College of Science
Department of Physics

M.Sc. Lectures
Semester I
Nano-physics

IMAGING TECHNIQUES FOR NANOSTRUCTURES

Dr. Laith Al Taan
Professor

IMAGING TECHNIQUES FOR NANOSTRUCTURES

the diffraction of electrons or X-rays can be used to determine structure in reciprocal space, which can then be inverted to find the real-space atomic arrangements

The solid's small size interrupts the periodicity of the lattice,
blurring ضبابية diffraction peaks,
and also produces a very small scattered signal.

Real-space probes that can directly determine the properties of the nanostructure.

These probes use the interaction of a typically an electron or photon, with the object under study, to create an image.

The techniques fall into two major classes:

*** Focal microscopy**,

The probe particle is focused by a series of lenses onto the sample.

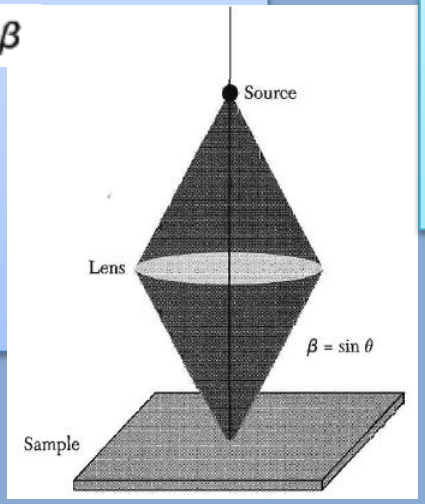
The ultimate resolution التحليل النهائيof the system is limited by the wavelike nature of the particle through the Heisenberg Uncertainty Principle, or, equivalently, diffraction.

This smallest feature spacing **d** that can be resolved is given by

$$d \approx \lambda/2\beta$$

β is the numerical aperture.

Achieving nanoscale resolution requires using particles with small wavelengths and maximizing numerical aperture.



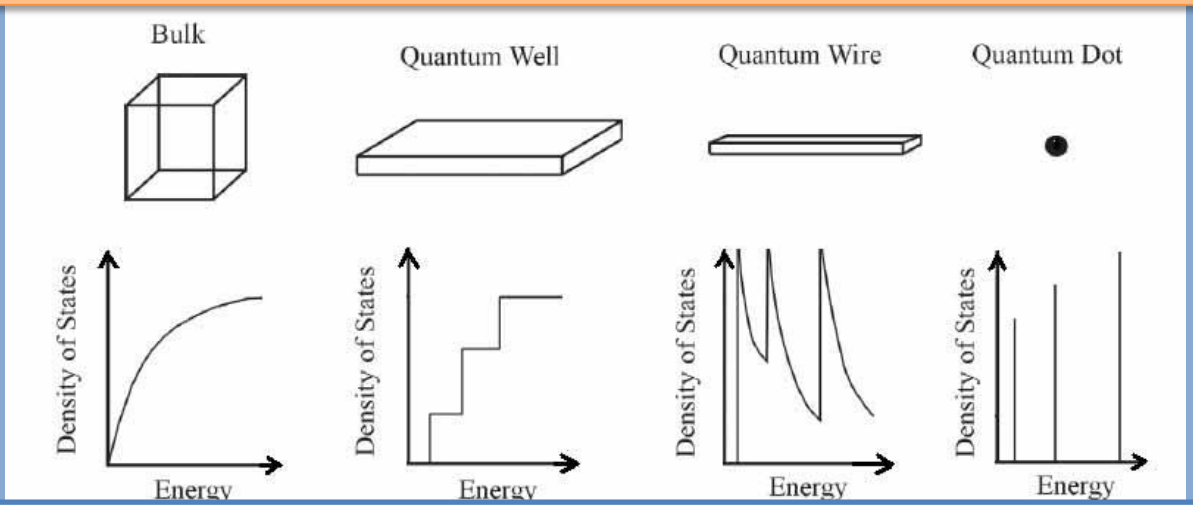
*** Scanned probe microscopy**,

by contrast, a tiny probe is brought close to the sample and scanned over its surface. The resolution of the microscope is determined by the **effective range** of the interaction between the probe and the structure under study, rather than by the wavelength of the probe particle

