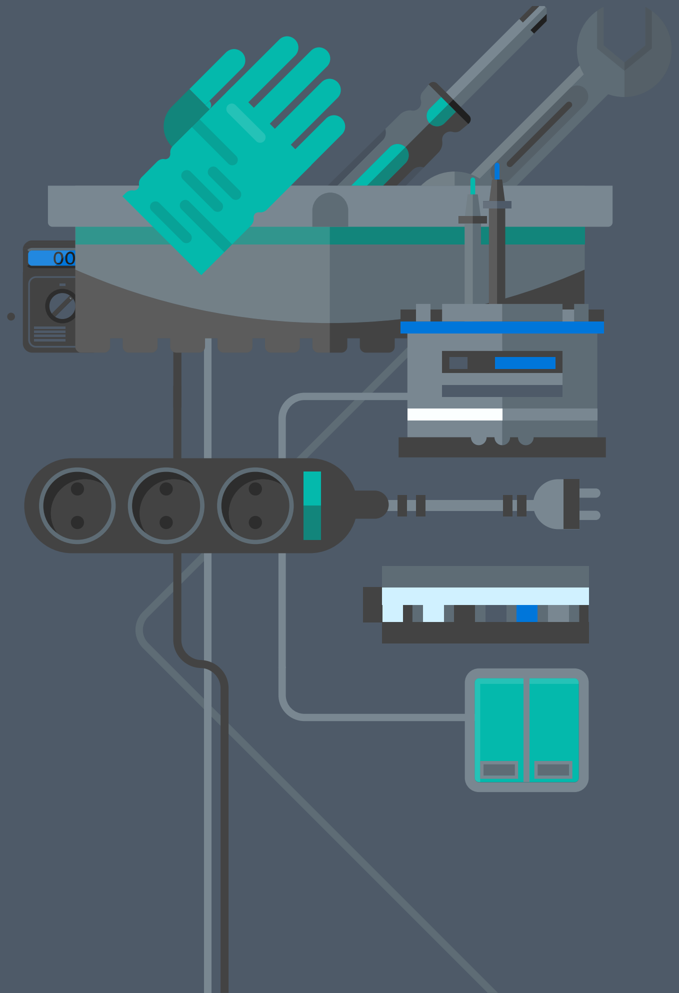

2D Materials in Electronics

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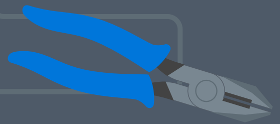


