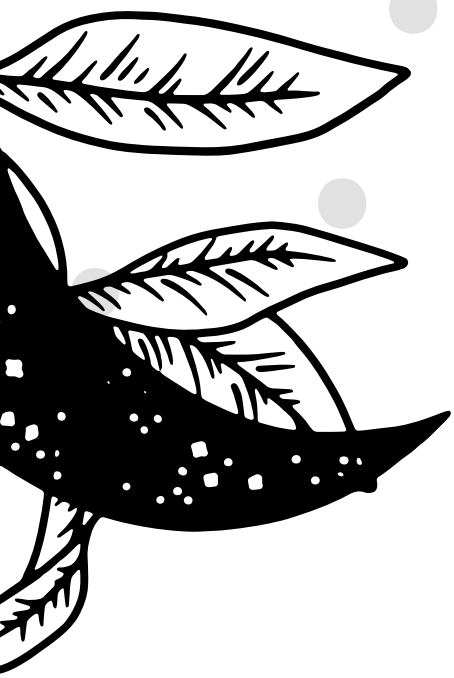
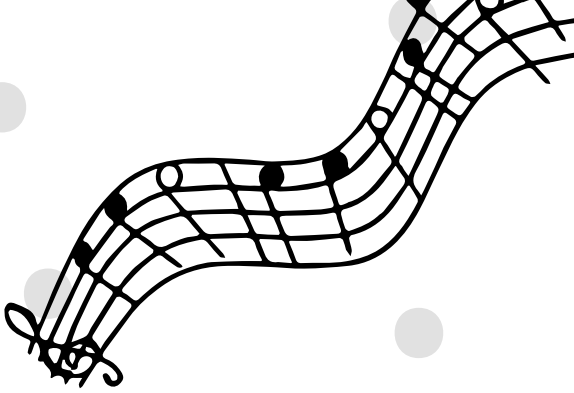




Swmic Majumder

NANONOTES

Discuss the importance of nanotechnological innovations in daily life (2020-21 1a)

[1] **Electronics and Computing**

Nanofabrication, formation of efficient electronics device, faster computing, and development of processor

[2] **Efficient Energy storage and Production**

Enhanced battery life, improved capacity, improvised solar cell.

[3] **Medicine and Healthcare**

Drug delivery, Diagnostics, Tissue engineering, Artificial organ development

[4] **Consumer Product**

Strain resistant coating, UV protection, Stronger building material, Cosmetics, Strain resistance clothing.

[4] **Environmental Impact**

Pollution cleanup, Efficient filtration, Energy efficient technology

[5] **Food and Agriculture**

Nano sensor and biosensor to detect contamination and application of nanotechnology for precise development goal increases yield and production.

[6] **Transportation**

Vehicle coating and efficient purification of fuel, exhaust gas purification all due to nanotechnological evolution.

1.b. Describe some important nanotools that has revolutionized our conception of the nano-world. Explain briefly their significances

[1] **Scanning Tunnelling Microscope**

It operates by scanning a sharp tip very close to a sample's surface and measuring the tunneling current of electrons between the tip and the surface. It visualizes and manipulates atom or molecule on surface. Uses quantum mechanical effect

for understanding surface chemistry, atomic-scale processes, and nanoscale materials.

[2] **Atomic Force Microscope**

AFM provides topographical and mechanical information at the nanoscale by using a sharp tip attached to a cantilever to measure forces between the tip and the sample.

[3] **Transmission electron Microscope**

TEM allows researchers to visualize the internal structure of materials at the atomic level. It uses a beam of electrons to transmit through a thin sample, creating high-resolution images. TEM has been crucial for studying the morphology, crystallography, and defects in nanomaterials, as well as biological structures like viruses and cells.

[4] **Secondary Electron Microscope**

SEM provides detailed three-dimensional surface imaging of materials and biological specimens at nanoscale resolutions. It uses focused electron beams to scan the sample's surface and collect secondary electrons.

[5] **X-Ray Crystallography**

X-ray crystallography helps determine the atomic and molecular structure of crystalline materials, including proteins, enzymes, and organic compounds.

[6] **Mass Spectroscopy**

It allows for the precise determination of the mass and chemical composition of molecules and nanoparticles.

Bottom Up

Bottom-up assembly is a manufacturing or construction method that starts with individual components or building blocks and assembles them into a larger, more complex structure. The goal is to produce desired product with strong and specific interaction.

[1] **Nanotechnology**-- techniques like self-assembly, where molecules or nanoparticles naturally arrange themselves into organized structures.

[2] **Chemistry**-- Use bottom-up assembly to synthesize complex molecules or materials.

[3] **Nanofabrication**-- Techniques like electron-beam lithography and molecular self-assembly are employed to build nanoscale features on substrates, which is essential for developing nanoelectronics devices and sensors.

[4] **Biology** – Complex macroscopic organism like fertilized egg with self-assembly feature provides inspiration for innovation.

Bottom-up assembly offers several advantages, including scalability, precision, and the ability to create highly customized and complex structures.

Self-assembly of complex structures requires achieving balance between entropy at a given temperature and the binding enthalpies of the various components.

Entropy is a thermodynamic quantity that describes the degree of disorder or randomness in a system. In the context of self-assembly, it plays a crucial role because molecules and components tend to move towards states of higher entropy. This means they naturally disperse or adopt more disordered arrangements when given the chance. Functional nanostructure involves self-assembly and necessary information is coded within molecule using weak force (Hydrogen bond, Van Der waal Force).

Binding enthalpy refers to the energy associated with the interactions between individual components in a self-assembling system. These interactions can be attractive (e.g., chemical bonds, van der Waals forces) or repulsive (e.g.,

electrostatic repulsion). Binding enthalpies determine how strongly components are attracted to each other and can overcome the natural tendency for disorder. Layers are reasonably stable that involves structuring and

Factors:

[1] Temperature

With low K.E (Low Temperature), molecule stays at ordered arrangement and binding energy is dominant to form ordered structure. But at high temperatures, entropy is dominant and self-assembly is less favorable.

[2] Kinetic Traps

Self-assembly can get "trapped" in intermediate states or kinetic barriers, preventing the formation of the desired structure. Techniques like controlling the **rate of assembly**, using **templates, or designing molecules** with specific interactions can help overcome these challenges.

Equilibrium nanostructures spontaneously assemble like nanostructures built by kinetically trapped metastable states.

Challenges:

[1] **Characterization and purification** of resulting compound requires **organic synthesis** like carrying out reaction.

[2] **High surface to volume ratio** refers to high density of atom at surface and **chemical bond requirement** with neighboring atom must be satisfied.

Monolayer formation

Monolayers are single-molecule thin layers prepared on surfaces – an ultra-thin layer of molecules of infinite breadth. Molecules attach to surface that are chemically attracted and leads to construction of denser layer. It enables modification in chemical properties.

Examples:

[1] A surface covered with methyl terminated alkanes(-CH3) is extremely hydrophobic where a surface covered in carboxylate groups (–COOH) is extremely hydrophilic.

[2] Alkanethiols with a wide variety of different end groups can be used to change the characteristics of the surface.

Self-Assembly Monolayer (2018-19 6b)

Presence of chemically bound molecule introduces modified interface. It's critical for determining and designing the interaction strengths of proximal molecules or analytes (i.e., sensing, electron transfer, cell adhesion, polymer adsorption) or for post-assembly modification of the film.

The incorporation of functional moieties such as chromophores, electroactive groups, or molecules due to processing or chemical environment that can bond within the SAM (i.e., covalent cross-linking between adjacent molecules or non-covalent hydrogen bonding) enables capabilities in sensing, electron transfer, molecular recognition, and other areas. The nature of interactions between molecules and substrates ranges from hard acid–base interactions to soft donor–acceptor charge transfer interactions.

[1] Surface modification [hydrophobic/hydrophilic, Catalyst, Reactivity]
[2] Biomolecule Formation [functionalized protein, DNA, peptide, also used in biosensor and drug delivery system, pH sensor]

[3] Nanotechnology [Nanoscale device fabrication, Nano sensor, Molecular electronics]

[4] Corrosion Protection

[5] Lubrication [lubricant and anti-wear coating, reduced friction]

[6] Nanopatterning

Self-Assembly method and invention and development of Scanning probe Microscope greatly enhanced ability to understand and optimize patterning and optimize as individual absorbates spatial distribution is directly measured.

Blodgett was able to transfer monolayer onto solid support. Such as: spontaneous formation of **alkyl amines on a platinum surface**, **ordered monolayer of thiols** (-SH) can be prepared on a gold surface by adsorption.

Adsorption—It's a process that occurs when a gas or liquid solute accumulates on surface of solid or liquid forming molecular or atomic film. Adsorbing species can be chemisorbed or physiosorbed, depending on the strength of the interactions between the adsorbate and the surface.

Physisorption—weak covalent adsoprion due to van der waals force. Reversible and done at low temperature.

Chemisorption—stronger chemical adsorption in formation of covalent and ionic bond. Irreversible and done at high temperature.

Alkanethiolate monolayers grown on coin metals (Ag, Au, Pt) are structurally simple and easy to construct molecular sheet is made of thiolate species with long alkyl chains

Most studied and readily assembled molecular monolayers consists of **alkane chains (–CH2– repeats)** modified at one end with a **thiol (–SH) group** that attaches chemically to a gold surface.

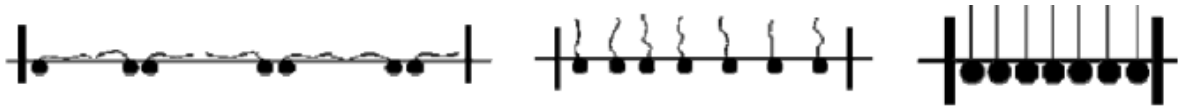
Longer chains (12 or more methylene units) pack together with **stronger van der Waals interactions** and therefore tend to form more ordered films, though reasonably well-ordered films can be formed by chains with as few as six or eight methylene units. **An ethanol solution of a few mM concentration of alkanethiol** is kept in contact with a clean gold surface for several hours. If the head group is not reactive, the film remains stable after the sample is pulled out of the solution and rinsed.

Langmuir-Blodgett methodology (2018-19 4d)

It is a technique used to deposit monolayers of molecules or nanoparticles onto a solid substrate with precise control over their thickness and organization. It is useful for creating well-ordered, organized molecular layers

[1] **Langmuir Monolayer**-- The process begins with air-water interface. The monolayer consists of **hydrophilic head and hydrophobic tail**. The amphiphilic molecule spreads into liquid surface forming **densely packed monolayer** with

tendency to align hydrophobic tails where hydrophilic heads with contact of liquid.



[2] **A Langmuir trough** is a specialized apparatus used to create and manipulate the monolayer at the air-water interface. It consists of a container with moveable barriers that can compress or expand the monolayer, thereby controlling its surface area and density. The surface pressure (the force per unit length acting on the interface) can be precisely controlled by adjusting the area.

[3] **Molecular Organization**--During compression, the monolayer undergoes structural changes, which can result in various organization patterns, such as a close-packed, hexagonal array. changes are monitored by techniques like surface pressure-area isotherms

[4] **Transfer to substrate**--Once the desired monolayer organization is achieved, a solid substrate (e.g., a glass slide) is carefully dipped or lifted through the monolayer at a controlled speed. This process transfers the monolayer from the air-water interface onto the substrate. The orientation and packing of the molecules in the monolayer are preserved during this transfer, allowing for precise control over the molecular arrangement on the substrate.

[5] **Layer Stacking**--By repeating the Langmuir-Blodgett process, it's possible to create multilayer films with a high degree of control over the number of layers and their organization. This can result in well-ordered stacks of monolayers.

Application:

[1] Development of ultra-thin films with controlled thickness and properties.

[2] Creation of nanoscale templates for the growth of nanoparticles or nanowires.

[3] Surface modification of substrates for sensors and electronic devices.

[4] Study of molecular interactions at interfaces

[5] Fabrication of functional materials for use in optics, electronics, and coatings.

Why is Gold chosen as Substrate? (2020-21 4a)

Gold is chosen as substrate due to-

[1] Chemical Inertness – stable SAM, no stable oxide, no chemisorption

[2] Thermodynamic Stability – forms bond with Sulphur(-SH) in thiol group and thermodynamically stable bond

[3] Smooth Flat Surface

[4] Excellent Conductivity – coin material

[5] Bio-compatible – non-toxic

[6] Versatility – wide range of molecules attached.

[7] Easy to make -- Thermal evaporation

[8] Easy Removal of deposit – by Piranha Solution H_2O_2(30%):H_2SO_4 = 1:3]

Patterning of SAM

Patterning of self-assembled monolayers (SAMs) involves selectively arranging and structuring SAM molecules on a substrate surface in specific regions or patterns.

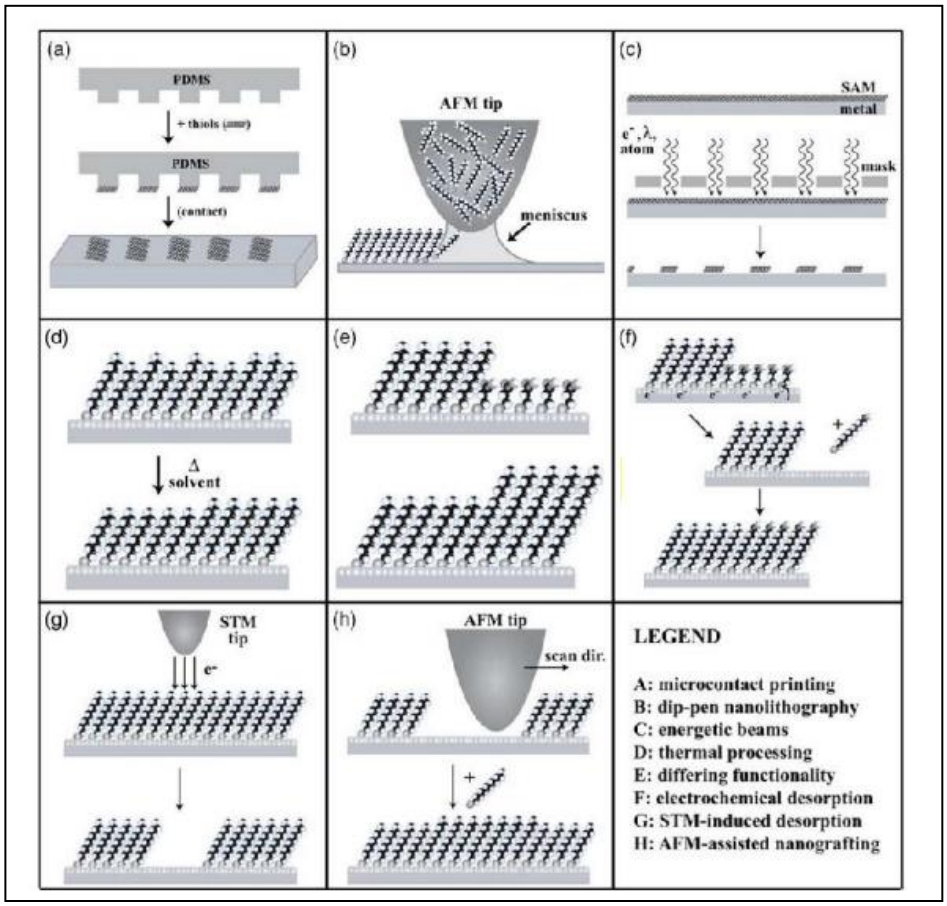
A. Microcontact Printing

Thiol-terminated, is adsorbed onto the stamp's surface. stamp is then brought into contact with the substrate, transferring the SAM molecules to the substrate surface in the desired pattern. The substrate is rinsed to remove any unbound molecules.

C.Electron Beam Lithography (EBL)

An electron-sensitive resist is deposited on the substrate. The electron beam is directed to write patterns on the resist, selectively exposing regions for SAM

formation. The exposed substrate is then immersed in a solution containing the SAM-forming molecules.



Photolithography

A photosensitive resist is spin-coated onto the substrate. UV light is directed through a photomask onto the resist, exposing selected areas. Unexposed areas are washed away, leaving patterned resist. SAM molecules are adsorbed onto the exposed regions.

B.Dip-Pen Nanolithography (DPN)

The AFM tip is coated with the SAM-forming molecules. The tip is brought into contact with the substrate, depositing molecules in a controlled pattern.

Dip Pen Nanolithography (DPN) is a versatile nanofabrication technique that can be effectively used for patterning Self-Assembled Monolayers (SAMs) on substrates with nanoscale precision. Patterning SAMs using DPN allows for the creation of tailored molecular patterns and functionalized surfaces.

Suspension containing SAM formation molecule and clean functionalized surface is required. We functionalized tip with SAM forming molecules. Functionalized Tip in contact with substrate and transfer via capillary force and chemical interaction. We control tip movement and dwell time to create desired pattern. We rinse to remove unbound molecule and Scanning probe microscopy and X-ray photoelectron spectroscopy verify quality of SAM

[1] Nanoscale precision

[2] Versatility (customized molecular pattern)

[3] non-lithographic (suitable for unconventional substrate and 3D surface)

[4] Tailored Functionalization

Thermal Processing

Define pattern of SAM coated substrate via mask or protective coating. Selective heating, desorption, or reaction to remove or modify SAM zones. Rinse to remove residues.

[E] Differing Functionality

Mask or protective layer on substrate to shield zone and patten printing. Functional group modified by chemical or physical treatment (plasma treatment, Ion beam irradiation)

[F] Electrochemical Desorption

Electrode setup (working and reference) with masking to pattern design. Immersion with electrode in electrolyte solution to do redox reaction. Potential applied to control deposition of SAM molecules in exposed areas.

[G] STM induced desorption.

STM with metallic top creates controlled tunnelling current and potential applied current controls desorption.

[H] AFM assisted Nano grafting

Sharp tip with cantilever maintains constant force or height with consistent interaction with interface to interact with molecule to exchange or remove SAM molecules for pattern transfer.

Nanografting is a nanofabrication technique used to precisely manipulate and pattern molecules or nanoparticles on a surface at the nanoscale. It enables the controlled placement of molecules or nanoparticles onto a substrate with high precision, allowing for the creation of custom-designed nanostructures and patterns.

[1] Substrate preparation

[2] Tip Functionalization

[3] Scanning Probe Microscope

[4] Manipulation via positioning and patterning via movement of tip

[5] Characterization

Application-- nanoelectronics, Molecular sensor, Photonics, Nano-biotechnology

SAM Applications

Sensor→Sensor needs a chemically active recognition layer and signal transducer. Most common SAM based bio-sensors are enzyme biosensor, also called catalytic biosensors. Glucose biosensor oxidizes glucose to Gluconolactone via glucose oxidase. Mediator like ferricyanide oxidized at electrochemical interface and current generated is proportional to amount of glucose oxidized. We get controlled immobilization on monolayer surface.

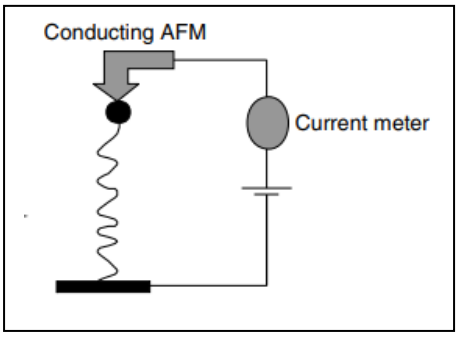
Affinity Biosensor→ Biorecognition molecule is the sensor element. Surface plasmon resonance, Quartz Crystal microbalance (change in oscillatory frequency) are common approaches for sensing.

Chemical Sensor→Recognition element non-biological and laboratory synthesizable. Electrochemical, Capacitance and plasmon resonance are common properties utilized in recognition. Detection of Cu(II) via Fe(III). Molecular imprinting for sensing occurs as molecule shape is imprinted on surface

pH Sensor→ Electroactive species on monolayer surface where one is pH sensitive and other act as reference.

Corrosion Prevention→Monolayer on surface where chain is long enough to offer protection and provides protection against ion penetration.

Wetting Control→Self-assembly of Alkanethiol on Au surface. Adding methyl group makes it hydrophobic where adding carboxyl group turns it hydrophilic. It can also be done by changing potential.



Molecular Electronics→Monolayer based electric contact is feasible. Van der waals force, Hydrogen force and covalent interaction makes monolayer attached to metallic surface.

Template→ SAM acts as template for nanofabrication. Monolayer protection allows nanoparticle to preserve it's size

and shape. Nanoparticle acts as monolayer anchor.

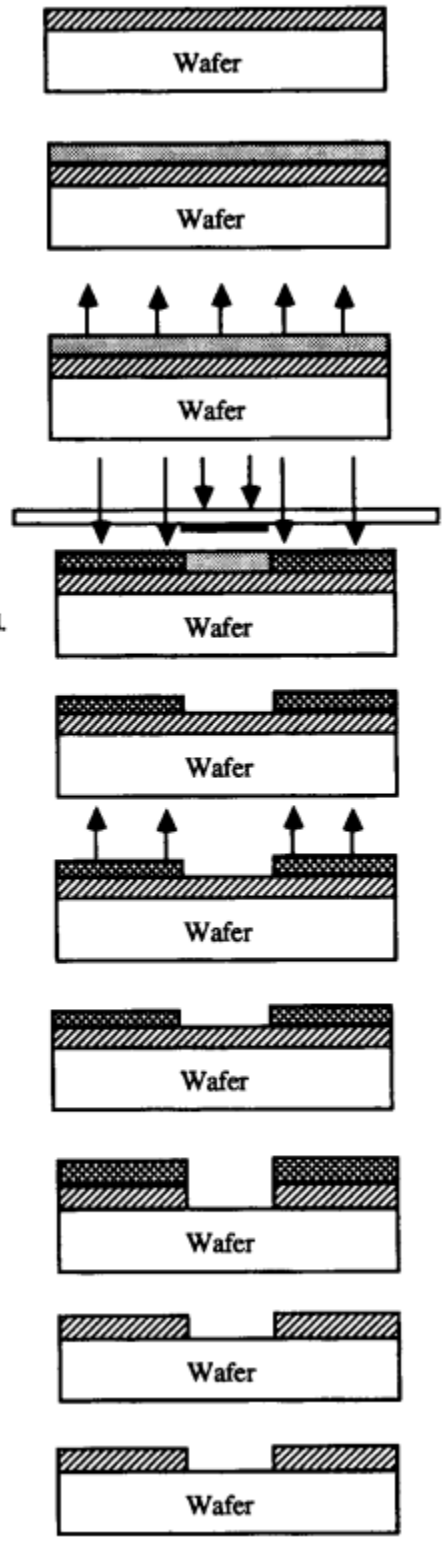
Crystal Growth→SAM nucleates crystal growth and its useful for building thin layer of material. Growth of other materials are possible at specific location of functional molecular surface. like: ZrO_2 crystal growth on SAM.

Complex Molecule→For production of protein on surface, SAM is a good alternative. Protein anchored to surface by patterned monolayer and no absorption at un-patterned zone, it provides spatial control on monolayer growth.

Multi-Layer Structure→Monolayer growth over each other results into multi-layer structure.

10 Step Pattern Processing

1. Surface Preparation	Clean and dry wafer surface
2. Photoresist apply	Spin coat a thin layer of photoresist on surface
3. Softbake	Partial evaporation of photoresist solvents by heating
4. Alignment and Exposure	Precise alignment of mask/reticle to wafer and exposure of photoresist. Negative resist is polymerized.
5. Development	Removal of unpolymerized resist.
6. Hard bake	Additional evaporation of solvents
7. Develop inspect	Inspect surface for alignment and defects
8. Etch	Top layer of wafer is removed through opening in resist layer.
9. Photoresist removal (strip)	Remove photoresist layer from wafer.
10. Final inspection	Surface inspection for etch irregularities and other problems



SPS SADH DEEP FIGHTER

Surface Preparation

Photoresist Apply

Soft bake

Alignment & Exposure

Development

Hard Bake

Develop Inspect

Etch

Photoresist Removal

Final Inspection

Fabrication and Processing

Si-Ingot→ Polished Wafer→SiO_2 formation→Pattern imposition→ Developed Chip Section→ Etched Chip Section→ Stripped Chip Section→Additional Layering→ Metal Deposition→ Wafer Production

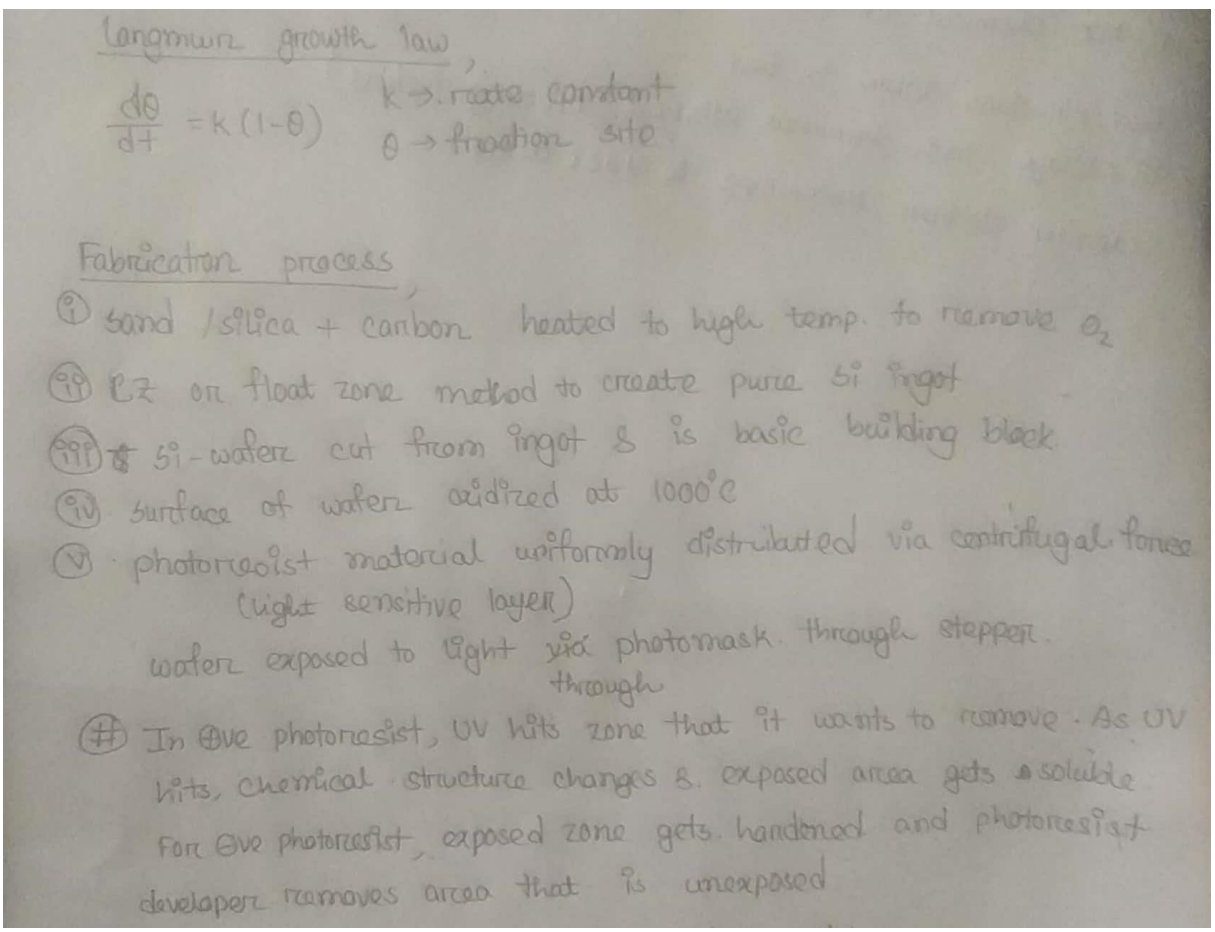
Material Preparation→ Crystal Growth and Wafer Preparation→Wafer Fabrication and Wafer Sort→Packaging→Final and Electrical Test

Moores Law

Moore's Law states that the number of transistors on a microchip (integrated circuit) doubles approximately every two years, while the cost of manufacturing these chips is reduced by a similar factor.

