

**Design Practice - 2**  
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**Lecture - 14**  
**Introduction to Transducers**

Hello and welcome to this Design Practice 2 module 14. We would like to today discuss some basic issues related to what are the kind of transductions which are there particularly with some you know important aspects of how you can sense electrochemically and then we will try talking about some of the basically the fabrication methodology which would be involved in the process.

So while doing this sensor we would focus mostly on the electrochemical sensor design although there are going to be other many sensors which can be discussed from time to time and then we will actually move into the actuators area where we will talk about certain you know small microfluidic tool designs for example micro valves or micro pumps or flow control using some of the microfluidic actuation schemes which can be available. So let us now look as of now into the aspects of transducers.

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**Transducers**

- These are the detector devices.
- Analytical methods in chemistry have relied on photometric transducers. (spectroscopic or colorimetric methods)
- Most transduction is electrochemical because of simplicity of construction, low cost and convert a response into electrical signals which is compatible with microprocessors and microelectronics.
- Now another thrust area of photon driven devices are emerging, so there is a shift towards optical fibers. ←
- Also emerging is the micro-mass controlled devices based on piezo electric crystals.

So these are sort of detector devices you can say analytical methods in chemistry for example have relied on a lot of optical transducers particularly photometric based transducers. It can be spectroscopic or it can be colorimetric. So either there is a change in color or change in the

absorption wavelength or you know frequency which gives you an idea of what are the kind of molecules which are present, which are responsible for this characteristic emissions.

Most transduction is electrochemical whether we talk about almost all the sensing devices which are in the current market or even if we are talking at the research grade level and one of the reasons why electrochemical sensors are reasonably well to do is the fact that you can integrate this very well with electronics the end you know process of such a sensor is almost always either a electron release or a electron depreciation and so you can integrate this very well with the overall concepts of miniaturization and particularly microelectronics.

And therefore electrochemical sensing happens to be one of the most primary levels of sensing. There are other reasons. Generally the construction is quite simple. You just need sensing electrodes in touch with an electrolyte or in touch with a analyte of interest and there should be some kind of a selectivity element which is there on the surface of the electrode which would be very specific to selecting what we are looking at.

Overall, low cost of this kind of transduction or you know how to convert a response into electrical signals compatible with microprocessors etc. would make these electrochemical sensing schemes much better in comparison to some of the other sensors. Also there is a new thrust area which is slowly developing although there has been some work towards it which is mostly photon driven devices just as you have electron driven you know devices dedicated to the microelectronics part you know of the industry.

There are also you know photon driven processes particularly photon guidance, photon capture, recording you know photometric data. This is all sort of based on various technologies particularly related to how to guide the photons look at for example optical fiber or photonic crystals. So you have generally a shift of the devices towards mostly optical grade devices from the electrical grade devices and one of the main causes driving this change is because of sensitivity issues.

The electron transition process itself may really depend on the overall you know molecular orientation of a media. So is the photonic aspect but you know there is always a more well-defined model which exist in the photon path okay or in determination of the photon path which will not be that well defined in the case of the path of an electron particularly when we are talking about solution chemistries etc.

Also emerging is a another very (( )) (04:22) area of micro-mass controlled devices for example you know we talk about quartz crystal micro balance or we talk about piezoelectric crystals. We should actually sense the mechanical mass and the change therein of this mass and make it a basis of sensing or recognition of some molecules or some analytes of interest.

So these are in general how many or what kind of transductions do exist in the industry out of which again the electrochemical still is at number 1 because of the relatively high spread okay of electrochemistry into almost all the as a general transduction scheme to almost all the sensing modalities particularly related to sensing of fluids or sensing of gases.

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### Types of Transducers

- Electrochemical
  - a) Potentiometric: Involving the measurement of emf of a cell at zero current.  
 $emf \propto \text{Log} [\text{Concentration of analyte}]$
  - b) Voltammetric: An increasing potential is applied to a cell until Oxidation (reduction) of the substance to be analyzed occurs. There is a sharp rise or fall in current.  
Peak Current  $\propto$  [Concentration of analyte]
  - c) Conductometric or impedometric: Change in conductance or impedance of a medium owing to the change in composition, measured electrically.
- Optical: These involve absorption, fluorescence, luminescence, Internal reflection and surface plasmon spectroscopy and light scattering.
- Peizo electric devices: Principally based on generation of electric currents from a vibrating crystal. Frequency of vibration is affected by the mass of material adsorbed on its surface.
- Thermal Sensors: All chemical or biochemical processes involve the absorption or production of heat that can be indicative of the substance to be analyzed.

