Design for Biosecurity

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Lecture 15

Principle, Setup and Applications of E-QCM-D

Welcome back! We're now entering the third week of our course, and as I mentioned in our previous session, we're going to delve into one of the foundational models in this area. To truly grasp the concepts we're discussing, you need to understand the Sorbet equation thoroughly, as well as the principles behind quartz crystal microbalance (QCM), piezoelectric materials, QCMD, and all the relevant derivations. This groundwork is essential because it lays the foundation for achieving a unique signature in our analyses.

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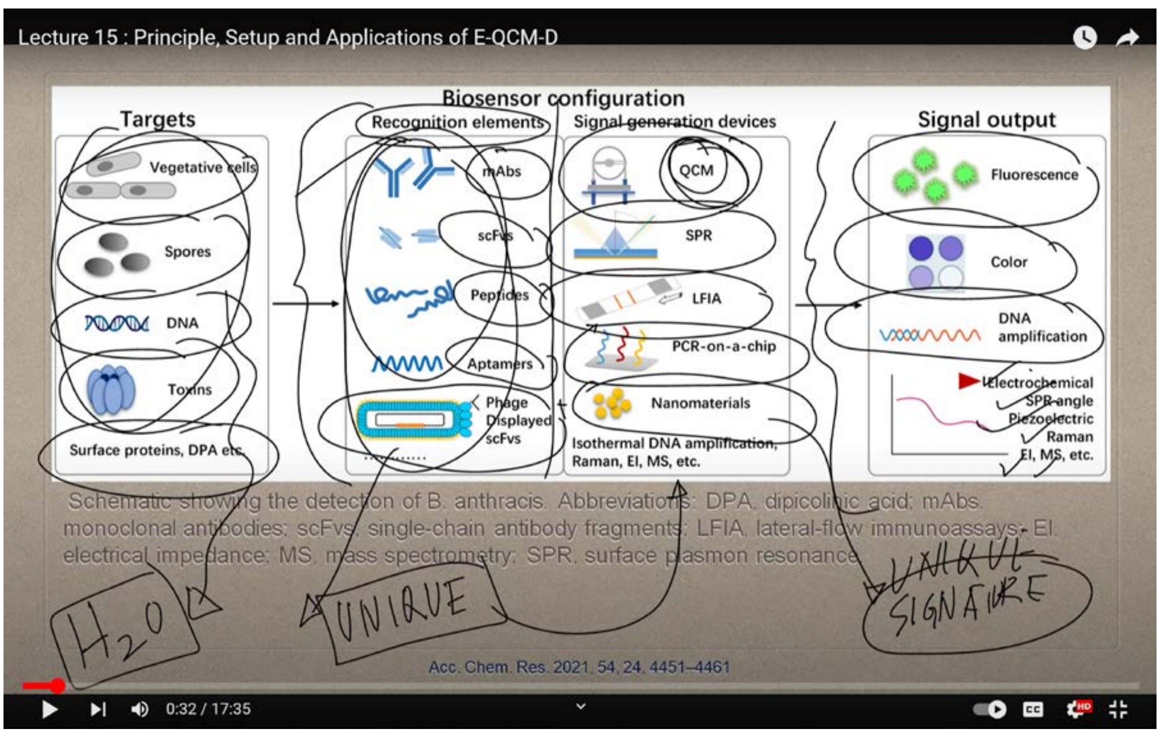

Now, if we take a closer look, you'll notice that the materials we're dealing with, these molecules, are predominantly soft matter and viscoelastic in nature. This understanding brings us back to the discussion on equivalent circuit models, which play a crucial role in interpreting our data. Here's where we are now: this is what your final output data will look like.

Let's revisit the setup with a schematic overview. You have the measurement chamber, which is equipped with flow modules where the quartz crystals are housed. A pump is integrated to ensure fluid movement, while an electronic unit controls and measures various parameters within the system. This entire setup is connected to a computer that runs specialized software to drive and manage the system, ensuring that everything is coordinated seamlessly.