Key Factors:

Transistor Density, Time Frame, Economic Implications, Innovation, Challenge for industry



Langmuir growth law,

$\frac{d\theta}{dt} = k(1-\theta)$ k → rate constant, θ → fraction site

Fabrication process,

(i) sand / silica + carbon heated to high temp. to remove O_2

(ii) CZ or float zone method to create pure Si ingot

(iii) Si-wafer cut from ingot & is basic building block

(iv) surface of wafer oxidized at 1000°C

(v) photoresist material uniformly distributed via centrifugal force (light sensitive layer)

wafer exposed to light via photomask through stepper.

(vi) In +ve photoresist, UV hits zone that it wants to remove. As UV hits, chemical structure changes & exposed area gets soluble. For -ve photoresist, exposed zone gets hardened and photoresist developer removes area that is unexposed

2018-19 7a, 2020-21 5b

(vi) Exposed part etched off by wet or plasma etching

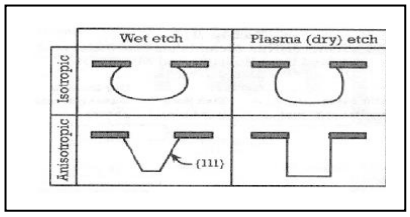
(#) (1) Wet etching involves immersion into chemical solution that reacts and dissolves materials to be removed, (2) wet chemical process, (3) less precise

Plasma etching is a (a) dry etching process that uses reactive ion or chemically active species in low pressure plasma to etch material (b) out of substrate. Ion bombards surface to remove material, high control, (c) precision, fine feature

(4) more chemical exposure (5) extensive safety precaution

(d) less " " (e) sophisticated machinery

[6] Isotropic etching [6] dependance on feature size and shape
[7] bulk material removal [8] Contamination probability



[f]anisotropic etching (removal in certain direction)

[g]better removal

(vii) Surface again oxidized & poly silicon deposited to insulated layer

(viii) Photoresist applied to design. polysilicon zone.

(ix) Doping (Ion implant)

(x) Another oxidation & photoresist applied. to pave room for metal contact

(xi) Chemical-mechanical process to polish excess material.

Test structure taken to test

(xii) package with terminal attached (cooling feature).

Scanning electron microscope to check defect

Layering->Patterning→Doping→Heat Treatment

Why positive Photoresist is preferred over Negative Photoresist? (2020-21 6b) (2018-19 8a)

When the photoresist is exposed to the UV light, the chemical structure changes and becomes more soluble in the photoresist developer. We receive an identical copy of the pattern, which is exposed as a mask on the wafer.

In negative photoresists, exposed zones become extremely difficult to dissolve. UV exposed negative resist remains on the surface while the photoresist developer solution works to remove the areas that are unexposed. This leaves a mask that consists of an inverse pattern of the original

Suppliers opt for positive photoresists due to their [1] **higher resolution capabilities**. Positive photoresists can maintain their size and pattern as the photoresist developer solvent doesn't spread in the areas that have not been exposed to the UV light. With negative resists, both the **UV exposed and unexposed areas are affected by the solvent**, which can lead to pattern distortions.

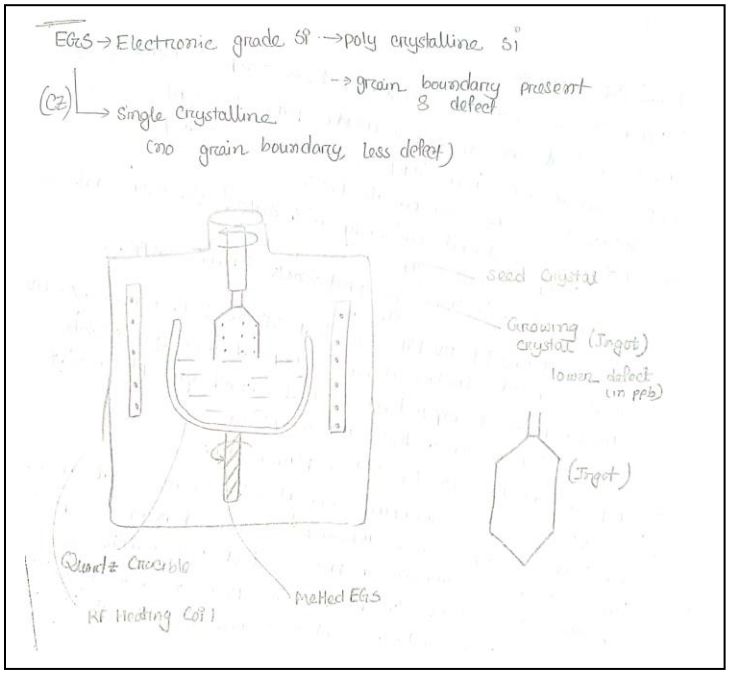
[2] Sensitivity -- Shorter Exposure time needed.

[3] Process simplicity-- simple and straight forward

[4] Shelf life-- more stable and higher shelf life

[5] Compatibility -- Compatible with Deep UV lithography

But negative resists have a **[1]faster photo speed**, **[2]multilayer structure design**, **[3]wider process latitude** and a significantly **[4]lower operating cost**. Negative photoresists also have better adhesion capabilities to certain substrate materials.



Crystal Growth technique

[1] Czochralski Crystal Growth technique

The Czochralski method is based on the principle of controlled solidification from a molten material. A single crystal is grown by dipping a seed crystal into a molten material and slowly withdrawing it while simultaneously rotating the crystal. The

Czochralski crystal growth technique's precise control over crystallographic orientation, purity, and crystalline quality makes it an essential process for manufacturing high-performance semiconductor materials. Electronic Grade Si(EGS) is converted to single crystalline(ingot).

[1] **Preparation**--Seed crystal with desired crystallographic orientation and a quartz (SiO_2) crucible (compatible with melt and prevents contamination) prepared to hold molten material. Seed crystal connected with pulling and rotating mechanism.

[2] **Melting & Growth**--single crystal is melted in the crucible, typically **using high-frequency induction heating or resistance heating**. The temperature is carefully controlled to maintain the material in a molten state. The seed crystal is dipped into the molten material, and a meniscus forms between the seed and the melt. The seed crystal is slowly pulled upward while being rotated. Material solidifies with same crystal orientation. The rate of pulling and rotation speed are controlled to ensure uniform crystal growth and prevent defects. Pulling rate/ velocity is inversely proportional to radius of ingot. So high pulling velocity, radius small and visa-versa.

[3] **Cooling & Annealing**-- The single crystal is gradually cooled to room temperature to ensure the formation of a defect-free crystal structure. It improves crystal quality and remove residual stress.

[4] **Cutting & Processing**-- The grown single crystal is cut into wafers or other desired shapes for use.

Merit—Compatible for large ingot

Demerit—Crucible starts melting and mixes with EGS and so Oxygen impurity is seen as SIO2 present in crucible. This introduces defect and contamination.

[2] Float Zone Crystal Growth Technique (2020-21 5b)

"Float zone," is a specialized method for growing single crystals with exceptional purity and crystalline quality. Zone refining, where a small molten zone is passed through a polycrystalline rod or ingot, effectively purifying, and growing a single crystal as the zone moves through the material. Principle is to maintain a localized

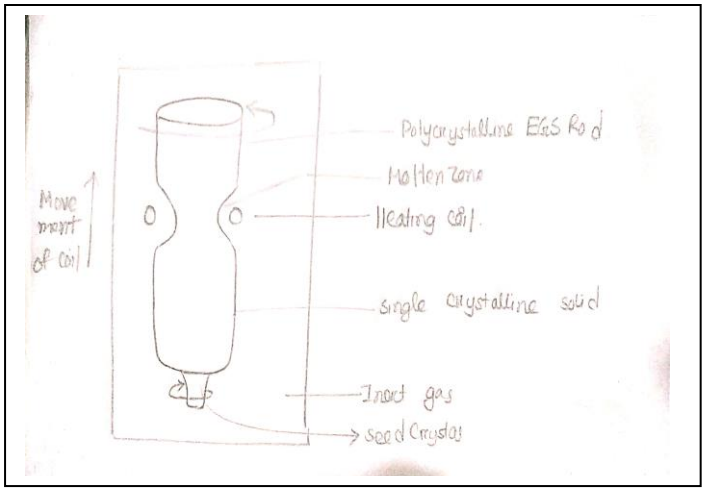
molten zone within the crystal as it is slowly pulled or "floated" through the material, allowing for the controlled growth of a single crystal.

Zone due to zonal heat and float as RF heating coil is movable.

[1] **Seed Crystal & Feed Rod**-- High-purity seed crystal and feed rod(larger in diameter than the seed crystal) of the desired material, is used with a specific crystallographic orientation. Both are mounted in a vertical orientation within a specialized crystal growth chamber. Heating elements are used to create a localized molten zone at the interface between the seed crystal and feed rod.

[2] **Floating Zone Formation**-- The heating elements are precisely controlled to generate a high-temperature, molten zone at the tip of the feed rod. The feed rod is slowly lowered, and the molten zone is maintained at a specific position within the rod. The seed crystal is dipped into the molten zone, allowing it to partially melt and solidify behind the moving molten zone.

[3] **Crystal Growth**-- As the molten zone and seed crystal move upward or downward (depending on the setup), they effectively sweep through the entire length of the feed rod. During this process, impurities and crystal defects are preferentially incorporated into the molten zone and are carried away from the growing single crystal. Molten zone has a higher degree of purity and crystalline perfection.



[4] **Cooling and Annealing**-- Single crystal is gradually cooled to room temperature to minimize thermal stresses as it improves the crystal's quality and remove any remaining defects.

Merit-- high purity (Impurities are less soluble in solid crystal rather than in molten form, Rod going vertically, EGS will melt and carries impurity downward) Semiconductor wafer, good crystalline quality, and reliability, small oxygen impurity, no need for quartz crucible.

Demerit—Small wafer production, more time consuming.

Difference (CZ Vs FZ)

[1] Melting in crucible vs localized heating and molten zone.

[2] pull crystal upward vs RF coil movable.

[3] comparatively higher defect, lower impurity vs high purity, low defect density

[4] large diameter wafer vs smaller diameter

[5] High volume production vs crystalline perfection

RCA Clean

The RCA clean is known for its effectiveness in achieving high levels of cleanliness and surface preparation. Safety guidelines and use appropriate protective measures when working with chemicals is necessary. The RCA cleaning process must be performed carefully and precisely, and the chemicals used should be handled with caution.

RCA-1: $NH_4OH:H_2O_2:H_2O$ = 1:1:5 or 1:2:7 (70^0C-80^0C to remove organic contamination)

RCA-2: $HCL:H_2O_2:H_2O$ = 1:1:6 or 1:2:8 (70^0C-80^0C to remove inorganic contamination)

RCA-3: DI water

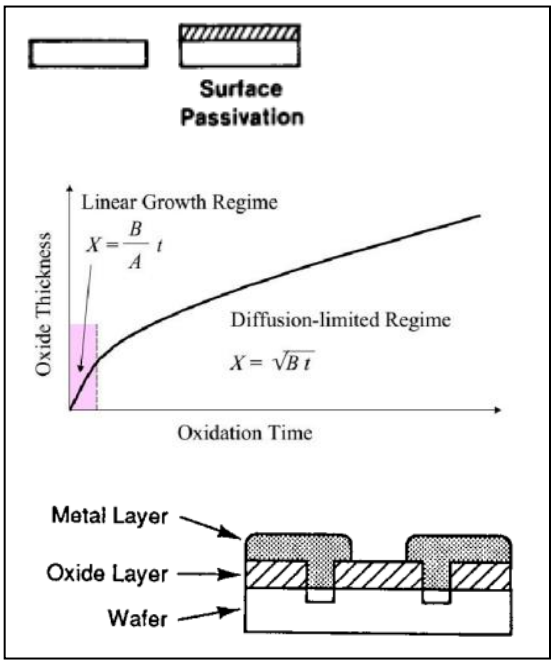
Cleaning Process

RCA-1 Bath(Organic Contamination removed) **>> Rinse** (RCA-1 Solution Removed) **>> RCA-2 Bath** (Organic and metal contamination removed) **>> Rinse >>Drying**

Oxidation (2018-19 7a)

Oxidation growth rate is limited by transportation or diffusion of oxygen through oxide layer already grown. Linear Stage and Parabolic Stage. Linear to Parabolic is dependent on oxidizing temperature and oxidation time.

The oxidation rate refers to the speed or rate at which a substance undergoes oxidation, a chemical reaction



in which a substance loses electrons. Oxidation is done for Diffusion Masking Layer,

Surface Passivation (screen oxide, pad oxide, barrier oxide- protection from external stress and abuse endurance in fabrication process, contamination away from surface), Isolation (Field oxide, LOCOS), Gate Oxide. It acts as

doping barrier (Dopant Introduced by ion implantation or diffusion, Dopant has slow rate of movement in SiO_2 layer, low penetration, SiO_2 expands and contracts in same rate as Si), physical protection, and surface dielectrics (Insulating property of SiO_2,prevents metal layers from shorting, Again charge buildup possible in metal layer to buildup charge in wafer surface and so it's called FIELD OXIDE)

The thicker the layer the lower the growth rate. Oxidation rate depends on-

[1] Temperature

[2] Wet or Dry Oxidation

[3] Thickness

[4] Pressure

[5] Wafer Orientation

[6] Silicon Dopant

Wet and Dry Oxidation (2020-21 6a)

When pure O_2 gas is used as oxidizing agent, growth of oxidation requires larger oxidation time. 900-1200C needed. Dry oxidation needs higher activation energy leading slower oxide growth, maintaining higher conc of O_2 is difficult compared to water vapor.

We get faster oxidation if water vapor is used instead of oxygen used as oxidizing agent. Hydroxyl ion diffuses through oxide layer faster than oxygen. Dopant diffusion is relatively slow. 800-1200 C needed.

Local oxidation of silicon (LOCOS)

It is a semiconductor fabrication technique used to create isolated regions of silicon dioxide (SiO_2) on a silicon wafer. Polished wafer is with oxide mask in high temp oxidation process. horizontal and vertical growth causes birds peak at edge.

Merit→ Electrical Isolation, Lower step, and side well height.

Demerit→Bird's beak, stress induced defect, rough topology

Doping

[1] Diffusion

Introducing dopant atoms into the semiconductor by **exposing the material to a high-temperature environment with a dopant source via hard mask**. Dopant atoms migrate through the crystal lattice of the semiconductor material until they reach a state of thermal equilibrium.

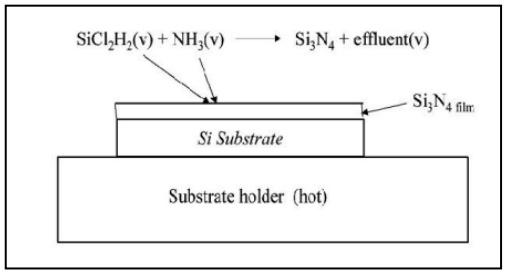
Diffusion relies on the **intrinsic diffusion properties of dopant atoms** in the semiconductor material. We adjust **time and temperature to get less precise control. No sharp or well-defined as profiles created by ion implantation**. Mostly an **Isotropic dopant profile**. **Batch process.**

[2] Ion Implantation

Acceleration of dopant ions to high energies and directing these ions onto the surface of the semiconductor material. It can be done at **Low temperature with photoresist mask.** The ions penetrate the material and come to rest at specific depths, forming a dopant distribution profile. Ion implantation allows **precise control over the depth of dopant penetration** into the semiconductor. **The energy and angle at which the ions are implanted** can be adjusted to control the depth of the dopant profile and ion dose. Its **well-suited for selectively doping specific regions of a semiconductor wafer without affecting neighboring areas**. Atomic and nuclear research. **Anisotropic dopant profile. Batch and single process.**

Annealing

After Diffusion or Ion implant, wafer undergoes a high-temperature annealing process to activate the dopants, modify electrical properties, remove vacancies and repair crystal lattice damage caused by the ion bombardment. It’s a heat treatment process.



Deposition Techniques

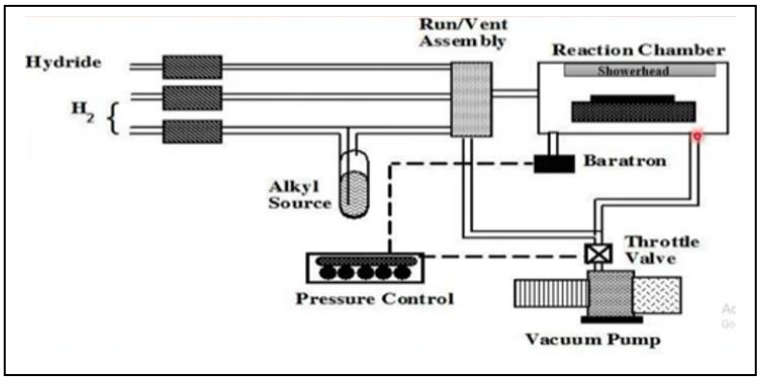
Chemical vapor Deposition

A widely used technique in materials science and semiconductor manufacturing for depositing thin films of materials onto non-volatile (not vaporized) substrates.

Precursor gas (carrier gas + reactive gas) contains thin film deposit material, surface with good adhesion property, vacuum controlled environment. Process parameters are **Temperature, Pressure, Gas Flow rate, deposition time, Substrate Material**.

Via controlled flow rate, thin layer forms on substrate. Reactant and carrier gas control reaction kinetics. Chemical reaction involves Thermal CVD (heating to achieve activation energy), Plasma enhanced CVD (plasma to enhance deposition), Low pressure CVD (Controlled pressure to dictate reaction kinetics and film quality). After reaction, byproduct flows out via gas flow, only coating remains. Substrate cooled after deposition.

Metal Organic CVD



MOCVD enhances high-quality, highly customized semiconductor materials tailored to specific device applications. Thickness control is of 1 atomic layer.

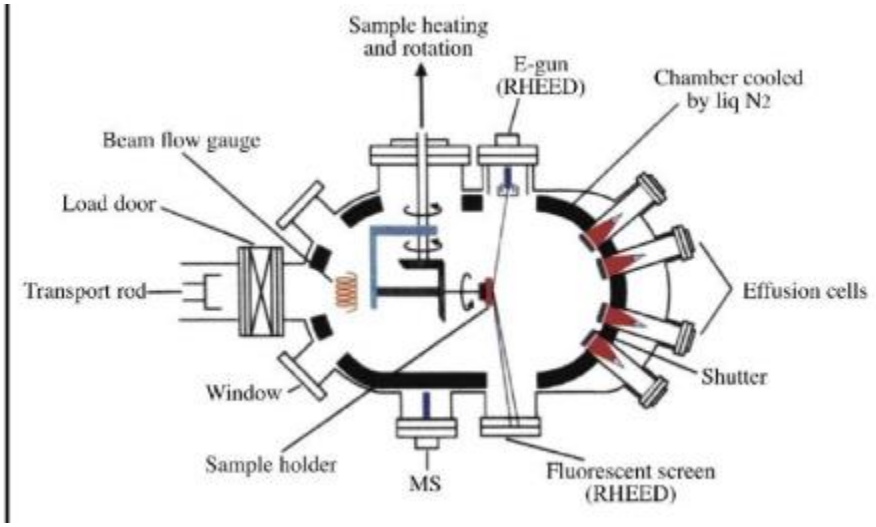
MOCVD employs metal-organic precursors, which are volatile compounds containing metal and organic elements. Substrate is semiconductor wafer as it's a low temperature process. Precursor (Group 3 metalorganics or Group-5 Hydrides) introduced to chamber via carrier gas (N2 or H2) to transport and disperse material on substrate. Substrate heated by rotating susceptor.

Chemical reaction under heat causes dissociation of compound and deposition of material. Layer-wise thin film growth gets possible with precise control over thickness and composition. Crystal structure and doping level can also be controlled. After growth substrate is cooled

Its used in LED, optoelectronic devices, Solar cell, Optical communication system.

Molecular Beam Epitaxy (2018-19 7b 2020-21 5a)

Molecular as molecules are involved instead of atom, Beam related to beam of atom, Epitaxy is orderly arrangement of molecule. A high-vacuum chamber for minimized contamination and interference during epitaxial growth. Multiple effusion cells or electron beam evaporators containing solid source material. These sources are heated to produce a vapor of the source material. Substrate (Single Crystal Semiconductor wafer) acts as **growth surface**.



Knudsen Effusion cell or electron beam evaporator contains material that would be evaporated and deposited into substrate. We get high purity as effusion cell vaporizes and condenses over substrate and multiple effusion cell input such as Ga and As near substrate react near substrate and forms GaAs crystal on substrate. Gaseous element may be adsorbed or desorbed or reflected. Temperature is precisely controlled to regulate vapor flux. **Substrate temperature, source flux rates, and growth rate controls composition and thickness**. It allows precise growth of multilayer structures. Deposition rate α Vacuum. **No carrier gas needed**.

[1] Low deposition rate

[2] Better vacuum

[3] Higher Substrate Temperature

[4] Directed atomic beam (Effusion cell)—interaction near substrate only.

The molecular beams are directed at the substrate surface. During the epitaxial growth process, the atoms or molecules from the molecular beams adsorb onto the substrate's crystal lattice and form a crystalline layer. This growth occurs layer by layer, with atomic or molecular precision. RHEED (**Reflection High Energy Electron Diffraction**) used to monitor growth rate, quality, composition, structure, characterize flux ratio, monitor surface temperature. Electrons interfere constructively and destructively based on parameter of crystal. Cryopump or cryo-panel act as sink for impurity in vacuum chamber while cooling.

Application-- HEMT, Quantum well, Superlattice.

Bonding & Packaging

Die Bonding, Wire Bonding (ball or wedge bonding), Package pin and leads.

Physical protection (encapsulation, protective shell from dust, moisture), Environmental protection, Heat Dissipation.

Cleanroom (2018-19 8a)

Contamination in a clean room can adversely affect product quality, yield, and safety.

Contaminants (PMC BAMC)

1. Particles (dust, dirt, skin flakes, clothing fiber) 2. Metallic ions 3. Chemicals (cleaning agent, Residue) 4. Bacteria-Microorganism (Bacteria, Virus, Fungi) 5. Cross-Contamination (contamination due to movement from one stage to other) 6. Airborne molecular contaminants (AMCs)

Source: (8a)

1. Air 2. The production facility 3. Cleanroom personnel

4. Process water 5. Process chemicals 6. Process gases

7. Static charge

--Air filtration system, Maintenance, Training, Hygiene protocol

Resolution (2018-19 5a)

Resolution refers to how closely two distinct points or objects can be positioned while remaining distinguishable in the resulting image. Shorter wavelength refers to greater resolving power. Resolution defines the smallest resolvable distance or feature size that can be observed and distinguished as separate entities. it determines the microscope's ability to reveal fine structural details and provide valuable insights into the composition, organization, and behavior of specimens at various length scales, from the macroscopic to the nanoscale.

Lateral Resolution refers to the ability to distinguish two adjacent points or features in the horizontal plane. Axia resolution pertains to the ability to distinguish objects or details along the optical axis of the microscope.

Abbe Criterion-- the smallest resolvable distance between two points is half the wavelength of the light used.

Rayleigh criterion: if two points are placed close enough, the closest distance at which they appear to be separated in image is:

d = 0.61*lembda/N.A.

Numerical aperture, N.A. = n.sin(theta), n is refractive index of the medium and theta is the semi-andular aperture of the lens.

Electron Microscopy

Basics: an electron when goes through a pot. diff. of V volts, it acquires kinetic energy of $1/2mv^2 = qV \Rightarrow v = \sqrt{[2qV/m]}$ and since $\lambda = h/mv$ (de Broglie), we have $\lambda = \sqrt{[h^2/2mqV]}$. From here we can derive, $\lambda = 1.23/\sqrt{V + 10^{-6}V^2}$

In electron microscopes the wave nature of the electron is used. Here electrons are used as source of illumination and the lenses are EM lenses. Electron microscopes use electron beams, which have much shorter wavelengths. The wavelength of electrons is inversely proportional to their momentum (de Broglie wavelength). Electron microscopes typically use electron energies in the range of a few kiloelectronvolts (keV) to hundreds of kiloelectronvolts (keV). This results in electron wavelengths that are much smaller than the wavelengths of visible light.

2020-21 2a

$V = 100\,kV$, $\lambda = \frac{1.23}{\sqrt{V^2 + 10^{-6} V^2}} = \frac{1.23}{\sqrt{10^5 + 10^{-6} \times 10^{10}}} = 38.896\ nm$.

$\frac{1}{2} m v^2 = eV$.

$\Rightarrow v = \sqrt{\frac{2eV}{m}} = \cancel{187.5}\ 1.8752 \times 10^8\ ms^{-1}$.