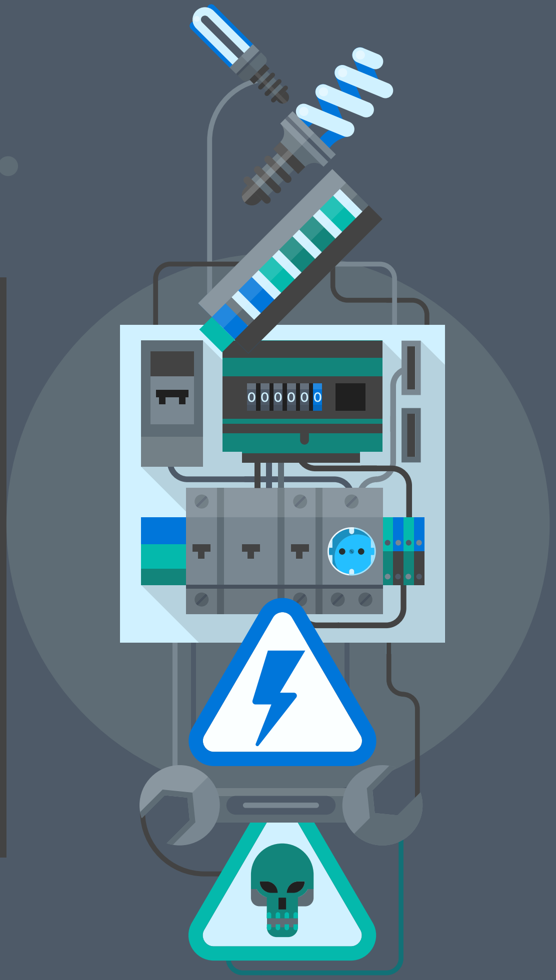
01

Introduction

What are 2D Materials & how they relate to Electronics

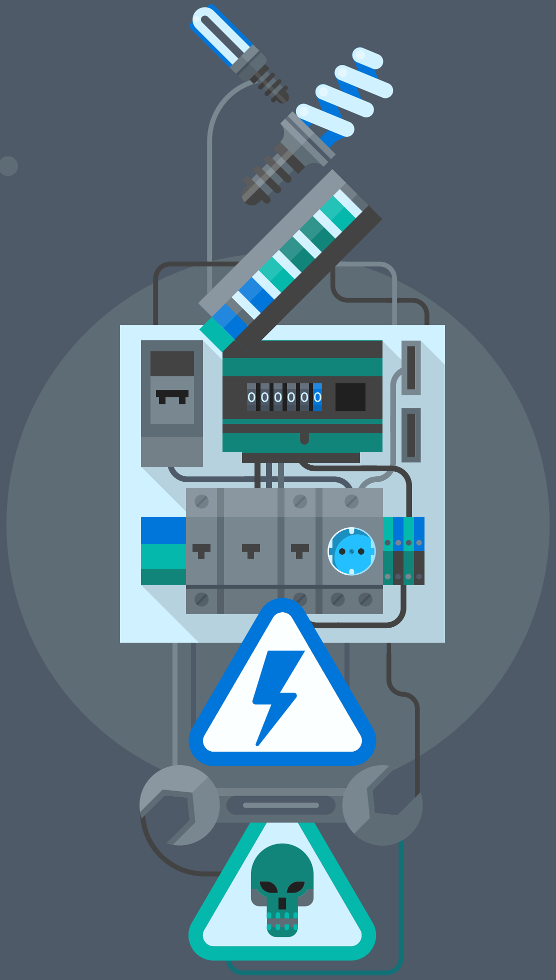
Introduction

- 2D Materials are one or two atoms thick
    - Excellent electrical conductivity
    - Huge impact on electronics industry
- Assist with semiconductors
    - Great electrostatic control due to thinness
- Addresses issues in traditional semiconductors:
    - Leakage currents
    - Thermal dissipation
    - Short-channel effects



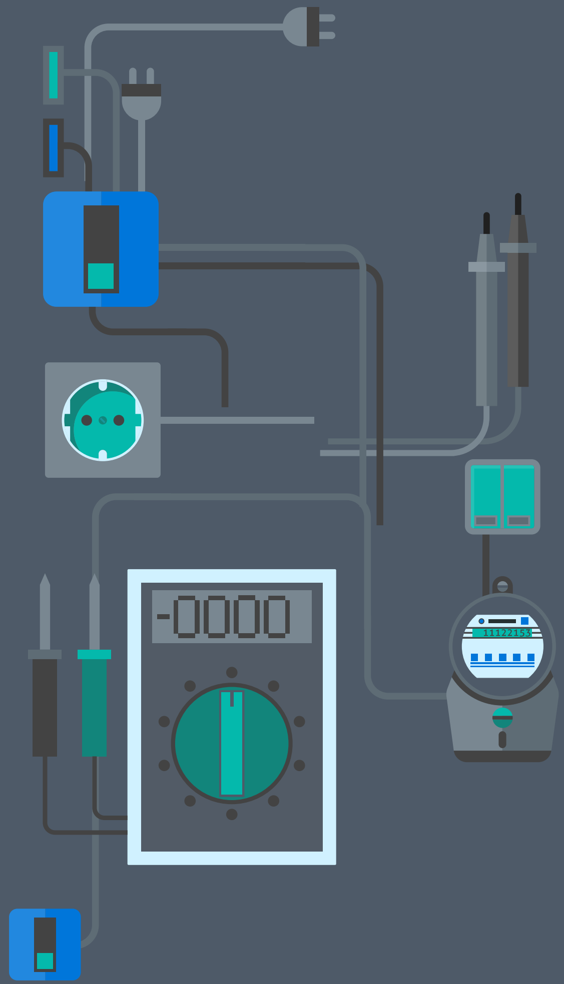
Introduction

- Important 2D Materials
  - Graphene
  - Hexagonal Boron Nitride (hBN)
  - Silicene
  - Molybdenum Disulfide (MoS2)
- Important attributes
  - Capability to create complex heterostructures
  - Enables, tunneling FETs, custom electronic circuits & memory devices