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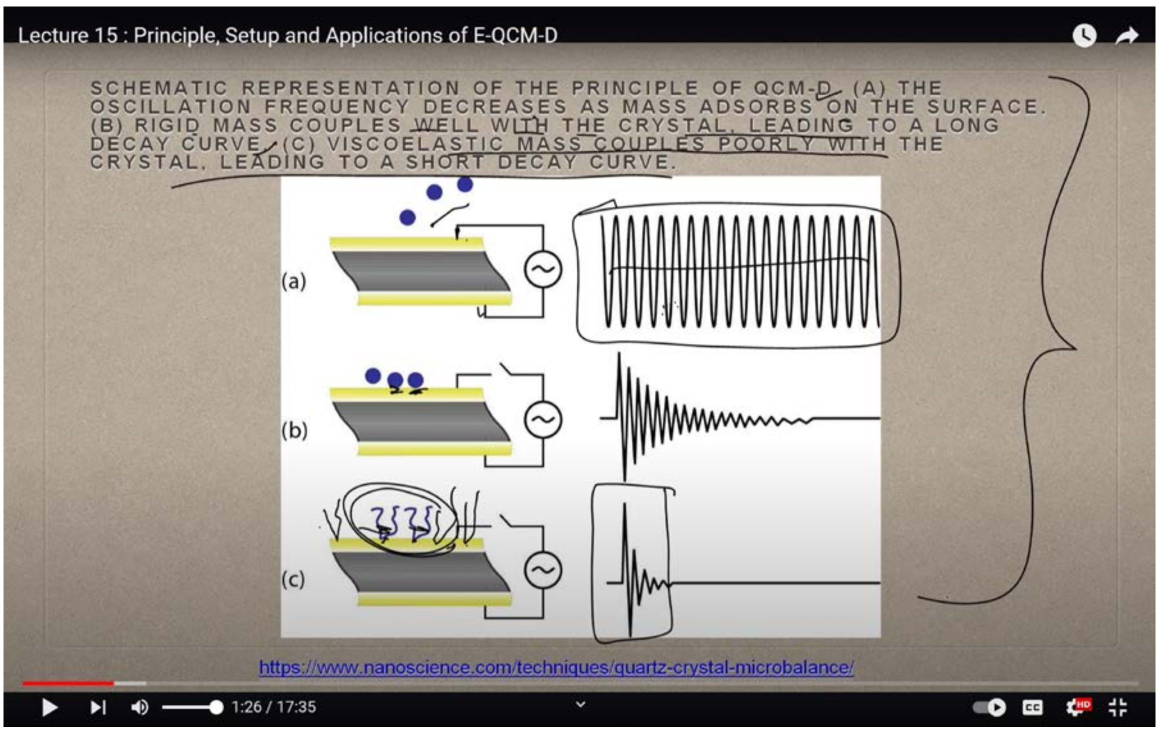

What I've just described is the most simplified version of QCMD. However, the actual apparatus is far more intricate and complex than it might appear at first glance. Understanding this complexity is key for you as we move forward.

One of the most significant recent advancements in this field is the coupling of an electrochemical setup with microbalance and dissipation monitoring, which is now known as EQCMD. The "E" stands for electrochemistry, "QCM" for quartz crystal microbalance, and "D" for dissipation. This cutting-edge tool is currently one of the most modern and powerful in-situ techniques available, especially for complementing electrochemical experiments.