Of particular importance is the electronic structure, expressed in the **density of states**. For a finite-sized system, the **density of states** is a series of delta functions

$$D(\varepsilon) = \sum_j \delta(\varepsilon - \varepsilon_j)$$

where the sum is taken over all the energy eigenstates of the system.
For extended solids, the density of states can be represented by a continuous function, **but for a nanostructure** the discrete sum form is necessary along the confined directions

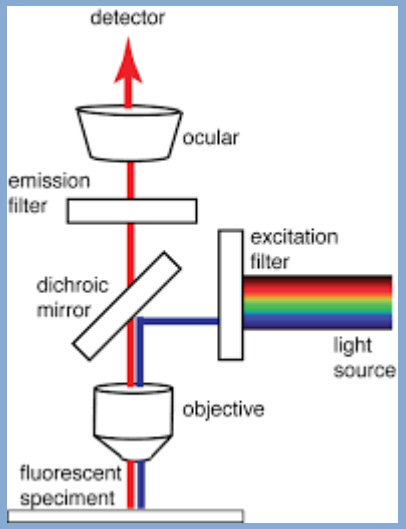


*This **quantized density of states** determines many of the most important properties of nanostructures, and it can be directly measured using the **techniques** described below:*

> Optical Microscopy
> Electron Microscopy
>Scanning Tunneling Microscopy
> Atomic Force Microscopy

Optical Microscopy

The optical microscope is the prototypical focal instrument.
Using visible light and a high numerical aperture (β = I),
the highest obtainable resolution is 200-400 nm.
For direct imaging, optical microscopy therefore only
reaches the edge of the nanoscale realm.
Some OM use an *elastic light scattering*, *absorption*,
luminescence, and *Raman scattering.*



Within the **electric dipole** approximation, Fermi's golden rule gives the transition rate between an initial state **i** and a higher energy state **j** due to **absorption.**

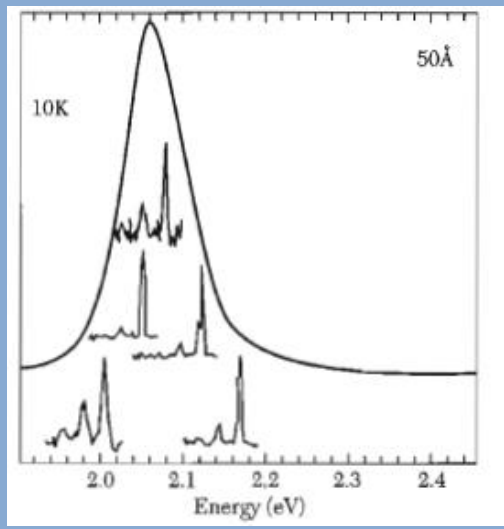
$$w_{i\to j} = (2\pi/\hbar)\left|\langle j|e\mathbf{E}\cdot\mathbf{r}|i\rangle\right|^2\delta(\varepsilon_j - \varepsilon_i - \hbar\omega)$$

Similarly, the **emission** rate from state **j** to **i** is given by;

$$w_{j\to i} = (2\pi/\hbar)\left|\langle j|e\mathbf{E}\cdot\mathbf{r}|i\rangle\right|^2\delta(\varepsilon_i - \varepsilon_j + \hbar\omega) + (4\alpha\omega_{ji}^3/c^2)\left|\langle j|\mathbf{r}|i\rangle\right|^2$$

The Fermi functions indicate that absorption only occurs when the initial state **i** is filled and the final state **j** is empty

The above relations show that absorption and emission can be used to probe the electronic energy level spectra of nanostructures.



In each spectrum, **the high-energy peak** is the primary ***transition*** between the lowest electronic state in the conduction band and the highest energy state in the valence hand. **The lower energy peaks** are associated transitions involving the emission of an LO phonon.

