ECE 340 Lecture 1
Semiconductor Electronics

Spring 2022
10:00-10:50am
Professor Umberto Ravaioli
Department of Electrical and Computer Engineering
2062 ECE Building

Introductory Lecture

- Background and Motivation
- Course Purpose & Objectives
- Introduction to Semiconductor Electronics

Background and Motivation

Electronics beginnings – 1

- **1875-1883** The “Edison effect” in incandescent bulb with an additional filament is discovered but not understood
- **1895** Guglielmo Marconi invents wireless telegraph
- **1897** Joseph Thomson discovers the electron
- **1902** Reginald Fessenden invents amplitude modulation (AM) for telephone; **1906** first AM radio transmission
- **1904** John Fleming realizes the vacuum tube diode (using the Edison effect)
- **1905** Einstein explains thermionic emission
- **1912** Lee de Forest invents Vacuum Tube Triode amplifier
- **1919** Edwin Armstrong invents the superheterodyne radio receiver
- **1920** Westinghouse starts KDKA commercial radio station in Pittsburgh

Electronics beginnings – 2

- **1923** Vladimir Zworykin invents television
- **1926** Transatlantic telephone service between London and New York
- **1932** Guglielmo Marconi realizes first microwave telephone link, between the Vatican and the Pope's Summer residence
- **1933** Edwin Armstrong invents frequency modulation (FM)
- **1935** Regular television transmissions begin in Germany, followed by England (**1936)** and USA (**1939**)
- **1935** Robert Watson-Watt invents the Radar
- **1938** Alec Reeves invents Pulse Code Modulation (PCM)

Solid State was working only in detectors

- **1874-1899** Karl Braun studied asymmetric conduction in various sulfide crystals with a metal point-contact (wire car whisker) and patented a device in **1906**
- **1901** Jagadish Bose patents a detector made with PbS galena crystal and a metal point-contact (considered the first patent on a semiconductor device)
- **1902** Greenleaf Pickard discovers rectification of radio waves with a crystal detector and patents a silicon point-contact rectifier in **1906**
- **1931** Nevill Mott and Walter Schottky develop theories for rectification effects in metal-semiconductor junctions, improved by Hans Bethe in **1942**

Solid State was not working in amplifiers

The first attempts were based on the "field-effect"

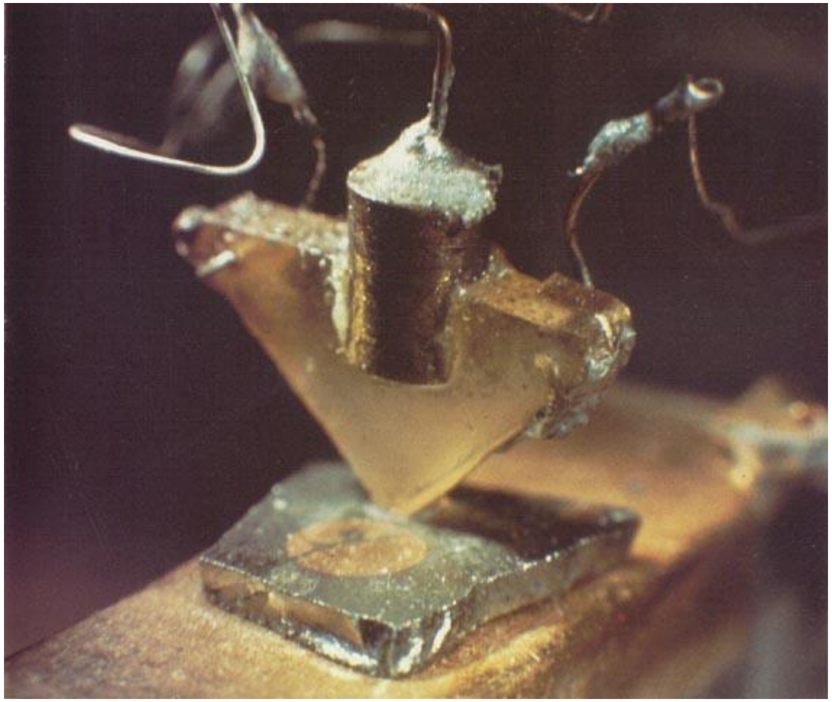
- **1926** Julius Lilienfeld files concept patent for a three-electrode amplifying device based on the semiconducting properties of copper sulfide
- **1934** Oskar Heil files a patent for controlling current flow in semiconductor via capacitive coupling of an electrode
- **1938** Robert Pohl and Rudolph Hilsch reported amplification at 1Hz with a potassium bromide three-terminal structure but leading to no practical device
- **1939** and later in **1945** William Shockley attempts to develop a solid-state amplifier with an oxide gate in a field-effect structure