SEM

Secondary electron microscope

Electron microscope that's used for imaging surface morphology samples at high resolution

a) Electron gun
b) Electron lenses
c) Scan coil
d) Electron Detector

SEM operates by scanning a focused beam of high energy e⁻ across surface of specimen and produces image by detecting secondary e⁻ from surface samples.

i) Electron Beam Generation - here we have focused high energy electron. e⁻ beam accelerated and focused by lens to form probe (W, LaB_6 - high temp)

ii) Sample Preparation - It's coated with thin conductive material to enhance conductivity and reduce charging effect

iii) Scanning & Imaging - Focused e⁻ beam is scanned across surface in systematic pattern. e⁻ beam interacts with sample and secondary & back scattered e⁻ emitted.

iv) Secondary e- emission

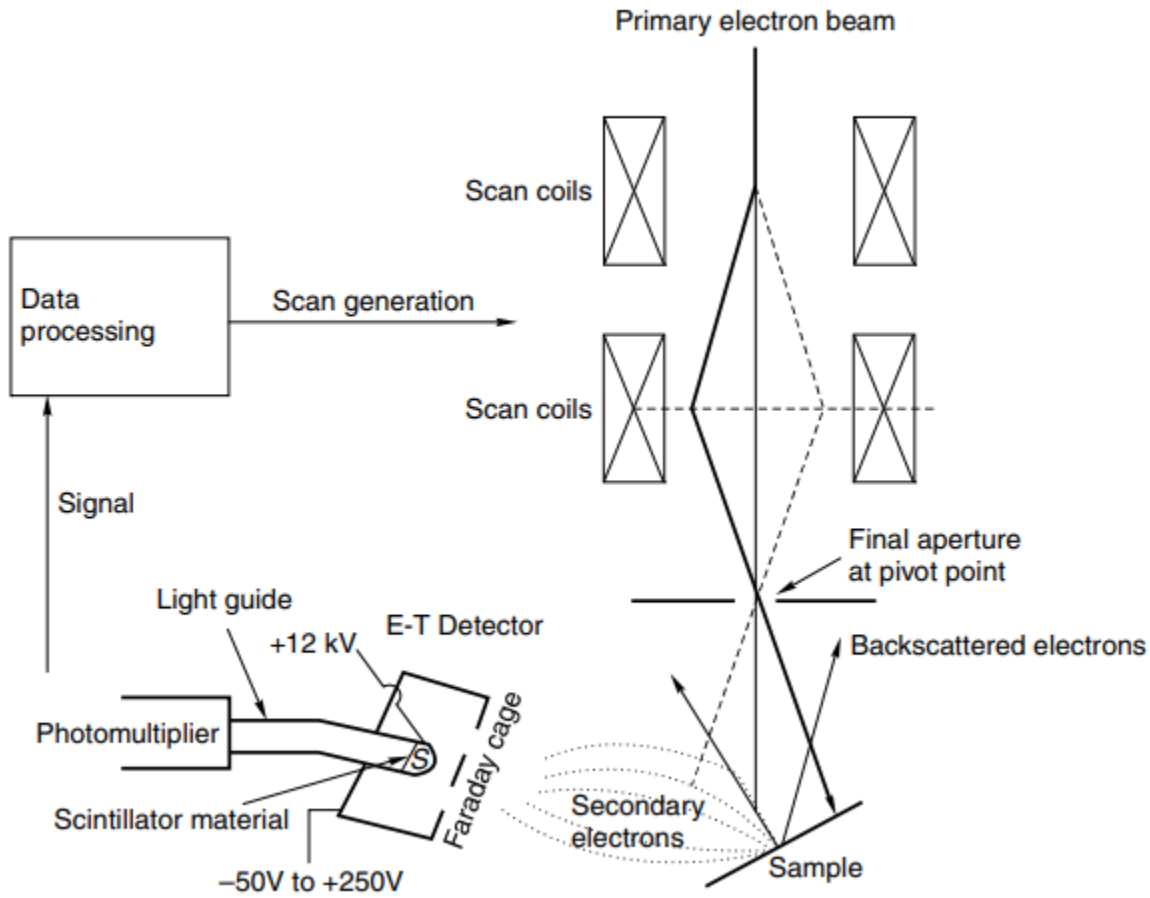
When high energy e- strikes sample surface, it can dislodge e- from atom in sample. The number and energy distribution of secondary e- influenced by tomography and composition of sample surface.

v) Image formation

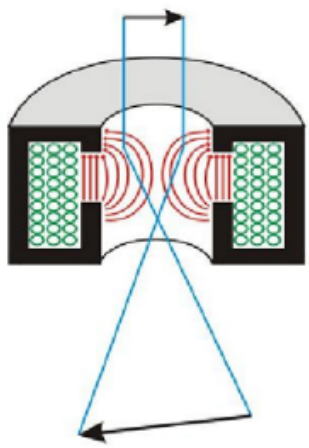
Detector collects secondary e- from surface and creates image. Brighter zone where more secondary e- are emitted. ~~and~~ indicating variation in surface height & composition

vi) 3D Information

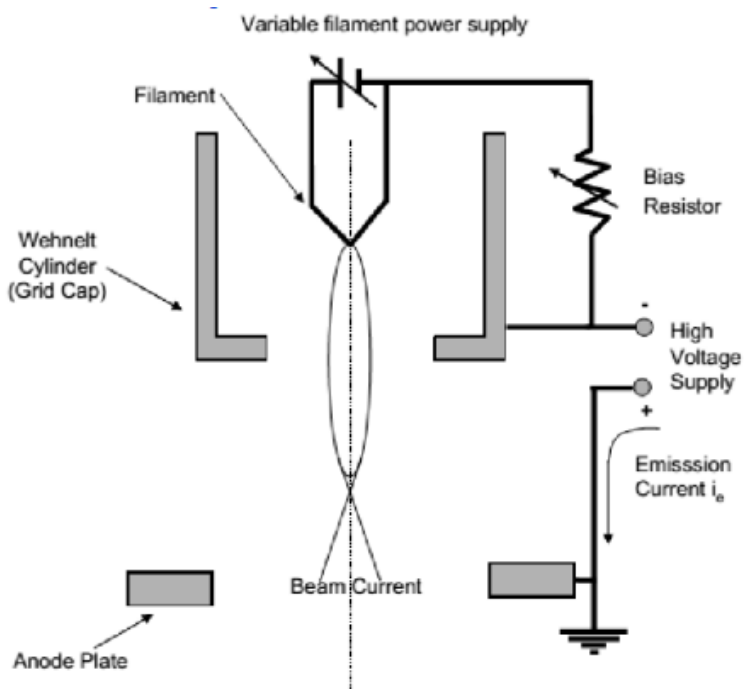
3D info like surface roughness, crack, particle and more features are visualized



We use vacuum column so that electron don't deviate from actual path.



Electron lens



Electron Lens

It consists of a **coil of wire** generating a magnetic field enclosed in an iron casing. A magnetic field is generated between the polepieces by applying a current through the coils. The electron in a magnetic field undergoes rotation. It **focuses electron beam to sample.**

The electron leaves the lens without any net change in the angular momentum. An electron travelling off-axis to the beam path will spiral through the lens towards the optic axis. The point from which the beam starts bending to the point where it crosses the lens axis is called the focal length.

Due to the hysteresis of iron, the extent of current used to energize a magnetic **lens cannot be used** to get the lens characteristics such as focal length. The focal length of the lens is directly proportional to the accelerating voltage. So **the image quality is affected by varying the electron velocity.**

lens aberration, **spherical aberration (electron far from trajectories are bent more strongly), chromatic aberration (due to different wavelength of light), aperture diffraction (wave nature of electron lets it diffract in narrow slit) , astigmatism (due to improper shape of surface)** are main challenges of lens.

Electron Gun

Tungsten Filament, Field emission gun where electron is accelerated to high energy. The confined beam is accelerated to the anode held at the ground potential and a portion of the beam is passed through a hole. The beam current measured at the anode is used to regulate the power supply which drives the electron gun for the desired current. **LaB6 has greater brightness and a longer lifetime as compared to tungsten.**

SFEs are operated at high temperatures. They are self-cleaning and their tips sharpen in the extraction field. In SFEs, the field at the tip is used to reduce the work function barrier.

Scan Coil

In SEM, **the scanned image is formed point by point and the scan is achieved by the scan coils.** There are two pairs of coils, one each for the X and Y axes. The scan coils lie within the column and move the electron beam as per the requirement across the specimen. **It lets electron beam to rotate via rotating lens**. They are **electromagnetic coils and are energized by the scan generator.** The scan generator is connected to other components such as **the cathode ray tube (CRT) and the magnification module.**

Electron Detector

There are two kinds of electrons coming out from the sample in an SEM; the backscattered electrons, with high energies being larger or lower than the primary beam energy, and the secondary electrons which have energies of a few eV, or less than a few tens of eV. The electrons can be made to undergo a series of **collisions on surfaces producing a cascade of electrons and a gain of 10^6** can be achieved this way. The detector has a high bandwidth, which means it responds to a rapidly varying signal. **The number of secondary electron depends on amount of atom present there and thus providing a topological explanation**.

Black → Absence of atom

Grey → Presence of atom

White→ High number of atoms.

Thus we can construct atomic topology of surface

TEM

Transmission Electron Microscope (TEM)

TEM operates on principle of transmitting e- through thin specimen and capturing e- to form high resolution image

a) Electron source - Tungsten (W) filament, field emission gun
e- accelerated to high energy

b) Electron lens - It's used for focus and shape e- beam

c) Specimen preparation - thin (~ 100 nm) to allow e- to pass

d) TEM column - It consists of multiple lens, aperture to precisely control and direct e- beam to specimen

e) Sample stage - specified sample holder that's tilted / rotated from different angle

f) Electron transmission & interaction
when e- passes it interacts with atom & e- causing elastic & inelastic scattering.

g) Image formation
Detector captures transmitted e- on opposite side and provide info about ~~the~~ variation in thickness and density. (Bright & Dark zone)

h) Image processing

e- gun → condenser aperture → Fixed aperture → condenser aperture 2 → sample holder → objective aperture → Selected area aperture → DCD camera → Viewing screen

Bright Field Image → thickness & density.

Dark Field Image → emphasize e- with diffracted e-

Reveals internal structure. Magnify about $3*10^5$ times.

Electron Gun → Releases electron

Condenser lens → focus and illuminate electron on specimen/ sample.

Condenser aperture→It allows beam flow in one direction only.

Objective lens→ 1st image of specimen.

Objective area aperture→ don't let electron beam to deflect much.

Magnifying Glass → Intermediate lens (focused to send to screen/ photographic plate), Projector lens (final lens before screen), magnifies and focus image.

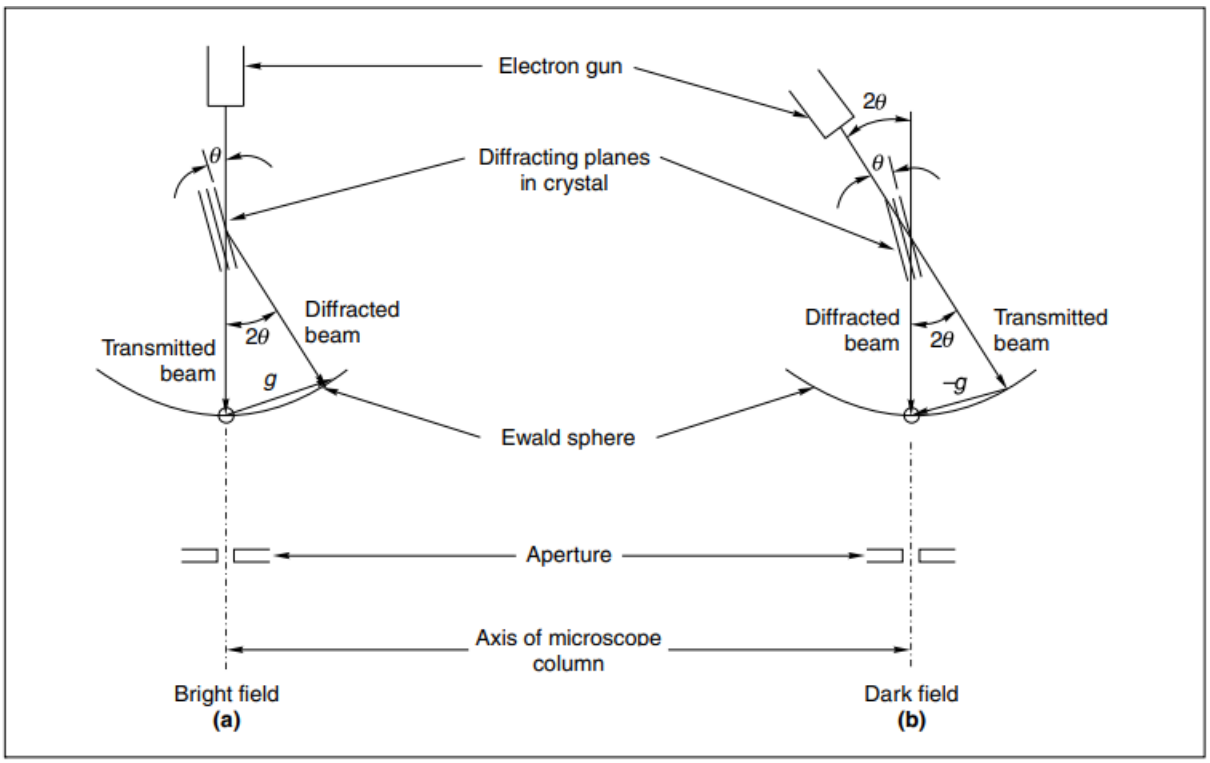


Fig. 2.8: *Two kinds of image collection: (a) bright field, and (b) dark field. In bright field, the transmitted beam is used for imaging. In dark field, the diffracted beam is used for imaging. The diffracted beam can be used for imaging either by using a movable aperture or by shifting the incident beam, keeping the aperture constant. Adapted from Thomas and Goringe, 1979 (Ref. 2).*

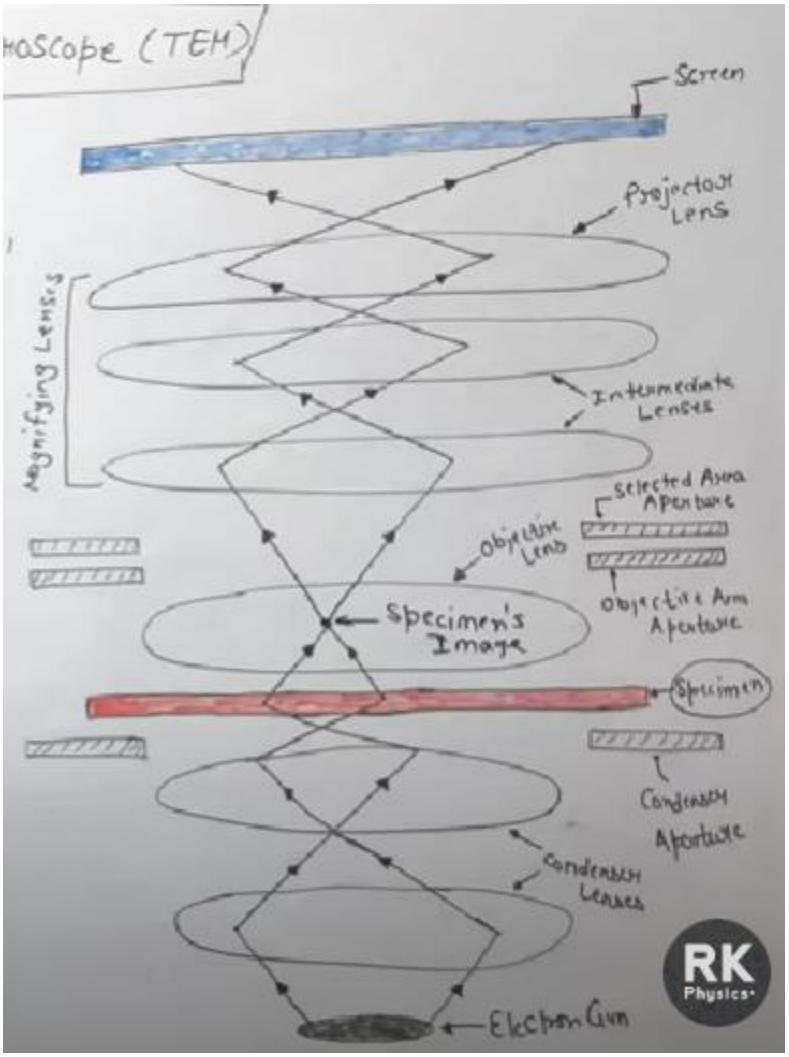
Principle of TEM is mass thickness or mass density.

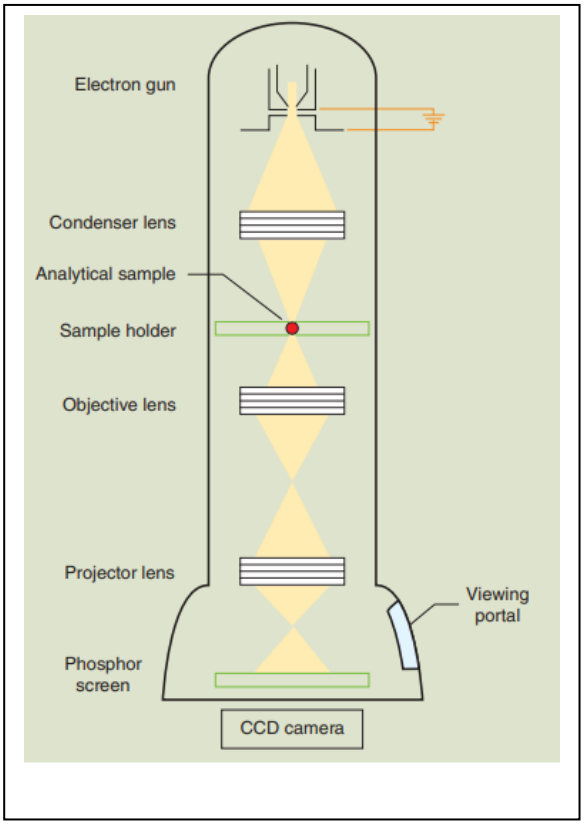
White → Higher mass thickness, atom in specimen is high

Grey → moderate mass thickness

Black→ Lowest mass thickness

Solid metal layering across sample with ability to scatter electron don't let beam to transmit. We get image via elastic and nonelastic scattering.





2020-21 2b

Why TEM>SEM?

[1] Internal Structure for better analysis vs Surface topology only

[2] Transmitted and diffracted beam both are used to get bright field and dark field image where secondary electron is used for imaging.

[3] Design or structure of lenses allow little diffraction and aberration compared to SEM

[4] We get thickness from bright field and internal interaction via dark field but only contrast due to surface topology is seen.

[5] We can also find shape of molecules via sampling method where SEM can't do that.

[6] high resolution imaging capability compared to SEM.

2020-21 2b

TEM improves optical resolution-

[1] Wave nature of electron

[2] Condenser, Objective and Aperture lens

[3] Contrast and Sampling Mechanism

STEM – SEM+TEM

STEM

SEM (Scanning electron microscopy) + ~~TEM (Tran~~

+

TEM (Transmission " ")

a) Electron beam.

b) Sample Interaction (like TEM, Tx e^-, scatter e^-, secondary e^-)

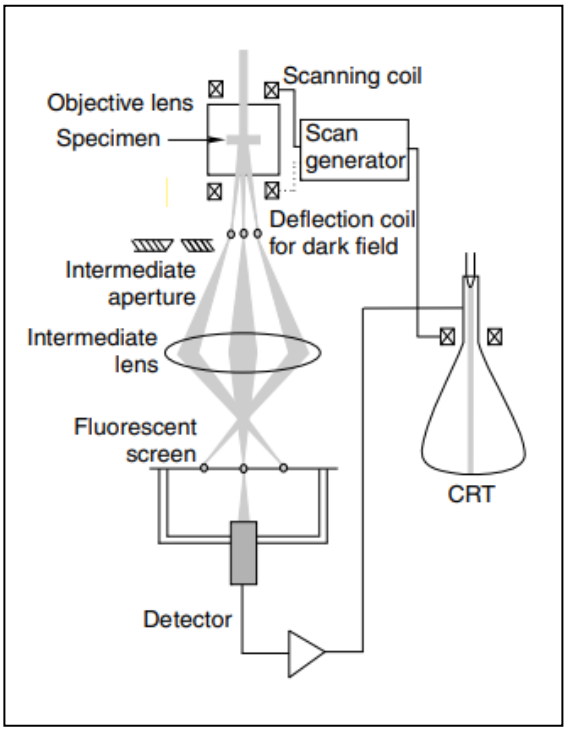
c) Image Formation (e^- pass through specimen & interaction creates image)

d) Scanning – (e^- probe to scan surface to get detailed image

SEM → high resolution image + electrical analysis.

TEM → investigate thicker section

STEM is a hybrid instrument with the features of both SEM and TEM. The electron beam is focused into a fine probe and scanned across the specimen, point by point. As the probe scans the specimen, various signals are collected, including transmitted electrons (bright-field STEM), backscattered electrons (dark-field STEM), and signals resulting from electron energy loss (EELS) or other interactions. These signals are used to form images and gather spectroscopic information about the specimen's composition, structure, and properties.



[1] High spectral Resolution

[2] Bright field STEM (Tx electron, thickness), Dark field STEM (backscattered or diffracted electron, caries with atomic number), High angle annular dark field STEM (for electron scattered at high angle)

[3] Elemental mapping (Energy loss and spatial distribution of atom)

[4] Tomography (3D Image)

Scanning Probe Microscopy (Tip→2020-21 1b)

The probe tip of a scanning probe microscope is important to the feature-resolving ability of atomic force and scanning tunneling microscopes. The probe is usually made of **silicon or Si_3N_4 for AFM and tungsten for STM**. In both cases, the probe is **sharpened to a fine tip**. Atomic probe methods rely on sharpened probes that are positioned as close to a sample surface as possible.

Piezoelectric devices are made of dielectric components that can convert mechanical stresses (e.g., sound waves) into electrical signals and vice versa. Common piezoelectric materials include quartz, various ceramics, and Rochelle salt. Electromechanical piezoelectric ceramic transducers are responsible for creating the mechanical motion required to scan AFM and STM specimens. Motion, or change in geometric shape, depends on the type of crystal, its shape, and the strength of the applied electric field.

Scanning Probe microscope makes 3D image.

STM (2018-19 5b, 2020-21 3a)

Applicable for conducting Sample. Lateral or horizontal resolution 0.1nm, vertical resolution 0.01nm.

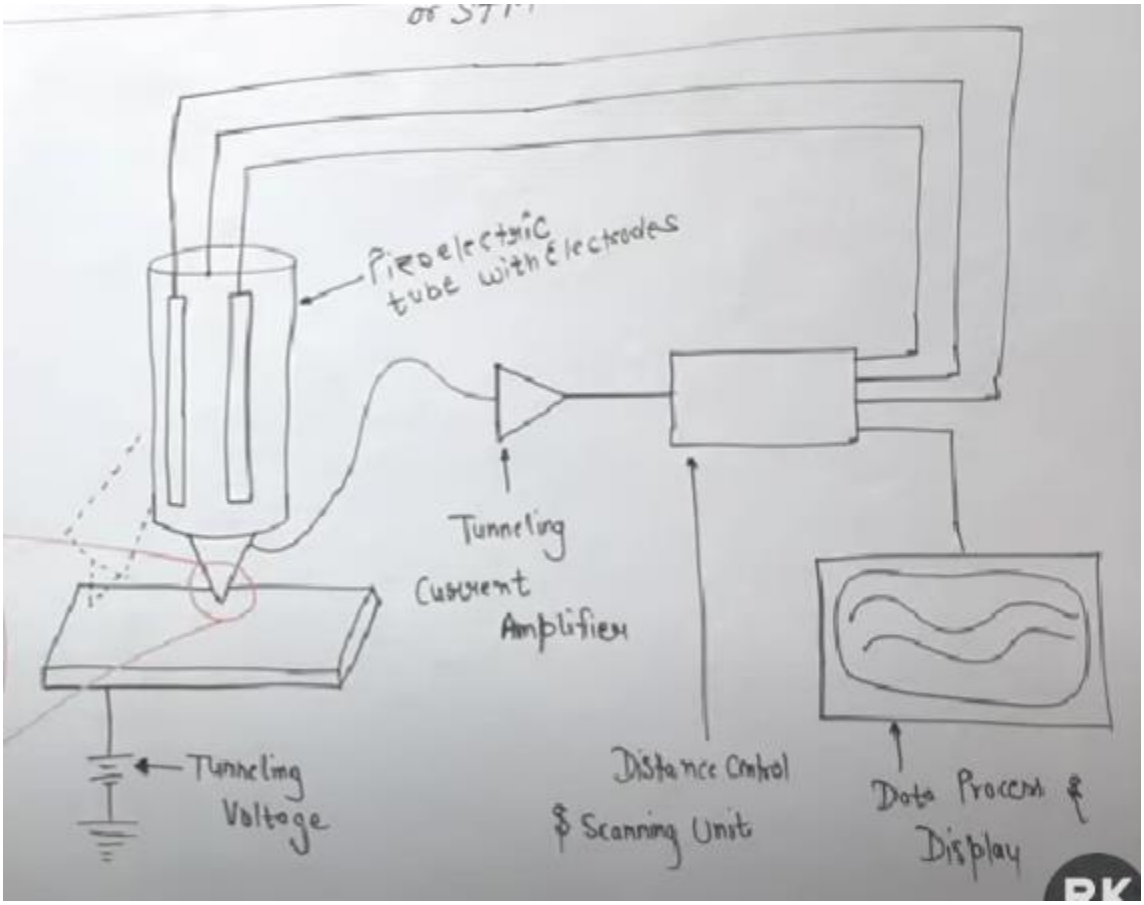
[1] Scanning Tip—W ot Pt-Ir made.

[2] Piezoelectric Tube – 2 electrodes

[3] Sample and Tunnelling Voltage

[4] Tunnelling Current Amplifier

[5] Scanning Unit & Monitor



Tunnelling → At motion, matter wave induced in particle. Wave character induced in particle in quantum mechanics.

Tunnelling Voltage is the voltage between scanning tip and sample. Due to wave character, the tunnelling voltage pushes electron to tip causing tunnelling current.

$$I \alpha V e^{-\sqrt{(8m\varphi)/h}\,2d};$$

Phi – local Tunnelling Barrier height or avg. work function

d – distance between tip and sample

If distance rises, then tunnelling current lowers exponentially.

For upper current, distance is reduced. So via const height or const current will give proper surface topography of sample.

[1] Const Height mode—height fixed, Tunnelling current varies.

[2] Const Current mode—Tunnelling current constant, height changed.

STM relies on an electronic signal to relay information about a sample—the strength of a tunneling current potential that exists between the probe tip and the substrate surface. Small changes in the distance between the probe tip and the substrate surface translate into large changes in the tunneling current. By this phenomenon, atomic scale resolution by STM is possible in the x, y, and z direction.

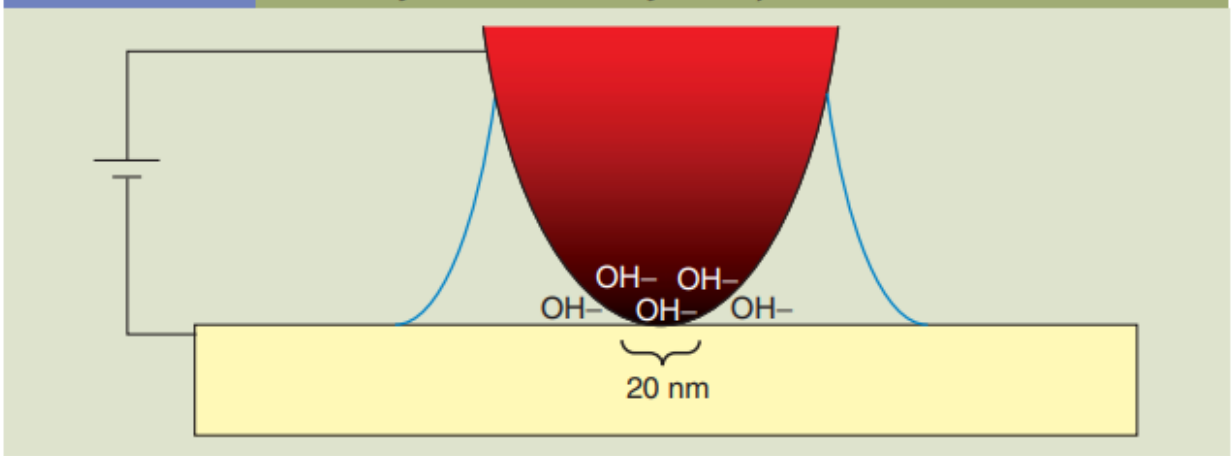
2020-21 1c

AFM tip to Au thin film, it works on molecules dissolved solution.Direct writing pattern in nanoscale. It allows printing on soft and hard material, 30nm resolution.Molecules transfer via capillary process

Challenges-- dynamic problem aries, Gold use in mica is a weak substrate, resolution dependent on grain size and surface, low speed

Merits→ high resolution pattern, nanoscale surface, repeated pattern possible, biomolecular application

FIG. 3.18 *Dip-pen nanolithography is a process that is capable of writing at the nanoscale. It involves a metal probe surrounded by a meniscus of water (capillary action at the nanoscale) that contains chemical species. Depending on the makeup of the solution, alterations to the sample surface are accomplished via specific and controlled chemical reaction: oxidation of a silicon surface by hydroxyl groups or, if the solution contains alkane thiols, self-assembly to form monolayers on a gold surface. In either case, the surface is altered to form a pattern.*



STM,

Scanning Tunnelling Microscopy - atomic scale resolution

It enables to visualize & manipulate atom & molecule on surface of material.

a) Principle of Tunneling -
metallic tip brought close to conducting surface, e- tunnel through small gap between tip and surface

b) Tip & sample
metallic tip mounted on piezoelectric element.
conductive sample beneath tip, ultra-high vacuum to avoid interference

c) Feedback loop -
When tip approaches sample, e- starts tunnelling & tunnelling current flows.. and feedback loop revises current /height to create pattern.

d) Scanning -
STM scans tip across surface to create topographic map of surface.

merits -

a) high resolution
b) surface analysis (topography, electronic property, defect).
c) Manipulation
d) Material Characterization
e) Catalysis
d) Surface Chemistry.