Variations in the nanocrystal size and local electronic environment shift the positions of the peaks. The broad peak is the spectrum obtained for an ensemble of nominally identical nanocrystals

***Electron* Microscopy**

A very powerful **focal** tool is the electron microscope. **A** collimated beam of electrons is accelerated by high voltages and focused through a series of electrostatic or magnetic lenses onto the sample under study.

1) The **transmission electron microscopy,** or **TEM,** the electron beam travels through the sample and is focused on a detector plate.

The ultimate resolving power **d** is set by the wavelength of the accelerated electrons;

$$d = \lambda/2\beta \cong 0.6\,\mathrm{nm}/(\beta\sqrt{V}) \ ,$$

d~0.1 nm has achieved

For typical accelerating (100 kV): the theoretical **resolving power is therefore subatomic**.

and **imperfections in the lenses, keep the TEM resolution well above this limit**

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This problem is overcome in

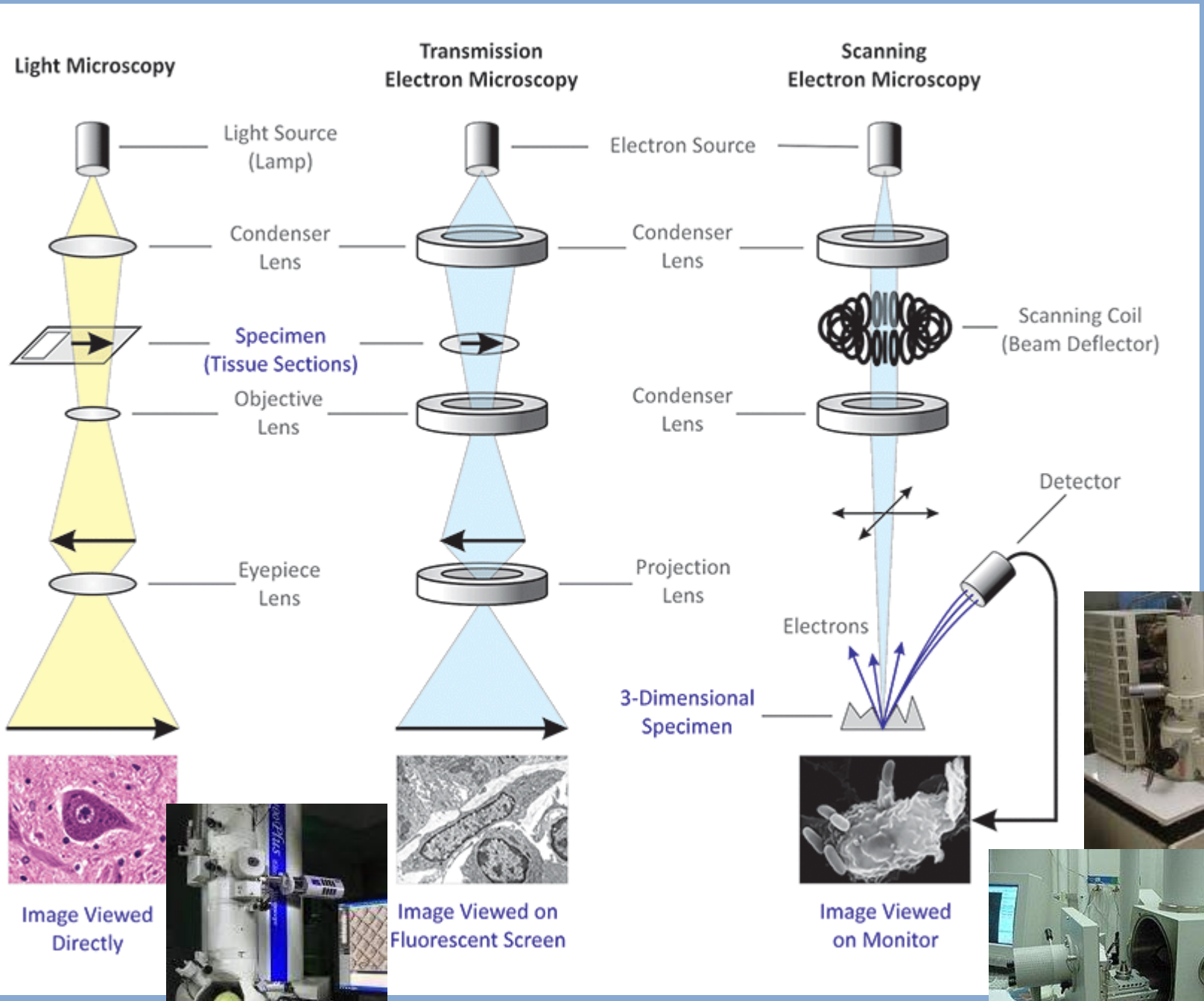
2)**the scanning electron microscope (SEM).**