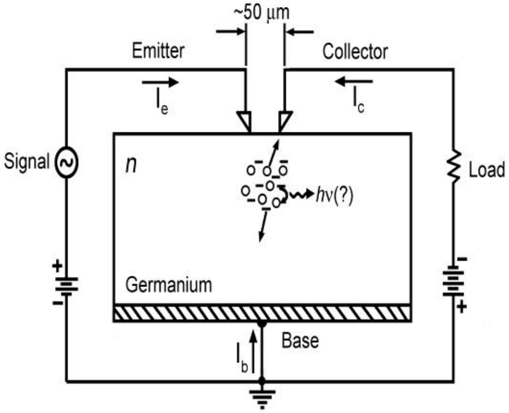
All these early attempts were unsuccessful

Why not Vacuum tubes?

- Vacuum Tube Triode
  - Hot cathode needs warm-up
  - Bad Reliability
  - Not amenable to complex systems or integration
  - ENIAC, the first all-electronic computer (1945) had
    - 20,000 vacuum tubes
    - 7,200 crystal diodes
    - 1,500 relays
    - 70,000 resistors
    - 5,000,000 hand-soldered joints
    - 27 tons; over 1,800 feet^2; 150kW; 5kHz

Discovery of Transistor by Bardeen and Brattain (1947)





Videos

https://www.youtube.com/watch?v=RdYHljZi7ys

Engineerguy: “How the first transistor worked”

Extended PBS documentary “Transistorized”:

https://www.youtube.com/watch?v=U4XknGqr3Bo

Major Milestones in Semiconductor Devices and Integrated Circuits (Illinois ECE Connection)

1947: First Bipolar Transistor (Bardeen & Brattain)
1958: Invention of Integrated Circuits (Kilby & Noyce)
1960: First MOSFET (Kahng and Atalla)
1962: First LED and Semiconductor Laser (Hall, Holonyak)
1963: Invention of CMOS (Wanlass and Sah)
1968: Invention of DRAM (Dennard)
1971: First Microprocessor (Intel)

UIUC ECE
B.S. '50, M.S. '51, Ph.D. '54
ECE Professor: 1963-2013

ECE Professor: 1951-1975

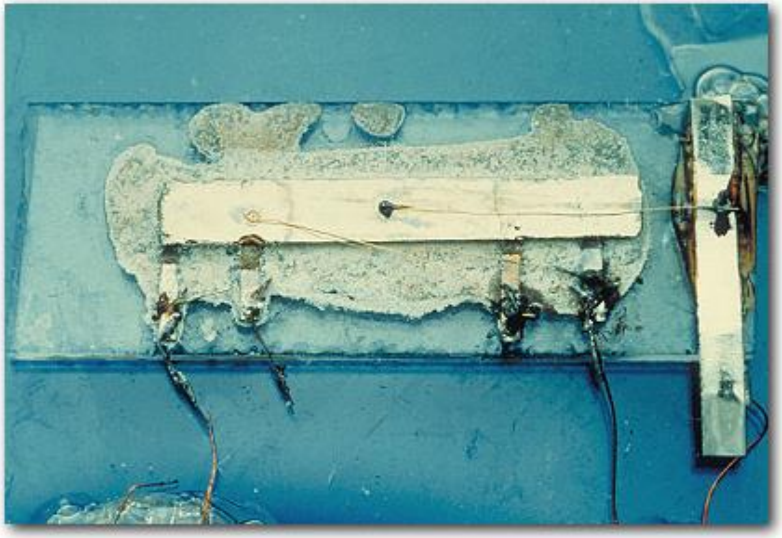
UIUC ECE
B.S. '53
ECE Professor: 1962-1988

