Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env. Pharmacol. Life Sci., Vol 10 [11]October 2021 : 192-198

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com
CODEN: BEPLAD
REVIEW ARTICLE **OPEN ACCESS**

Quartz Crystal Microbalance Sensors in Various Engineering Fields: A review

Paramita Banerjee[1*], Sunipa Roy[2], Ayantika Goswami[2]
[1]Applied Electronics and Instrumentation Engineering
[2] Electronics and Communication Engineering
Guru Nanak Institute of Technology, Sodepur, Kolkata, India
email: [1*]paramita.banerjee@gnit.ac.in

ABSTRACT

This paper describes the use of the Quartz Crystal Microbalance sensor in various engineering fields. Quartz Crystal Microbalance or QCM is a piezo based mass sensor which utilizes the principle of operation as change in the system resonance frequency with the change in the mass. The measuring object when placed on the surface of the piezoelectric sensor then any change in the mass of it affects the resonance frequency of the sensor assembly. The application areas of QCM sensors reviewed in this particular chapter are detection of Food Quality, Bioaerosols and Chemicals, the application in Space Technology and application in various medical applications. In space technology, QCM sensors are mainly used to quantify the contamination generated by outgassing processes of materials in satellites, missiles and space crafts. In the medical field, the QCM sensors are used in cell biology detection, cervical cancer detection, detection of tuberculosis, bimolecular interactions, bacteria testing, immunosensing etc. The use of different Nano materials with various structure, make it possible to measure very small changes in its volume quantitatively even in the milli and micro order range. QCM sensors when used for the liquid medium, instead of measuring the change in the resonance frequency, the energy dissipation is measured as a function of the change in the mass. The later one is termed as QCM-D sensors. This review work provides a detailed study on the use of the QCM, nano layered QCM as well as QCM-D sensors in the above mentioned applications.

Keywords—Piezoelectric Sensors, Mass Sensor, Resonance Frequency Analysis, QCM, Nanomaterials, QCM-D

Received 21.06.2021 Revised 11.08.2021 Accepted 15.10.2021

INTRODUCTION

Piezoelectric elements have the property that when potential difference is applied across the surface of the crystal, the crystal is stressed. The reverse effect is also applicable for piezo crystals. The application of a sinusoidal excitation with variable frequency if applied across the piezo crystals, the vibration of the crystal changes according to the input frequency and the frequency, at which this vibration reaches maximum, is known as its resonance frequency. This resonance frequency changes for various reasons such as the direction of application of the input excitation, the amplitude of the input excitation, the shape and size of the piezo crystal, the type of the piezoelectric material etc. When a typical piezo electric crystal of a specific material and shape excited with a fixed the amplitude of input excitation voltage applied in a predefined direction, the resonance frequency changes if there is any addition or alteration of any kind of mass on the crystal. This change in the resonance frequency with the change in the mass is the basic principle of piezoelectric mass sensors [1]. The method of measurement is known as the Resonance Frequency Analysis or RFA technique. This is a widely used method as this is quantitative method and can measure very small changes in mass, even in the order of milli or microrange.

These piezo electric mass sensors are commercially known as Quartz Crystal Microbalance or QCM sensors. The piezo element is sandwiched between two electrodes and is allowed to oscillate by exciting it with an appropriate excitation. The frequency of oscillation of the piezo element changes with the change in the mass, either addition or removal, on the surface of the electrodes. There are various application areas of QCM sensors which include the field of chemistry, biomedical and material sciences [2, 3, 4, 5, 6, 7, 8]. The quartz crystal microbalance with dissipation or QCM-D sensor is a variety of conventional QCM sensor which is versatile and more sensitive than the conventional QCM sensor. The QCM-D sensor is used for simultaneous measurement of change in frequency as the conventional QCM as well as due to the change in mass as well as change in energy dissipation by periodically switching off the driving power over the crystal and recording the decay of the damped oscillation [9].

