Salahaddin University-Erbil
College of Science Physics
Department

“Postgraduate academic degree”
lectures for a master's degree
in

Metal Oxide-Based Photodetector and gas sensor

Chapter 3

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Chapter Three (Metal Oxide-Based Photodetector)

1. **Introduction.(Metal Oxide Thin Film Photodetectors: Harnessing Light with Precision)**
2. **Definition and significance of photodetection in various fields.**
3. **Importance of photodetectors in modern technology.**
4. **Overview of different types of photodetectors.**
5. **Advantages of using metal oxides in thin film form for photodetection.**

   .Commonly used metal oxides in thin film photodetectors (e.g., zinc oxide, tin oxide, indium oxide).

6. **Principles of Operation:**

•Mechanism of photodetection in metal oxide thin films.

•Generation and transport of charge carriers.

•Factors influencing photoresponse (bandgap, defect density, morphology).

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Introduction

- Transition metal oxides have distinct geometrical, electrical, and magnetic properties due to the role of d-orbital electrons in bond formation. Because of these properties, metal oxide is a particularly appealing candidate for use in awide range of applications, including gas sensing, photocatalysis, solar cells, and photodetectors .
- Photodetectors (PDs), one of these sensors, show great promise for use in future nanodevices. Photodetectors (PDs) are optoelectronic devices those detect optical signals using electronic processes. They are widely used in a variety of applications, including fibre optic communication networks, digital cameras, medical imaging, and scientific instruments.
- The three stages of a typical photodetector operation are: 1. Generation of charge carriers by incident light 2. Carrier movement and/or multiplication 3. Collection of charge carriers to generate the output signal.

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Metal-Semiconductor-Metal Photodetector

- A photodiode with two Schottky metal contacts placed back-to-back on a coplanar surface is referred to as an MSM (Metal-Semiconductor-Metal) photodetector. Metal contacts are commonly interdigitated stripes, and the semiconductor material absorbs light in the space between the metal contacts. This type of photodetector has the advantage of being easy to construct and fabricate, with a simple design.
- At low applied voltages, photocurrent in MSM photodetectors typically increases with voltage because of the rise in the depletion area, which improves the device’s internal quantum efficiency. However, the photocurrent eventually saturates at higher voltages

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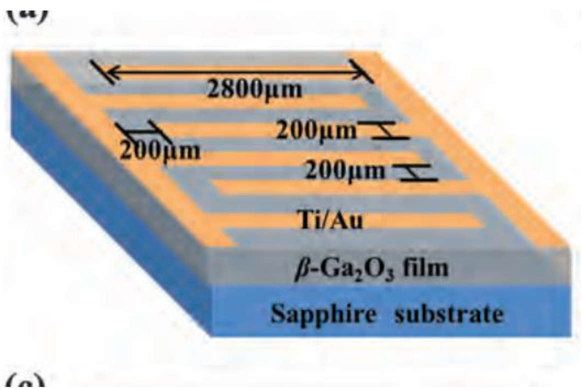