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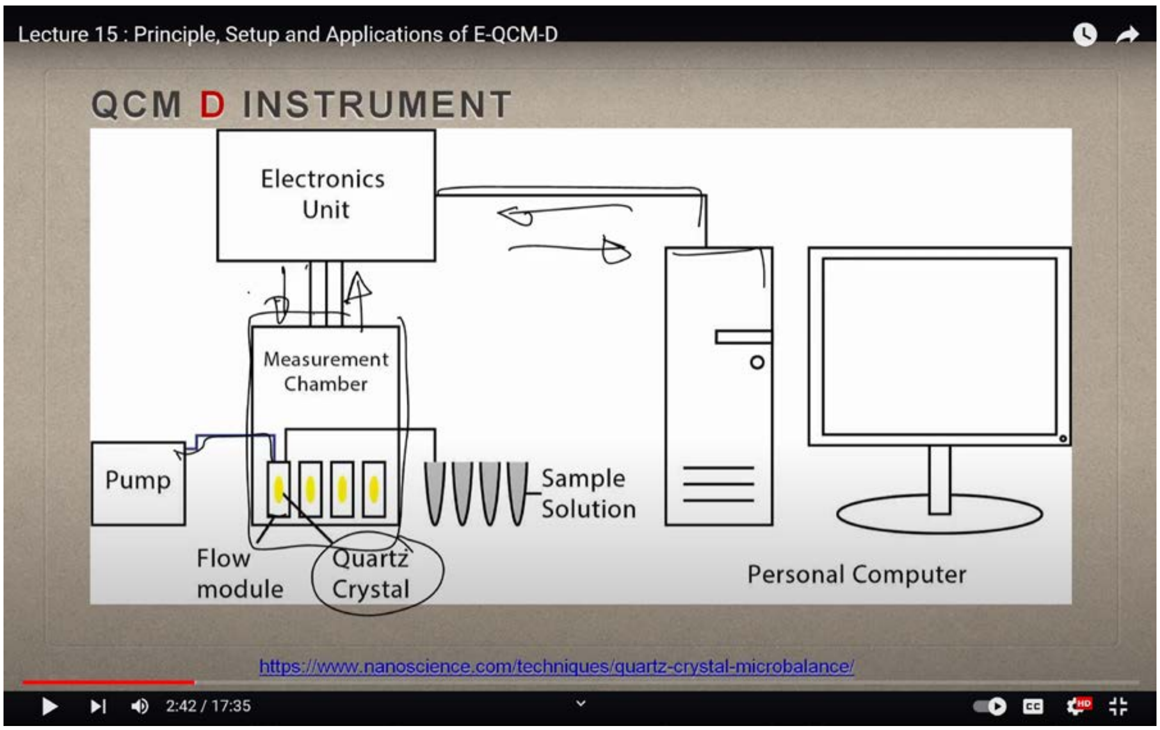

When we discuss electrochemical experiments, we're referring to scenarios where electrical changes are occurring within the system. For example, consider a situation where proteins are undergoing electron transfer during their attachment or detachment process on a surface. In such cases, two significant electrical events are typically taking place, which we will explore in greater detail in the coming weeks.

This marks an exciting point in our journey, as EQCMD represents the forefront of technology in our field, and I’m eager to guide you through its intricacies in the upcoming sessions.

First, let’s consider what we’re detecting on the surface: the viscoelastic properties, conformational changes, and interactions of molecules. These aspects pertain to the structural parameters of the system. However, if you're interested in observing electron or ionic transfers, you need to integrate the setup with electrochemical techniques. This allows you to monitor if a molecule is releasing an electron, whether it's being absorbed by the surface or transferred to another molecule.