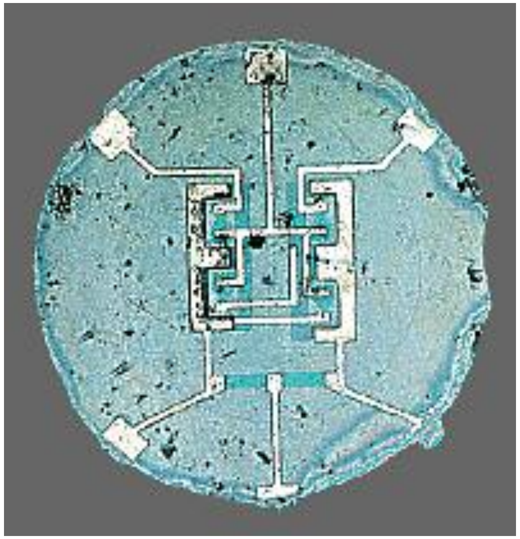
Kilby & Noyce: Integrated Circuit, 1958

Jack Kilby

Robert Noyce

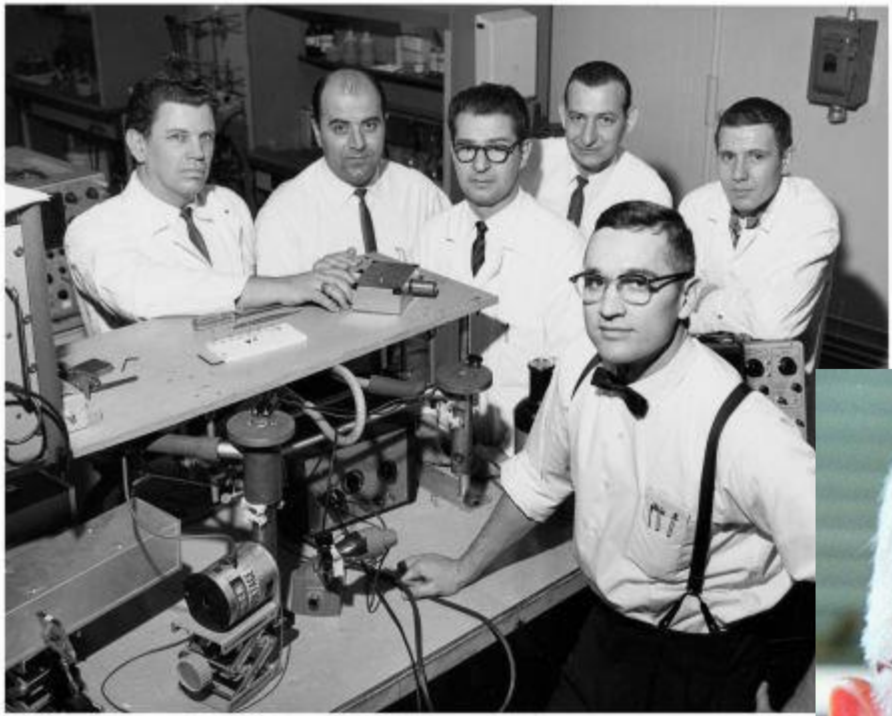