→ metal probe consist of 3 piezoelectric element.
↳ change dimension due to applied voltage

P_x, P_y → to scan.
P_z → control height of probe

→ atomic ~~so~~ scale → 3Å (scan).
resolution > 45Å

→ Resolution gets limited by radius of probe.

AFM (2020-21 4b)

AFM, (Atomic Force Microscopy)

Study mechanical, electrical & chemical property of material at nanoscale, surface topography

a) Probe & Cantilever (nm).

b) Sample surface

c) When probe is close to sample surface, interaction like van der waals, electrostatic, magnetostatic & chemical force ~~comes~~ occurs. and causes cantilever deflection. This deflection is sensitive to distance between ~~probe~~ surface & tip.

d) Deflection monitored and a feedback system adjusts vertical position to maintain constant cantilever deflection / force

A piezoelectric actuator controls. height

AFM can also maintains constant height as tip scans across surface.

e) Tip scans surface to maintain desired interaction or constant distance & variation in tip produces ~~tomogra~~ topographic image of surface

$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{m}}$.

distance deflection 0.16 Å via Ionic Force 10^{-8} N 10nN.

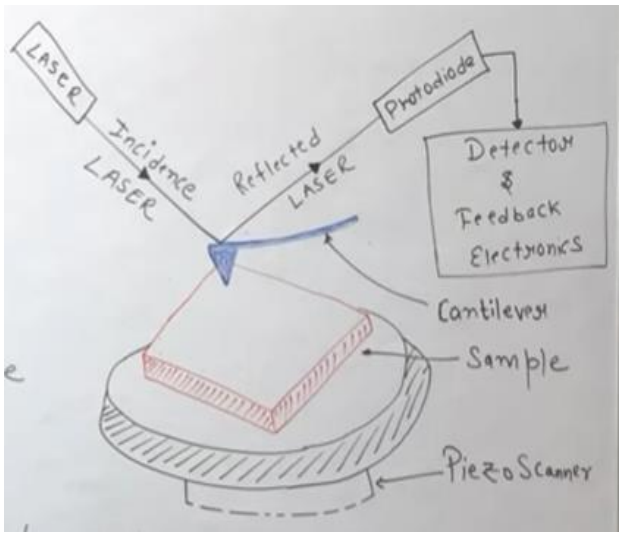
weak van der waals produces 10^{-11} ~10pN force.

Force detected by cantilever spring. & detection scheme

It can also manipulate, pulling molecule, stretching, painting

Detection, Laser → probe → photodetector – controller → pc.
(mirror, sensor, error)

probe ↑ piezoelectric scanner ↓ surface, probe tip ↓ surface



Applicable for **insulating Materials**.

Vertical resolution—1nm

Lateral/ horizontal resolution – 0.1nm

[1] **Cantilever Tip**

Detect tiny deflection-- flexible cantilever, resonant frequency of vibration for cantilever is present, 10nN (ionic) 10pN (Van Dar Waals), detectable in spring and detection scheme.

[2] **Photodiode**

Detects laser beams that's reflected by cantilever to detect minute deflection in cantilever position.

If d lowers due to surface peak, then we will get repulsion force and cantilever also goes higher. And d higher due to surface trough, then cantilever lowers. Light reflection gets modified also. Thus, we get surface topology.

nanomanipulation tool capable of individual molecules movement, stretching and painting nanoscale structure. High resonant frequency minimizes influence of building vibration like in STM the slowest response comes from piezoelectric tube.

2020-21 3b

The "weak spring" refers to the mechanical stiffness of the cantilever. In AFM, the cantilever is like a tiny spring that deflects when it interacts with the sample's surface. A weak spring means that the cantilever is relatively flexible and has a low spring constant.

The "high resonant frequency" indicates the frequency at which the cantilever oscillates when excited. A high resonant frequency means that the cantilever vibrates rapidly when excited by an external force.

For low massed flexible cantilever we can get high resonant frequency. It's desirable because a high resonant frequency allows for faster scanning and more

sensitive measurements, which are critical in achieving high-resolution AFM imaging and accurate force measurements on the nanoscale.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

- k is the spring constant (related to the stiffness of the cantilever).
- m is the mass of the cantilever.

It balances between stiffness and mass is essential for achieving optimal AFM performance.

STM vs AFM

Scanning probe

AFM preferred over STM due to capability of imaging insulating surface AFM also measures mechanical property.

Fluroscent imaging, technique - broke limit of resolution

#AFM vs STM

→ mechanical interaction between tip & surface
vs tunnelling of e- from tip to surface

→ van der waals force, electrostic force causes deflection
vs. tunneling phenomenon causes deflection, sensitive to distance between tip & sample

→ image conductive & nonconductive surface vs.
" " surface only

→ AFM has sub-nm level resolution vs.
STM has atomic scale "

→ AFM used for mechanical, electrical, magnetic property
STM used for electrical & atomic property

→ AFM can operate in any environment vs
STM " " in vaccum

2018-19 6a (laser Tweezer vs AFM cantilever)

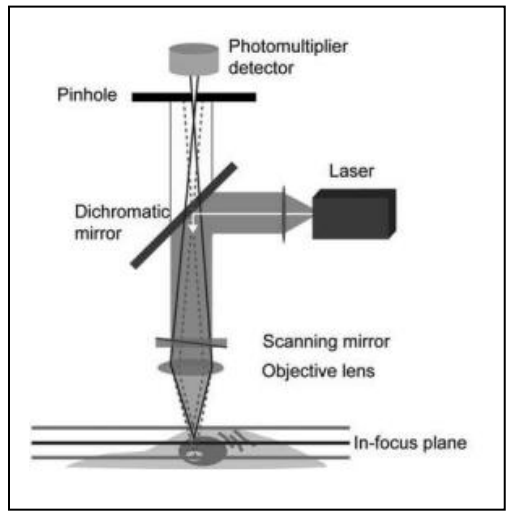
Laser tweezers and atomic force microscopy (AFM) cantilevers are two distinct techniques used for single-molecule manipulation, and they have different principles of operation and capabilities.

Laser tweezers use **focused laser beams** to trap and manipulate small particles or molecules in a solution. The laser beam generates a gradient of optical forces that can trap and move particles along the beam path. well-suited for **manipulating individual molecules,** such as DNA strands or microspheres. **highly sensitive to forces**, allowing for precise measurements of forces applied to trapped molecules.

sub-nanometer precision. **biological and biophysical research** for studies involving single-molecule mechanics, protein folding, and molecular interactions.

AFM uses a **sharp tip mounted on a flexible cantilever** to interact with a sample's surface. The **deflection of the cantilever** as it interacts with the sample provides information about the sample's topography and mechanical properties. **applied to both hard and soft materials**. capable of **measuring forces at the nanonewton** (nN) level, making them suitable for studying interactions between single molecules and probing mechanical properties. **relatively slower** compared to laser tweezers, precision depends on the design of the AFM tip and cantilever.

Confocal Microscopy

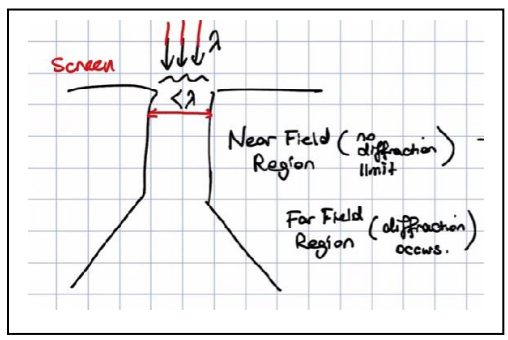


Laser Source-- focused

Pinhole filter—filters diffracted beams, cutout unwanted fluorescence

Gives 3D info via changing laser power to picture small optical plane. Combine 2D image we can get sharp detailed 3D image.

Scanning Near-Field Optical Microscopy



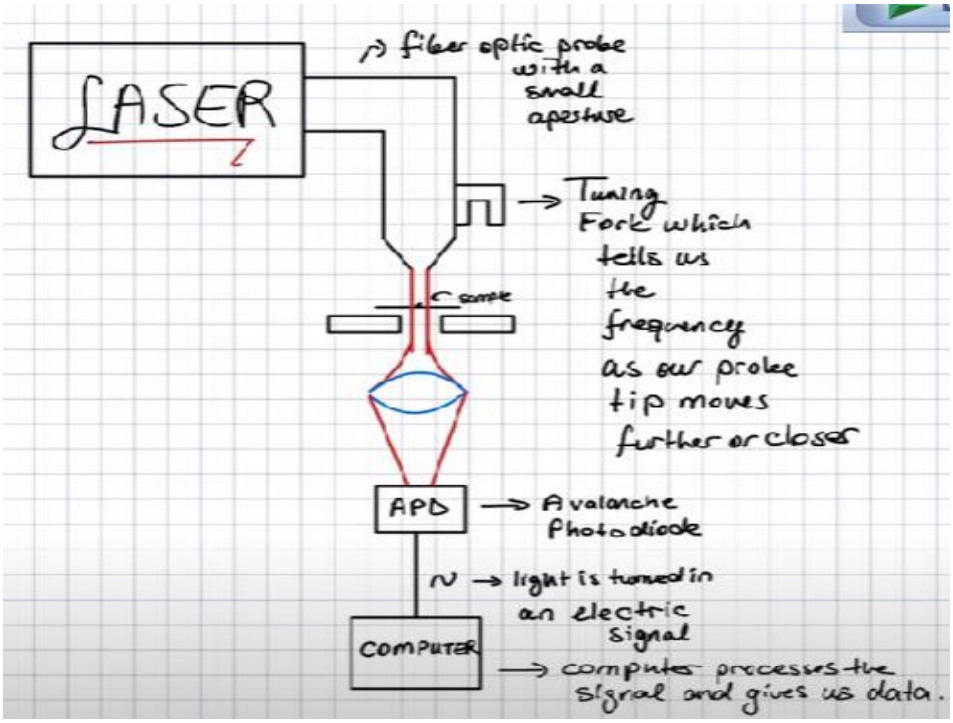
We can't size image due to diffraction of light and make it blur. Abbe and Rayleigh criterion present.

Near field region—no diffraction limit

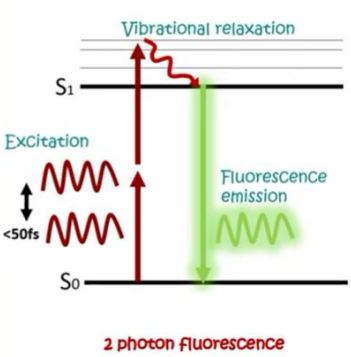
Far Field region – application of diffraction limit as near field decays exponentially.

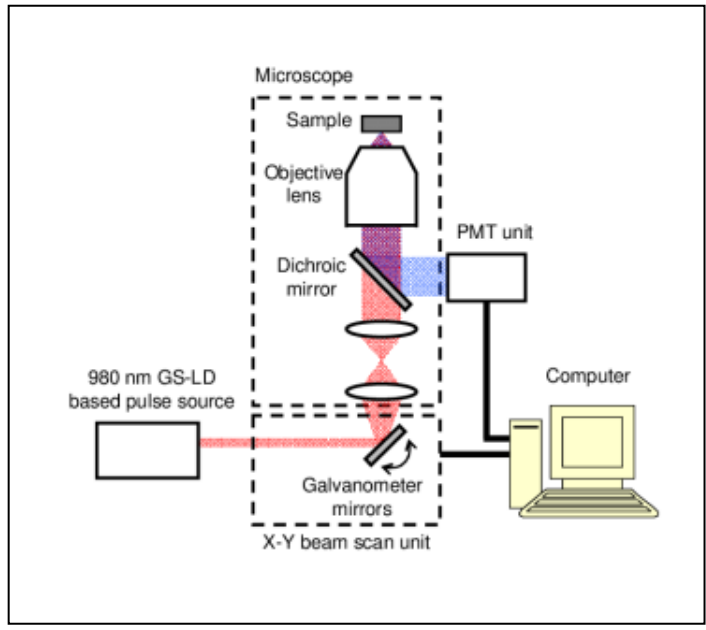
[1] Laser from fiber optics, [2] Sample before near and far field

[3] Near and Far field region built [4] Avalanche Photodiode takes optical signal to turn it into electrical signal [5] Computer process data



Two Photon Fluorescence Microscopy

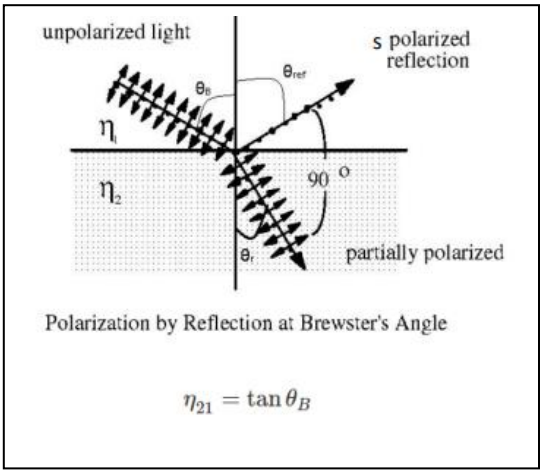




Lower energy flux is used as 2 photon utilized reducing photo bleaching or phototoxicity chance.

High wavelength results to lower scattering.

High resolution, only fluorescence level protein or spots gets coincided 2 photon together in coherence and thus point seen at focal plane while in other point photon don't get coherent. Customizable microscope, image 500um deep from surface, low scattering.



Brewster Angle Microscopy

Polarize light at certain incident light and we get polarizer light.

Electron Probe Microanalysis

Electron beam enters and interacts. Routine non-destructive analysis. 1um3 can be analyzed Backscattered, secondary electron detector present.

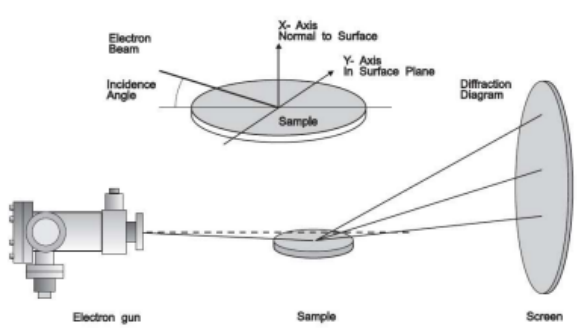
It relies on the interaction between high-energy electrons and the sample to excite and subsequently detect characteristic X-rays emitted by the sample's elements.

excited energy knock out inner shell, electron from outer shell moves to inner shell, showing interaction in reflected beam, detectors measures energy, Quantative and microscale analysis

Field Emission Electron Microscope

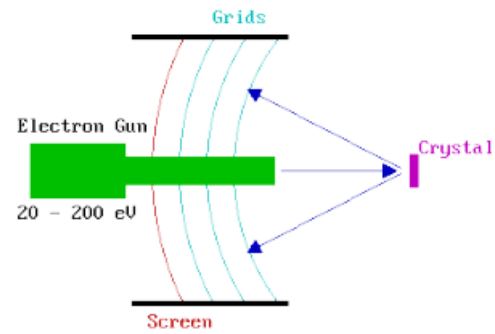
Demonstrate quantum mechanical effect in metal. It shows crystal structure of tungsten needle tip. High vacuum present, 10KV applied. Electron continuously emitted and impact on ZnS plate. 500k magnification, arrangement of atom is seen. High density electron tunnel and cause change in work function and we get imagery

Reflection High Energy Electron Diffraction

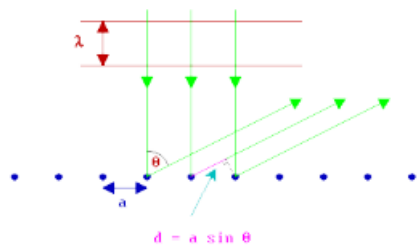


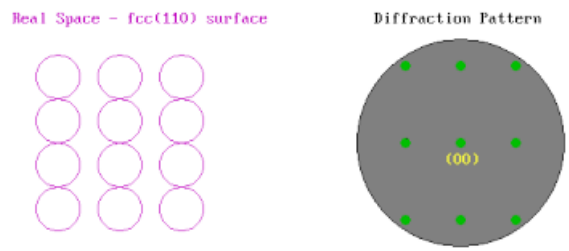
RHEED uses an electron gun to send high-energy electrons(10-100 KeV) at a grazing incidence to the substrate. After undergoing diffraction, the electrons interfere constructively at specific angles according to the crystal structure and spacing of the atoms at the sample surface and the wavelength of the incident electrons. A fraction of these electrons collide with a phosphorescent detector, creating specific diffraction patterns according to the surface features of the sample. The surface configuration and kinetics can be inferred by analysis of the diffraction patterns.

Low Energy Electron Diffraction



- The LEED experiment uses a beam of electrons of a well-defined low energy (typically in the range 20 - 200 eV) incident normally on the sample. The sample itself must be a single crystal with a well-ordered surface structure in order to generate a back-scattered electron diffraction pattern.





Lateral Force Microscopy

Works like AFM. Insight on adhesion force and insight of surface. Analyzes lateral forces. Measures friction, adhesion, lateral interaction.

Chemical Force Microscopy

Functionalized tip to interact with sample. AFM setup, Si3N4 tip plated with gold when a functional group is added, Tip interacts due to chemical bond formation with sample. Frictional force is measured and used to measure bond strength. Adhesion force is present between tip and sample to map chemical distribution of sample.

Scanning environment can impact result as water vapor forms in meniscus, minimization of vapor or vacuum environment is required, capillary force doesn't hamper much and doesn't cause much issues in liquid.

Magnetic Force Microscopy

Scan for magnetic property to map for long range magnetic force. Magnetized cantilever deflected due to magnetization of tip.

Scanning Tunneling Spectroscopy

like STM but It provides insights into the electronic structure and energy levels of materials at the same scale.

Atomic Probe Tomography

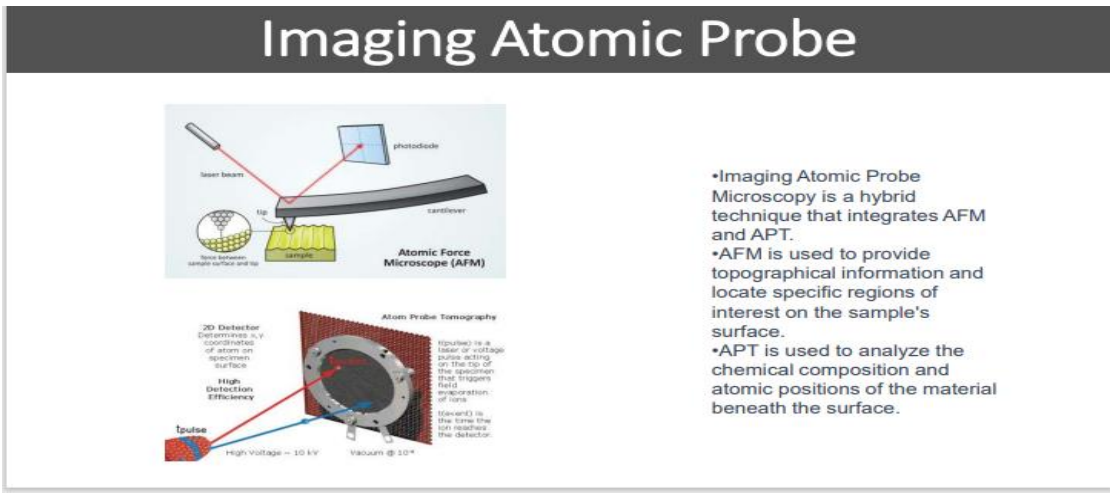
3D Imaging and composition measurement, Tip 20-100nm, Freezing system and biased at high voltage and field induced and laser and high voltage pulsing, 1 atom from tip strike surface and find ion impact position and flight time. We get 3D reconstruction of sample.

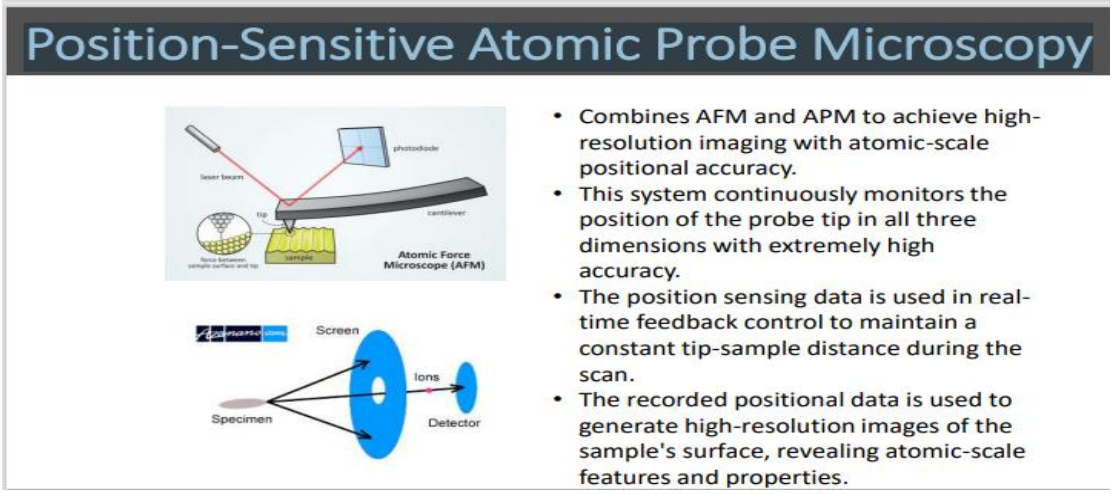
Field Ion Microscopy

Vacuum chamber, detector with single atom sensitivity, Freezing system, High voltage generator, Inert gas, Sample

High electrical field created, and atoms are polarized and strikes detector.

we get atom, crystallographic pole in image of detector.





Secondary Ion-Mass Spectroscopy

In SIMS, a primary ion beam (typically composed of cesium ions or other heavy ions) is directed onto the sample's surface. This ion bombardment causes sputtering, leading to the emission of secondary ions from the sample's surface.

The secondary ions are extracted, mass-analyzed, and detected to determine their mass-to-charge ratio (m/z) and intensity.

Elemental Analysis (determination of trace elements and isotopic ratios)

Depth Profiling: It is valuable for depth profiling to investigate layered structures, thin films, and interfaces in materials science.

Isotope Ratio Analysis: capable of high-precision isotope ratio measurements

Surface Characterization: It can provide surface information, including chemical composition and molecular identification

Demerits: [1]SIMS can introduce surface damage, chemical change

[2]Proper calibration and normalization procedures are required

Rutherford backscattering spectrometry

alpha particle deflected via nucleus. energized atom hit (elastic) and reflected and no energy lost. We measure angle of reflection to find out material.

Non-destructive, elemental composition and depth profiling is done.

Nuclear Reaction analysis

nuclear spectroscopy to obtain concentration and depth of distribution. Ion with energy penetrates surface and loses energy via interaction. Ion goes to nuclear reaction with film's atom. Then we can find energy distribution of reaction products and depth of distribution.

Casimir Force (2018-19 4e)

Casimir Force:

It's a quantum mechanical phenomenon that arises from interaction of 2 closely spaced parallel conductive or dielectric surface in vaccum or medium.

- certain mode of vibration allowed or fit in cavity
  this lowers zero point energy density.
- vaccum fluctuation
  Empty space filled with virtual particle & electromagnetic field fluctuation. It leads of particle-antiparticle pair creation.
- Pressure Difference.
  When closely spaced surface brought in proximity, ~~emf~~ electromagnetic field gets restricted and causes pressure difference between surfaces.
- Attactive force
  pulls 2 surface together.
- $F \propto \frac{1}{d^4}$. force is dependent on shape & curvature of interacting surface.
- Temperature dependent (thermal fluctuation).

We get temporary fluctuation of dipole, quantum fluctuation leads to imbalance in pressure causing net force pushing 2 barrier closer.

Surface Tension (2020-21 2a)

Surface tension is a property of liquids that arises due to the cohesive forces between the molecules or atoms at the surface of the liquid. It's force per unit length acting in the plane of the liquid's surface, which tends to minimize the surface area of the liquid. Surface tension is the tendency of a liquid surface to contract and behave like a stretched elastic sheet, where molecules or atoms at the surface experience an inward attractive force, causing the liquid to form a rounded shape when in contact with another surface or interface.

Surface Tension

Surface Tension is a physical property that arises due to cohesive forces between molecule at surface of liquid. It's the tendency to minimize area and behave like stretched elastic membrane

Surface tension is defined as free energy required to create & extend an interface of area, A. $\gamma = \left(\frac{\partial G}{\partial A}\right)_{T,P}$

It depends on chemical interaction between surface

Fowkes-Girifalco-Good approximation

It provides way to predict surface tension by considering polar, dispersive components of intermolecular force between liquid molecules

↳ Van Der Waals force (London's dispersion force)
(γ_d) weak, temporary
($\propto$ # of molecule & polarizibility)

(γ_p)
polar → permanent dipole moment; polarity.
force

$$\gamma = \sqrt{\gamma_d^2 + \gamma_p^2}$$

$$W^{coh} = 2\gamma_1 A, \quad W^{adh} = 2\sqrt{\gamma_1\gamma_2}\, A$$

Cohension work - attractive force to hold molecule or particle in same substance
keeps liquid work done to overcome cohesive force ie is W_{coh}
Adhesion work, " " to " adhesive " is W_{adh}
" " to " " of different substance.

crucial for capillary action

Nano-application of Surface Tension:

[1] Nanoparticle Synthesis-- precise control size and shape

[2] Nano-Imprint & Lithography

[3] Nano-emulsion and encapsulation-- stabilize nano emulsion and drug delivery

[4] Self-Assembly -- SAM behavior influenced, hydrophobic or hydrophilic

[5] Wetting and Contact angle control

[6] Nano-coating-- thin film, sensor, catalyst

2018-19 8b, 2020-21 3b

Wetting means spreading of liquid over solid surface and de-wetting is withdrawal of liquid from surface.

Wetting is a phenomenon that occurs at the interface between a liquid and a solid surface when the liquid meets and spreads over the solid surface. The degree to which a liquid wet a solid surface depends on several factors, including **the nature of the liquid, the nature of the solid surface, and the interactions** between them. Wetting can be characterized by the contact angle formed at the three-phase boundary where the liquid, solid, and gas (or another liquid) meet.

The contact angle is the angle at which the liquid-vapor interface meets the solid-liquid interface and measured through liquid interface.

If the contact angle is close to 0 degrees, the liquid is said to "wet" the surface completely, spreading out over the surface with high affinity. This is known as **complete wetting or perfect wetting**.

If the contact angle is between 0 and 90 degrees, the liquid partially wets the surface, forming a droplet shape with a curved interface. This is called **partial wetting.**

If the contact angle is 90 degrees, the liquid neither wets nor repels the surface, resulting in a spherical droplet that sits on the surface without spreading or wetting. This is known **as non-wetting or non-wettable.**

If the contact angle is greater than 90 degrees, the liquid tends to bead up into a compact shape, indicating that it does not wet the surface effectively. This is referred to as **repelling or superhydrophobic behavior**.