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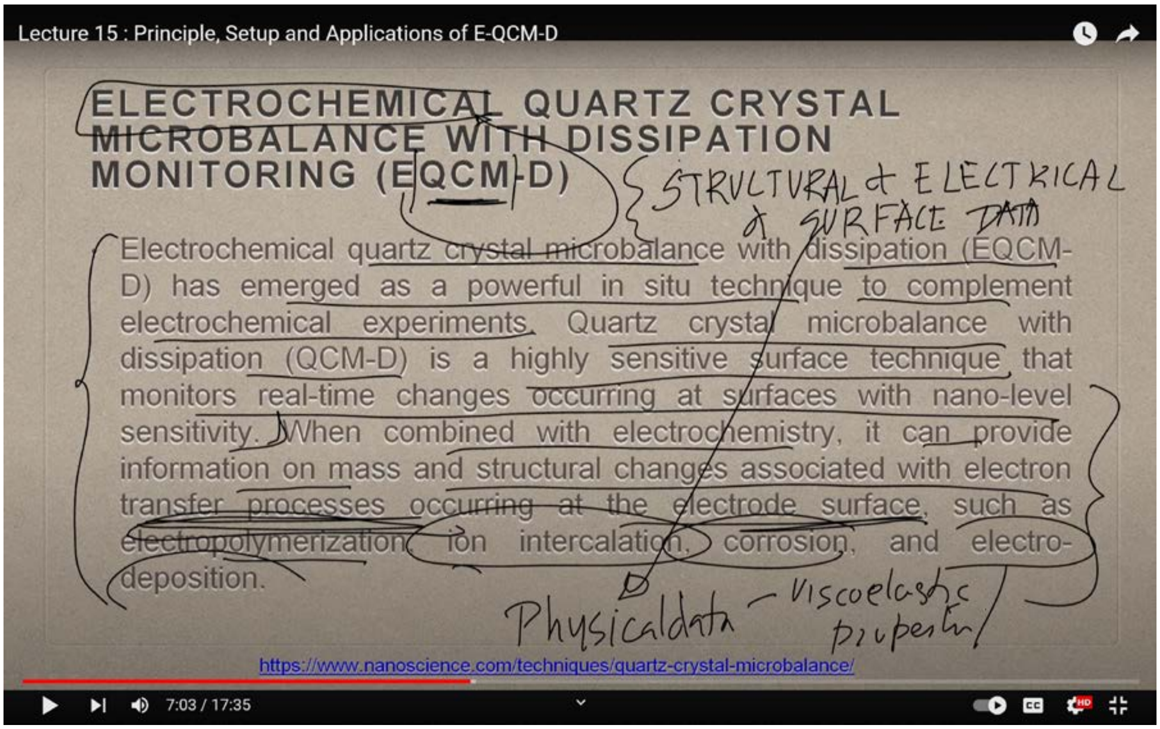

For instance, imagine a scenario where proteins are deposited on a surface, and electrons are hopping between different types of proteins, say Protein A and Protein B. Capturing these electron transfers, these are crucial signatures of molecular interactions, requires coupling your setup with an electrochemical system. When you do this, you elevate your analysis to a whole new level.

Quartz Crystal Microbalance with Dissipation (QCMD) is already a highly sensitive technique, capable of detecting surface changes with nano-level precision. We’ve discussed how it measures interactions such as adsorption, viscoelasticity, electrostatic, and covalent interactions. However, when combined with electrochemistry, QCMD can reveal even more detailed information about mass and structural changes related to electron transfer processes occurring at the electrode surface. This includes phenomena such as electropolymerization, ion intercalation, corrosion, and electrodeposition.