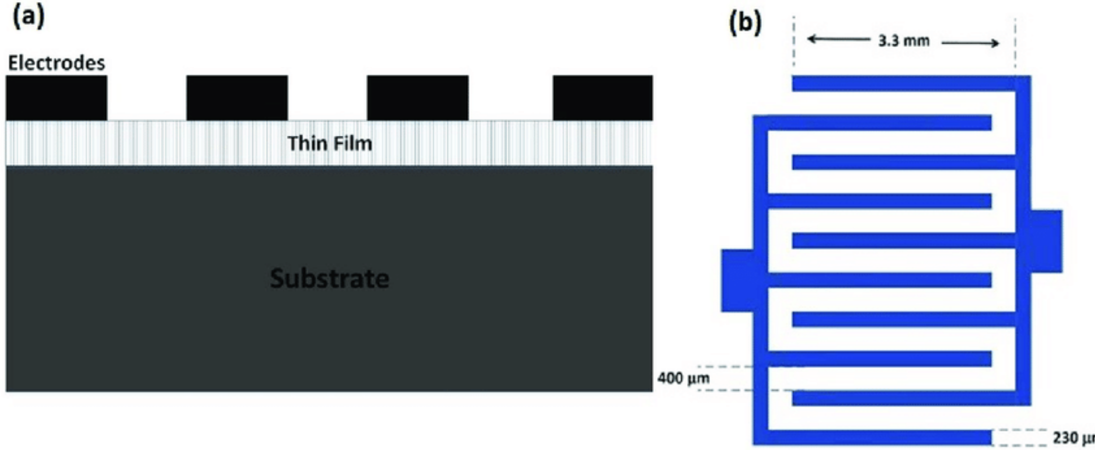

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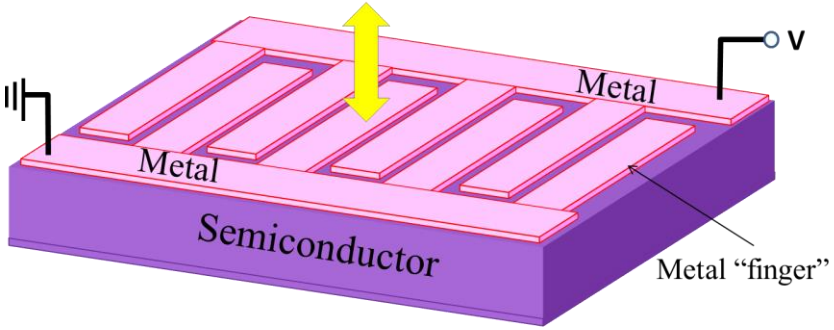

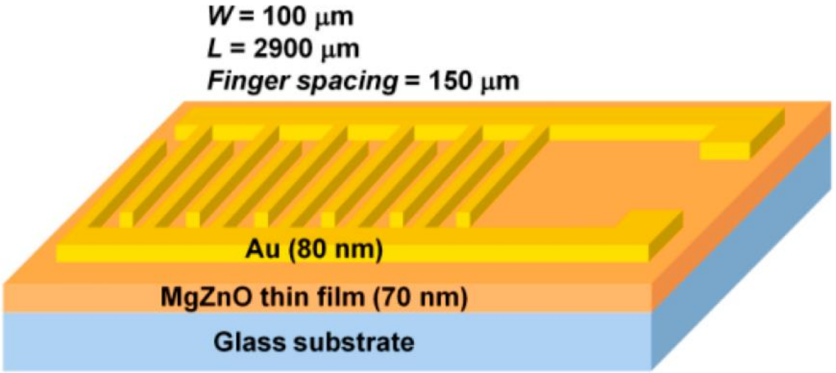

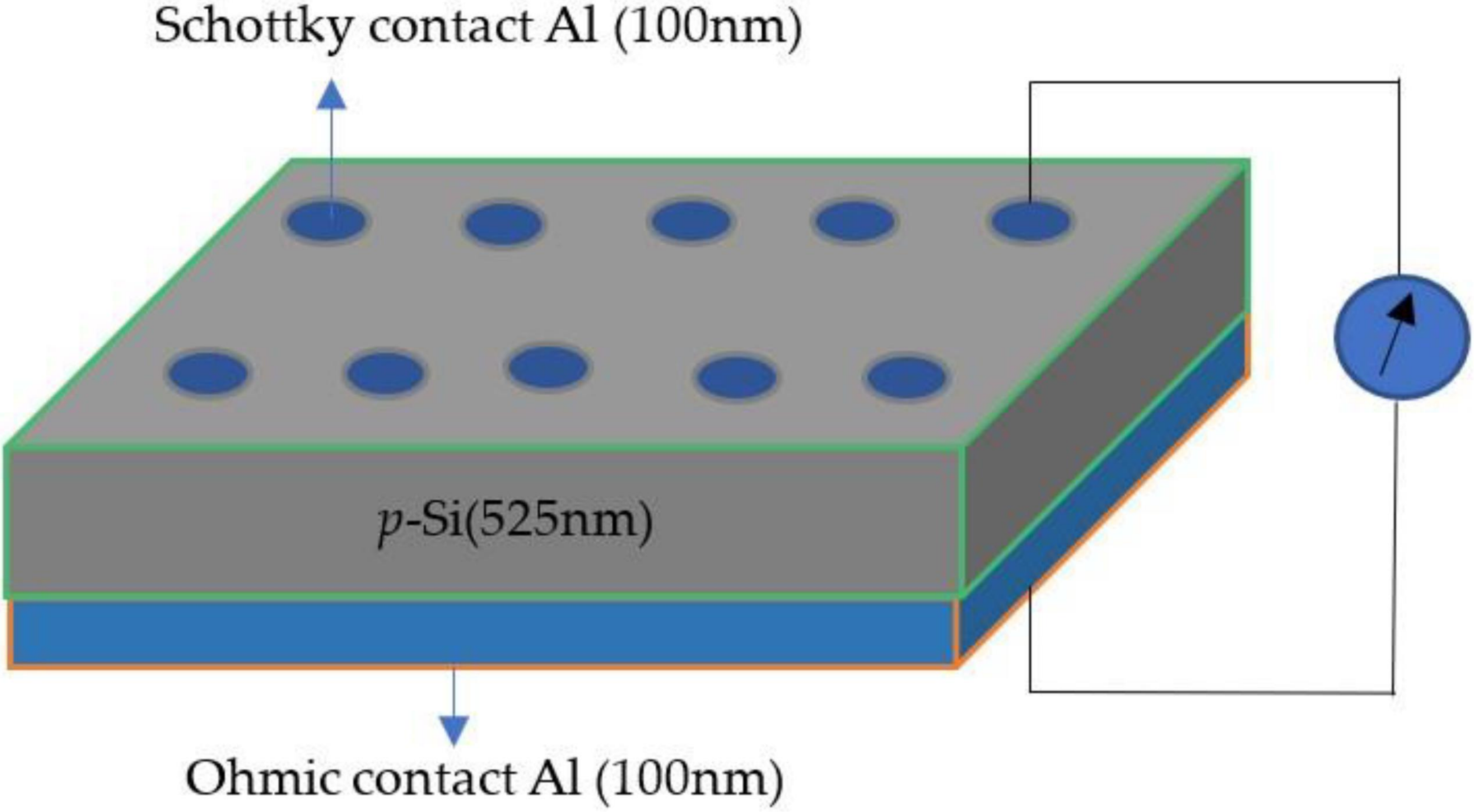
Schottky contact Al (100nm)
p-Si(525nm)
Ohmic contact Al (100nm)