02

Graphene



Graphene

Material Structure

- Hexagonal lattice:
  - A single layer of carbon atoms
  - Stable & High electrical conductivity
- Band Structure:
  - Zero bandgap semi-metal property
  - High mobility due to massless Dirac fermions
- Flexibility & strength:
  - 100x stronger than steel
  - Light, flexible & durable

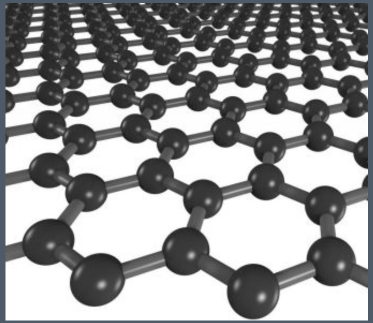
Electromagnetic Properties

- Remarkable electrical conductivity
- Responds well to Terahertz radiation
  - Ideal for wireless communication, photonics, & optoelectronics
- EM Shielding
  - Effective against EMI & RFI

Graphene

Mechanical & Thermal Properties

- Tensile Strength: about 130 GPA
- Flexibility
  - Suitable for flexible electronics
- High thermal conductivity: 5,300 W/m-K
  - Used for thermal management



Future of Graphene

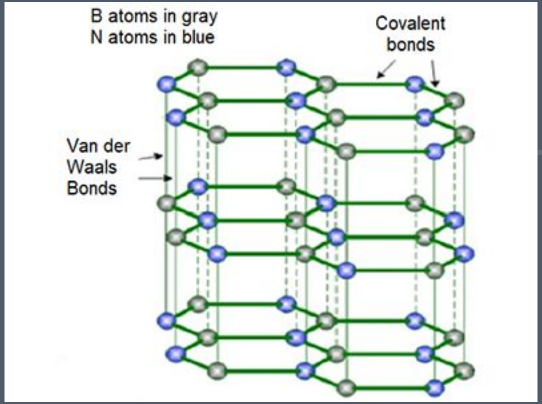
- Challenges
  - Difficult to scale & control properties
- Transistors:
  - Faster
  - More efficient alternative to silicon
- Sensor:
  - High sensitivity for biosensing & environmental monitoring
- Displays:
  - Transparent & conductive
  - Could replace ITO in screens

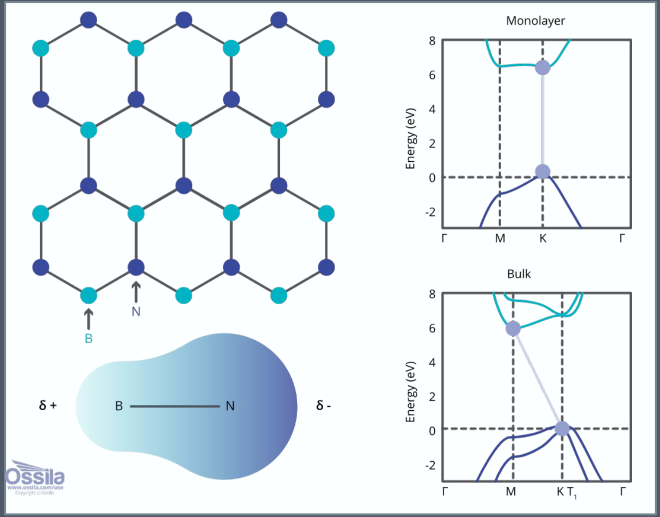
03

Hexagonal Boron Nitride (hBN)

Hexagonal Boron Nitride (hBN)