Complete wetting is characterized by $\theta = 0$, which implies (from equation 3.20)

$$\gamma_{LV} = \gamma_{SV} - \gamma_{SL} \tag{3.21}$$

at equilibrium (out of equilibrium, this relation may not hold). The Cooper–Nuttall spreading coefficient S is

$$S = \gamma_{\tilde{S}V} - \gamma_{SL} - \gamma_{LV} \tag{3.22}$$

where $\gamma_{\tilde{S}V}$ is the interfacial tension of a dry solid. Three regimes can thus be defined:

1. $S > 0$. This corresponds to $\gamma_{\tilde{S}V} > \gamma_{SV}$, i.e. the wetted surface has a lower energy than the unwetted one. Hence wetting takes place spontaneously. The thickness h of the film is greater than monomolecular if $S \ll \gamma_{LV}$. The difference $\gamma_{\tilde{S}V} - \gamma_{SV}$ can be as much as 300 mJ/m^2 for water on metal oxides. Such systems therefore show enormous hysteresis between advancing and receding contact angles. Other sources of hysteresis include chemical and morphological inhomogeneity (contamination and roughness).
2. $S = 0$. Occurs if $\gamma_{\tilde{S}V}$ practically equals γ_{SV}, as is typically the case for organic liquids on molecular solids.
3. $S < 0$. Partial wetting. Films thinner than a certain critical value, usually ~ 1 mm, break up spontaneously into droplets (cf. Section 8.1.2).

S is the spreading coefficient.

γSL is the solid-liquid interfacial tension (energy per unit area at the solid-liquid interface). **γSV** is the solid-vapor interfacial tension (energy per unit area at the solid-vapor interface). **γLV** is the liquid-vapor interfacial tension (energy per unit area at the liquid-vapor interface).

If S>0, the spreading coefficient is positive, indicating that the liquid wets the solid surface. **The larger the positive value, the better the wetting**.

If S<0, the spreading coefficient is negative, indicating that the liquid does not wet the surface effectively and tends to bead up.

If S=0, the spreading coefficient is zero, indicating a critical wetting condition where the liquid's wetting behavior is on the verge of transitioning between wetting and non-wetting.

Dewetting, Wetting

Its due to interaction between liquid & solid surface

Wetting is the ability of liquid to spread over solid ~~liquid~~ surface.

here cohesive force > adhesive force

liquid forms thin, uniform layer on solid surface

so ~~high~~ contact angle (between liq-solid interface) $\rightarrow 0$. (<90).

Dewetting - " " > 90

- liquid droplet can't spread in solid

Wetting →

Grooved - small → Acute (<90) — Droplet spread along groove
→ Right ($=90$) - angle not affected
→ Obtuse (>90) - Droplet spreads

Ridged — small → $0°$ —
— Not too small - acute ($<90°$).

States,

(i) Wenzel State → liquid droplet fully wets rough solid surface

It confirms microscopic irregularities of surface (surface roughness)

liquid fills the gap and follows contour of surface maximizing contact. effective contact angle < intrinsic contact angle.

a) Increased contact area

b) enhanced adhesion (between liquid & solid)

c) stability (typically stable).

(ii) Cassie-Baxter state

shows how liquid interacts with rough / textured surface

~~a) Reduced~~ It doesn't wet rough surface, rather sits on top of surface. Air/gas is trapped between structure & liquid

so composite interface where liquid-air interface is in contact with solid surface

a) Reduced contact area (compared to wenzel).

b). Increased effective angle.

c) Non-wetting behaviour

d) enhanced air trapping.

Surface	Hysteresis	Contact Angle	Observation
Grooved	Small	Acute (i.e. $\theta < 90°$)	Droplet would spread along the grooves and θ would be small.
		Right (i.e. 90°)	Angle would not be affected.
		Obtuse (i.e. $\theta > 90°$)	Droplet spreads and θ would become more obtuse.
Ridged	Small	= 0°	The droplet would spread over surfaces of any kind and degree of roughness.
	Not Too Small	Acute (i.e. $\theta < 90°$)	The spreading or contraction of the droplet would be obstructed.

Capillary Force

Capillary force is the phenomenon where liquid rises through narrow tube or porus material due to surface tension, adhesion, cohesion.

→ minimize surface area.

capillary action when adhesion > cohesion.

contact angle >90 → capillary rise.
<90 → " . falls

Capillary action at nanoscale

Dominance of surface force (As surface to volume ratio high)

enhanced capillary rise.

precise control.

nanoscale lubrication

Fluid flow & transport

Energy storage, nanoporous structure

Slide example - ~~absorp~~ capillary action of carbon nanotube to absorb molten Pd.

What surface actions are important for bottom-up processes?

High surface to volume ratio, quantum nature comes to play

Quantum Confinement (characteristic size<= coherence length)

Absorption edge, adsorption peak

Unique magnetic property (r<r0, ~10snm, single domain, large susceptibility—super-paramagnetism,zero hysteresis)

[1] Chemical Bond – strength and bonding chemistry depends on substrate surface.

[2] Self-Assembly – Surface interaction like van der waals force, hydrogen bond, hydrophilic or phobic property all play role in building SAM

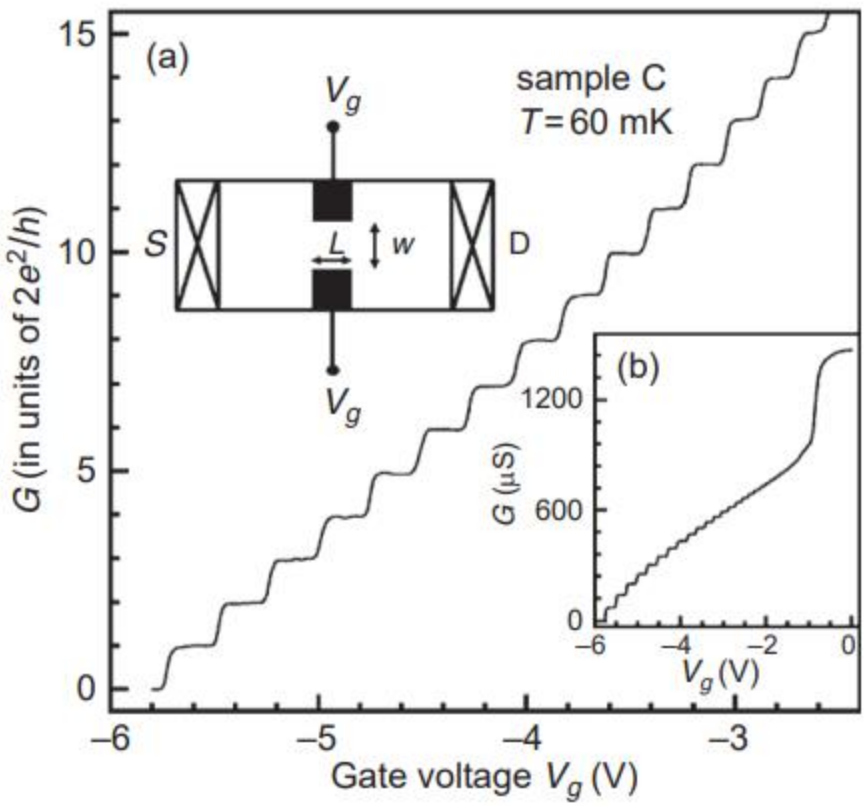
[3] Wetting – Adsorption, spreading and assembly of molecule

[4] Capillary & Meniscus Force – interaction in liquid and solid surface.

[5] Solvent Effect – Hydrophobic or philic molecule on surface

[6] Surface modification and Functionalization

[7] Nano-coating and ligand



Analyze the image

Here we get quantum conductance at split gate Quantum Point Contact. At 0 bias, 2DEG is present everywhere. At negative bias in 2 Schottky contact gate, 2DEG gets depleted from geometrical edge of gate and at narrow zone, 1DEG is formed. But 1DEG density is reduced as gate is made more negative till it vanishes between split gates.1DEG is defined by width of gate and shape of depletion zone around contact.

As gate voltage gets more negative than -0.5V, we get sudden drop in conductance due to full depletion of 2DEG under gate and formation of **QUANTUM POINT CONTACT**. Till further reduction , we get slower reduction, almost like step-like reduction caused we know quantum conductance in $2e^2/h$, all due to quantum mechanical effect.

The conductance quantization of a QPC can be understood by considering the quantum mechanics of electron transport through a narrow construction. The electrons can only pass through the constriction if their energy is greater than the energy of the highest energy mode that is supported by the constriction. As the

gate voltage is changed, the width of the constriction changes, and the energy levels of the modes supported by the constriction change. This means that only a certain number of conductance channels can be open at a given time, and the conductance of the QPC can be changed by varying the gate voltage.

phenomenon of *equipartition of current* is a unique consequence of the cancellation of energy terms in the 1D density of states and the electron group velocity (Eq. 5.8). Due to the equipartition of current, we may therefore simply write the total current flowing through the QPC as

$$I = N\frac{2e^2}{h}V_{SD}, \tag{5.9}$$

which means that the corresponding conductance is given by

$$G = \frac{I}{V_{SD}} = N\frac{2e^2}{h} \equiv NG_0. \tag{5.10}$$

In other words, at low temperatures and under conditions of ballistic transport, the linear (i.e. small signal) conductance of a QPC should be quantized in units of $2e^2/h$, which is exactly the behavior observed in experiment (Fig. 5.2).

Properties:

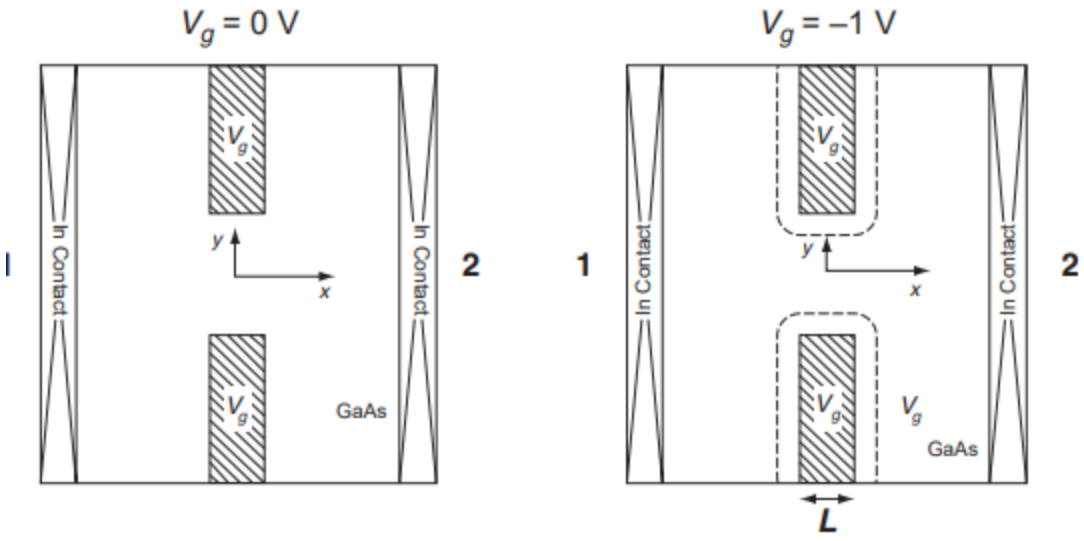
1. Narrow channel for electron flow
2. Quantum Tunable Conductance

Contrast to Metallic Contact: (Metal vs Point-Semiconductor)

High electron density, smaller electron wavelength

(vs)

Fermi wavelength comparable to structure, electron mean free path longer than QPC length, travels ballistically.


$V_g = 0$ V
$V_g = -1$ V
1
2
In Contact
In Contact
V_g
V_g
y
x
GaAs
L

Landauer Formula- Basics & Derivation

In semiconductors, charge fluctuations near the barriers may substantially affect the potential near the barriers. In spatially heterogeneous distribution of barrier in 1D potential distribution is analyzed in landauer formula.

Current $= \frac{e}{\pi\hbar}\int_{\mu_1}^{\mu_2} dET(E).$

that the energy dependence of *T(E)* is negligible, the current becomes simply

$$I = \frac{2e}{h}T(\mu_1 - \mu_2). \tag{3.31}$$

regime, we can approximate this charge rearrangement by an average density in the ideal leads on either side of the scattering structure characterized by different Fermi energies μ_A and μ_B as shown in Fig. 3.8. The actual voltage drop V across the scattering structure is then given by

$$eV = \mu_A - \mu_B, \tag{3.32}$$

which is less than the voltage between the reservoirs, $\mu_1 - \mu_2$, the difference representing a *contact* potential drop. We need to find the potential difference

To do this, we can write the 1D density in the ideal lead on the left side as

$$n_a = \frac{1}{\pi}\int_{-\infty}^{\infty} dk f_a(E) = \frac{1}{\pi}\int_{-\infty}^{\infty} dk\{(2-T)f_1(E) + Tf_2(E)\}, \tag{3.33}$$

where $f_a(E)$ represents the near-equilibrium distribution function in the left lead, characterized by a Fermi energy μ_A. The integral over $\pm k$ considers carriers

Density at right

$$n_b = \frac{1}{\pi}\int_{-\infty}^{\infty} dk f_b(E) = \frac{1}{\pi}\int_{-\infty}^{\infty} dk\{(2-T)f_2(E) + Tf_1(E)\}.$$

If we now assume that the difference between the Fermi energies is sufficiently small that we may neglect the energy dependence of T and the inverse velocity, dk/dE, then (3.35) may be simply integrated to give

$$\mu_A - \mu_B = (1 - T)(\mu_1 - \mu_2). \tag{3.36}$$

to the number of unoccupied states (holes) below [73]. The number of states occupied above μ_B on the right side due to injection from the left is $TD(E)$ $(\mu_1 - \mu_B)$, where $D(E)$ is the density of states in energy corresponding to positive k only ($1/2$ the total density of states). Likewise, the number of unoccupied states below μ_B is given by $2D(E)(\mu_B - \mu_2) - TD(E)(\mu_B - \mu_2)$, the states below μ_2 being completely filled. Equating the two gives

$$T(\mu_1 - \mu_B) = (2 - T)(\mu_B - \mu_2). \tag{3.37}$$

Similarly, on the left side, μ_A is defined from

$$(1 + R)(\mu_1 - \mu_A) = [2 - (1 + R)](\mu_A - \mu_2), \tag{3.38}$$

where the left side is the number of occupied states above μ_A, and the right side is the number of unoccupied states below. Combining the two equations gives (3.36) above.

Substituting (3.36) into (3.31) gives

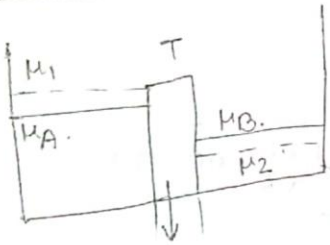
$$I = \frac{2e}{h}\frac{T}{1 - T}(\mu_A - \mu_B), \tag{3.39}$$

or, in terms of the conductance using (3.32),

$$G = \frac{I}{V} = \frac{2e^2}{h}\left(\frac{T}{1 - T}\right) = \frac{2e^2}{h}\frac{T}{R}, \tag{3.40}$$

which is finally the single-channel *Landauer formula* [71], [72]. We see

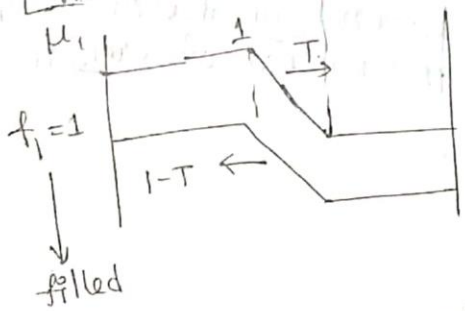
One characteristic of mesoscopic systems is that their conductance properties may be governed by transport through a few such channels, giving rise to characteristic changes of precisely $2e^2/h$



localized scatterer

here T is transmission coefficient that shows how many carrier transmits through localized scatterer

A channel of length L with distrubuted scattering with mean free path λ, then $T = \frac{\lambda}{L+\lambda}$ (not needed.



(Quasi Fermi level)

It shows occupation of state

$f = 0$. T refers to occupation of state

here electrochemical potential μ_1, μ_2 tells us degree of filling of state.

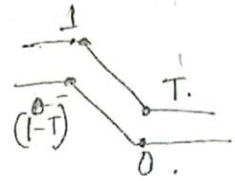
so $\mu_1 - \mu_2 = qVf$

here, current $I = G_B \cdot \frac{\mu_1 - \mu_2}{q} = G_B \cdot V f = G_B V T$

here we get difference in fermi level state $1-(1-T) = T$

$\therefore f = T$.

$\Rightarrow \frac{I}{V} = G_B T$

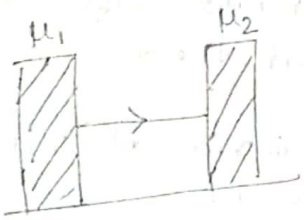


lets find voltage across scatterer

$\delta V = (V - TV) = ((1-T)V - 0) = V(1-T)$.

$\Rightarrow \delta V = \frac{I}{G_B T}(1-T) \Rightarrow \frac{I}{\delta V} = G_B \cdot \frac{T}{1-T} = G_L$.

here G_B is conductance of nanowire with no local scatterer



here mean free path depends on
i) temperature
ii) Impurity
iii) Defect

Ballistic conductance if mean free path >> length

we know, current density $J = -enV_d$.

$$\mu_1 - \mu_2 = -eV$$

$$n = \int_{\mu_2}^{\mu_1} dn = \int_{\mu_2}^{\mu_1} \frac{dn}{dE} dE$$

$$= \frac{dn}{dE}(\mu_1 - \mu_2)$$

here n is number of e^- travelling through wire volume

volume = Area of wire × length of wire

$$n = \frac{N}{Al} \Rightarrow N = nAl.$$

Total energy $= E = N\varepsilon$. $\varepsilon \rightarrow$ energy at each carrier, $N \rightarrow$ number of carrier.

$$\Rightarrow E = nAl\varepsilon hf. \quad (\varepsilon = hf).$$

$$\Rightarrow dE = Alhf\, dn$$

$$\Rightarrow \frac{dn}{dE} = \frac{1}{Alhf} \qquad \frac{dn}{dE} = \frac{2}{Alhf}$$

due to spin degeneracy

$$n = \frac{2}{Alhf}(\mu_1 - \mu_2)$$

Now current density $J = \frac{2}{Alhf}(\mu_1 - \mu_2) \cdot eV_d$.

$$= \frac{2}{Alhf} \cdot eV \cdot \frac{l}{T}$$

$l \rightarrow$ length of channel

$T \rightarrow$ period taken

$$= \frac{2e^2V}{Ah}$$

$$\Rightarrow I = A \cdot J = \frac{2e^2}{h}V$$

$$\Rightarrow \frac{I}{V} = G_B = \frac{2e^2}{h}$$

For N mode

$$G = NG_B = \frac{2e^2}{h}N.$$

The catch is how one would devise leads to actually measure this voltage without influencing the conductance of the structure. In a two terminal measurement, the voltage and current are measured through the same set of leads and so there remains an interference of conductance

same set of leads. In this case, the voltage measured is

$$eV = \mu_1 - \mu_2, \tag{3.41}$$

which from (3.31) clearly gives

$$G = \frac{I}{V} = \frac{2e^2}{h} T, \tag{3.42}$$

without the factor $1 - T$. The reason is that now in addition to the potential drop across the scattering structure, we are measuring a contact potential drop across the ideal leads due to the self-consistent charge build-up characterized by a contact resistance

$$R_c = \frac{h}{2e^2}. \tag{3.43}$$

Of course, if T *is* very small, then the series resistance of the barrier dominates, and the two-terminal and four-terminal measurement give identical results.

Significance of landauer formula

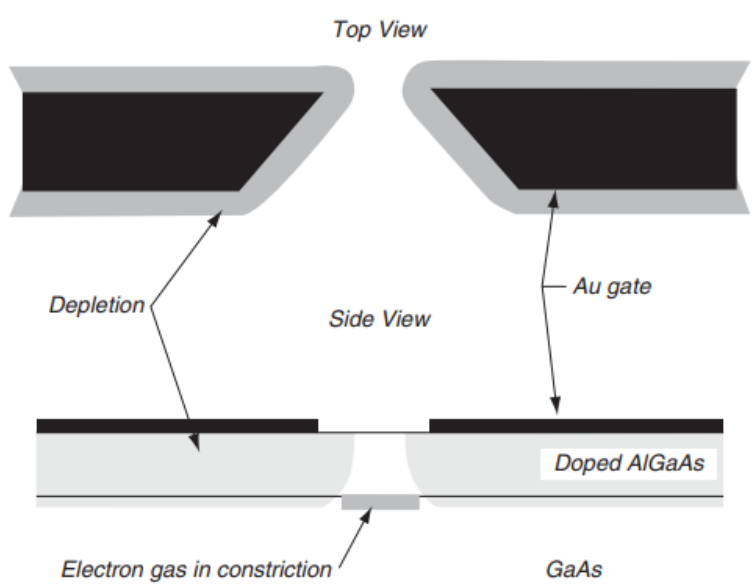


Fig. 1.2 Structure of the metal gates used to define a constriction to observe quantized conductance.

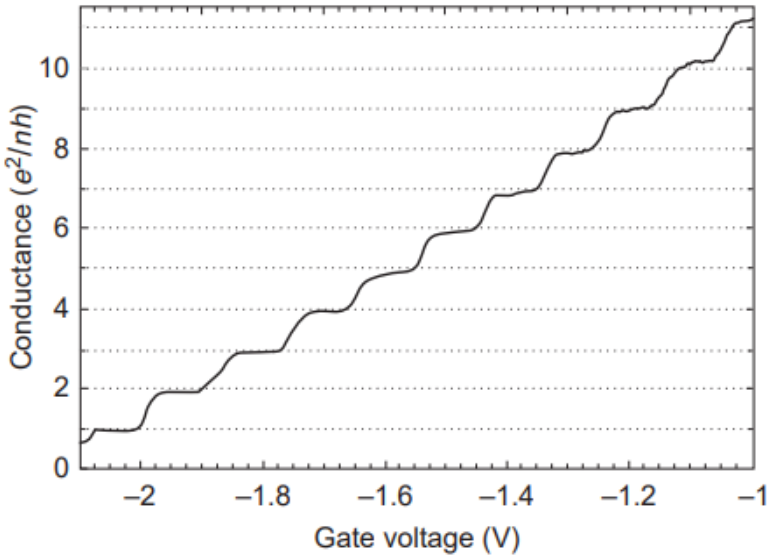
1. Foundation of nanoelectronics

Ballistic transport results into higher mobility 2DEG at GaAs and AlGaAs interface. T=0/1 depending on channel sub band energy > or < fermi energy. Gate produces harmonic potential and so sub bands are equally spaced. Bias changes number of gates as saddle potential gets higher or lower. At large negative bias, chnnel gets pinched off and G drops to 0.

2. Quantization of conductance

Constant value of conductance at certain state.

Fig. 1.3 The conductance obtained from a typical GaAs/AlGaAs structure such as that of Figure 1.2. (Reprinted with permission from van Wees *et al.* [16] Copyright 1988 The American Physical Society.)



3. Quantum transport description

Phase coherence maintained in quantum device. Application: Quantum Computing

2018-19 1b: Derive the thermal broadening function. Why it is important for current flow?

[2018-19] ① (b)

From landauer formula, $I = \frac{2e}{h} \int_{-\infty}^{\infty} T_e(E)\left(f_s(E) - f_d(E)\right) dE$

$f_{s,d}(E)$ are fermi distribution function at source-drain contact

$$I = G \Delta V$$

$$\therefore G = \frac{2e^2}{h} \int_{-\infty}^{\infty} T_e(\varepsilon) \left(-\frac{\partial f}{\partial \varepsilon}\right) dE$$

Now the derivative of fermi function,

$$-\frac{\partial f}{\partial \varepsilon} = \frac{1}{4 k_B T} \left[\cosh\left(\frac{E - E_f}{2 k_B T}\right)\right]^{-2}$$

It's also called thermal broadening function

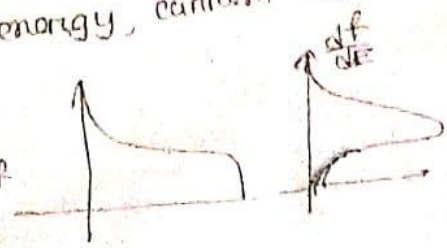
here $E_f \rightarrow$ fermi level

It dictates -

i) energy distribution of e^-, range of e^- energy.

ii) conductance value (quantum) depends on it

high temperature means wider thermal broadening function, that means wide range energized e^- can contribute in current flow and due to thermal energy, current flow in metal raises with temperature.



It determines probability of e^- to excite from VB to CB.

Multidimensional Conductance (2018-19 1a)

Conductance Dimensionality

In 1D,

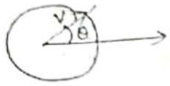
particle can have an average velocity $\frac{|v|+|-v|}{2} = v$.

Diffusion coefficient $\bar{D} = v^2\tau$

mean free path $= \frac{2\bar{D}}{\bar{v}}$

(for backscattering)

In 2D,



$$\bar{v} = \frac{\int_{-\pi}^{\pi} d\theta\, |v\cos\theta|}{\int_{-\pi}^{\pi} d\theta}$$

$$= \frac{2\int_{-\pi/2}^{\pi/2} v\cos\theta\, d\theta}{2\int_{-\pi/2}^{\pi/2} d\theta}$$

$$= \frac{v\,[\sin\theta]_{-\pi/2}^{\pi/2}}{\pi} = \frac{v}{\pi}$$

Diffusion coefficient, $\bar{D} = v^2\tau \frac{\int_0^{2\pi} d\theta \cos^2\theta}{\int_0^{2\pi} d\theta}$

$$= v^2\tau \cdot \frac{\frac{1}{2}\int_0^{2\pi} d\theta\,(1+\cos 2\theta)}{2\pi} = \frac{v^2\tau}{2}.$$

(Diffusive)

$G = \frac{q^2 D}{2t}$ here, time, $t = \frac{L^2}{2D} = \frac{L^2}{2\bar{D}}$

$$= \frac{q^2 D}{2\cdot\frac{L^2}{2D}} = \frac{q^2 D\bar{D}}{L^2} = \frac{A}{L}\cdot\frac{q^2 D\bar{D}}{AL}$$

σ

$\bar{D} = \langle v_z^2 \tau \rangle$

(Ballistic)

We know,

conductance $G = \int_{-\infty}^{+\infty} dE\left(-\frac{df_0}{dE}\right) G(E)$

solving it, we get,

$G = \frac{q^2 D}{2t}$

here D is density of state and time t taken for e− to travel

At Ballistic transport,

$t_B = \frac{L}{\bar{v}}$ $\quad \bar{v} \to$ avg velocity.

$$\boxed{G_B = \frac{q^2 D\bar{v}}{2L}}$$

we know density of state is proportional to volume

so $\frac{D}{L}$ depends on Area.

so increasing length keeping ~~tem~~ area same, almost no change in conductivity

DOS = D.

For 1D Conductor,

$\frac{2t}{D} = h$

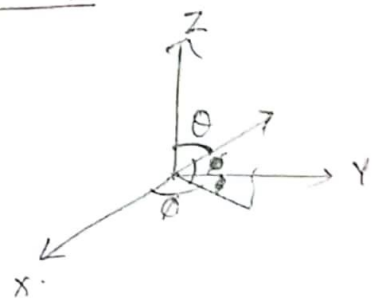
here, $G_B = \frac{q^2}{h}$

From uncertainity

$\Delta E \approx \frac{h}{t}$

$\bar{v} = \langle |v_z| \rangle$;.