1. Ohmic Contact:

1. An Ohmic contact is a **low-resistance** electrical connection between a metal and a semiconductor.
2. It **obeys Ohm’s Law** and conducts current in both forward and reverse bias conditions.
3. Ohmic contacts are essential for **signal transmission** into and out of a semiconductor.
4. They are formed when the **work function** of the metal is **similar** to that of the semiconductor.
5. Ohmic contacts exhibit a **linear I-V curve**.
6. Examples include **heavily doped silicon-metal contacts**.

2. Schottky Contact:

1. A Schottky contact is a **rectifying junction** between a metal and a semiconductor.
2. It has a **nonlinear characteristic** and behaves as a diode.
3. Schottky contacts are formed when the **work function** of the metal is **different** from that of the semiconductor.
4. They create a **barrier** at the interface, leading to **rectification** of current flow.
5. Schottky contacts are commonly used in **semiconductor devices**.
6. Examples include **Schottky barrier diodes**.

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Metal-semiconductor contacts can be ohmic or rectifying (allowing current flow only in one direction)

The metal-semiconductor (MS) contact is an important component in the performance of most semiconductor devices in the solid state. As the name implies, the MS junction is that a metal and a semiconductor material are contacted closely. Basically, there are two types of MS contacts that are widely used in semiconductor devices:

1. Rectifying Schottky Diodes
2. Non-rectifying Ohmic contac

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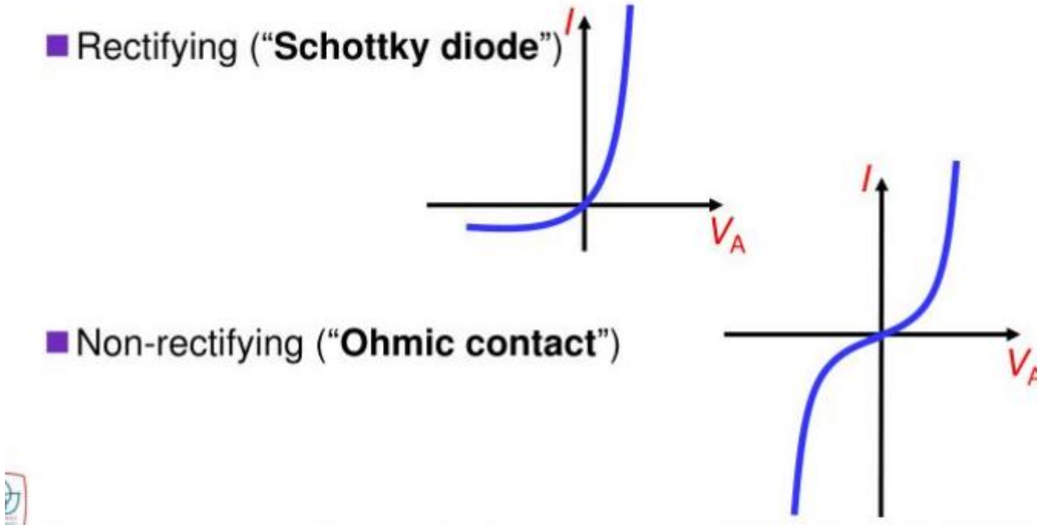