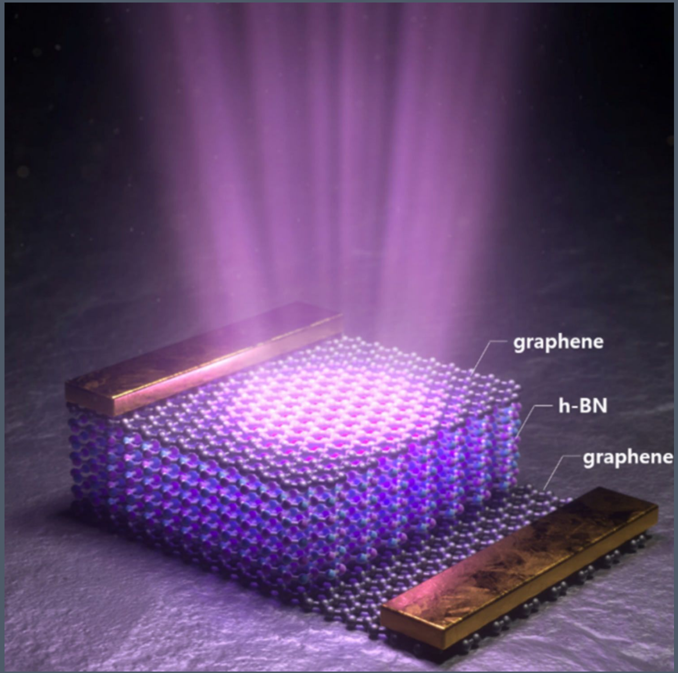
- **Structural Overview:**
  - 2D Hexagonal lattice, insulating
  - High chemical stability, optical transparency, & atomically smooth surface
    - Ideal substrate for van der Waals heterostructures
  - Layer-dependent bandgap
    - Monolayer: direct bandgap (about 5.76 eV)
    - Multilayer: Indirect bandgap (about 5.955 eV)
- **Synthesis:**
  - Chemical Vapor deposition (CVD) most consistent method
  - Monolayer hBN:
    - Achieved through triangular or hexagonal lattice on Cu substrate
  - Multilayer hBN:
    - Improves carrier mobility in graphene FETs





Hexagonal Boron Nitride (hBN)

- **Applications:**
  - DUV LEDs
    - Sterilization, water purification, & photocatalysis
    - Parallel emission = more effective beam
  - DUV Photodetectors
    - Flare detection, air purification, & advanced communication technologies
    - More responsive PD through adding other material
  - IR Absorbers/Emitters
    - Radiative cooling, IR sensors, & biosensing
- **Challenges:**
  - Difficult to scale
  - Reproducibility of high-quality hBN

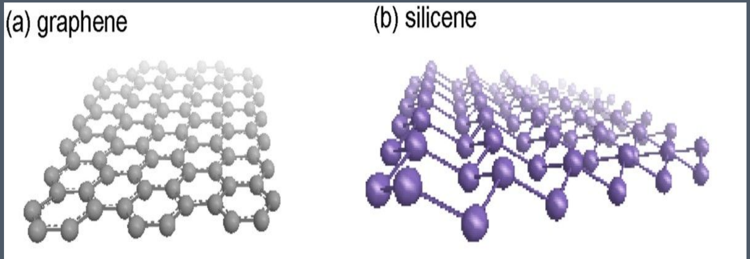


04

Silicene

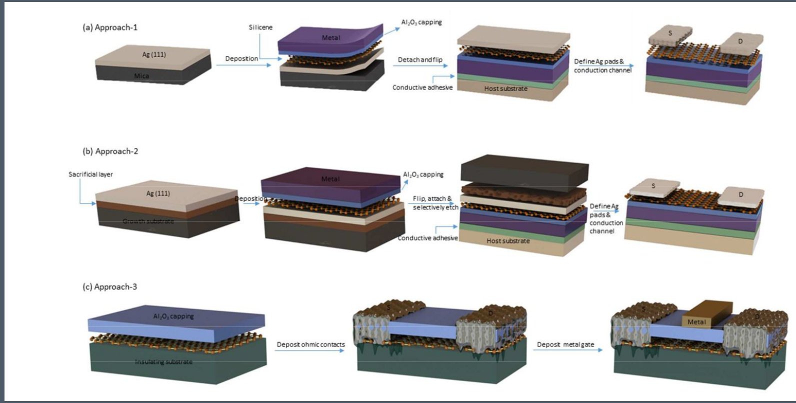
Silicene

- Structure & Composition
  - 2D hexagonal structure w/ silicon atoms
  - Buckled topology
- Manufacturing Challenges
  - Techniques from graphene not transferred due to buckling
  - Reactive with air, losing key properties
    - Solution: encapsulation & passivation