In 3D,



average velocity,

$$\langle V \rangle = \frac{\int d\phi \cdot \int d\theta \sin\theta \, |v\cos\theta|}{\int d\phi \int_0^{\pi} \sin\theta}$$

$$= \frac{\int_0^{2\pi} d\phi \int_0^{\pi} |v\cos\theta| \sin\theta \, d\theta}{\int_0^{2\pi} d\phi \int_0^{\pi} \sin\theta \, d\theta}$$

$$= \frac{2v\int_0^{\pi/2} \sin\theta \cos\theta \, d\theta}{2\int_0^{\pi/2} \sin\theta \, d\theta}$$

$$= \frac{v}{2} \frac{\int_0^{\pi/2} \sin 2\theta \, d\theta}{\int_0^{\pi/2} \sin\theta \, d\theta} = \frac{v}{2}$$

Diffusion coefficient,

$$\bar{D} = \tau \frac{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin\theta \, v^2 \cos^2\theta}{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin\theta}$$

$$= \tau v^2 \frac{\int_0^{\pi} \sin\theta \cos^2\theta \, d\theta}{\int_0^{\pi} \sin\theta \, d\theta}$$

$$= \frac{\tau v^2}{3}$$

$$\frac{1}{2} 2\sin\theta \cos^2\theta$$

$$\frac{1}{2} \sin 2\theta \cos\theta$$

$$= \frac{1}{2} [\sin(3\theta) + \sin(\theta)]$$

$$\frac{\frac{1}{4} \left[-\frac{\cos 3\theta}{3} - \frac{\cos\theta}{1} \right]_{\pi}^{0}}{\left[\cos\theta\right]_{\pi}^{0}}$$

$$= \frac{\frac{1}{4} \left(-\frac{1}{3} + 1 + \frac{1}{3} + 1 \right)}{2}$$

$$= \frac{1}{8} \cdot \frac{8}{3}$$

$$= \frac{1}{3}.$$

1D 2D 3D

$$\bar{V} = v \left\langle 1, \frac{2}{\pi}, \frac{1}{2} \right\rangle$$

$$\bar{D} = v^2 \tau \left\langle 1, \frac{1}{2}, \frac{1}{3} \right\rangle.$$

$$\lambda = \frac{2\bar{D}}{\bar{V}}$$

$$\lambda = v\tau \left\langle 2, \frac{\pi}{2}, \frac{4}{3} \right\rangle.$$

Nanolithography

Lithography refers to the transference of a desired pattern onto a substrate. The primary technique to accomplish this in modem IC technology involves a resist, which when selectively exposed to a particular radiation source, changes its chemical bonding in such a way that the irradiated portion dissolves when immersed in a developer, while the unexposed resist remains (positive resist), or vice versa (negative resist). To realize quantum confinement in the lateral directions, the dimensions must be such that the quantized energies are resolvable from thermal broadening and broadening due to the existing disorder in the system.

Nanolithography is a branch of nanotechnology and microfabrication that focuses on the process of creating extremely small patterns, structures, or features on the nanoscale.

Critical dimension < 0.1um**, diffraction limits on wavelength of limitation** and **phase-shift masks and immersion lithography** takes lithography below 100nm width.

Electron Beam Lithography (EBL)

Electron Beam Lithography (EBL) is a nanolithography technique used for the precise and high-resolution patterning of materials on the nanoscale. It utilizes a focused beam of electrons to write patterns directly onto a substrate or resist material.

Here characteristic wavelength in order of 30-20KeV, corresponding to atomic distance. Limitation on the resolution is related to scattering due to the **inelastic loss processes** as the high-energy electrons lose energy to or are reflected by the substrate.

It can be performed by modification of **Scanning Electron Microscope (SEM)**. Its done in **direct-write** fashion where electron beam is rusted over resist material like PMMA (poly methyl-methacrylate). Developed PMMA act as etch-mask and evaporated material are employed to transfer metal on substrate. **Scanning tunneling lithography and atomic force lithography** both allows atomic level control.

The basic principle of the STM is that of the exponential relation between tunneling current and the thickness of the barrier separating the electrodes (One is **substrate** and other is **fine metallic tip**). As the tip is moved across the surface, the tunnel current provides a sensitive measure of the proximity of the tip to the charge density on the substrate. This technique has allowed atomic level mapping of the atomic structure on material surfaces.

Electron Beam Source → Substrate/ Resist Material → Pattern Design → Exposure → Chemical Development→ Pattern Transfer

Merits – High Resolution and accuracy, Direct Write (no photolithographic Step), Versatility (wide range of material used)

Demerits—Slow Throughput, Beam Damage, Complexity and Cost.

Oxidation Lithography

Its done in ambient condition, locally oxidizing surface of substrate of interest, not like high vacuum needed in EBL. It breaks down surface absorbed water and locally oxidizes surface (anodic oxidation). Scanning AFM creates oxidized line and oxidation causes complete depletion of 2DEG under it. Nanostructure can be arbitrability designed. Quantum point contact with 0.7 feature (conductive in quantized state of $0.7*2e^2/h$).

AFM anodic oxidation to realize QPC. By horizontal line, effective conduction width is reduced, and we get **steplike variation in conductance**.

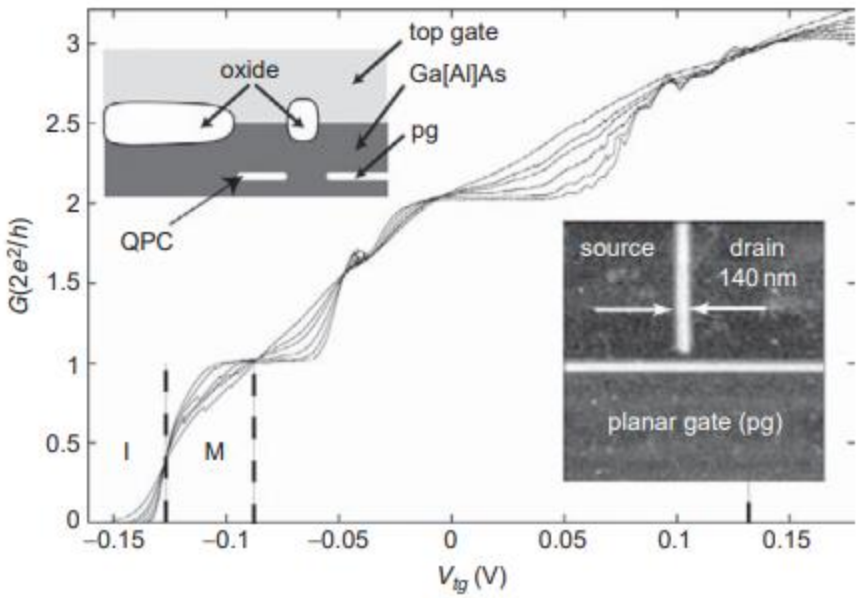


Fig. 2.15 The lower inset shows a quantum point contact formed by AFM oxidation. The point contact is formed by the two oxide lines (which appear bright). The upper inset shows a schematic cross section of the device (which also features a deposited top gate that allows for further control of the conductance). The main figure shows the conductance as a function of the top gate voltage at temperatures between 1.7 K and 20 K ([88], with permission).

Erasable Electrostatic Lithography

Surface oxidation leads to **permanent structural change** via Scanning probe Surface Modification but its reversible. It involves local charging of insulated substrate under low temperature, ultra-high vacuum. 2DEG close to surface and isolation present. Here surface charging induced by scanning probe can be eliminated via reverse polarity and illumination 2DEG by light. **Quantum Dot** is formed by two pairs of line that connects to metallic electrode.

Merits—Flexibility, High Resolution, Non-Contact, Compatibility with conventional techniques.

Focused ion-beam (FIB) technology, in which charged ions replace electrons as the high-energy incident particles. It allows direct in-situ etching with 10nm resolution.

Nanostructure

A nanostructure is a material or object that has dimensions on the nanometer scale, typically ranging from one to a few hundred nanometers in size. Quantum confinement refers to a quantum mechanical phenomenon that occurs when the motion of particles, typically electrons and holes (electron vacancies), is restricted within a limited spatial region, often on the nanometer scale. Quantum Confinement is done in **two different ways**:

(i) **Growth of inhomogeneous layer structures** resulting in quantization perpendicular to the substrate surface

(ii) **Lateral patterning using ultrafine lithography techniques**.

Quantization of carrier motion due to confining potential at interface barrier and well due to band bending.

Quantum confinement better when **low surface density at interface of lattice matched barrier** (GaAs and AlxGa1-xAs, GaAs and AlAs lattice constant close and so little strain at interface), **Lower conduction mass**.

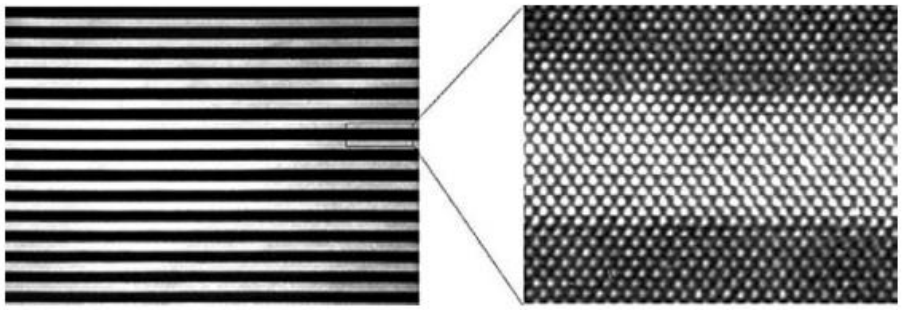


Fig. 2.1 Image of a GaAs/AlGaAs superlattice, illustrating the near atomic-level quality of the material. Picture provided courtesy of A. Trampert and O. Brandt, Paul-Drude Institute, Berlin.

Modulation Doping

Dopant provides free carriers in heterostructure and spatially separated (superlattice). Growth of undoped smaller bandgap GaAs spacer layer in doped wider bandgap AlxGa(1-x)As. Here ionized impurity is reduced and so mobility high.

Self-Assembled Nanostructure

Self-assembly is a fundamental concept in nanotechnology and materials science that refers to spontaneous formation through natural processes, often driven by molecular interactions or thermodynamic forces.

InAs quantum Dot (3D) formed on GaAs substrate at thin layer. Here difficulty arises **in control electrical contact in structure**. Top and substrate electrode controls charge number in quantum dot and generates single entangled photons for quantum computing.

Carbon Nanotubes are single or multi-wall structure dependent on graphene layers that can be metallic or semi-conducting. It forms high conductive nanoscale interconnects for ultra-high-density circuit and channel for FET due to ballistic transport at room temperature. We get magneto conductance oscillation due to AB effect.

AB effect— Magnetic field confined in space, behavior of magnetic field influenced by field in vicinity, interference pattern shift caused by wavefunction phase shift and depends on enclosed magnetic flux.

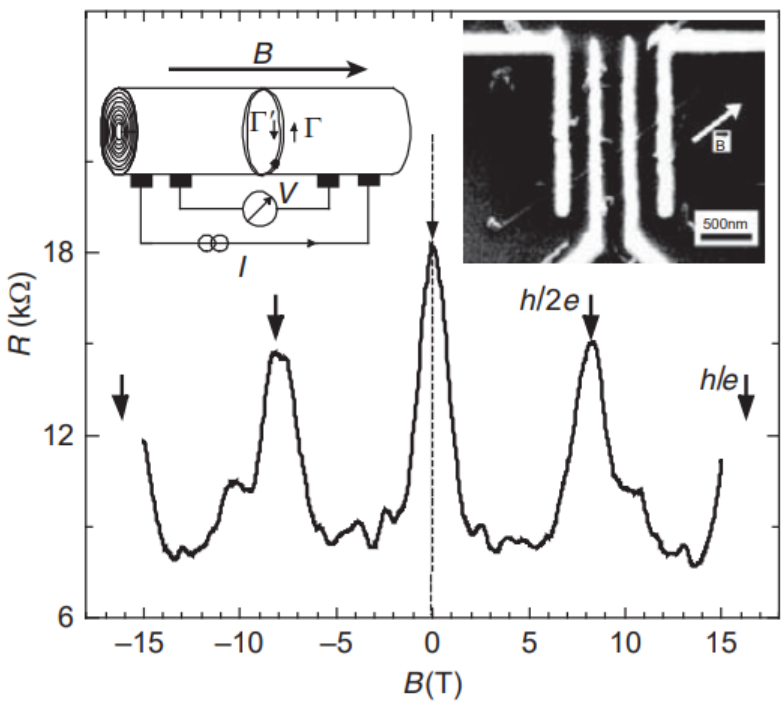


Fig. 2.2 The upper image is a scanning-electron-microscope image of a single-walled CNT that is electrically contacted by four different electrodes. At the bottom the magneto-resistance of a multi-walled CNT is shown. The magnetic field is oriented along the axis of the CNT, as indicated in the inset, and the magneto-resistance shows oscillations associated with the AB effect ([26], with permission).

Problems: (Synthesis method-CNT)

Arc-Discharge–Carbon evaporated in inert He environment by electrical discharge between electrodes.

Laser ablation—Laser pulse to ablate(remove) carbon source with metal catalyst.

In both method, output is full of debris and huge effort needed to refine.

Vapor Phase Synthesis (Vapor Liquid Solid Mechanism)

Vapor-liquid-solid (VLS) mechanism uses metallic nanoparticles as seed sites to stimulate the self-assembled growth of nanowires. The desired semiconductor system is introduced in terms of its gaseous components and the entire assembly is heated to a temperature beyond the **eutectic temperature** (critical temperature point in the phase diagram of a binary alloy system. It is the lowest temperature at which a specific combination of two elements or components in a mixture will melt or solidify at a constant temperature and composition) of the metal/semiconductor system. Under these conditions, the metal forms a liquid droplet, with a typical size of a few nanometers. Once this droplet becomes supersaturated with semiconductor, it essentially nucleates the growth of the nanowire from the base of the droplet. This method is utilized in **RTD, single or multiply coupled quantum dot, single electron tunnelling structure**.

Merit—Strong Confinement, high crystalline quality, robust quantum transport character,

Si nanowires grown by the VLS method using gold nanoparticles as the seeding droplets. The high crystalline integrity is seen in this nanowire.

Si/NiSi nanowire shows clear metallic behavior.

Difference in transport in Nano vs Bulk

Transport properties in nanomaterials and bulk materials can differ significantly due to the quantum mechanical effects that become more pronounced at the nanoscale. Like:

[1] Granular/ discrete nature of electronic charge vs continuous

Quantization of particle momentum and energy and envelope function of carrier is localized within space and decays away playing role in tunnelling. Schrodinger equation also backs it via oscillatory motion within domain of potential. Discrete energy states and quantum confinement presents unique electronic and optical property. Quantum tunnelling, Quantum Hall effect (2DEG), Coulomb blockade (discrete and steplike change in conductance or charge transport) all due to quantized nature of charge.

[2] Preservation of phase coherence of electron wave in short dimension

Potential variation in length is smaller than phase coherence length (represents the distance over which the phase of a wavefunction remains well-defined or coherent) and so transport is defined via reflection and transmission of matter wave. We find ballistic transport when L< lambda (mean free path) and so high mobility. Step conductance is seen at negative bias not present in bulk.

Processing Technology

Bulk Transport:

[1] Scattering process occur at single point in space.

[2] Instantaneous [3] At low field, scattering is weak.

[4] Time of scattering is comparable to mean free time.

Nanostructure—Nanodevice—Mesoscopic device (larger than atomic level)

Atoms are randomly distributed (variance $\sqrt{N}$)

Moore's law, Greater integration leads to lowering of cost, high performance, quantum effect (ballistic transport, Quantum Tunnelling), phase interface effect.

1980—0.5M device/ cm2

2007 – 2Gb—48nm

INTEL & AMD

Background Study of Molecular Electronics

Aviram and Ratner -- molecular rectification

Tour et al – spiro-switch

Ultra-miniaturization of electronics—nanofabrication

Methods –

[1] Mechanosynthesis

Fabrication of nanostructure using nano probes like in STM,AFM or micro electromechanical system (MEMS) chips with both STM and AFM

[2] Chemosynthesis

Self-assembly of nanostructures. Martil et al. used self-assembled Langmuir-Blodgett film to demonstrate molecular rectification. Perdue University has used

self-assembly to fabricate and demonstrate functioning electronic quantum confinement structures connected by molecular wire.

Nanocomposite formation, Thin Film deposition (CVD,MOCVD), Surface Functionalization, Nanopatterning, Nanowire growth (1D) are fabricated via chemosynthesis.

Molecular Wire

A molecular wire refers to a nanoscale conductive structure composed of organic or inorganic molecules that can transmit electrical charge or electrons over relatively long distances at the molecular level.

[1] Conduction mechanism—Charge Transport, electron hop from one molecule to other, length in nm level.

[2] Composition – Organic, Inorganic

[3] High conductivity

[4] Application – Molecular Diode, Sensor

[5] Challenges—control molecular alignment, address thermal fluctuation

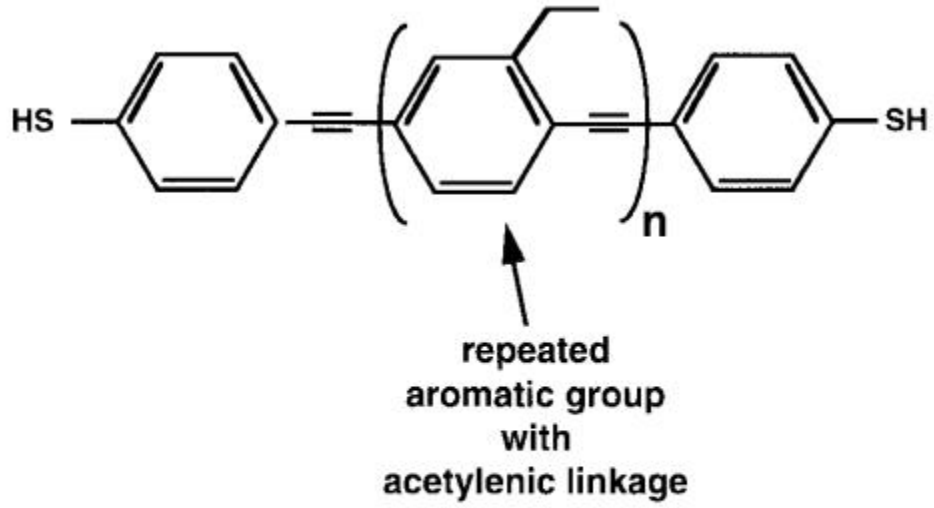
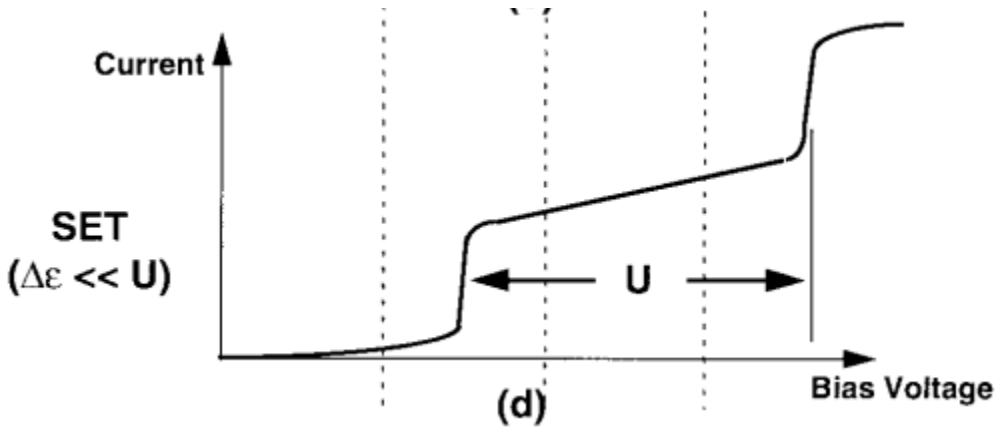


Fig. 7. Molecular wire. Chain molecule composed of repeating units bound together by conjugated π-bonds was demonstrated to conduct electrical current [195].

1st molecular wire with one end in Au (conducting molecule), other in STM tip. Recently gold electrode mounted on both end to complete circuit and show quantum device effect. Purdue self-assembled molecular electronic circuit array has characteristic “staircase” pattern of Coulomb blockade.

Thiol group(-SH) absorbs well to gold surface and act as alligator clip for attaching electronic unit to metal substrate. Extended repeating sequence is connected by acetylene linkage and orbital cloud of pi electron forms single large orbital through length of wire for mobile electron to flow.

“**BuckyTube**”, cylindrical carbon nanotube and its filled with conducting material to provide structural integrity and conductivity. Structure strength comes also from C-C bonds. Carbon atom is bonded in virtually flawless hexagonal array.



Quantum Effect of Molecular Device

Coulomb Blockade-- Coulomb blockade leads to the suppression of electrical current through a device until a certain voltage threshold is reached. In quantum dots and SETs, electronic energy levels are quantized, meaning electrons can only occupy specific energy states. With enough voltage, electron tunnel out and we get stepwise increase in current, its also known as coulomb’s oscillation.

It has application in nanoelectronics, quantum computing, and single-electron devices, ultra-sensitive detectors and provides insights into electron transport in nanoscale systems.

Molecular RTD--

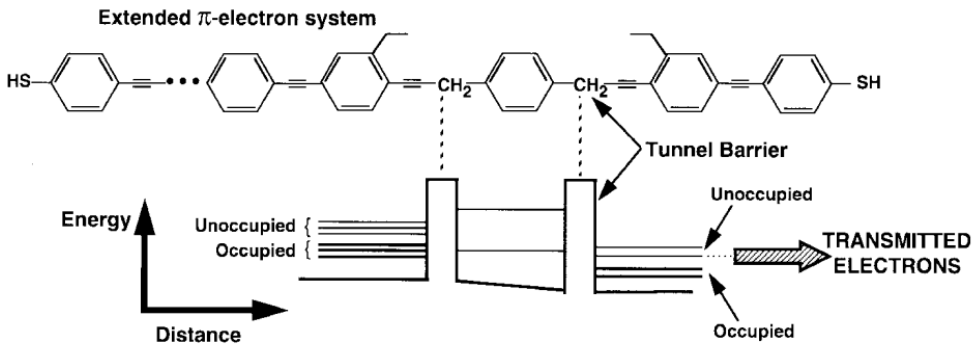


Fig. 8. Structure and mechanism for possible molecular RTD proposed by tour [94]. (a) Conducting chain molecule, like that shown in Fig. 7, but with insulating barrier groups that may generate (b) potential well for quantum confinement that could (c) create a resonant tunneling effect when the molecule is subjected to a voltage bias, permitting a current of electrons to be transmitted through the device. Compare this schematic with that in Fig. 3 for an analogous, but much larger, solid-state device.

Electromechanical Molecular Electronic Device (2020-21 7b, 2018-18 3b)

Molecular switch controlled by deforming or reorienting a molecule rather than shifting around electrons. Application in nano-computing.

a) Single-Molecule Electromechanical Amplifier

Buckyball in between STM tip and conducting substrate. STM header press (reversible) deforms buckyball producing on-off of resonance. It has vibrational frequency of 10THz (10^{13}).

b) Atom Relay

Its made of carefully patterned line of atom on substrate. Low energy requirement, high speed.

[1] If the switching atom is in place, the whole device can conduct electricity.

[2] If the switching atom is displaced from the two wires, the resulting gap dramatically reduces the amount of current that can flow through the atom wire.

[3] A third atom wire that passes near the switching atom is termed the “gate” of the atom relay in analogy to the gate of a field effect transistor. Placing a small negative charge on the gate wire moves the switching atom out of its place in the wire. The switching atom is pulled back into place by a second “reset” gate after each use of the switch.

Challenges:

[1] Difficult for precise demonstration of how 2 wires will cross.

[2] Not much energy would be required to evaporate a switching atom off the substrate and out of the plane of the atom wires, thereby destroying the switch. So, atom relays are suitable to work at very low temperature.

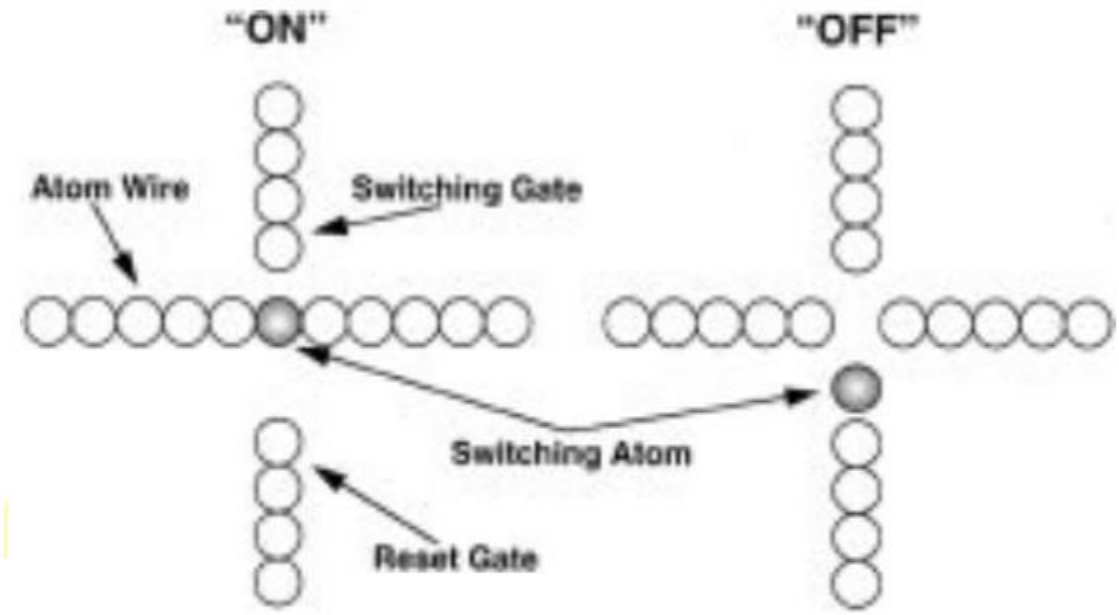


Fig. 9. Atom relay proposed and modeled by Wada *et al.* [170]. (a) Upon charging a line of atoms termed a switching gate, a mobile switching atom (shaded circle) is moved into a line of conductive atoms or "atom wire" in order to turn on a current through the wire. (b) The current is turned off by charging the reset gate to move the mobile atom back out of the atom wire.

Refined Molecular Relay-1

Atom movement might use the rotation of a molecular group to affect an electric current. Attaching the switching atom to a rotating group, or "rotamer." This rotamer would be part of a larger molecule, perhaps affixed to the same surface as the atom wires. The electric field of a nearby gate would force the switching atom to rotate in or out of the atom wire. When the switching atom is in the atom wire, the conductance of the atom wire is high—i.e., the switch is "on." When the switching atom is rotated out of the wire, a second group takes its place. This replacement group hinders the flow of current through the atom wire, turning the switch "off." A large third group on the rotamer could prevent it from rotating freely

due to thermal energy. Alternatively, hydrogen bonding might provide a resistance to rotation just adequate to stop the rotamer in the conducting position, but not so much that reversing the gate voltage would be insufficient to turn the rotamer. prevent the evaporation of the mobile switching atom, alleviating one of the principal weaknesses of the atom relay

Challenges-- Rotating switch based upon a methyl-like rotamer group is that there are three different switch positions associated with the three groups attached to the rotamer but suitable is having 2 states only.