The use of nanoparticles (1-100 nm), are increasingly rapidly in our day to day life. But there are so many side effects also in using it and it is better to avoid potential adverse effects of nanoparticles in human life. QCM offers a distinctive method of understaning nanoparticle interactions both in liquid and gas phase. metals, ceramics, polymers and carbon materials all are the source of nanoparticle which can be engineered. Both physical and chemical properties of nanoparticles may be different compared to bulk materials. .2-dimentional material like graphene changed the physics and chemistry of material. Mechanical properties of graphene remain less explored. Due to the low mass density of graphene it is used now in nano-electromechanical systems (NEMS), e.g., for extremely small mass sensing. Integration of QCM with graphene yields a practical device for measuring mass density and interfacial mass change of graphene.

This paper presents a descriptive approach on the various applications of piezo based mass sensors, QCM and QCM-D, mainly in the field of bio-sensing and also the technological advances associated with this type sensors.

QCM SENSOR CONSTRUCTIONAL DETAILS AND OPERATING PRINCIPLE

QCM sensor is made from a thin quartz disk, cut into specific orientation, either AT or BT cut and is coated with electrodes as shown in Fig.1. The AT or BT cut is required so that the acoustic wave propagates perpendicularly to the crystal surface. The resonant frequency of the quartz single crystal depends on the angles with respect to the optical axis at which the wafer was cut from the crystal. The frequency of QCM decreases due to the deposition of mass on its surface. The mass sensitivity of QCM is dependent on the thickness of the crystal, which determines its resonant frequency. The thinner is the QCM, the higher is its resonant frequency and sensitivity [10].

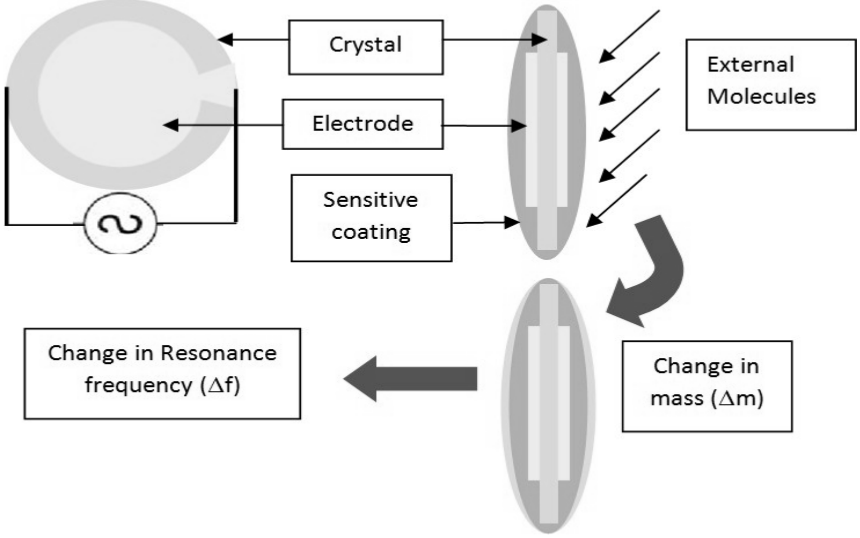

Fig1: QCM sensor

The QCM sensor measures the mass changes on the basis of a relation between the resonance frequency and the mass which was in 1959 by Günter Sauerbrey. The Equation is:

$\Delta m = C \times \Delta f/n$ Eq.1

Where,

Δm is the change in the mass due to the added layer.

C is a constant related to the properties of quartz

n is the odd overtone number, and can be 1, 3 ,5 ,7 ,… etc.

This model assumes that the thin, added layer is a part of the oscillating crystal itself and should be rigid and firmly attached to the crystal surface. If the layer on the sensor is soft, thick or not coupled to the surface, the equation is not valid. In these situations, the model will fail, and the calculated mass will be underestimated. In that case, QCM-D principle is used where the energy dissipation is measured instead of measuring Δf.