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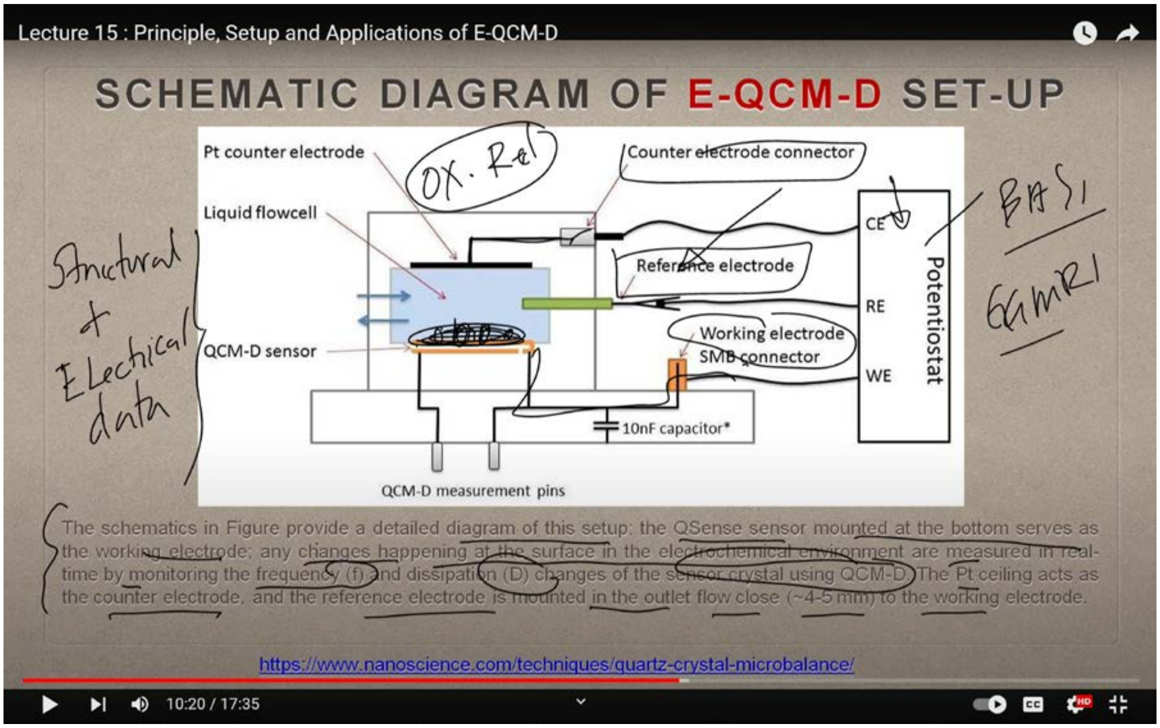

By integrating electrochemical techniques with QCMD, you effectively enhance the capabilities of both methods, allowing for a more comprehensive analysis of molecular behavior and interactions at the surface.

With this setup, you are obtaining real-time data on structural, electrical, and surface properties, which then informs various physical characteristics such as viscoelastic properties, changes in interactive forces, and molecular interactions. The setup typically looks like this: a QCMD sensor is positioned in the system, alongside a liquid flow cell and three electrodes.

The three electrodes include:

1. Working Electrode: This is the primary electrode where the main measurements are taken. We'll delve deeper into its function later.

2. Reference Electrode: This electrode provides a stable reference point for measurements. Just as a meter is measured relative to a standard length, the reference electrode is compared against a standard, typically the Standard Hydrogen Electrode (SHE). This ensures that all measurements are consistent and accurate.

3. Counter Electrode: This electrode helps complete the electrical circuit and supports the working electrode by balancing the current flow.

In this setup, the QCMD sensor is mounted at the bottom of the flow cell, functioning as the working electrode. The system monitors changes in the electrochemical environment in real-time by tracking frequency, dissipation, and the sensor crystal using QCMD technology. The platinum ceiling acts as the counter electrode, while the reference electrode is positioned in the outlet flow, 4 to 5 millimeters away from the working electrode.