So let us look at now some of the electrochemical transducers and types of transducers which may exist. So one of the electrochemical transducers is otherwise known as the potentiometric transduction process, transducer is a potentiometric transducer. So this involves the measurement

of the emf of a cell at zero current. EMF we know is proportional to the log of concentration of a particular analyte.

So if the concentration of the analyte increases the emf would change suitably proportional to the log of the concentration and so therefore any electrode which is dipped inside a particular you know analyte of interest would show some kind of a recorded emf with respect to electromotive force with respect to maybe another standard reference which in place because obviously potential cannot be measured in absolute terms always as difference is.

So therefore we need to have a reference okay for doing it. So normally all potentiometric measurements are found with respect to what you call the standard hydrogen electrode or SHE okay. Then electrochemical sensing can be done through voltammetry, again very common technique where we study the oxidation reduction property of the chemical system which is in place.

So an increasing potential with some kind of a potential scale is applied to a cell until the oxidation or reduction of the substance which is there in the cell takes place that means either the substance releases electron. So there are substance releases electrons thus making a positive ion or vice versa that is it releases an electron and makes another existing positive ion convert into the you know the either the non-ionic state or even negative ionic state.

So this is how voltammetry is generally carried out. So we must look at the current while such a voltage sweep is provided at a certain critical threshold voltage when the species get all oxidized or all reduced. There is either a dip in the overall current or an increase in the overall current depending on what is really flowing current. You must remember conventionally is treated to be the you know flow of positive charges opposite to that of the electron migration.

So suitably some systems can be developed for doing this kind of voltametric measurements. So in this voltametric measurement, the peak current of course which is generated okay when an oxidation state or a reduction state exist is proportional to again the concentration of the analyte

of interest and so we can record an analyte in terms of its characteristic oxidation and reduction potentials okay.

So we can say how much analyte is present looking at what is the current at which oxidation of such a species would happen and what is the voltage. So then we have in the electrochemical domain yet another set of sensors which are known as the conductometric or impedometric sensors. So in such transduction there is a change in conductance or impedance of a medium going to the change in composition.

For example if we look at an example of look at a case of you know presurgical or postsurgical diagnosis of those patients who are going to have a cardiac surgery there is a very important test which is also known as the prothrombin international ratio test PT INR test which happens you know in such setups where the coagulation property of a of the general human blood is recorded okay.

So the coagulation is recorded also as a function of putting a standard concentration of a agent called prothrombin which creates clotting factor so that the blood gets you know the rheology of the blood changes and it gets more and more viscous and the idea is that the measurements are made in a manner so that the electron flow which is going to be there, which is going to be carrier of you know the current within the blood having a changing viscosity also gets suitably restricted because of this change in viscosity.

So therefore the impedance goes up because owing to the static nature of the clotting blood sample slowly the electromigration effects would reduce and the impedance would change. So the PT INR test is a very commonly administered test to record what is the efficacy of a patient's blood and based on it doctors may actually try to investigate how much amount of coagulants or let us say anticoagulants have to be given based on the the thinning property of you know the biofluid, the blood biofluid within the patient.

And so those determination of certain coagulants or anticoagulants could happen through the PT INR ratio. But then again it is based on that impedance measurement okay. So it is a change of

some kind of a resistance or conductance let us say of a highly viscous sample of blood as opposed to relatively thinner blood samples, okay. Because of the change in the clotting factors, the clotting factors initially are initiated through that recognition element which is the prothrombin in this particular case.

So we can measure such changes electrically by looking at the conductance data. Or the impedance data would be a more appropriate description because you know because if supposing the overall Ohms resistivity is low then it is always the frequency you know based impedance which would come up because of the capacitative nature of the sensing scheme and so there has to be a measurement either with frequency, in frequency domain or you know in the ohmic domain.

So again there can be optical transducers which would be involving the way that photons are released or photons are absorbed within a material so you can have absorption as a phenomena which can be recorded. What is the wavelength for example at which most of the species are absorbing. The photons would actually come up on such a scale once you know you have a light beam from one side given to the sample and a collected light from the other side.

So you actually scan at different wavelengths and see that what are the wavelengths across which all the photons seem to be absorbed and that gives you an idea of what is the material which is present, the analyte which is present. For example there can be an absorbance of the body fluids like blood etc. in the biological window which is about 800 nanometers plus minus. So there can be fluorescence assisted optical detection.

This means that overall there is a change in the fluorescent property of the material as sensing happens. For example if we look at in the clinical diagnostics there is a particular you know genetic I mean a test which brings home the gene sequence okay. It is in the molecular biology domain and the gene sequence is multiplied by copying the gene many time using a process called the polymerized chain reaction process wherewith every time there is the alteration of the overall fluorescence which comes into picture as the amplification process starts to happen okay.