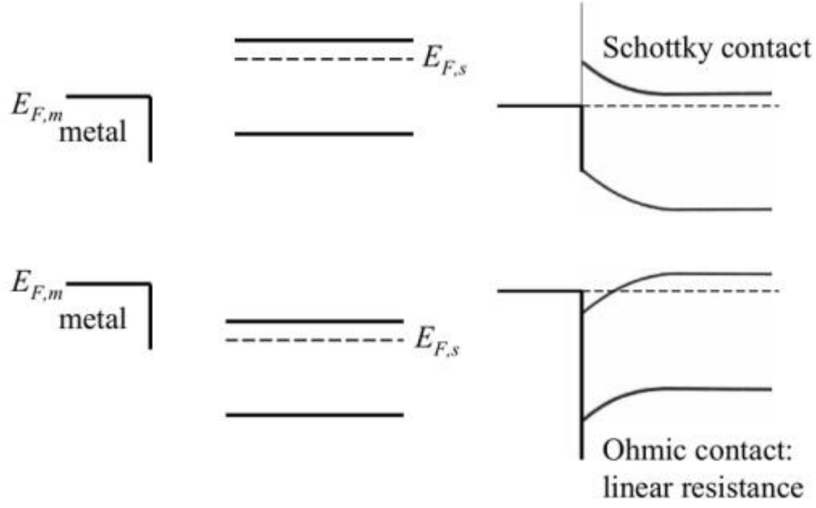

specific contact resistance: $R_c = \left(\frac{\partial J}{\partial V}\right)^{-1}$ $\Omega\text{-cm}^2$

- For the ideal MS contact, several assumptions are made:

1. The metal and the semiconductor are contacted intimately, which means that there is no oxide or charge layers between the contact on the atomic scale.
2. No intermixing and inter diffusion between the metal and the semiconductor.
3. There are no impurities at the MS interface.

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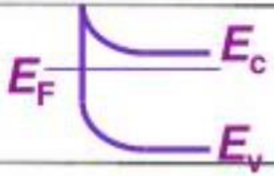
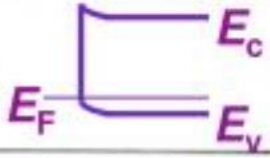
Metal-Semiconductor Contacts

	n-type Semiconductor	*p-type Semiconductor*
$\Phi_M > \Phi_S$	 Rectifying	 Ohmic
$\Phi_M < \Phi_S$	 Ohmic	 Rectifying

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- Since there is **no barrier structure for electron flow** from the semiconductor to metal, even a very small forward bias voltage (VA > 0 V A > 0) will rise a large forward bias current.

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- Schottky contacts are indeed useful in optoelectronic devices. These contacts, which form between a metal and a semiconductor, create a rectifying (unidirectional current flow) behavior due to the formation of a barrier at the metal-semiconductor interface.

1. **Rectifying Properties**: Schottky contacts are often used in devices where a rectifying action is desirable, such as photodiodes, solar cells, and light detectors. This rectifying property is due to the Schottky barrier, which allows current to flow more easily in one direction than the other, providing inherent diode-like characteristics.
2. **Fast Response Times**: The inherent barrier structure in Schottky contacts can contribute to faster response times in optoelectronic devices compared to p-n junctions. This characteristic makes them suitable for high-speed applications, such as photodetectors and high-frequency circuits.

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- In ohmic contact is a metal-semiconductor interface that allows for efficient current flow in both directions without significant resistance or rectification effects. Here's why they are useful in optoelectronic devices:

1. **Efficient Charge Transfer**: Ohmic contacts ensure low-resistance pathways for carriers (electrons and holes) to enter and exit the semiconductor. This property is vital in optoelectronic devices where you want efficient charge transport, such as LEDs, photodetectors, and solar cells.
2. **Stable Operation**: Ohmic contacts provide stable electrical connections, which is crucial for the reliability and longevity of optoelectronic devices. The stability and reliability are especially important in applications where devices are subject to varying environmental conditions or long operating times.