Silicene

- Bandgap Properties
  - A semi-metal = no bandgap
  - Bandgap can be modified
    - Topological changes
    - Introducing an element
- Aplications
  - Benefits in miniaturization of transistors
  - Layers give opportunity for new transistors

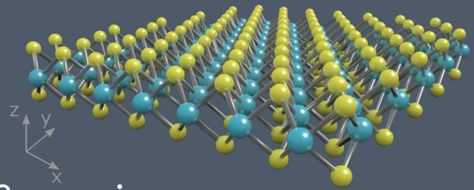


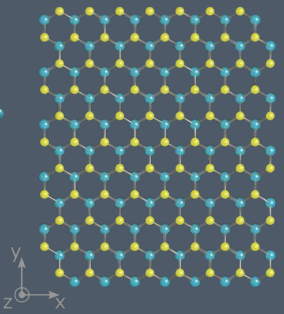
05

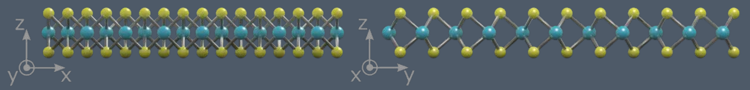
MOLYBDENUM DISULFIDE (MoS2)

MoS2 Structure and Properties

- **MoS2 & Properties:**
  - Transition metal dichalcogenide (TMDC) layered with S-Mo-S
  - Monolayer, direct bandgap
    - Ideal for photodetectors & transistors
  - Reduced mobility due to indirect bandgap
    - Thinner = Better mobility
    - Thicker = more scattering
- **Phase Transitions:**
  - 2H Phase, semiconducting (hexagonal)
  - 1T Phase, Metallic (tetragonal)
  - Creates tunable applications in logic, memory, & sensing

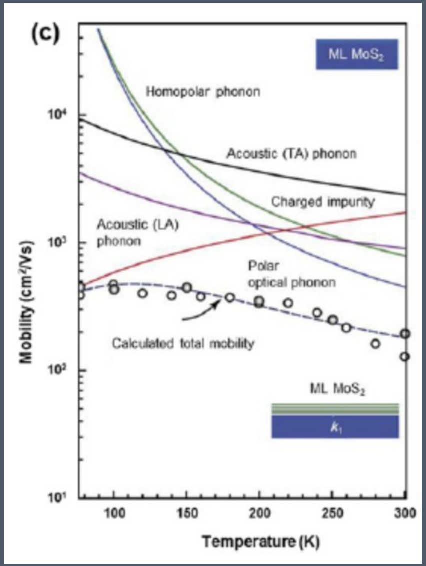






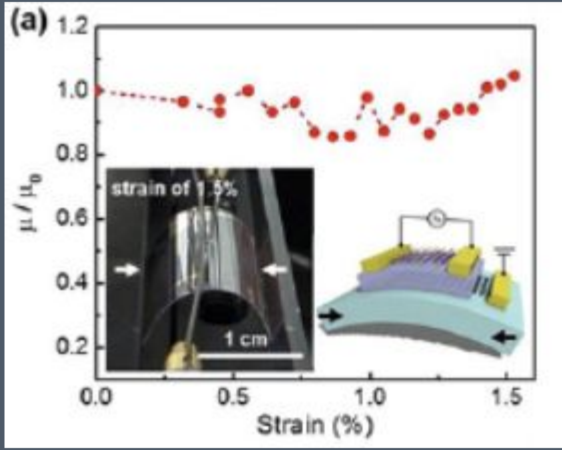
MoS2 Challenges and Optimization

- **Challenges:**
  - Mobility is limited:
    - Photon scattering
    - Surface impurities & dielectric film interactions
- **Optimization**
  - Intrinsic mobility achieved by:
    - hBN as an encapsulation layer
    - Using graphene as a contact electrode
  - Can have high mobility after techniques