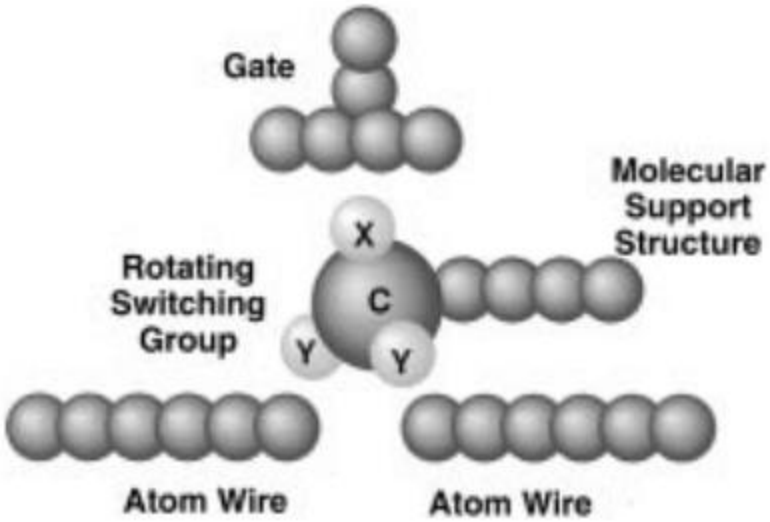


Fig. 10. Refined molecular switch, Type 1. The atom switch depicted in Fig. 9 might be refined by attaching the switching atom to a rotating molecular group. The orientation of the rotating group is to be controlled by a nearby gate molecule, to which a voltage can be applied for that purpose.

Refined Molecular Relay-2

A voltage on a nearby gate might force the cyclohexene to 1 of 2 configuration affecting conductivity. The remaining ring carbons would be replaced by groups tailored to use steric repulsions or chemical attractions to reduce undesired switching caused by thermal energy, while also sterically protecting the conducting atom from chemical attack. Refined relays could be packed in three dimensions, attaining much higher packing density. This should not cause overheating since the energy dissipated in their operation ought to be very low.

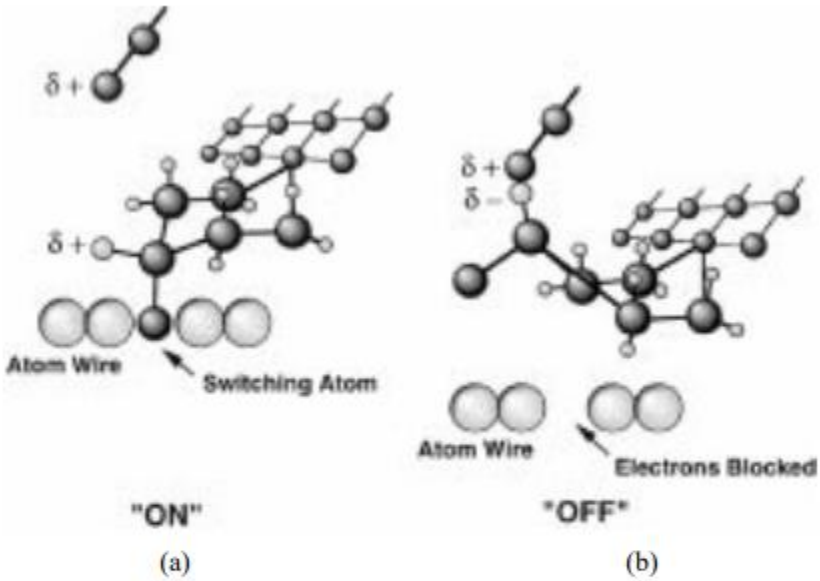


Fig. 11. Refined molecular switch, Type 2. Switching atom might be attached to a "rotamer" that permits the atom to (a) be swung into position to turn the switch "on" by filling the gap in the atom wire, or (b) the switching atom is swung up out of the wire to turn "off" the current in the wire. Orientation of the rotamer is to be controlled by adjusting the polarity of the charge on the gate molecule, shown at the very top of both (a) and (b).

Molecular Shuttle Switch

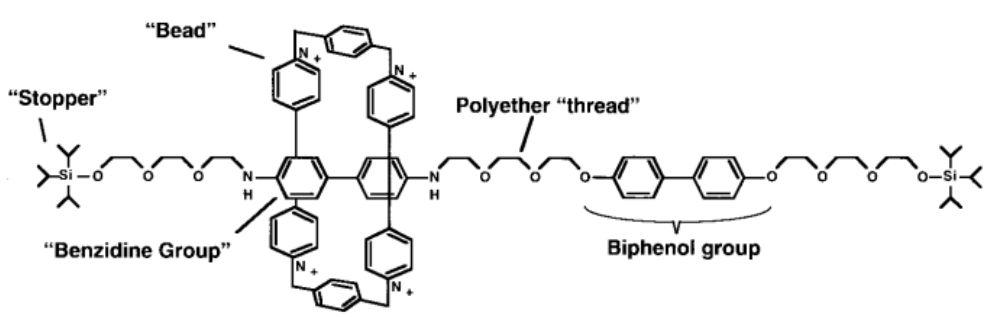


Fig. 12. Reversible molecular switch synthesized by Bissel *et al.* [121]. Ring-like "bead" molecule slides along wire-like chain molecule to perform switching function as described in the text.

"shuttle" is a ring shaped molecule that encircles and slides (i.e., "shuttles") along a shaft-like chain molecule. Two large terminal groups at the end of the shaft prevent the shuttle ring from coming off the shaft. The shaft contains two other functional groups, **a biphenol group and a benzidine group**, which serve as natural

“stations” between which the shuttle moves. The shuttle molecule contains four positively charged functional groups, which cause it to be attracted to sites on the shaft molecule with extra negative charge. The shuttle can be forced to switch to the bi-phenol station by the removal of an electron from the benzidine station. This process is known as electrochemical oxidation.

Since both the altered benzidine station and the functional groups on the ring are positively charged, they repel each other. In this state, the shuttle spends most of its time at the bi-phenol station. When the missing electron is added back to the benzidine station, the switch will return to its original state. A charged gate would be established at one or both ends of the molecule to force the shuttle to move between switching positions.

Large numbers of this type of device can be synthesized chemically at relatively low cost. Extremely high packing density and the rate of switching is high. Shuttle switches might pack into a three-dimensional lattice, creating an even larger space savings.

Challenges: the speed of electron transfer to and from the benzidine, and the sluggish motion of the ring, which is very heavy compared to an electron

Tunnelling

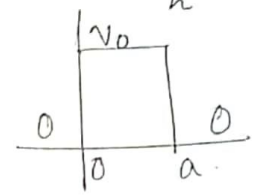
at (ii), $-\hbar$

Time independent schrodinger equation,

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + (V-E)\psi = 0 \quad [\text{at ii}]. \quad \text{let } \gamma = \sqrt{\frac{2m(V-E)}{\hbar^2}} \quad -(a)$$

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + E\psi = 0 \quad [\text{at i, iii}] \quad \text{let } K = \sqrt{\frac{2mE}{\hbar^2}}$$

We know, $\frac{\partial^2 \psi}{\partial x^2} = 1$



a solving differential equation,

$$\psi(x) = \begin{cases} Ae^{ikx} + Be^{-ikx} & x < 0 \\ Ce^{\gamma x} + De^{-\gamma x} & 0 < x < a. \\ Ee^{ikx} & x > a. \end{cases}$$

here we eleminate Fe^{-ikx}. as ~~a reflange e will make the~~ ~~whole term negligible~~ the wave reflected back to barrier is and most wave are forward to barrier.

at $x=0$, function is continuous, it's differential is also continuous,

$$\left[ik.Ae^{ikx} - ike^{-ikx}B\right]_{x=0} = \left[C.\gamma.e^{\gamma x} - D\gamma e^{-\gamma x}\right]_{x=0}$$

$$A + B = C + D.$$

$$ikA - ikB = \gamma C - \gamma D. \Rightarrow ik(A-B) = \gamma[C-D]$$

$$\begin{bmatrix} 1 & 1 \\ ik & -ik \end{bmatrix}\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \gamma & -\gamma \end{bmatrix}\begin{bmatrix} C \\ D \end{bmatrix}$$

at $x=a$,

$$Ce^{\gamma a} + De^{-\gamma a} = Ee^{ika}.$$

$$C\gamma e^{\gamma a} - D\gamma e^{-\gamma a} = ikEe^{ika}$$

$$\begin{bmatrix} e^{\gamma a} & e^{-\gamma a} \\ \gamma e^{\gamma a} & -\gamma e^{-\gamma a} \end{bmatrix}\begin{bmatrix} C \\ D \end{bmatrix} = \begin{bmatrix} e^{ika} \\ ike^{ika} \end{bmatrix} E$$

$$\begin{bmatrix} C \\ D \end{bmatrix} = \begin{bmatrix} e^{\gamma a} & e^{-\gamma a} \\ \gamma e^{\gamma a} & -\gamma e^{-\gamma a} \end{bmatrix}^{-1} e^{ika} \begin{bmatrix} 1 \\ ik \end{bmatrix} E$$

$$= \frac{e^{ika}}{-\gamma - \gamma} \begin{bmatrix} -\gamma e^{-\gamma a} & -e^{-\gamma a} \\ -\gamma e^{\gamma a} & e^{\gamma a} \end{bmatrix} \begin{bmatrix} 1 \\ ik \end{bmatrix} E$$

$$= \frac{e^{ika}}{2\gamma} \begin{bmatrix} \gamma e^{-\gamma a} + ik e^{-\gamma a} \\ \gamma e^{\gamma a} - ik e^{\gamma a} \end{bmatrix} E$$

$$= \frac{e^{ika}}{2\gamma} \begin{bmatrix} e^{-\gamma a}(\gamma + ik) \\ e^{\gamma a}(\gamma - ik) \end{bmatrix} E$$

$$\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ ik & -ik \end{bmatrix}^{-1} \begin{bmatrix} 1 & 1 \\ \gamma & -\gamma \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix}$$

$$= \frac{1}{-ik - ik} \begin{bmatrix} -ik & -1 \\ -ik & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ \gamma & -\gamma \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix}$$

$$= \frac{1}{2ik} \begin{bmatrix} ik & 1 \\ ik & -1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ \gamma & -\gamma \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix}$$

$$= \frac{1}{2ik} \begin{bmatrix} ik + \gamma & ik - \gamma \\ ik - \gamma & ik + \gamma \end{bmatrix} \frac{e^{ika}}{2\gamma} \begin{bmatrix} e^{-\gamma a}(\gamma + ik) \\ e^{\gamma a}(\gamma - ik) \end{bmatrix} E$$

$$= \frac{e^{ika}}{4ik\gamma} \begin{bmatrix} \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot & \cdot \end{bmatrix} E$$

here, $A = \frac{e^{ika}}{4ik\gamma} \left[e^{-\gamma a}(\gamma + ik)^2 - (\gamma - ik)^2 e^{\gamma a} \right] E$

$$A = \frac{e^{ika}}{4ik\gamma} \left[(\gamma^2 - k^2)(e^{-\gamma a} - e^{\gamma a}) + 2\gamma ik (e^{-\gamma a} + e^{\gamma a}) \right]$$

$$= \frac{-e^{ika}}{4ik\gamma} \left[-4\gamma ik \cosh(\gamma a) + 2(\gamma^2 - k^2) \sinh(\gamma a) \right] E$$

$$A^* = \frac{e^{-ika}}{4ik\gamma} \left[4\gamma ik \cosh(\gamma a) + 2(\gamma^2 - k^2) \sinh(\gamma a) \right] E^*$$

$$|A|^2 = \frac{1}{16k^2\gamma^2} \left[4(\gamma^2 - k^2)^2 \sinh^2(\gamma a) + 16\gamma^2 k^2 \cosh^2(\gamma a) \right] |E|^2$$

$$\cosh^2 x - \sinh^2 x = 1$$

$$\frac{|E|^2}{|A|^2} = \frac{16k^2\gamma^2}{4(\gamma^2-k^2)^2 \sinh^2(\gamma a) + 16\gamma^2 k^2 \cosh^2(\gamma a)}$$

$$= \frac{16k^2\gamma^2}{4(\gamma^2-k^2)^2 \sinh^2(\gamma a) + 16\gamma^2 k^2 (1+\sinh^2(\gamma a))}$$

$$= \frac{16k^2\gamma^2}{16\gamma^2k^2 + \sinh^2(\gamma a)\cdot 4\left[(\gamma^2-k^2)^2 + 4\gamma^2k^2\right]}$$

$$= \frac{1}{1 + \frac{(\gamma^2+k^2)^2}{4k^2\gamma^2}\cosh^2(\gamma a)} = T$$

It's tunneling probability

In reverse biased p–n junctions, Zener breakdown occurs when electrons in the valence band can tunnel across the gap into the conduction band if a sufficiently high electric field is applied to bring these two bands to the same energy levels.

Gate Insulator for MOSFET is **SiO_2 or HfO_2**.

RTD

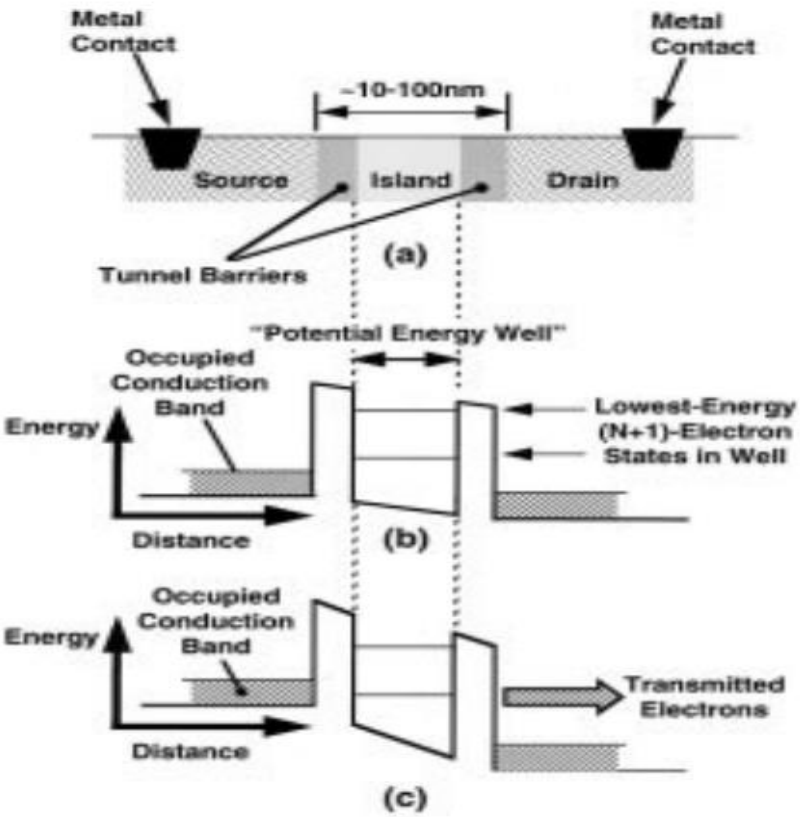


Fig. 3. Schematic of cross section and operation for an RTD. (a) RTD, shown in cross section, consists of a small island region between thin barriers. (b) Barriers create a potential well around the island, and usually prevent charge from flowing through the device, even when it is under a small voltage bias (downward slope in energy from source to drain), as shown. (c) Increasing the bias shifts down the energy for all the states in the well and brings them into resonance with the mobile electrons in the occupied conduction band in the source, so that an electron current can be transmitted through the device.

Increasing the applied voltage bias across the device progressively lowers the energy of all the states in the well relative to the energies the electrons in the source. When the bias potential is sufficient to lower the energy of an unoccupied one-electron quantum state inside the well to be within the range of energies for the source conduction band, the quantum well is said to be “in resonance” or “on,” and current can flow onto the island and out to the drain. Otherwise, current through the device is blocked—the device is “out of resonance” or switched “off,”. This use of a variable applied bias to switch a tunneling current on and off characterizes the operation of a two-terminal resonant-tunneling device called a resonant-tunneling diode or RTD.

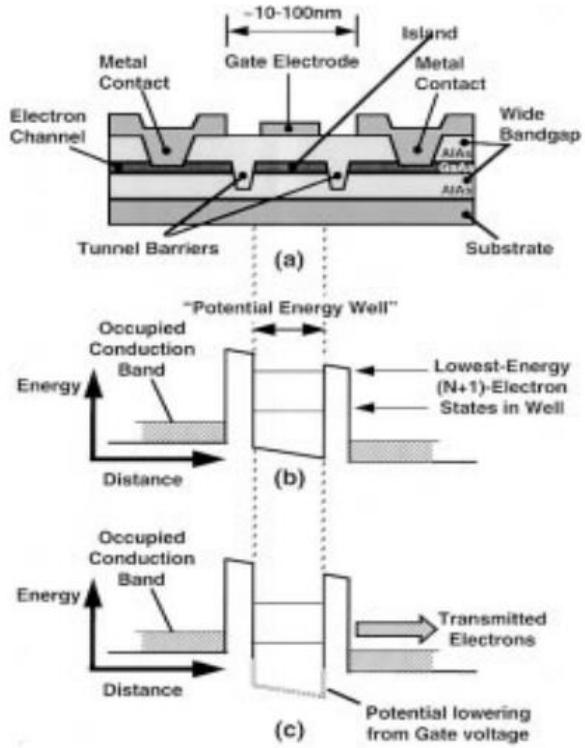


Fig. 4. Schematic of cross section and operation for the resonant tunneling transistor (RTT). (a) Cross section is for a lateral RTT of the type constructed by Randall *et al.* [155]. (b) Barriers in device create potential well around the island, and usually prevent charge from flowing through the device, even when it is under a voltage bias (downward slope in energy from source to drain), as shown. (c) Potential well has configuration similar to that for the RTD shown in Fig. 3 until the gate electrode is charged, lowering the energy for all the states in the well and bringing them into resonance with the mobile electrons in the occupied conduction band in the source, so that an electron current can be transmitted through the device.

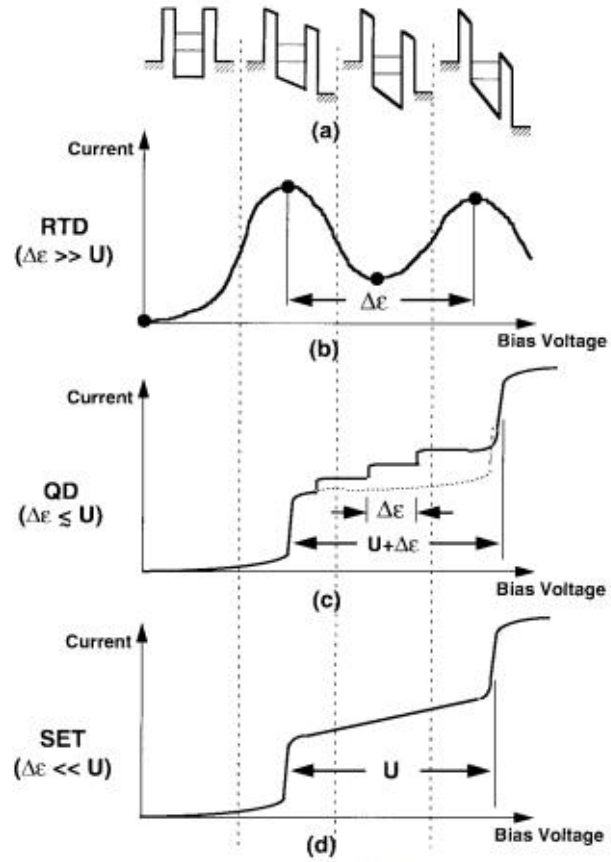


Fig. 5. Current (I) versus bias potential (V) plotted for three categories of solid-state nanoelectronic devices. (a) Snapshots of the variation in the quantum well due to the change in the applied bias potential; (b) I versus V plot for RTD; (c) I versus V plot for QD; (d) I versus V plot for SET.

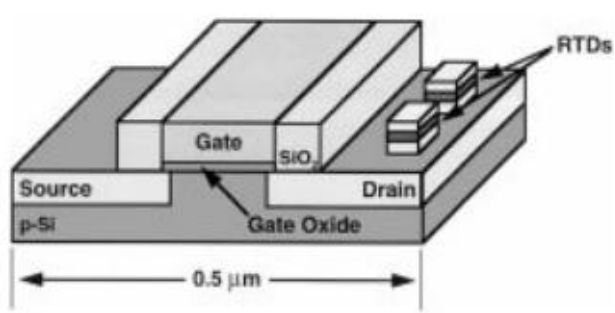


Fig. 6. Schematic of hybrid RTD–FET. Nanometer-scale RTD's are built into the drain of a micron-scale FET, creating a "hybrid" microelectronic-nanoelectronic device which has more logic states than a regular FET and is easier to build into circuitry than the tiny RTD.

Similar adjustment can be done by applying voltage at gate not source. Its termed as **Resonant Tunnelling Transistor**.

RTT can perform as both switch and amplifier. superior switching property than MOSFET.

Multiple States (2018-19 2b)

RTD's and RTT's can have multiple on and off states associated with multiple discrete quantum levels inside the potential well on a very small or very narrow island. if each level is spaced widely enough, then each of the different levels in the

well can be brought successively into and out of resonance with the source conduction band in succession, as the bias voltage (or gate voltage) is increased. The peaks in the plot correspond to the alignment of the energy levels in the well with the occupied part of the conduction band for the source. The current falls off between the peaks on the curve as the voltage is varied to make the energy of a quantum level in the well pass below the energy of the conduction band edge. And so we find differential negative resistance as increasing bias reduces current.

Comparable multistate behavior can be obtained by varying the gate voltage in an RTT. Quantum-effect devices has led investigators to build hybrid microelectronic-nanoelectronics devices, in which tiny quantum-effect RTD's are built into the drain (or source) of a micron-scale MOSFET. The hybrid RTT also exhibits multistate behavior—the drain current can be switched on and off several times for various values of the bias voltage. The logic density of circuitry containing such hybrid devices can be made much higher without a significant decrease in the feature sizes on the chip

Fabricating circuits with this relatively large, hybrid type of three-terminal RTT is easier than fabricating circuits with the much thinner, complex structures for purely nanoelectronics RTT.

Obstacles in Further Miniaturization (2018-19 2a)

[1] **High Electric Field**

Bias voltage at short distance may cause avalanche breakdown knocking huge electron at high energy resulting into current surge and damage.

[2] **Heat Dissipation of Transistor**

Limited thermodynamic efficiency causes overheating resulting into malfunction and limits density of circuit.

[3] **Vanishing Bulk Property and nonuniformity of doped semiconductor**

Quantum effect (Tunnelling, Ballistic transport, energy quantization) dominates. Dopant atom forming regular array, or no doping can be utilized as solution.

[4] **Shrinkage of depletion zone**

Thin depletion zone causes tunnelling from Source to Drain despite device turned off. Leakage current rises.

[5] **Shrinkage and Unevenness in Thin oxide layer**

Gate prevents electron from leaking out of gate to drain and leakage due to thin oxide act as a hotspot for tunnelling.

[6] **Manufacturing Precision**

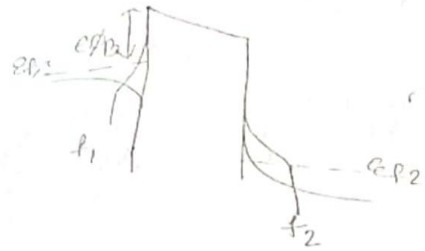
Fabricating and assembling tiny components with high precision is technologically demanding. It enables to create and integrate nanoscale features accurately and consistently. Miniaturized devices require smaller and more densely packed interconnects, which can increase resistance, capacitance, and signal propagation delays.

[7] **Cost**

Developing and manufacturing miniaturized devices can be expensive due to the precision and specialized processes required.

As device gets smaller, we find decrease in effectiveness of doping and increase in utilizing quantum mechanical effect.

TSU- ESDKT Model



Some assumption –

(i) Effective mass approximation

Different mass correspond to band structure that are lumped into single valued effective mass.

(ii) parabolic band

$$\varepsilon = \frac{\hbar^2}{2m_{eff}}(k_x^2 + k_y^2 + k_z^2)$$

here wavevector, $k = k_x e_x + k_y e_y + k_z e_z$.

net tunnelling current, $J = J_{1\to2} - J_{2\to1}$

let, $E = E_z + E_t = \frac{\hbar^2 k_z^2}{2m^*} + \frac{\hbar^2 k_t^2}{2m^*}$ (on ~~right~~ left)

$E = E_z + E_t = \frac{\hbar^2 k_z^2}{2m^*} + \frac{\hbar^2 k_t^2}{2m^*} + E_{c,R}$ (on ~~left~~ right)

$$dJ_{1\to2} = qT(k_x)\, v_x\, g_1(k_x) f_1(\varepsilon)(1 - f_2(\varepsilon))\, dk_x$$

$$= qT(k_x)\, v_x\, g_1(k_x) f_1(\varepsilon)(1 - f_2(\varepsilon))\, dk_x$$

$$dJ_{2\to1} = qT(k_x)\, v_x\, g_2(k_x) f_2(\varepsilon)(1 - f_1(\varepsilon))\, dk_x$$

[$T(k_x) \to$ Transmission coefficient.

$k_x \to$ wave vector.

$f_1(\varepsilon), f_2(\varepsilon)$ $\to$ distribution func. at left & right

Here transmission coefficient depends on momentum perpendicular to interface.

Density of k_x states is $g(k_x, k_y, k_z)$.

quantized wave vector component of cube with length L.

$$\Delta k_x = \frac{2\pi}{L}, \quad \Delta k_y = \frac{2\pi}{L}, \quad \Delta k_z = \frac{2\pi}{L}$$

$$\therefore g(k_x, k_y, k_z) = \underbrace{2}_{\text{spin degeneracy}} \times \frac{1}{\Delta k_x \Delta k_y \Delta k_z} \times \frac{1}{L^3}$$

$$= \frac{1}{4\pi^3}.$$

Now velocity & tunnelling energy component in tunnelling direction, (momentum, $p = \hbar k$).

$$v_x = \frac{1}{\hbar}\frac{\partial \varepsilon}{\partial k_x} = \frac{\hbar k_x}{m_e^*} \implies \frac{1}{\hbar}\partial \varepsilon_x = v_x\, dk_x$$

$$dJ_{1\to 2} = q\,T(k_x)\; g_1(k_x)\; f_1(\varepsilon)\,(1-f_2(\varepsilon))\; v_x\, dk_x$$

$$= q\,T(k_x)\cdot \frac{1}{4\pi^3}\int_0^\infty\int_0^\infty f_1(\varepsilon)\,(1-f_2(\varepsilon))\,\frac{1}{\hbar}\,d\varepsilon_x\, dk_y\, dk_z$$

$$\left[\because g_1(k_x) = \int_0^\infty\int_0^\infty g_1(k_x, k_y, k_z)\,dk_y\,dk_z\right]$$

$$= \frac{q}{4\pi^3\hbar}\,T(k_x)\,d\varepsilon_x \int_0^\infty\int_0^\infty f_1(\varepsilon)\,(1-f_2(\varepsilon))\,dk_y\,dk_z$$

$k_p = \sqrt{k_y^2 + k_z^2}$ $\quad k_y = k_p\cos(\gamma)$. $\quad \Rightarrow \frac{1}{\hbar}\frac{\partial\varepsilon}{\partial k_x} = \frac{\hbar k_x}{m^*}$

$\gamma = \tan^{-1}\left(\frac{k_z}{k_y}\right)$. $\quad k_z = k_p\sin(\gamma)$. $\quad \Rightarrow \partial k_x = \frac{m^*}{\hbar^2 k_x}\,\partial\varepsilon_x$.

evaluating relation,

$$J_{1\to 2} = \frac{4\pi m^* q}{(2\pi)^3\hbar^3}\int_{\varepsilon_{min}}^{\varepsilon_{max}} T(\varepsilon_x)\,d\varepsilon_x \int_0^\infty f_1(\varepsilon)\,(1-f_2(\varepsilon))\,d\varepsilon_p.$$

similarly,

$$J_{2\to 1} = \frac{4\pi m^* q}{(2\pi)^3\hbar^3}\int_{\varepsilon_{min}}^{\varepsilon_{max}} T(\varepsilon_x)\,d\varepsilon_x \int_0^\infty f_2(\varepsilon)\,(1-f_1(\varepsilon))\,d\varepsilon_p$$

using fermi dirac function,

$$f_{1,2}(E_z, E_t) = \frac{1}{1+e^{(E_z+E_t-E_f)/k_BT}}$$

$$J_T = \frac{q m^* k_B T}{2\pi^3\hbar^3}\int_{\varepsilon_{min}}^{\varepsilon_{max}} T(\varepsilon_x)\,d\varepsilon_z\left[\ln\left[\frac{1+e^{(E_f-E_z)/k_BT}}{1+e^{(E_f-eV-E_z)/k_BT}}\right]\right]$$

It's Tsu-Esaki formula.