APPLICATION AREA OF QCM SENSORS

Detection of Chemicals

QCM sensors with molecularly imprinted polymers have the ability to detect vapors of small organic molecules with greater sensitivity and selectivity than the traditional amorphous polymer coatings. The behavior of the imprinted polymer films is characterized by the dynamic and steady- state response of the QCM frequency to pulses of organic vapors in dry air [11]. QCM with Azobenzene Functionalized Coatings are extensively used for detection of nitroaromatic materials [12]. The detection and quantification of organophosphates with chemical gas sensors can be effectively done by using QCM Sensors with an extraordinary high sensitivity (up to 260 Hz/ppm) and neglecting the influence of the humidity and cross-interferences of common volatile organic compounds [13]. Sartore et al presented an application of Polymer-grafted QCM chemical sensor for the detection of heavy metal ions in the aqueous solution. This type of QCM sensors can selectively absorb various types of heavy metals like copper, lead chrome, cadmium etc in the range of 0.01 to 1000 ppm [14]. In environmental pollution detection QCM sensors are widely used for the detection of Volatile Organic Compound (VOC) in the air. Exposure of VOC in indoor and outdoor environments for short or long period of time is very much injurious to health. Pentacene- layered QCM is capable of detecting this VOC which can be used as a pollutant detector at room temperature, both in wet and dry air [15]. In [16], QCM Senor, coated with Chromatographic Adsorbents, has been used for a rapid identification of organic volatile compounds specifically elevated olive oil sensory connotation, with excellent repeatability.

Food Quality Detection

Quartz crystal microbalance is (QCM) a label free piezoelectric biosensor for the detection of pathogenic microbes and toxins present in the food. The conventional methods for food quality detection are lengthy and time consuming. In this context, the biosensors are one option due to their high specificity, convenience and quick response. In the field of food science and technology, biosensors technology for the detection of food borne pathogens is more fascinating to the current researchers [17]. Shen et al in have developed a new design of QCM sensor based on a phosphate- modified dendrimer film with high sensitivity and the short response time for direct detection of Cu (II) metal ion in water. This is very much required so as to identify the presence of heavy metals in water which may enter the food chain to threaten human health [18]. For real-time monitoring of of Salmonella enterica serovar typhimurium cells in food samples can be determined using QCM sensors combined with aptamer-based magnetic separation system. This combination shows specific detection of Salmonella cells at 100 CFU mL(-1) from model food sample (i.e., milk). Subsequent treatment of the QCM crystal surface with NaOH solution regenerated the aptamer-sensor allowing each crystal to be used several times [19]. Ali et al have developed poly-dimethylsiloxane (PDMS) coated QCM sensor to sense the aroma of 3- Carene volatile in Indian Mango varieties namely Langda and Chausa cultivars of mango. Validation of the proposed sensor with real mangoes is carried out by correlating the frequency deviation of the sensor with the estimations of 3-carene obtained from gas chromatography mass spectrometry and it showed better sensitivity [20]. Array of QCM sensors have been successfully utilized in monitoring apple [21-22], orange [23] and also banana [24] by sensing their flavour. Furthermore, QCM sensors have also been used to discriminate Indian Black Tea varieties by sensing the important volatile organic components (VOC) in the tea which is responsible for aroma of tea [25]. Similar work has been done to detect the Geraniol in Black Tea [26].

QCM as Immuno-sensor

The use of QCM as Immunosensors requires a binding layer on the crystal surface which actually acts as an receptor of the target molecule. The target molecules may be of several types such as a bio-molecule, macromolecule, protein, enzyme, antigen, nucleic acid (DNA or RNA), peptide nucleic acid (PNA), tissue, microbial entity, polysaccharide etc. These are attached to the receptors by chemical, physical or biological reactions. The target molecules are complementary structures to the receptors. QCM sensors used for detection of antigen- antibody reactions typically contain immobilized antibody on the electrode surface and they are able to recognize antigens. The opposite reaction is possible as well i.e. the Immunosensors can contain immobilized antigen and can be used for the recognition of an antibody and just antibody is the analyzed molecule. In the field of immuno-sensing, the technique of immobilization of antigen or antibody for appropriate binding with specific target molecules is a very important issue as it improves the selectivity and the sensitivity of the sensor itself. Many researchers have done their research in this area and have suggested specific method and material to enhance the immobilization of antigen or antibody on the sensor surface.