Popular MoS2 Applications

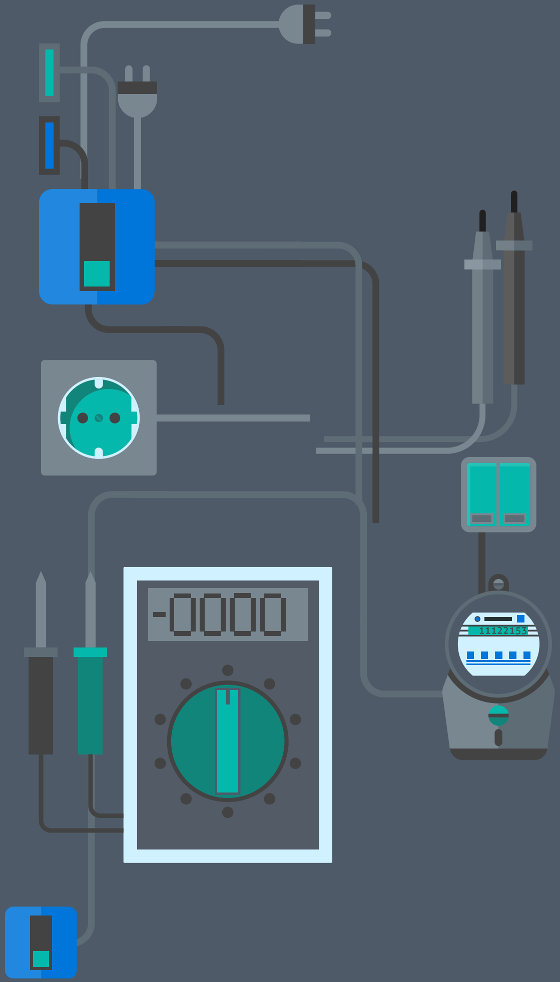
- **In Flexible & Optoelectronic Devices :**
  - Flexible electronics
    - Used in trilateral FETS & durable under 1.5% strain
  - Opto electronics:
    - Visible light sensitive photo transistors
  - Piezoelectrics
    - Odd layer MoS2 effects
- **In 2D Tunnel Devices**
  - In tunnel FETs for low power electronics
  - Bilayer MoS2 & doped Ge
    - Enables quantum tunneling