It will be 2*pi^2

Tsu-Esaki formula describes the current-voltage characteristics of RTDs and plays a crucial role in understanding and designing these devices.

[1] Predict Tunnelling Current-- predict current flowing in device.

[2] Device Design -- Optimization of parameters like barrier height, thickness for high-speed operation or low power consumption.

[3] Quantum Transport -- It incorporates quantum principles into its formulation.

Application -- High speed electronic device, Detector, Sensor

Common III-V compound semiconductors used include:

GaAs (Gallium Arsenide)

InP (Indium Phosphide)

AlGaAs (Aluminum Gallium Arsenide)

InGaAs (Indium Gallium Arsenide)

Silicon (Si) and silicon-germanium (SiGe) heterostructures have been used to create RTDs. By carefully engineering the layers and interfaces, researchers can achieve the necessary energy band alignment for resonant tunneling.

Island, Potential & Quantum Effect

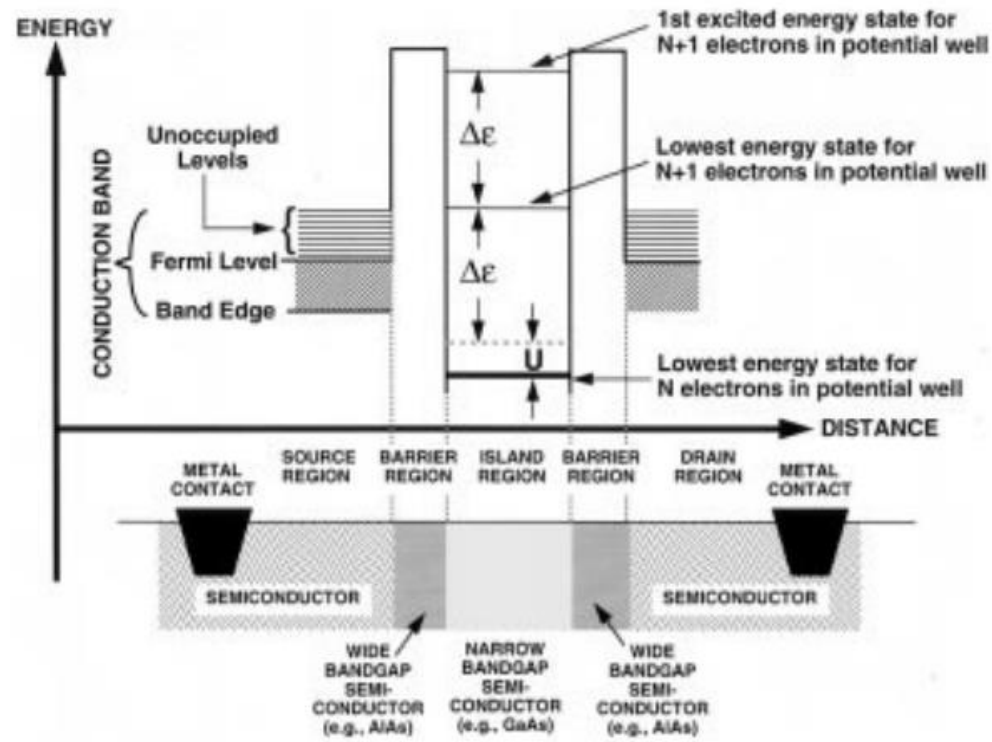


Fig. 2. Quantum well for a resonant tunneling diode (RTD). The barrier regions around the island in the RTD shown at the bottom of the figure create the potential energy "well" graphed in the top part of the figure. Energies of the electrons trapped in the well on the island are "quantized"—they can only have the energy states or "levels" shown. Mobile electrons in the source region (and the drain region) occupy the energy levels between the band edge and the Fermi level, with unoccupied energy levels above that in energy. If N mobile electrons are on the island, the energy cost of adding one more from the source has two components: the charging energy U, plus the excitation energy $\Delta\epsilon$. For an RTD, U usually is even smaller, relative to $\Delta\epsilon$, than is shown in the figure.

Island is embedded between two narrow walls of some other material, or an insulating oxide of the island material, or an insulating defect zone in the substrate. the island is surrounded by potential energy barriers that impedes electron in and out of island zone. Within the island, **mobile electrons will tend to form a puddle** that usually is much smaller than the dimensions of the island. The puddle is surrounded by a depletion region that forms because electrons in the **puddle are repelled from surface charges** that collect on the boundaries of the island. the physical features that form the island may have to be fabricated many times the size of the useful region for electron confinement. This is one factor that **works against the miniaturization of such quantum-effect and single-electron solid-state devices**.

First, **quantum mechanics restricts each electron's energy** to one of a finite number of one-electron energy levels (discrete and quantized energy**). Smaller the distance between the barriers (i.e., the smaller the island), the more widely spaced in energy** are the levels for the electrons in the potential well between the barriers. Spacing present between energy levels.

Second, **if the potential barriers are thin enough** (approximately 5–10 nm or less, depending on the height of the barriers), electrons occupying energy levels lower than the height of the barrier have a **finite probability of "tunneling"** through the barrier to get on or off the island. An electron of a given energy to tunnel through a barrier, there must be an **empty state with that same energy waiting in other side**.

Energy quantization and tunneling, strongly influence the flow of electrons through a nano-electronics device. When a **bias voltage is applied** across the island, it induces mobile electrons in the conduction band of the source region **to attempt to move through the potential well in the island region** to get to the region of lower potential in the drain region. The only way for electrons to pass through the device is **to tunnel on to and off the island** through the two high potential barriers that define the island and separate it from the source and the drain.

But tunneling can occur and charge can flow toward the drain only if there is an **unoccupied quantum energy level in the well at an energy** that matches one of the occupied energy levels in the source band. the **allowed energy levels** for electrons are so **closely spaced** that they **form bands over a range energy** in contrast to the discrete energy levels in a single atom or in a nanometer-scale potential well. Band range continuously in energy from that of **the lowest energy level in the band at the "band edge" to the level of the highest energy conduction electrons at the "Fermi level.** There are many available unoccupied one-electron quantum states at energies above this band, as well. So, once an electron can tunnel from the source to the island under a bias, it is usually free to complete its passage through the device by tunneling once again from the well onto the drain.

SOLID-STATE QUANTUM-EFFECT & SINGLE-ELECTRON NANOELECTRONIC DEVICES

Island of a nanoelectronics device assumes a role analogous to that of the channel in an FET. The composition, shape, and size of the island gives distinct properties. Most solid-state nanoelectronics devices incorporate semiconductors made from combinations of elements from groups III and V of the periodic table—e.g., gallium arsenide (GaAs) and aluminum arsenide (AlAs).

Quantum Dot-- 0 classical degree of freedom

Resonant Tunnelling Device -- confines electron with 1 or 2 degrees of freedom

Single electron device -- Island confines electron with 3 degrees of freedom

Quantum Electron Device

RTT--> Resonant-tunneling transistor is a device that uses an applied control voltage to modulate the difference between the energy levels of the quantum well and the energy of the incident electrons. The resonant-tunneling current through the double barrier can be made to peak at one or more values of the control voltage, corresponding to the different energy levels having multiple on and off states, corresponding respectively to the peaks and valleys of the I-V curve.

Conceptually, the simplest way to build a resonant- tunneling transistor is to form a contact with the heavily doped quantum well of a double barrier. low resistance contact would serve as the control terminal electron. Current flowing from the emitter to the collector is controlled by a bias voltage that varies the energy barrier between base and emitter.To achieve multiple peaks in the dependence of collector current on base-emitter voltage we exploit space charge buildup in the quantum wells.

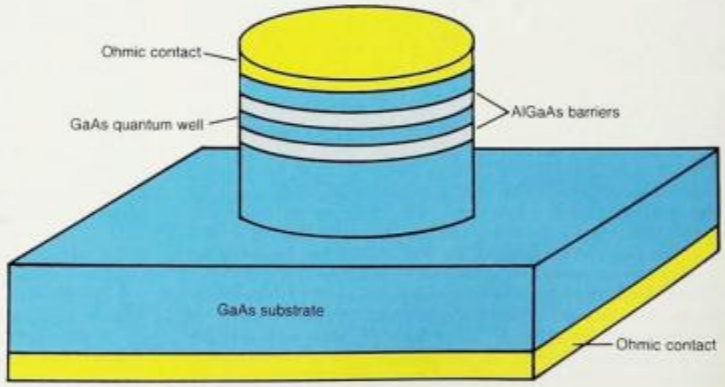
Unipolar resonant-tunneling transistors—devices involving only one type of carrier. excellent peak-to-valley ratios and high-frequency operation at liquid nitrogen temperatures. The performance degrades significantly at room temperature because of increased thermalization of electrons injected into the base.

Superlattice--

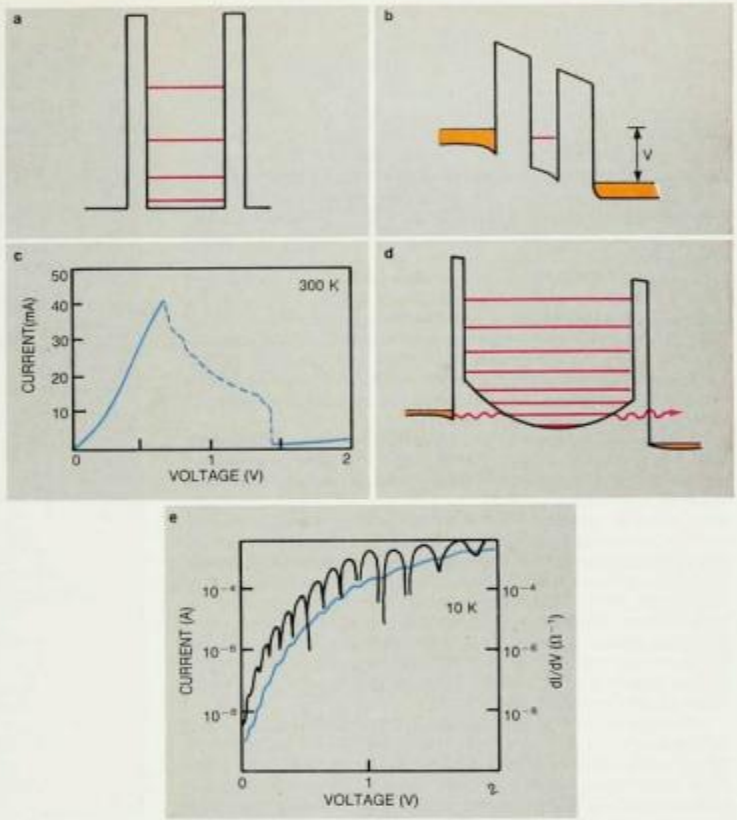
The barrier layers should be thin enough to allow significant tunneling. Structure breaks up into allowed bands separated by forbidden gaps expected in periodic structure. Artificial superlattice is typically 30-100 A, whereas the period of the crystal lattice is only a few angstroms, n the energy levels of the potential wells, are typically much narrower—on the order of 10 meV-- minibands, 1D superlattice field must be substantially increased above that required for negative differential resistance. High field transition to higher miniband causes suppression of bloch oscillation. wavefunction localization may cause negative resistance. As the electric field increases, the overlap between the states in different wells decreases.

If the field is further increased so that the ground state of a well is brought into resonance with the excited states of the neighboring well, one expects to see a series of peaks in the current-voltage characteristic due to sequential resonant tunneling.

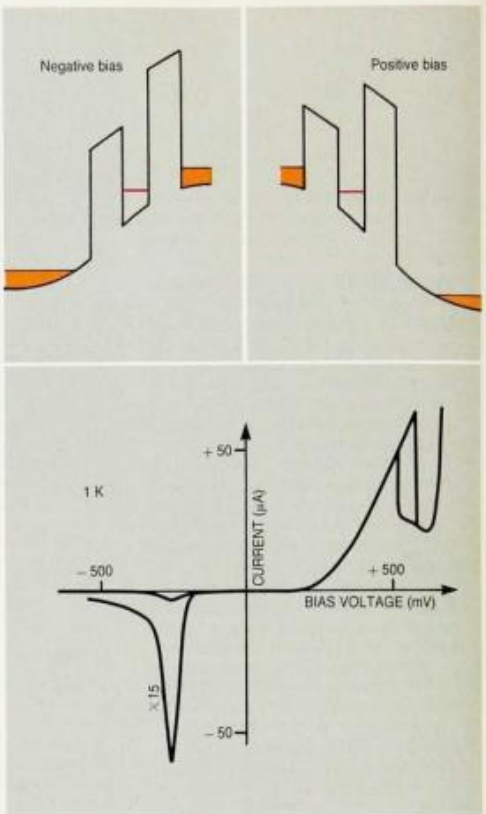
To obtain large interference effects it is usually necessary to restrict the range of wavelengths. In electromagnetics one commonly uses single-mode wave- guides and single-frequency sources. Electron microscopists, working with electron waves in vacuum, use a monoenergetic and well-collimated beam of electrons.



Resonant tunneling diode. AlGaAs barrier layers a few nanometers thick bracket a GaAs layer of comparable thickness to form a quantum potential well for electrons. **Figure 2**

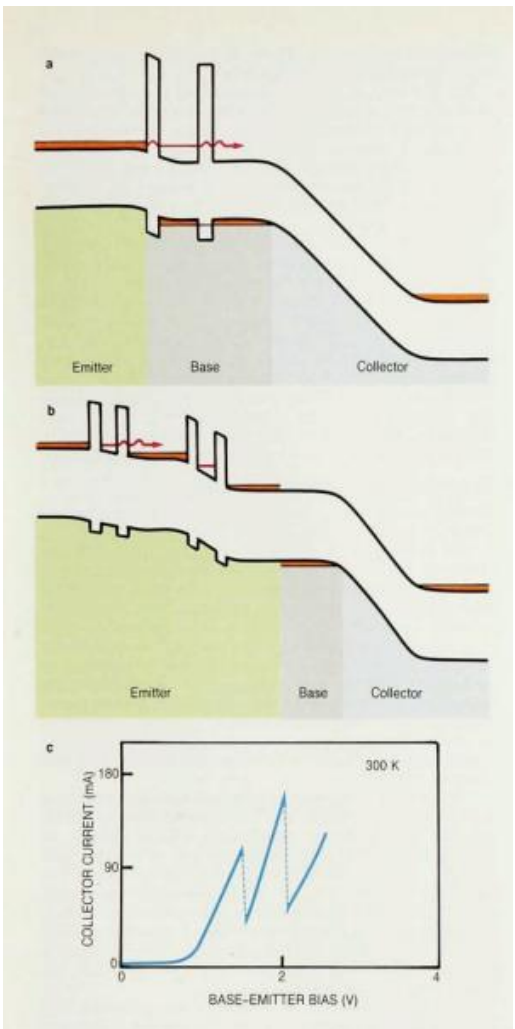


Quantum well of a resonant-tunneling diode. **a:** Conduction-band energy diagram at equilibrium, with no voltage bias across the diode. Because the AlGaAs has a wider bandgap than the surrounding GaAs, it forms potential barriers about 300 meV high. The horizontal lines represent the quantized electron energy levels in this "box." **b:** Energy diagram under operating conditions, with a bias voltage V applied between the heavily doped contact layers. The colored areas indicate the range of occupied conduction-band energies in these outer layers at low temperatures. **c:** Current–voltage characteristic curve[4] of a resonant-tunneling diode at 300 K. **d:** Biased-conduction-band diagram of a resonant-tunneling diode having a parabolic potential profile. The compositionally graded AlGaAs well is 43 nm thick.[5] **e:** Current (blue curve) and differential conductance (dI/dV) vs. voltage across the parabolic-well diode in panel d show 13 resonances[5] at 10 K. **Figure 3**



Bistability in an asymmetric double-barrier diode. Because one potential barrier is higher than the other, the band-energy diagram (top) and current–voltage characteristics (bottom) look quite different under negative (left, top and bottom) and positive (right) voltage bias.[6] Only the positive-bias *I–V* curve shows intrinsic bistability. The negative-bias curve is shown expanded vertically for visibility. **Figure 4**

Resonant-tunneling bipolar transistors with p-doped bases and n-doped collectors and emitters.[11] **a:** Energy diagram of a transistor incorporating a single resonant-tunneling structure in the base to control the current injection from the emitter. When the applied bias between base and emitter exceeds a threshold, the transmitted current is reduced as in figure 3c. **b:** Multistate transistor with two resonant-tunneling structures in the emitter. **c:** Output current vs base–emitter voltage for the structure shown in panel b. As the bias is increased, the resonant tunneling through the two structures is suppressed sequentially, leading to two peaks in the *I–V* curve. The energy diagram in panel b is for a bias between these peaks. **Figure 5**



Quantum Dot

Quantum dots (QDs) are nanoscale semiconductor particles that exhibit unique quantum mechanical properties due to their small size.

[1] **Size-Dependent Properties:** The electronic and optical properties of quantum dots are highly size-dependent. As the size of a QD decreases, its energy levels become quantized, leading to discrete energy states and thus we find domination of quantum mechanical property.

[2] **Bandgap Control:** Quantum dots have a tunable bandgap, which means they can emit light at different wavelengths depending on their size.

[3] **High Quantum Yield:** Quantum dots often exhibit a high quantum yield, meaning they efficiently emit light when excited. This property makes them attractive for use in displays, lighting, and biological imaging.

[4] **Colloidal Stability:** It's stable in solution. This colloidal stability is essential for their use in biological and biomedical applications.

Application

Display Technology (LCD), Biological Imaging (Medical Imaging, Tracking or labeling of cell or biomolecules), Photovoltaics (efficient solar cell to harvest power with high efficiency), Sensor (acts as sensor for precise control over emission of wavelength), Drug Delivery(QD can be functionalized with targeted drug delivery), Quantum Computing (Due to discrete energy state, Quantum information processing is possible)

Single Electron Transistor

A Single Electron Transistor (SET) is a nanoscale electronic device that operates by controlling the flow of individual electrons. It exploits quantum mechanical effects to achieve precise control over the passage of electrons.

SET is a small conducting island that is connected to source and drain electrodes. The island is typically connected to a reservoir of electrons on one side and is capacitively coupled to a gate electrode on the other side.

Coulomb's Blockade--The fundamental principle of an SET is Coulomb blockade. Due to its small size, the island can hold only a limited number of electrons. When a voltage is applied to the gate electrode, it affects the energy levels of the island's electronic states. As a result, electrons can only tunnel onto or off the island one at a time, leading to Coulomb blockade.

Coulomb blockade arises from the quantization of electric charge. Electrons within the system have discrete energy levels due to quantum confinement effects. These energy levels are influenced by the system's capacitance and the number of excess electrons on the island. When the energy required to add or remove an electron from the island (EC) is much greater than the thermal energy (kT, where k is the Boltzmann constant and TT is the temperature), the system exhibits Coulomb blockade. In this regime, electron transport across the island is highly suppressed. When the applied voltage exceeds the Coulomb energy (eV>EC), electrons can overcome the energy barrier, and current can flow.

The extent of Coulomb blockade depends on temperature. At low temperatures, the blockade is more pronounced because the thermal energy is smaller relative to EC, whereas at higher temperatures, the blockade becomes less significant

Current Control: An SET can control the flow of current between the source and drain electrodes by modulating the energy barrier for electron tunneling. At low barrier, electron can tunnel easily where at high barrier, electron flow suppressed by coulomb blockade.

Sensitivity: SETs are extremely sensitive to changes in gate voltage or charge on the island. A small change in voltage can result in a large change in current flow, making them highly sensitive detectors of charge, voltage, and other physical quantities.

Typically, SETs require operation at very low temperatures, close to absolute zero, to minimize thermal fluctuations that could disrupt the discrete charging effects.

Drawbacks and Obstacles to Solid-State Nanoelectronic Devices

Introduction

Development of bio-sensor and AI algorithms to monitor parameter and model tissue. Tissue-engineered models are used for targeted drug delivery to improve treatment efficiency and may replace animals in drug testing.

Integration of cellular, tissue, and organ levels is crucial for modeling complex biological systems, such as tumors. It can aid in designing targeted treatment regimens that address multiple levels of tumor and cancer biology. Nanoscale scaffolds promote cell adhesion, growth, immune system advancement and regeneration of damaged or lost tissue.

Nanotech-based **"organs-on-a-chip"** are miniature, microfluidic devices that replicate the structure and function of human organs. These systems allow researchers to study drug responses, disease mechanisms, and potential treatments in a highly controlled and realistic in vitro environment.

3D bioprinting, a cutting-edge technique that creates custom-made tissues and organs layer by layer. Nanomaterials are often incorporated into bioinks to enhance structural integrity and cell viability, bringing us closer to the prospect of lab-grown organs for transplantation.

Medical diagnostics and imaging through the creation of nanoscale contrast agents and sensors, allowing for earlier disease detection and more accurate monitoring of patient health.

Understanding Life's Intricacies

X-Ray Diffraction – It played role in discovering double helix structure.

AFM – STM not usable as chemical reaction most likely deforming biomolecular surface but AFM can map with sub-nm accuracy. High speed AFM method is used to visualize protein with high resolution (like stepwise movement of myosin).

Human Genome Project – This project determine the complete sequence of the human genome, identify all the genes contained within it, and understand their functions. Humans has a mere 21000 genes in a two-meter DNA strand. Multiple genes with non-genetic factors interact with environment evolve and manipulates

the DNA code and thus we get a biological outcome. Genome Sequencing of 3 billion base pair is an international project and data is on open source for researchers. It facilitated the discovery of genes associated with various diseases, including cancer, heart disease, and genetic disorders.

Cell as Living Computer—Stem cell contribute to repair tissue and organ, immune cell senses pathogen to detect tumor and cancer cell. Electrical signal is passed between neuron via axon.

DNA Nanotechnology

Why DNA used in nanotechnology?

[1] Self-assembly [2] Optimized orientation [3] Predictable

[4] Structural stiffness and flexibility [5] Highly customizable

[5] Experimentally successful

DNA Replication-- Two complementary DNA strands produced and spontaneously hybridize together to form a double-stranded DNA helix structure.

Sticky End— One strand longer with no complementary base pair with ability to fuse 2 DNA segments.

Holliday Junctions-- Holliday junctions are formed when two DNA double helices temporarily exchange strands and create a four-way junction with two crossover points. It's a versatile and stable structural motif in DNA nanotechnology. DNA strands from different double helices cross over each other. It can play a role in processing and transmitting information within DNA networks.

DNA Origami-- By introducing complementary strands and creating Holliday junctions at specific locations along the scaffold, researchers can fold the long DNA strand into complex and predetermined shapes and patterns (**DNA ORIGAMI-CUBE, OCTAHEDRON**). DNA tiles are smaller DNA nanostructures that can assemble into larger arrays through Holliday junction formation. Double Crossover (DX) tiles creates rigid structure.

[1] DNA origami typically begins with a long single-stranded DNA molecule known as the "scaffold DNA".

[2] Shorter DNA strands, called "staples," are designed to complement specific regions on the scaffold.

[3] When the staple strands bind to the scaffold at their complementary regions, they cause the scaffold to bend and fold into the desired shape.

[4] The DNA origami structures can be further functionalized by attaching molecules, nanoparticles, or other materials to specific regions on the structure.

DNA Nanorobot -- Specific functional, precise shape and structure, drug delivery, autonomous motion.

Challenges— [1] Build stable structure [2] Reduce process cost

[3] Increase Yield [4] Immune response to foreign DNA

Protein Nanotechnology

Why?

It can furnish more multipurpose building materials compared to DNA.

With stable shape, it has right assembly and disassembly properties and act as nano-walkers. Self-assembling natural proteins like Ferritin, S-layers and hydrophobics are also used to build 2D large lattices. Biological sensor, Nanomedicine, Drug delivery, Vaccine development.

Challenges--

[1] right conditions of temperature, pH, and concentration of salts, the amino acid sequence folds spontaneously into a functional three-dimensional protein structure. Optimum structure determination is costly and require heavy computation.

[2] No absolute ways to predict protein behavior.

Solutions--

[1] AI incorporation with existing technology

[2] continuous research to evolve property for drug delivery and other mechanism.

[3] Research on quantum physics

Nano in Medicine

Antibiotic resistance-- **mutation and conjugation**

Mutation of DNA when cell divides, DNA evolves to bring change in strand to bring abnormalities. Gene transfer for desired property.

[1] drug design using protein structure, controlled drug release, minimum side-effect.

[2] Protein design for bio-organism detection (virus)

[3] Nanostructure with target receptor

[4] enhanced permeability and retention

[5] Cancer Treatment

Challenges in drug Delivery--

[1] Difficult to convey to right cell (insulin --> Liver cell)

[2] Tumor cell not well-aligned

Cancer Immunotherapy

• Immune Cell Activation

• Combination Therapies

• Personalized Medicine

• Reducing Side Effects

• Immune Cell Tracking

• Vaccine Development

Nanoparticles: Unlocking the Potential of Gene Editing and Delivery

Gene Editing & Delivery, Immunotherapy (Nanoparticle Vaccine), RNA interference, mRNA vaccine

Polymeric material--> polymer selection, drug encapsulation, pH responsive release, bio responsive patch, controlled drug release.

Super-enhanced immune system--> stem cell therapy(tissue regeneration, blood disorder, organ transplant), Nutrition control, Immunomodulatory drug.

Stem cell--> cell Transplantation (embryonic, induced pluripotent, adult)

Single molecule-- Cell-Cell Interaction--Cell-Matrix Interaction--Scaffold

Early Scaffold--> Collagen Matric, Polymers, Bio-compatible and bio-degradable material, bone graft material

Tissue Engineering

Cell Source & Scaffold Material-- Cell-seeding & Culture-- Biomimicry-- Growth factor-- Vascularization-- Mechanical and Functional Testing

Self-assembly--Phase separation--Electrospinning

Nanotool -- quantify mechanical property

Mathematical model

Tisue engineering Gap

Application -- Orthopedics, Cardiology, Neurology, Dermatology.

Challenge -- Lacking full tissue functionality, immune rejection, long term viability

Vascularization Difficulties--

[1] Diffusion of nutrient and oxygen

[2] finding source for developing tissue to meet demand

[3] Engineering Tubular and non-tubular structure

[4] Production of solid organ

Solution--

[1] Delivery of protein to simulate blood vessel

[2] Development of supporting cell to form high quality vessel

Engineered Organ

[1] Engineer blood vessel (Cell Culture and Expansion, Cell seeding, Culture chamber, Engineered vessel, biodegradable scaffold)

[2] Engineered liver (inhibition of immune response, adding parental vessel cell)

[3] Engineered Heart (Tissue engineering, decellularized organ)

3D Bioprinting

3D structure, tailor for biological application, layer by layer construction

Design-->

Selection of Bio-ink--> Preparation of Bio-ink-->Bio-printing--> Cross-linking and solidification--> Maturation and Culturing--> Post-Processing--> Analysis and Testing --> Application

Future Scope-->

Organ Transplant, personalized medicine, Drug Testing & Delivery, Biological Research, regenerative medicine, Cosmetic and aesthetic application, Space exploration, Bio-fabrication, Hybrid, or multi-material printing

Nanohybrid--> Trans material robot