Thanh et al designed and fabricated a QCM system based on immobilization of the antibodies onto a MHDA-SAM onto gold surface with NHS ester as reactive intermediate for the rapid detection E. Coli O157:H7 bacteria. In this paper the authors optimized the immobilization process to improve the performance of biosensor and it was established that SAM method for making a piezoelectric immuno-sensor is better than protein A method [27]. A new, reusable, simple, and sensitive piezoelectric immunosensors has been developed by Wang et. al, which incorporates a modified SAM as a functional basement membrane for the efficient covalent immobilization of SjAg in a serum. It was established that the system described in this study is a potential alternative to current diagnostic methods for SjAg -

mediated diseases in the clinical laboratory or for analysis in the outside of the laboratory [28]. Development of a QCM immuno-sensor with PLL–dsDNA nano-film for the detection of antibodies to dsDNA in blood serum in flow-injection mode has been done by Fakhrullin et. al. The results confirm the high sensitivity and stability of the immune sensor's response. It was also reported that such a sensor can be used as a disposable element of a sensing system [29]. In [30], Label-free QCM immuno-sensor was used in active (lever oscillator and frequency counter) and passive (impedance analyzer) modes for rapid detection of three strains of E. coli. Different approaches for antibody immobilization were compared among which the immobilization of reduced antibody using Sulfo-SMCC was most effective. It was also established that the sensor properties are not limited by the frequency evaluation method but mainly by affinity of the antibody. Yang et al proposed a method for the initial screening of cervical lesion using piezoelectric immunosensors [31].
Wang et al. and Liu et al. utilize QCM with a low fundamental frequency of 8MHz to identify E.coli using different recognition material which are antibodies [32] and enzyme [33]. QCM sensor using antibody as bioreceptor has high sensitivity compared to enzyme. Castro et al. investigated biofilm growth of Staphylococcus epidermidis using uncoated thickness-shear mode resonators. Large frequency shift has been observed for non-biofilm sample compared to medium and high biofilm [34]. Using antibody modified quartz crystal microbalance sensor and nanoparticles amplification system cancer biomarkers analysis was developed by Uludag et al. The developed QCM assay shows a promising technology for cancer biomarker analysis in patient samples [35].

QCM-D sensors
The applications where the adsorbed film is not rigid in those cases Sauerbrey relation becomes invalid. A film that is viscoelastic will not fully couple to the oscillation of the crystal, as a result the Sauerbrey relation underestimates the mass at the surface. A soft film dampens the sensor's oscillation. So, the measurement of energy dissipation (*D*) of the sensor's oscillation provides accurate result
D is defined as:

$$D = E_{lost} / 2\pi E_{stored}$$ Where,

E_{lost} is the energy dissipated during one oscillation cycle E_{stored} is the stored energy during one oscillation cycle