So I am not getting into the details of the modalities. There is another course for this kind of you know work but because you are studying sensors you must look at what exactly is the change and we try to understand from practical problems that I am throwing that what are the areas where such sensors can be very common place. So the fluorescent signal generally happens in a manner so that the emission always happens at a higher wavelength lower frequency.

Such a shift in the wavelength is known as the Stokes shift. So the excitation signal which is coupled to the sample is always you know lower in wavelength, higher in frequency and that gets coupled in terms of the you know the energy states across which a fluorescent an electron has to transition in order to record the fluorescent signal okay. So then there is luminescence based data for example what happens within fireflies which glow in the dark is basically an enzyme luciferin which causes this luminescence to happen okay.

Or let us say internal reflection based sensing where when there is a sort of a total guidance of the wave in the TIR, the total internal reflection mode across the surface and there is some kind of an absorption of the species that are grazing incidence on the surface, particularly the surface species come up very well in terms of their absorption characteristics. Okay, so that can be an internal reflection based optical sensor.

There can also be sensors based on surface plasmon spectroscopy plasmon typically is an electron wave which would happen in a medium because there is going to be a negative and a positive charge center and there are going to be oscillations of the negative you know charge center about the positive charge centers and if these oscillations are carried out you know there is a certain natural frequency at which such oscillation would happen and if there is a coupled electromagnetic radiation which is at a similar frequency it is going to create a large amplitude motion of these charge centers and it is going to dissipate the energy rapidly.

Okay, so that is again the principle of surface plasmon spectroscopy. So in such kind of a case when the electron energy or the photon energy which is coupled to the system is able to create a resonating condition, it is going to rapidly dissipate at that particular energy, that particular

wavelength okay in terms of you know and that has that will be shown up in the spectra okay as such. So then there are again optical measurements done with light scattering.

Scattering again is a phenomena where light is randomly sent to almost all the directions okay as it is coupled into the medium, typically happens due to the turbidity and other aspects associated with the medium. So then again there is a sensing which lies in that domain, optical domain through which you can you know make your measurements based on how much light is scattered.

So there are also piezoelectric transducers devices which would generate electricity based on mechanical forces or mechanical motion for example piezo crystal is typically one which vibrates at a certain frequency and is able to generate an electric current because of such vibration. It is basically about the mechanism or the cage like structure of these piezo materials where there is a change in polarization state because of such mechanical deformation okay or such mechanical sort of modification to the structure as a function of time.

So a frequency of vibration is sort of affected by the mass of the material absorbed on its surface. So therefore as there is some absorption, the fundamental frequency of vibration will change and this can be implicated in terms of a change in the current signal if we are using a piezo sensor. There are very many cases where cantilevers, micro cantilevers are based on this principle that there is a small piezo film which is coated on the cantilever and because of a change because of an absorption of mass across one of the surfaces or both the surfaces there is going to be a change in the overall you know piezo response okay.

The piezo current changes okay and which can give you an idea of how much mass have been absorbed and if this mass was supposed to be something for which there was a selection element or a recognition element you could precisely know the analyte of interest, the quantity of the analyte of interest in the medium which we are investigating. Transducers can also be thermal in nature. It can be temperature based.



So all chemical or biochemical processes are monitored you know using change in total amount of temperature okay. So it involves the absorption or production of heat. If this can be rapidly sensed it can be indicative of the presence of a substance not all substances can be analyzed using thermal sensors but you know when we talk about night vision goggles, or when we talk about the sensors which would operate in the dark, okay.

So they prepare an infrared map you know of a warm body, particularly a living body and so it is also based on suitably the change of resistance associated with certain elements okay based on whatever infrared waves are being detected okay at a certain distance from the sensor. So such change in resistance can be very small owing to the extremely less amount of energy in the infrared domain.

You have to remember it is a high wavelength, low energy domain that we are scanning and so there are many instruments like microbolometer etc. which are specifically catering to this particular you know change in the thermal domain and thermal maps or infrared cameras or thermal maps are created through these kind of you know infrared cameras etc. particularly for warm body. So that is another way of carrying out sensing.

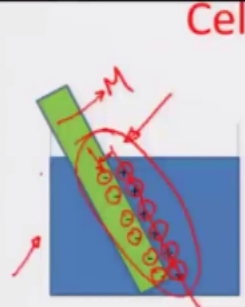
Okay, so I think I have mentioned enough of the different transduction processes. Let me just go a little bit deeper now into one of the sensing modality that is the electrochemical sensing process where you would understand what exactly we mean through electrochemical sensing. So this is only to give you a flair of what is the basic level understanding that one must have for doing this designing of these kind of sensors.