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Basic Sensing Characteristics

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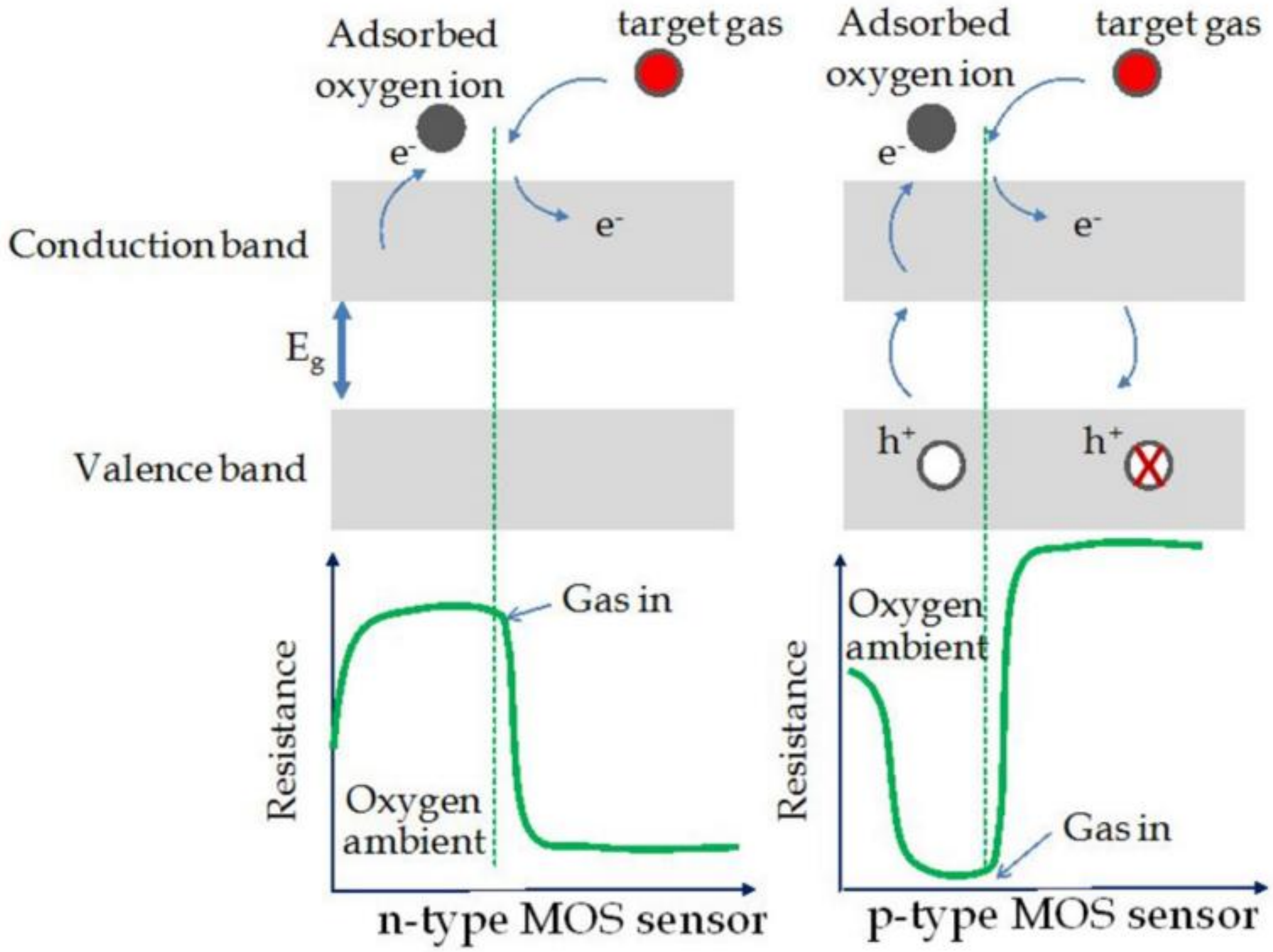

Schematic diagram for change of the sensor resistance upon exposure to the target gas (reducing gas) in the cases of n-type and p-type MOx sensors

Sensing Mechanism

- The mechanism of analyte detection by sensitive semiconductor material can be described as follows: oxygen adsorption on the sensitive layer surface, electron transfer from material to oxygen, analyte adsorption, chemical reaction, electron transfer to the semiconductor, and desorption of the products
- The oxygen adsorption includes both physical and chemical process. Besides oxygen, water molecules and hydroxide groups are also adsorbed on the MOx surface