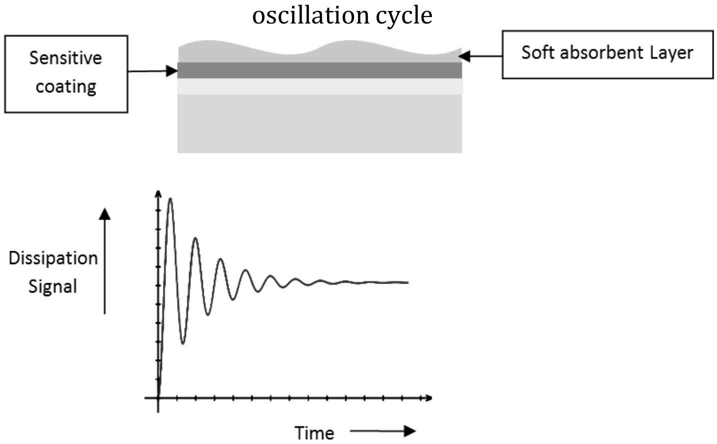

Fig2: QCM-D sensor

QCM-D is a suitable for viscosity analysis of solutions, such as high concentration protein, where low sample volume and non-destructive analysis is preferable. QCM-D can be used for viscosity measurements of fluids of varying character. It can also be used to study other parameters like frequency dependence and surface adsorption processes associated with the properties of the sample. [36]. Martinez et al investigated the use of QCM-D for the measurement of nanoparticle- platelet interactions. The interactions were also studied and it was found that QCM-D was able to measure nanoparticle-induced platelet microaggregation for all nanoparticles tested at concentrations that were undetectable by light aggregometry and flow cytometry [37]. In the past 15 years, QCM-D has been increasingly used as a tool to characterize the biological interactions of engineered surfaces. QCM-D crystals have been mainly applied to monitor the binding efficacy of probing surface of biosensors as well as to verify the bio-fictionalization of nanoengineered surface [38-40].

QCM-D sensors was applied in the study of cell-surface interactions as the piezoelectric mass sensing combined with the monitoring of dissipation changes was related to different colonization stages of cells on surfaces [41,42,43].

NANO-LAYERED QCM SENSORS

There is a high demand of QCM sensor to quantify the reaction of nanoparticles in nanoscale. Figure 3 depicts the fabrication process of QCM sensor with Graphene nano layer. Zhihua et.al. [44] studied QCM sensor with graphene and used for the detection of VOC. frequency shift was measured which is the function of adsorption of vapor at the surface of grapheme layer. It was found that frequency shifts were linear to the concentrations of analytes in the range of 10 and 100ppm with the correlation coefficients of above 0.996. To study the particle behaviour while depositing on the surface, the rate of mass change i.e. slope of the sensor frequency and the rate of rigidity change i.e. the slope of the energy dissipation) versus time plots are useful. QCM-D sensors can be used to study the interaction between nanoparticle and cell membrane. Kakenov et.al.[45] determined the mass density of graphene which was found larger by monitoring the resonant frequency due to the presence of wrinkles and residues on it. They used transfer printing technique to integrate large area single-layer graphene on QCM. Quanitification of nanoparticle is really a promosing task. Characterization of dissipation has been taken care of in QCM D sensor. The dissipation can offer sole information about the mechanical properties of the contact zone between nanoparticles and the surface on which they are found of. Meléndrez, et.al. [46] report on the adsorption dynamics of phospholipid membranes on graphene-coated substrates using the quartz crystal microbalance with dissipation monitoring (QCM-D) technique. We compare the lipid vesicle interaction and membrane formation on gold and silicon dioxide QCM crystal surfaces with their graphene oxide (GO) and reduced (r)GO coated counterparts, and report on the different lipid structures obtained.

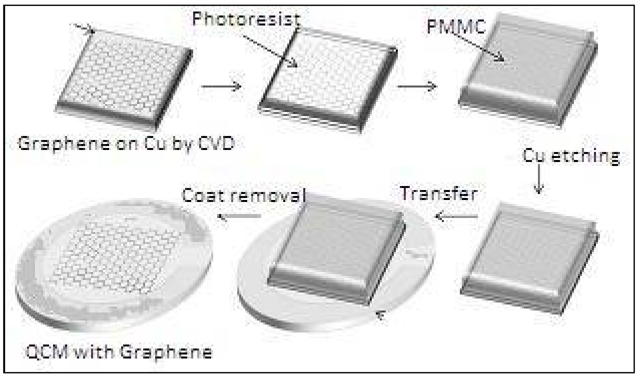

Fig 3: Transfer of Graphene on QCM sensor

CONCLUSIONS

The reviewed literature highlighted the role of QCM as well as QCM-D technology as a new and non-conventional facility to be used as mass sensor in real time using a label-free methodology. When compared to the conventional methods having the same feature, piezoelectric biosensors can be manufactured with quite low costs and with high sensitivity. This type of technology has a versatile filed of applications due to its diversified advantages. Among several promising applications some are reviewed in the present study. On the other side, this methodology suffers from some drawbacks such as stability and repeatability. The method of immobilization of the sensitive or active layer on the surface of the crystal for selective binding with the target molecules is need to be further studied.
Therefore, a huge scope exists in further technological improvements of the piezoelectric mass sensor both in constructional and behavioral aspects.