A high-energy (100 V to 100 kV), tightly focused electron beam is scanned over the sample. The number of backscattered electrons and/or the secondary electrons generated by the beam that emerge from the sample . These electrons are collected by an electron detector, and an ***image is formed by plotting this detector signal as a function of the beam location.***

This powerful technique can be used on most kinds of samples, but it typically has a lower resolution (>1 nm) than the TEM.

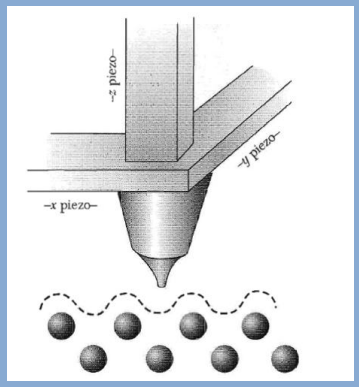
the SEM beam can be used to expose an electron sensitive material and draw small features in a technique known as

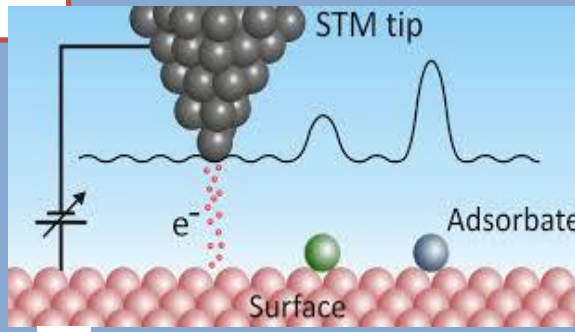
3) **electron beam lithography.** The ultimate resolution (<10 urn) is **very high**, but it is a slow process>


Light Microscopy
Transmission Electron Microscopy
Scanning Electron Microscopy
Light Source (Lamp)
Condenser Lens
Specimen (Tissue Sections)
Objective Lens
Eyepiece Lens
Electron Source
Condenser Lens
Condenser Lens
Projection Lens
Scanning Coil (Beam Deflector)
Detector
Electrons
3-Dimensional Specimen
Image Viewed Directly
Image Viewed on Fluorescent Screen
Image Viewed on Monitor

Scanning Tunneling Microscopy

In an **STM**, a sharp metal tip, preferably one with a single atom protruding from the end, is brought to within a nanometer of the conducting sample to be studied. The position of the tip is controlled with picometer precision using piezoelectric materials that expand or contract in response to electrical signals from a control system





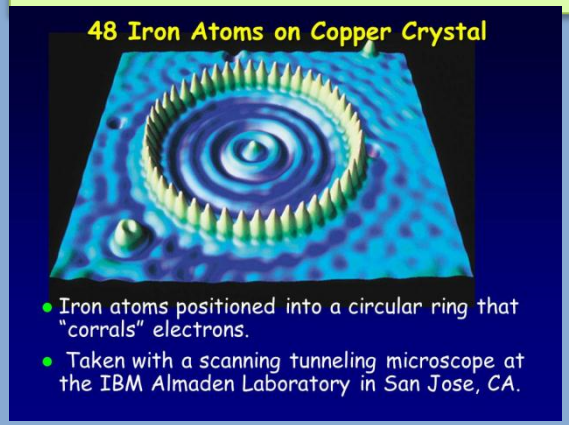
A voltage bias **V** is applied to the sample, and a tunneling current **I** flowing between the tip and the sample is measured.