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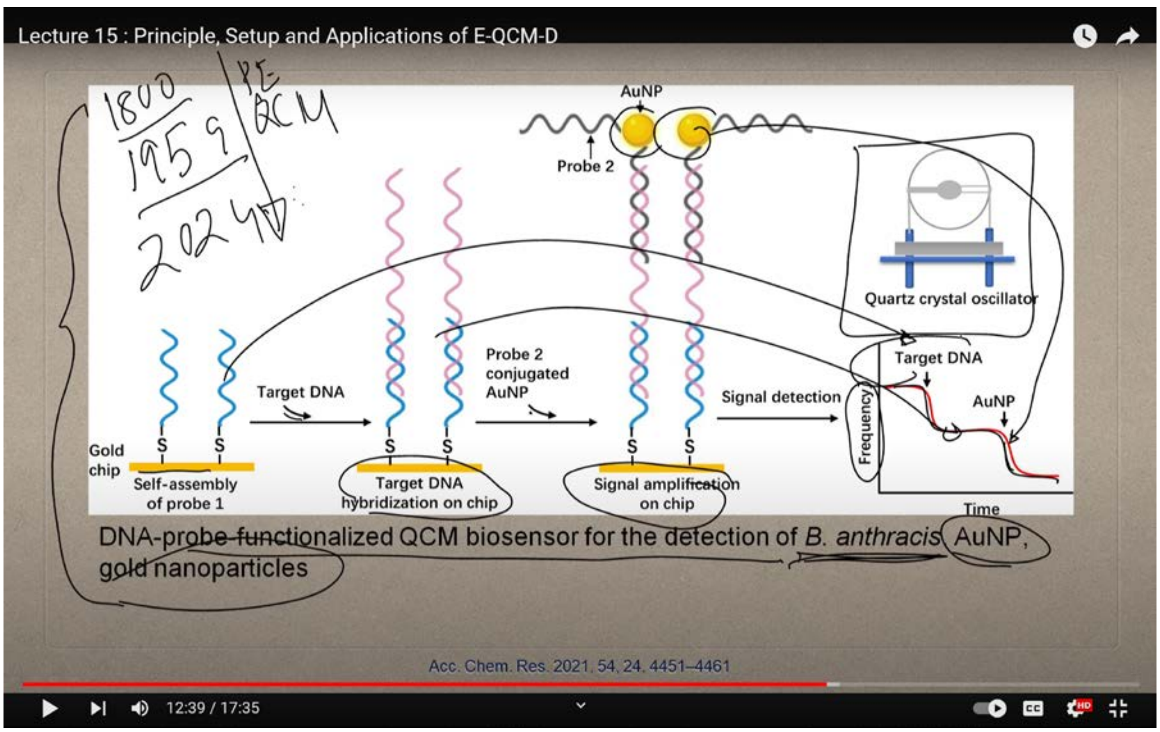

This arrangement allows for precise monitoring of electrochemical activity and surface processes, enabling detailed analysis of molecular and atomic interactions.

Next, we introduce the potentiostat, a crucial component in this setup. There are various potentiostats available, such as those from BASI and GAMRY, among others. These devices are essential for modern instrumentation and biosensing, where multiple techniques are integrated into a single platform.

On this platform, you obtain comprehensive structural and electrical data along with a range of physical parameters, including surface characteristics, viscoelastic properties, molecular interactions, and electron transfer processes. In essence, you are also capturing data related to oxidation and reduction reactions. During electron transfer, the substance losing electrons is oxidized, while the one gaining electrons is reduced. This simultaneous acquisition of diverse data makes the setup particularly valuable and intriguing.

To illustrate this, consider the DNA probe used for detecting Bacillus anthracis. The QCM biosensor for this application employs gold nanoparticles. The configuration includes a self-assembled DNA probe on a gold chip, with target DNA hybridized on the chip and conjugated with gold nanoparticles to enhance the signal.

As you measure the changes, the mass of the target DNA increases, affecting the frequency reading. The presence of gold nanoparticles amplifies the signal, resulting in a noticeable decrease in frequency. This setup highlights the efficiency of combining different techniques to achieve precise and insightful measurements.

Let's start with this illustration. To fully grasp this image, it's essential to delve into the history of quartz crystal technology. The evolution of quartz crystal oscillators, whether referred to as resonators or another term, is rooted in a long and rich history. The foundations of what we see today were laid long before the current era, dating back to around 1851 when the piezoelectric effect was first discovered. Fast forward to 1959, and now we are in 2024, witnessing over 200 years of progress.