REFERENCES

1. Der HoWu,Wen Tung,ChienCheng ShengChen, Hsin HuaChen. (2006). Resonant frequency analysis of fixed-free single-walled carbon nanotube-based mass sensor. Sensors and Actuators A: Physical, Vol 126, Issue 1, 26, pp 117-121
2. Selyanchyn R., Korposh S., Wakamatsu S., Lee S.W. (2011).Respiratory Monitoring by Porphyrin Modified Quartz Crystal Microbalance Sensors. Sensors. ;11(1), pp:1177–1191. doi: 10.3390/s110101177
3. Bai Q.S., Huang X.H. (2016). Using Quartz Crystal Microbalance for Field Measurement of Liquid Viscosities. Journal of Sensors doi: 10.1155/2016/7580483.
4. Zhang X.R., Chen J., Liu H.X., Zhang S.S. (2015). Quartz crystal microbalance detection of protein amplified by

nicked circling, rolling circle amplification and biocatalytic precipitation. Biosens. Bioelectron.;65:341–345. doi: 4.1016/j.bios.2014.10.055.
5. Diltemiz S.E., Keçili R., Ersöz A., Say R. (2017). Molecular Imprinting Technology in Quartz Crystal Microbalance (QCM) Sensors. Sensors. ;17:454. doi: 10.3390/s17030454.
6. Cho N.J., Frank C.W., Kasemo B., Hook F. (2010). Quartz crystal microbalance with dissipation monitoring of supported lipid bilayers on various substrates. Nat. Protoc.;5:1096–1106. doi: 10.1038/nprot.2010.65
7. Yao C.Y, Qu L., Fu W.L. (2013). Detection of Fibrinogen and Coagulation Factor VIII in Plasma by a Quartz Crystal Microbalance Biosensor. Sensors. 13:6946–6956. doi: 10.3390/s130606946
8. Yang L., Huang X.H., Sun L., Xu L. (2016). A piezoelectric immunosensor for the rapid detection of p16 (INK4a) expression in liquid-based cervical cytology specimens. Sens. Actuators Chem. B. 224:863–867. doi: 10.1016/j.snb.2015.11.002.
9. Kwon H. J, Bradfield C. K, Dodge B. T, Agoki G. S. (2009). Study of Simultaneous Fluid and Mass Adsorption Model in the QCM-D Sensor for Characterization of Biomolecular Interactions. Proceedings of the COMSOL Conference 2009 Boston.
10. Vashist S. K, and Vashist P. (2011). Recent Advances in Quartz Crystal Microbalance-Based Sensors. Journal of Sensors. Volume 2, Article ID 571405.
11. Fu Y, Finklea H.O. Quartz Crystal Microbalance Sensor for Organic Vapor Detection Based on Molecularly Imprinted Polymers. Analytical Chemistry.200375205387-5393
12. Ponrathnam T, Cho J , Kurup P , Nagarajan R , Kumar J. (2012). Investigation of QCM Sensors with Azobenzene Functionalized Coatings for the Detection of Nitroaromatics. Journal of Macromolecular Science. Part A. Volume 48, Issue 12, pp 1031-1037
13. Sen Z, Sen Z, Gural I, Gumus G. (2010). Organophosphate Sensing with Vic-Dioximes using QCM Sensors Proceedings of IEEE Sensors. DOI - 10.1109/ICSENS. 5690501.
14. Luciana S, Marzia B, Laura B, Elza B. (2011). Polymer-grafted QCM chemical sensor and application to heavy metal ions real time detection. Sensors and Actuators B: Chemical. Volume 155 (2) – 20, 2011
15. Andrea B, Antonella M, Paolo P, Iole V, Emiliano Z .(2017). A study of a QCM sensor based on pentacene for the detection of BTX vapors in air. Sensors and Actuators B: Chemical, Volume 240 – 1:9-13.
16. Escuderos M. E, Sanchez S, Jimenez A. (2011).Application of a Quartz Crystal Microbalance (QCM) System Coated with Chromatographic Adsorbents for the Detection of Olive Oil Volatile Compounds. Journal of Sensor Technology, 1, 1-8 doi: 10.4236 /jst. 2011.11001.
