soft matter research, Springer, Switzerland, 2015.

[10] E. Ferre-Pikal, J. Vig, J. Camparo, L. Cutler, L. Maleki, W. Riley, S. Stein, C. Thomas, F. Walls, and J. White, "Ieee standard definitions of physical quantities for fundamental frequency and time metrologyrandom instabilities," 2008.

[11] C. R. Kirkendall and J. W. Kwon, "Sub-picogram resolution mass sensing in a liquid environment using low-loss quartz crystal microbalance," IEEE Sensors Conference, pp. 1783-1786, 2010.

[12] J. Vig, F. Walls, and U. Command, "A review of sensor sensitivity and stability," Proceedings of The 2000 IEEE/EIA International Frequency Control Symposium & Exhibition, pp. 30-33.