This extensive journey has led to the sophisticated quartz crystal microbalance (QCM) and piezoelectric crystal technology we use today. It’s crucial to recognize and appreciate the monumental scientific, technological, mathematical, physical, and biological advancements that have brought us to this point. Understanding even a single figure in this context requires a solid grasp of these foundational principles.

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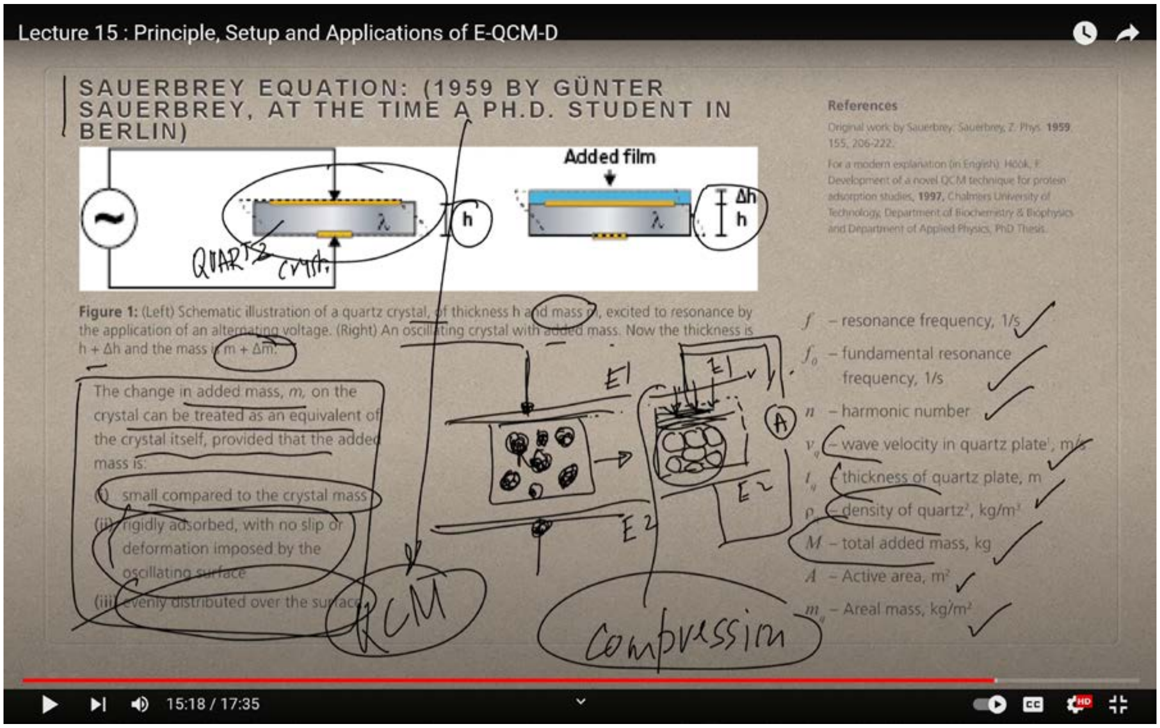

Looking at the figure related to frequency domain based on dissipation, you'll notice that it bears similarities to the earlier figure. The changes in the figure reflect ongoing developments and increasing complexity in sensor technology. As we advance, you'll see how these sensors have evolved over time.

Our first complete profile is that of a QCM sensor developed for anthrax detection, as detailed in a 2021 publication in Chemical Research. This paper provides comprehensive references to leading researchers and their pioneering work in this field. Reviewing this paper will give you further insights into the applications of QCM technology. I will continue to reference such studies as we progress, assuming that your understanding of the fundamentals is now clear.

Let's revisit our journey with quartz crystal microbalance (QCM) technology. We began our exploration from the basics and have evolved to the current state of the art. At its core, a quartz crystal exhibits a fascinating interplay of mechanical and electrical properties. For instance, compressing the crystal generates changes in its electrical properties, such as voltage or current, or applying a voltage causes it to compress.