17. Singh A. K, Verma N. (2014). Quartz Crystal Microbalance Based Approach for Food Quality. Current Biotechnology. Volume3, Issue 2, DOI: 10.2174/22115501026661311251556 22.
18. Shen C.Y, Lin Y. M, Hwan R.C. (2016). Detection of Cu (II) Ion in Water Using a Quartz Crystal Microbalance. Journal of Electrical and Electronic Engineering. Volume 4, Issue 2, Pages: 13-17.
19. Ozalp V. C, Bayramoglu G, Erdem Z, Arica M. Y. (2014). Pathogen detection in complex samples by quartz crystal microbalance sensor coupled to aptamer functionalized core-shell type magnetic separation. Journal of Analytica chimica acta -12-4.
20. Ali S. B, Ghatak B, Dutta Gupta S, Debabhuti N, Chakraborty P, Sharma P. (2016) Detection of 3- Carene in mango using a quartz crystal microbalance sensor. Sensors and Actuators B: Chemical http://dx.doi.org/ 10.1016/j.snb.2016.03.005.
21. Herrmann U, Jonischkeit T, Bargon J, Hahn U, Li Q. Y, Schalley C.A, Vogel E, Vögtle F. (2002). Monitoring apple flavor by use of quartz microbalances. Analytical and Bioanalytical Chemistry. 372, 611– 614. Doi: 10.1007/s00216-001-1230-6.
22. Yamanaka T, Matsumoto R, Nakamoto T. (2003). Study of apple flavor using odor recorder with five components. Sensors and Actuators B: Chemical 89, 112–119. doi:10.1016/S0925-4005(02)00451-3.
23. Munoz-Aguirre S, Yoshino A, Nakamoto T, Moriizumi T. (2007). Odor approximation of fruit flavors using a QCM odor sensing system. Sensors and Actuators B: Chemical123, 1101–1106. doi: http://dx.doi.org/10.1016/ j.snb.2006.11.025.
24. Somboon P, Wyszynski B, Nakamoto T. (2007). Novel odor recorder for extending range of recordable odor. Sensors and Actuators B: Chemical121, 583– 589; doi:10.1016/j.snb.2007.01.030.
25. Sharma P, Ghosh A, Tudu B, Bandyopadhyay R, Bhattacharyya N. (2012). Electronic Nose With Quartz Crystal Microbalance Sensors to Discriminate Indian Black Tea Varieties. Proceedings of Sixth International Conference on Sensing Technology, IEEE.
26. Sharma P, Ghosh A, Tudu B, Bhuyan L. P, Tamuly P, Bhattacharyya N, Bandyopadhyay R, Das U. (2015). A Quartz Crystal Microbalance Sensor for Detection of Geraniol in Black Tea. IEEE Sensors Journal, Vol. 15, No. 2, 1-8.
27. Ngo V. K. T, Nguyen D. G, Nguyen H. P. U, Tran V. M, Nguyen T. K. M, Huynh T. P, Lam Q. V, Huynh T. D, Thi Ngoc Lien Truong T. N. L. (2014). Quartz crystal microbalance (QCM) as biosensor for the detecting of Escherichia coli O157:H7. Advances in Natural Sciences: Nanoscience and Nanotechnology, 5 045004 (8pp).
28. Wang S, Yin T, Zeng S, Che H, Yang F, Chen X, et al. (2012) A Piezoelectric Immunosensor Using Hybrid Self-Assembled Monolayers for Detection of *Schistosoma japonicum*. PLoS ONE 7(1): e30779. https://doi.org/10.1371/journal.pone.0030779.
29. Fakhrullin R. F, Vinter V. G, Zamaleeva A. I, Matveeva M. V, ourbanov R. A, Belayhun K. Temesgen B. K, Ishmuchametova D. G, Abramova Z. I, Konovalova O. A, Salakhov M. K. (2007). Quartz crystal microbalance immunosensor for the detection of antibodies to double-stranded DNA. Analytical and Bioanalytical Chemistry 388(2):367-75 DOI: 10.1007/s00216-007-1230-2