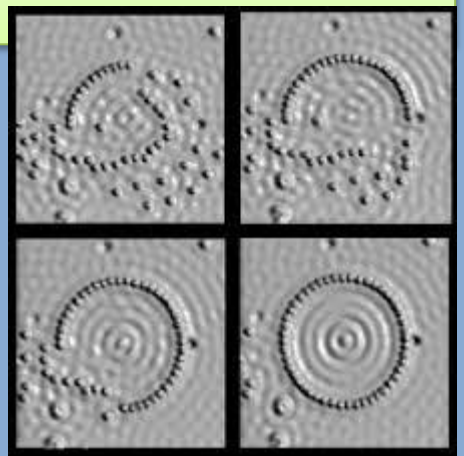
The current is proportional to the tunneling probability through the gap between the tip and sample

$$\mathcal{I} \propto \exp(-2\sqrt{2m\phi/\hbar^2}\, z)$$

a 0.1-nm change in the tip position leads to an order of magnitude change in $\mathcal{I}$

When the STM operates in feedback mode, **I** is maintained at a constant value by changing the tip height **z**. The STM thus tracks the surface topography, and very small changes in the height of the surface can be detected (<1 pm)





Atomic force microscope

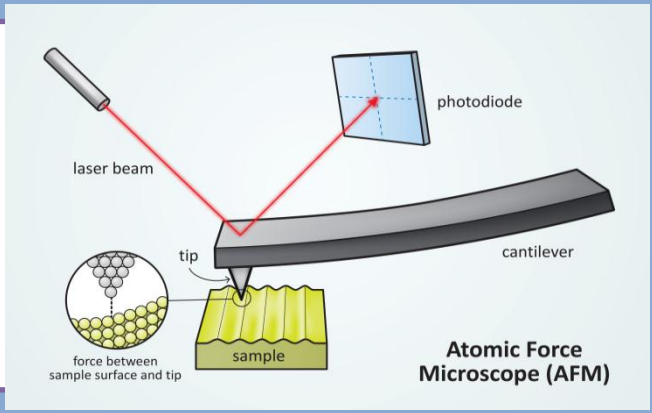
(**AFM**) is a much more flexible technique than STM and can be used on both conducting سلوكand insulating عزلsamples. However, it typically has poorer resolution.

An ***AFM measures the force between the tip and the sample***, rather than the **tunneling current**. A sharp tip is mounted on the end of a millimeter-sized cantilever

$$F = C\Delta z$$

The **displacement of the cantilever** is measured as a function **of tip position**, often by using the back of the cantilever as a reflector for a laser beam.

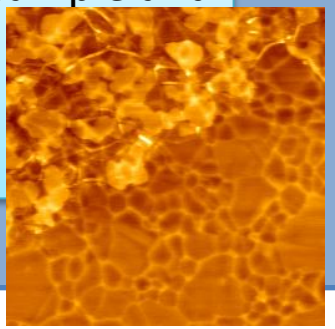
Motion of the reflector changes the path of the laser beam, which is detected using a photodiode array; picometer-scale displacements can easily be measured



Noncontact or intermittent-contact imaging modes are less invasive اقل ضررا,

and they also can give information about the long-range forces between the sample and the tip.

In these techniques, the **cantilever oscillates just above the sample** due to an applied driving force of amplitude F, near the cantilever resonance



the magnitude of the cantilever response at a frequency ***w*** is given by

$$|z_\omega| = \frac{F_\omega}{C} \frac{\omega_0^2}{\left[(\omega^2 - \omega_0^2)^2 + (\omega\omega_0 / Q)^2\right]^{1/2}}$$

Note that on-resonance,
w = wo,, the response is Q times larger than at low frequencies, making the detection of small forces possible