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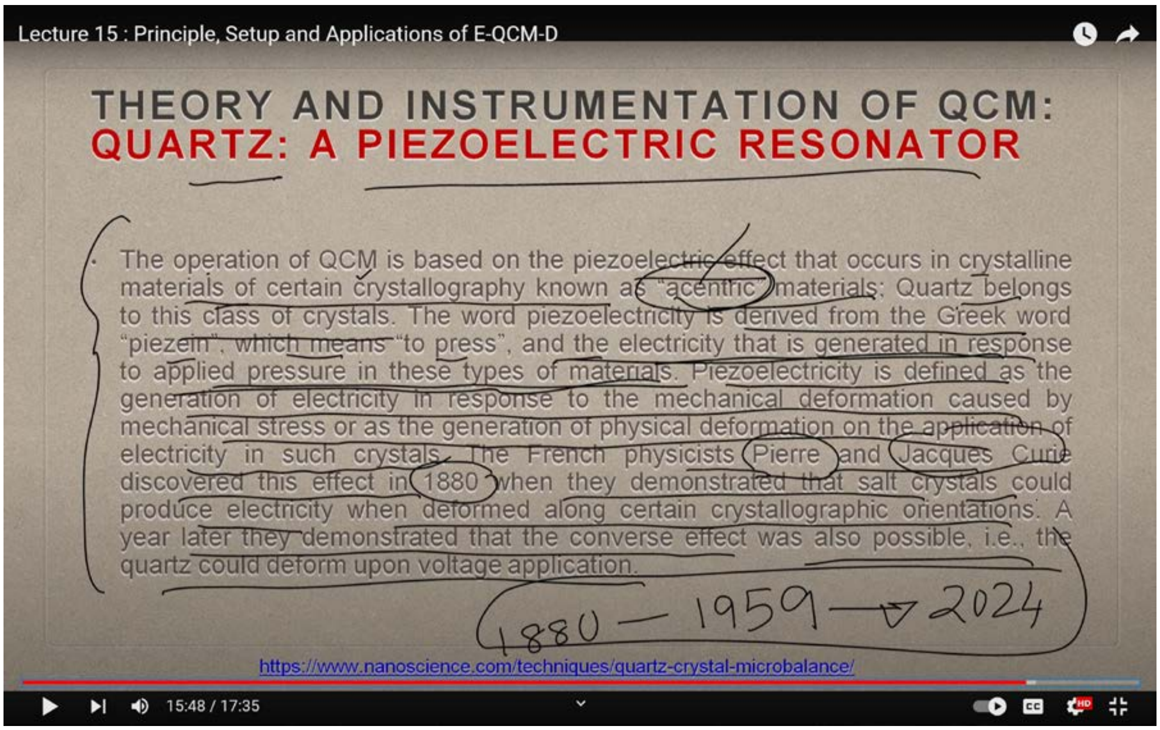

The foundational principle of the piezoelectric effect was first discovered by Pierre and Jacques Curie in 1880. Fast forward to 1959, and with the development of the Sorber equation, we have significantly advanced in understanding and applying these principles. This timeline is indeed modest compared to the many other significant milestones that have shaped this field. However, due to time constraints, we can only highlight these pivotal discoveries that have led us to the modern piezoelectric resonator and QCMD devices.

Currently, we are approaching the cutting edge of technology with the Electrochemical Quartz Crystal Microbalance with Dissipation (EQCMD), which combines electrochemical setups with QCMD. This advanced model is particularly notable for its application in detecting Bacillus anthracis.

In our future classes, we will explore additional biosensing techniques, including Atomic Force Microscopy (AFM), Surface Plasmon Resonance (SPR) biosensors, and Electrochemical Biosensors. Thank you for your attention.