UIUC ECE
B.S. '47



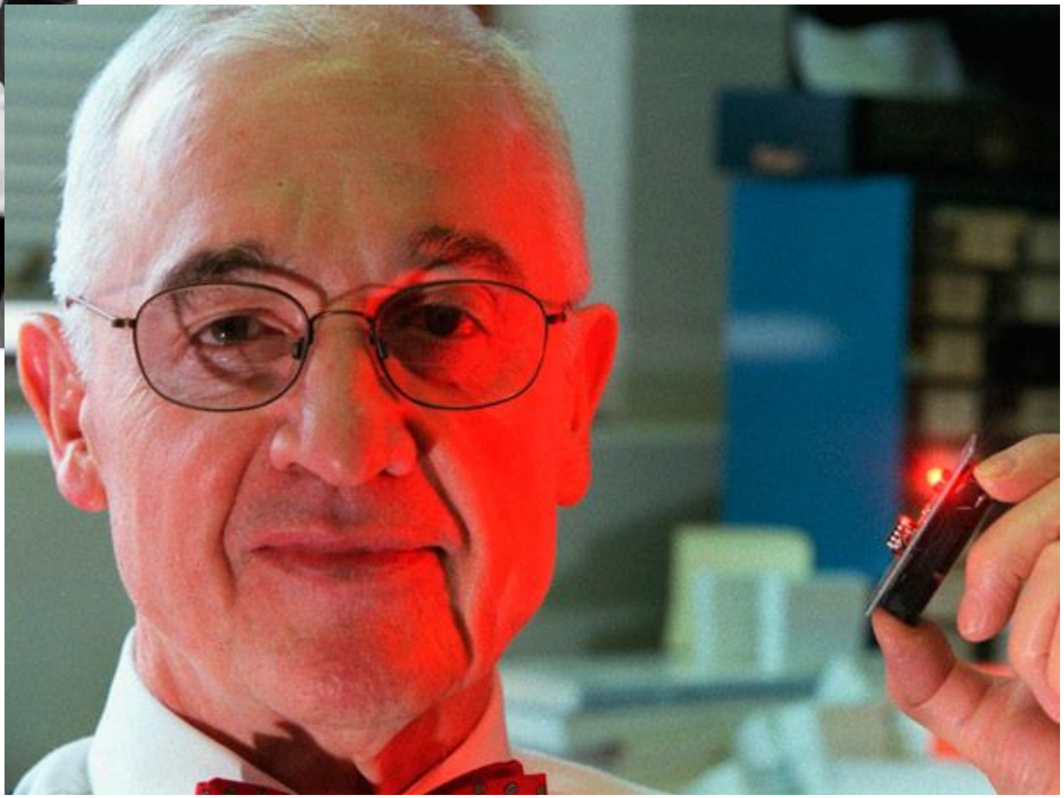


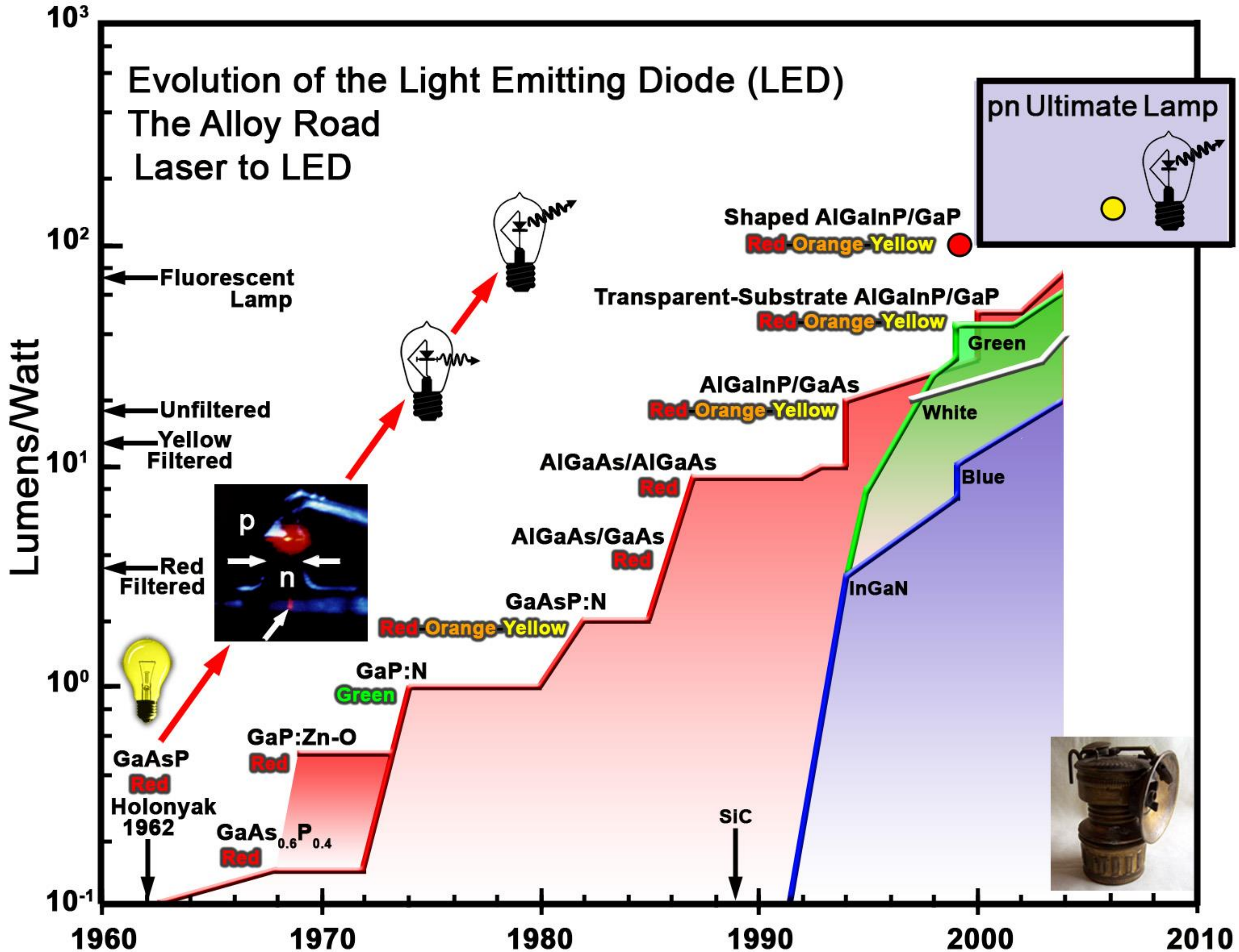
http://www.mainbyte.com/ti99/history/history.html