06

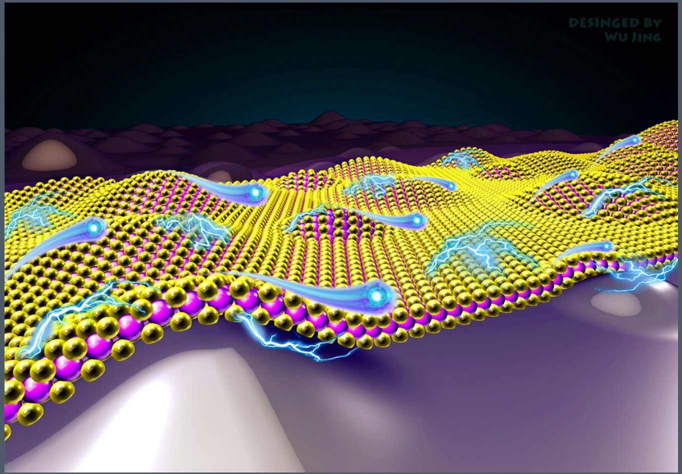
2D Materials in Electronics

How the materials work in Electronics



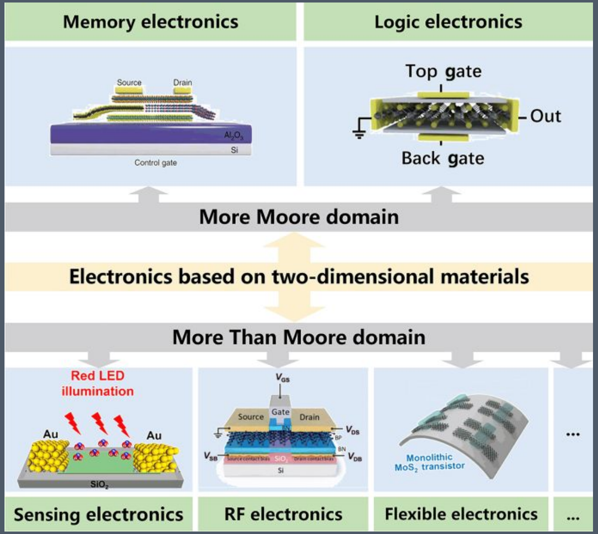
2D Materials in Electronics

- **Important in semiconductors**
    - Due to their properties
    - Helping develop
    - Solve key semiconductor issues
- **Semiconductor Integration**
    - Chemical Vapor Deposition (CVD)
        - Most effective
    - Adhesive Wafer Bonding
        - Integrates delicate 2D materials
        - Uses polymer based adhesive
    - Van der Waals Assembly
        - Naturally held together
        - Provides stability
    - Transfer & Buffer Layer Techniques
        - Move CVD grown 2D fils to target
        - Protects 2D layers during processing



2D Materials in Electronics

- **Key Device Applications**
  - Logic & Transistors
    - MoS2 & Graphene: Ultra thin & high mobility
    - Integration with silicon via back end of line
  - Flexible Electronics
    - Work under physical strain
    - Enables low-temp integration
  - Optoelectronics
    - MoS2 visible for light detection
    - hBN for DUV LEDs/PDs
  - Quantum & Tunnel Devices
    - Ideal for low power
    - High efficiency logic
- **Industry Direction**
  - Fabrication: defect control & layer uniformity
  - Interfaces: contact resistance



07

Flexible Electronics with 2D Materials

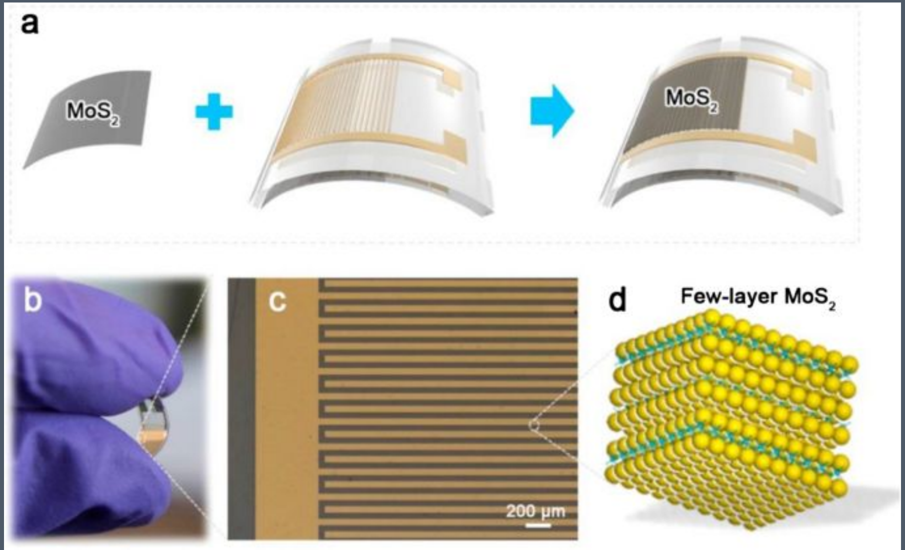
Flexible Transistors

Formed by depositing 2D materials on PET or polymer films via CVD

FET Type	Why It Works	Example Applications
TMD’s	Sizeable bandgap (~2 eV), high ON/OFF ration → compatible with CMOS logic	Flexible CPUs Memory for Foldable electronics
BP	High carrier mobility, tunable bandgap → fast, controllable switching	RF Amplifiers Wireless Wearables
Graphene	Extremely fast mobility & transparent	Wearable analog electronics