30. Farka Z, Kovar D, Skládal P. (2015). Rapid Detection of Microorganisms Based on Active and Passive Modes of QCM. Sensors, 15, 79- 92; doi:10.3390/s150100079.
31. Yang L, Huang X. (2014). A novel piezoelectric immunosensor for early cervical cancer detection. Proceedings of the 2014 Symposium on Piezoelectricity, Acoustic Waves, and Device Applications. DOI: 10.1109/ SPAWDA.2014.6998622.
32. Wang L, Wei Q, Wu C, Ji J, Liu Q, Yang M, Wang P. (2007). Detection of E. coli O157:H7 DNA by a novel QCM biosensor coupled with gold nanoparticle amplification. Internal conference on Nanotechnology 7th IEEE.
33. Liu F, Li Y, Su X. L, Slavik M. F, Ying Y, and Wang J. (2007). QCM immunosensor with nanoparticle amplification for detection of Escherichia coli O157:H7. Sensing and Instrumentation for Food Quality and Safety. Vol. 1, pp.161-168.
34. Castro P, Resa P, Durán C, Maestre J. R, Mateo M, Elvira L.(2012). Monitoring of bacterial biofilm growth using uncoated thickness- shear mode resonators. IOP Conference Series: Materials Science and Engineering, 1-9..
35. Uludag Y, Tothill I. E. (2010). Development of a sensitive detection method of cancer biomarkers in human serum (75%) using a quartz crystal microbalance sensor and nanoparticles amplification system. Talanta. Volume 82, Issue 1, 30, Pages 277-282
36. QCM-D viscosity analysis for microlitre protein samples. Application Note: 16. Q-Sense, Biolin Scientific.
37. Maria Jose Santos-Martinez M. J, Inkielewicz-Stepniak I, Medina C, Radomski M. W. (2012). The use of quartz crystal microbalance with dissipation (QCM-D) for studying nanoparticle-induced platelet aggregation. International Journal of Nanomedicine 7:243- 55.DOI: 10.2147/IJN.S26679.
38. Chen Q, Tang W, Wang D, Wu X, Li N, Liu F.(2010). Biosens Bioelectron. 15; 26(2):575-9.
39. Xu J, Liu K. W, Matthews KS, Biswal S. L.Langmuir. 2011 Apr 19; 27(8):4900-5.
40. Ertekin O, Oztürk S, OztUrk ZZ Sensors (Basel). 2016 Aug 11; 16(8).
41. Saitakis M, Gizeli E. (2012). Cellular and Molecular Life Sciences. 69(3):357-71.
42. Tymchenko N, Nilebäck E, Voinova MV, Gold J, Kasemo B, Svedhem S. (2012). Biointerphases.7(1-4):43.
43. Tonda-Turo C, Carmagnola I, Ciardelli G. (2018). Quartz Crystal Microbalance With Dissipation Monitoring: A Powerful Method to Predict the in vivo Behavior of Bioengineered Surfaces. Frontiers in Bioengineering and Biotechnology.12; 34-38
44. Liang Z, KaixinV S, Weiwei H, Zhihua Y, (2012). Characterization of Quartz Crystal Microbalance Sensors Coated with Graphene Films. Procedia Engineering 29 pp.2448 – 2452.
45. 46. Kakenov N, Balci O, Salihoglu O, Balci S, Kocabas C, (2016);. Weighting graphene with QCM to monitor interfacial mass changes, Applied Physics Letters, 109, pp. 053105.
46. Meléndrez D, Jowitt, T, Iliut M, Verre A.F, Goodwin S. Vijayaraghavan A, (2018). Adsorption and binding dynamics of graphene- supported phospholipid membranes using the QCM-D technique, Nanoscale, 5, 2555-2567.

CITATION OF THIS ARTICLE

P Banerjee, S Roy, A Goswami. Quartz Crystal Microbalance Sensors in Various Engineering Fields: A review. Bull. Env. Pharmacol. Life Sci., Vol 10[11] October 2021 : 192-198