First Practical LED: 1962



Nick Holonyak



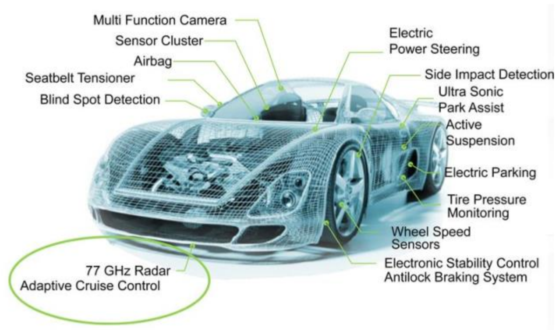


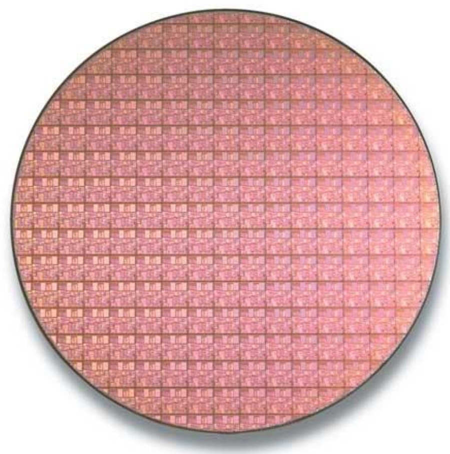
Evolution of the Light Emitting Diode (LED)
The Alloy Road
Laser to LED
pn Ultimate Lamp
Shaped AlGaInP/GaP
Red-Orange-Yellow
Transparent-Substrate AlGaInP/GaP
Red-Orange-Yellow
Green
AlGaInP/GaAs
Red-Orange-Yellow
White
AlGaAs/AlGaAs
Red
Blue
AlGaAs/GaAs
Red
InGaN
GaAsP:N
Red-Orange-Yellow
GaP:N
Green
GaP:Zn-O
Red
GaAsP
Red
Holonyak
1962
GaAs0.6P0.4
Red
SiC
Fluorescent
Lamp
Unfiltered
Yellow
Filtered
Red
Filtered
p
n
Lumens/Watt
10³
10²
10¹
10⁰
10⁻¹
1960
1970
1980
1990
2000
2010

Motivation

Why is this course important?

Semiconductors Are Everywhere





2017 Worldwide Semiconductor Sales: $408.7 Billion

Larger Than Most Countries' GDP (Only ~27 Larger), Global Software $406.6 Billion