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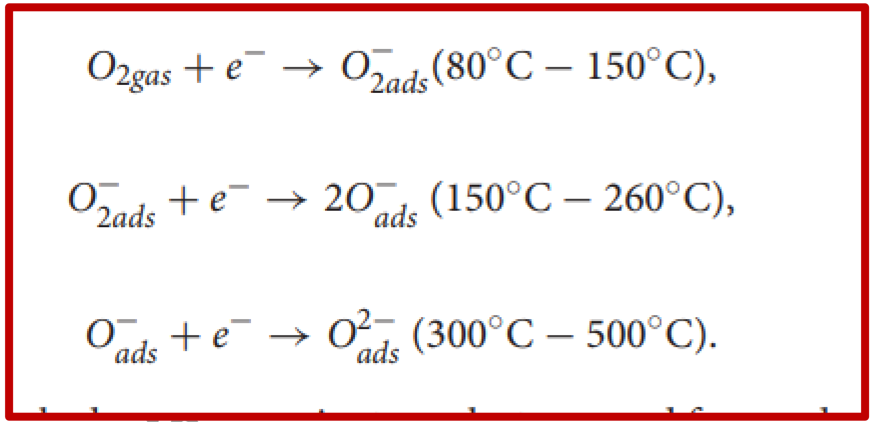

$$O_{2gas} + e^- \rightarrow O^-_{2ads} (80^\circ C - 150^\circ C),$$

$$O^-_{2ads} + e^- \rightarrow 2O^-_{ads} \; (150^\circ C - 260^\circ C),$$

$$O^-_{ads} + e^- \rightarrow O^{2-}_{ads} \; (300^\circ C - 500^\circ C).$$

Depending on the temperature, oxygen can be present in the molecular (O− 2) or atomic (O− and O2−) form. The molecular oxygen form can be found at the temperature below 150◦C, whereas above 150◦C the atomic forms exist

Depending on the charge carrier, two main types of semiconducting MOx materials are reported in the literature: ptype, where the charge carriers are the holes, and n-type, where the charge carriers are electrons. In fact, the charge carriers in wide band gap oxide semiconductors are determined either by doping aliovalent cations or by oxygen non-stoichiometry.

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Sensing Mechanism of N-Type MOx

- the gas sensing mechanism of MOxs is fundamentally a surface-related issue resulting in a change in sensor resistance that is tightly related to the adsorption or desorption processes of target gases.
- Oxidation/reduction of the semiconductor: the charge carrier concentration and electron structure of the sensitive materials affects by the gas concentration due to the change of the surface or bulk stoichiometry. - Ion exchange: the change of ions leads to the formation of the surface layer with the other electron structure in comparison to the base material.

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- After the n-type nanostructure is exposed to air, oxygen molecules are adsorbed on the surface. Due to the electrons transfer from the semiconductor powder to the surface, the development of potential barriers on the particle surface occurs, which affects in relatively few oxygen adsorption sites available on the n-type semiconductor surface
- Depending on the temperature, adsorbed oxygen ion species (O− 2 , O−, and O2−) are formed by the extraction of conduction band electrons and by generating a space charge conduction area. This causes an increase in sensor resistance. When the target gas is injected, it is adsorbed on the material surface and then gets oxidized if the gas is a reducing gas resulting in the return of electrons back to the conduction band. As a consequence, this reduces the space charge width and the resistance proportional to the concentration of analyte.

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- When the gas is an oxidizing one, it gets reduced by taking electrons from the conduction band, leading to the proportional increase of the resistance Thus, in the case of n-type semiconductors, the presence of reducing gases causes the conductivity increase, and oxidizing gases decrease the sensor conductivity.

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Sensing Mechanism of P-Type

- MOx Compared to the n-type MOx sensors, for p-type semiconductors, the sensing mechanism in accordance to the resistance change is opposite. Figure 1 shows the change in sensor resistance of n- and p-type MOx gas sensors upon the exposure to the reducing gas. The adsorption of oxygen molecules following by their ionization generates a hole accumulation layer on the material surface and thus resulting in a decrease of resistance. Upon exposure to a reducing gas, the target molecules react (via oxidation) with the adsorbed oxygen species on the surface, leading to the release of the trapped electrons back to the conduction band, which then increases the sensor resistance as a result of the hole accumulation layer becoming thinner. If the target gas is an oxidizing one, it will get reduced by taking electrons from the conduction band and thus resulting in the decrease of resistance.

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