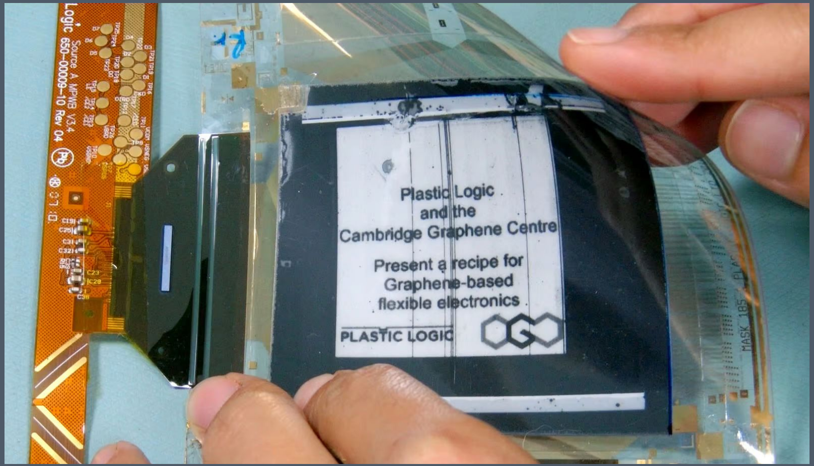
Flexible Photodetectors

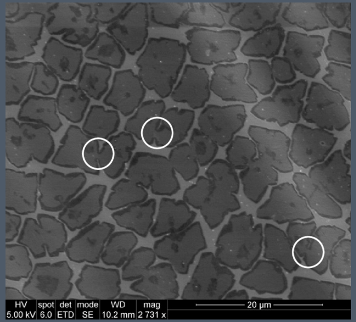
- Created through embedding TMD nanosheets into polymer matrices (MoS_2 & $MoSe_2$)
- Able to detect light across a broad spectrum and target specific wavelengths via layer-blending techniques
- Useful for foldable cameras, wearable optical sensors, and medical imaging



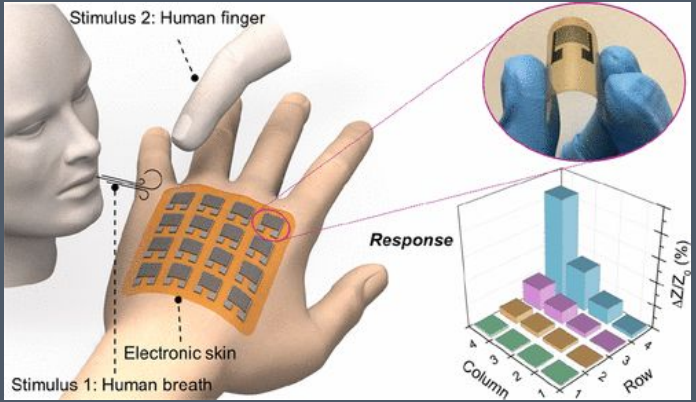
Flexible Screens

- Graphene has 97.7% light transmission
- Able to withstand 3% uniaxial tension and 0.3% uniaxial tensile strain
- Maintained electric performance under deformation by forming “islands” that prevent shatter



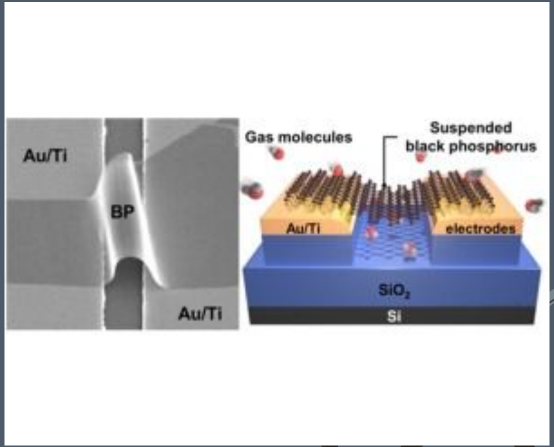


Flexible Sensors



- Detect changes in pressure, temperature, strain, and touch via changes in graphene's resistance

- BP's direction-dependent conductivity and tunable bandgap make it effective for pressure and gas sensing.



08

Conclusion

Concluding 2D Materials in Electronics

Concluding

- 2D materials such as graphene, MoS_2, hBN, and silicene are changing the future of electronics.
- Although there are challenges in increasing production, keeping quality high, and making sure they work well with other materials, continuous research and development are revealing the technological potential and commercial success of these materials.

THANK YOU!