So I am going to talk about electrochemistry and I am going to talk about the charge transfer which will happen once you know there are two phases which come together. For example there is a solid phase which have been dipped into a liquid or for example there is a oil like phase which is again mixed with liquid thus creating droplets of oil in a liquid. Or even there is a you know let us say two different solids at two different zeta potentials coming together.

There is always going to be the formation of so called dual layer of charges okay and I am going to explain this from a solid liquid model as seen in this figure right here.

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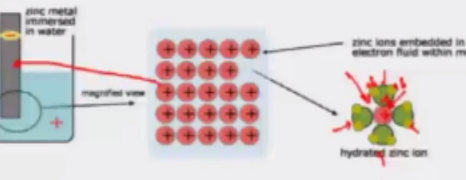
### Cells and electrodes



- When a piece of metal (such as silver) is inserted in water or a solution containing ions (such as silver ions), there is a charge separation in the boundary.
- Small no. of zinc atoms leave the electrode and go as ions into solution. The electrons are left in the electrodes.

Example :  $Zn \rightarrow Zn^{+2} + 2e^-$

- As this process goes on the electrons within the zinc electrode keep building and makes it increasingly difficult for the +ve ions to go freely into solution and it results in a stable charge bilayer or double layer.



- The degree of charge unbalance produces an electric potential between the two phases (solid and liquid).
- Electrochemistry is all about the no. of charges that cross thru the interface between the two phases.

This is a piece of metal M which is being inserted into a solution. So in this particular case I would like to explain what is the behavior of the charge transport process. Once a piece of metal, let us say in this case we have zinc or silver and it is inserted in a water based solution which are containing ions. This may be some kind of a salt water solution, brine. It may be  $Na + Cl^-$  ions floating around. And we would like to see what is the charge transport phenomena which happens because of such a orientation.

So the first thing which will happen is that let us say if there is a zinc electrode in a solution there are going to be bond vibrations and there are going to be enough amount of you know molecular level vibrations of the surface of the zinc electrode because we have to remember that we are operating at room temperature and such vibrations come to almost 0 value when we are talking about hitting absolute zero.

But because it is room temperature there are going to be some finite amount of vibrations which are going to be there. And also the fact there is a ionic environment in which such vibrations takes place sometimes lead to a situation when maybe an atom escapes the surface as an ion and because you know there is a bulk orbital in metals and the electrons are in that bulk orbital state

you know leaves those electrons the outermost electrons which are in the outermost you know there is a valence orbital and goes into the solution without them.

So let us say the zinc in this case has a oxidation number of 2. So it actually leaves the surface into the solution as  $Zn^{+2}$  and in principle it keeps the 2 electrons, you know it loses the 2 electrons to the electrode. The electrons are really not the ones which would go into the solution unless you create some kind of a plasma where such electron and ions are initiated in the medium okay to give flow to or give path to the electron flow.

So this 2 these 2 electrons which are transported to the atoms are recorded here in the green area because they are going to be sent in the bulk of the material or the metal and the positive ions, the zinc positive ions which are actually in the solution are in the solution itself and there is some kind of a capacitance okay which would come up because the moment this  $Zn^{+2}$  goes into the water solution a case like this would happen where this  $+2$  is engulfed with a lot of you know water molecules okay.

So the water molecules have as you know a slight electronegativity and electro positivity on the oxygen and the hydrogen respectively. So maybe it formulates a shell around the positive ion because of the negative slight electronegative role that oxygen has to play and once this has formulated the ion simply cannot go back from the solution into the electrode and it is sort of separated from the electrode and keeps in that state.

Now when we look at such a charged layer which has built up by virtue of molecular oscillations and the corresponding opposite charge on the electrode we automatically know that there is an electric field which will be set up between the plane of such charges separated from the electrode and the negative charge which is there on the electrode and this electrode, this electric field is sort of opposite to the you know to the migration direction of the  $Zn^{+2}$  ion.

And so therefore it will be a self-limiting film in terms of you know limiting the diffusion rate of  $Zn^{+2}$  into the solution anymore. Because the electric field is against the flow of such charge. So the self-limiting process will allow it to hit an equilibrium state where you have a bilayer of

charges across the material and this bilayer of charges is across which any charge transport should take place typically to which we know as electrochemical sensing.

So we must go from a fundamental aspect of what is actually the role of an electrode with respect to a solution in order to start doing the sensing design. I am going to bring in a lot of other modalities probably at a later state but looking at the time today, I will like to close on this particular module, probably in the next module we will look at some other things or other aspects related to sensors followed by how we can miniaturize them followed by again reintroducing back some calculations and some design principles associated with electrochemical sensors. Till then until then, thank you very much.