Behind the Cloud

Supercomputer Optical Interconnects

Server Room

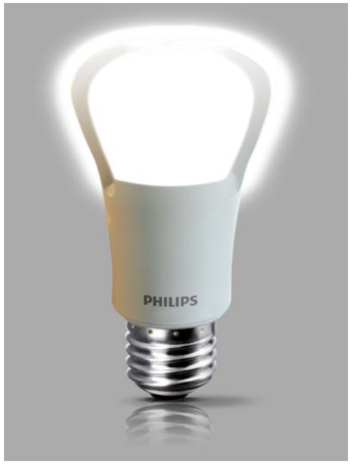
Data Center

LED Applications

LED Traffic Signals

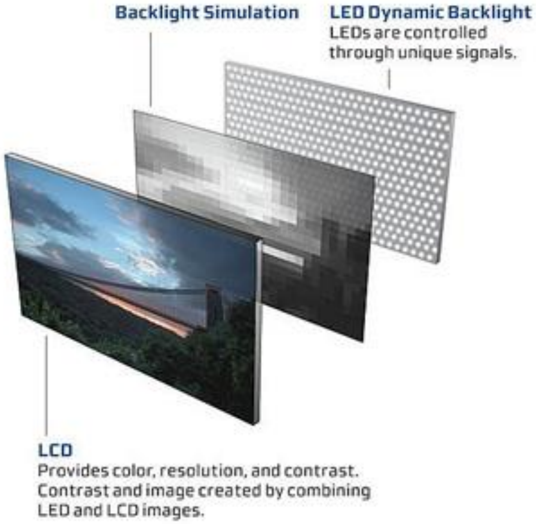
Source: gelightingsolutions.com

LED General Lighting



Source: led-resource.com

LED Backlit TV



Source: digitaltrends.com

Architectural Lighting

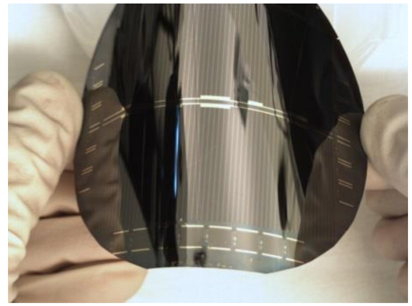
Source: vividleds.us

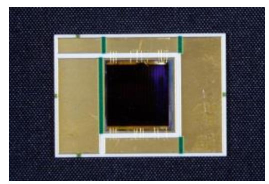
Automotive

Source: spie.org

High Efficiency Solar Cells

Terrestrial Power





UAV

Space

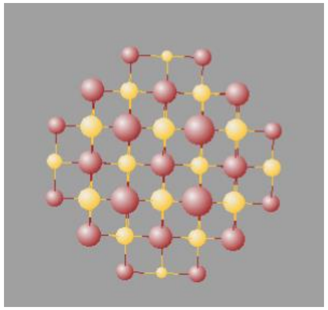
Military

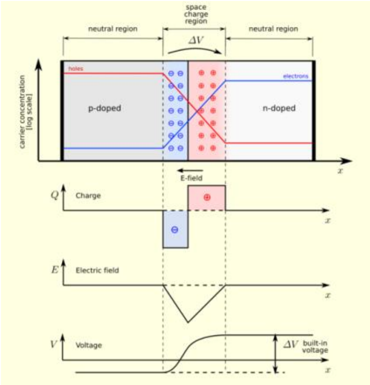
Wireless

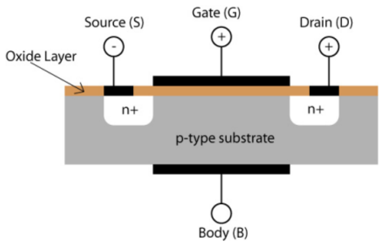
Course Purpose and Objectives

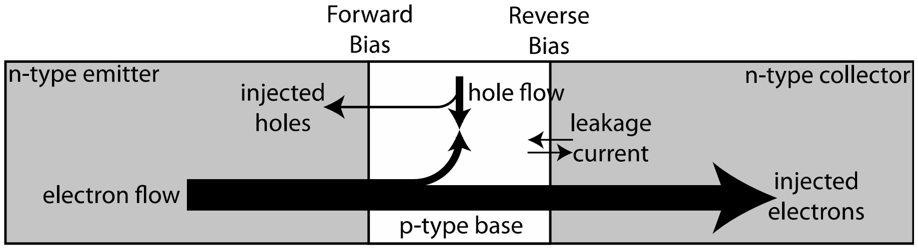
Course Purpose & Objectives

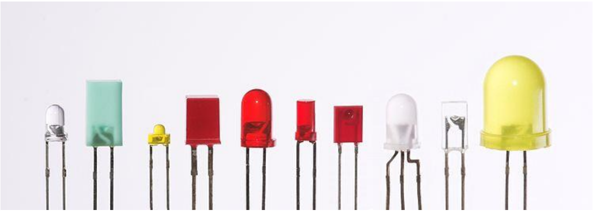
- Introduce key concepts in semiconductor materials
- Provide a basic understanding of p-n junctions
- Provide a basic understanding of light-emitting diodes and photodetectors
- Provide a basic understanding of field effect transistors
- Provide a basic understanding of bipolar junction transistors











Semiconductor Materials

Periodic Table of the Elements

	1	2	3	4	5	6	7	8	9	10	11	12	III	IV	V	VI	17	18
1	1 H Hydrogen 1.00794	Atomic # Symbol Name Atomic Mass																2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

C Solid · Hg Liquid · H Gas · Rf Unknown

Metals: Alkali metals · Alkaline earth metals · Lanthanoids · Actinoids · Transition metals · Poor metals

Nonmetals: Other nonmetals · Noble gases

II

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Ptable.com

Important Material Systems

- **Elemental Semiconductors**

  Silicon

  Germanium

- **Binary Semiconductors**

  Column IV

  SiGe

  SiC

  Columns III & V

  InP

  GaAs

  GaN

  InAs

  Columns II & VI

  ZnS, ZnSe, ZnO

  CdS, CdSe, CdTe

Important Material Systems

- Ternary Semiconductors

  AlGaAs

  InGaAs

  GaAsP

  InGaN

  HgCdTe

  ZnCdS

- Quaternary Semiconductors

  InGaAsP

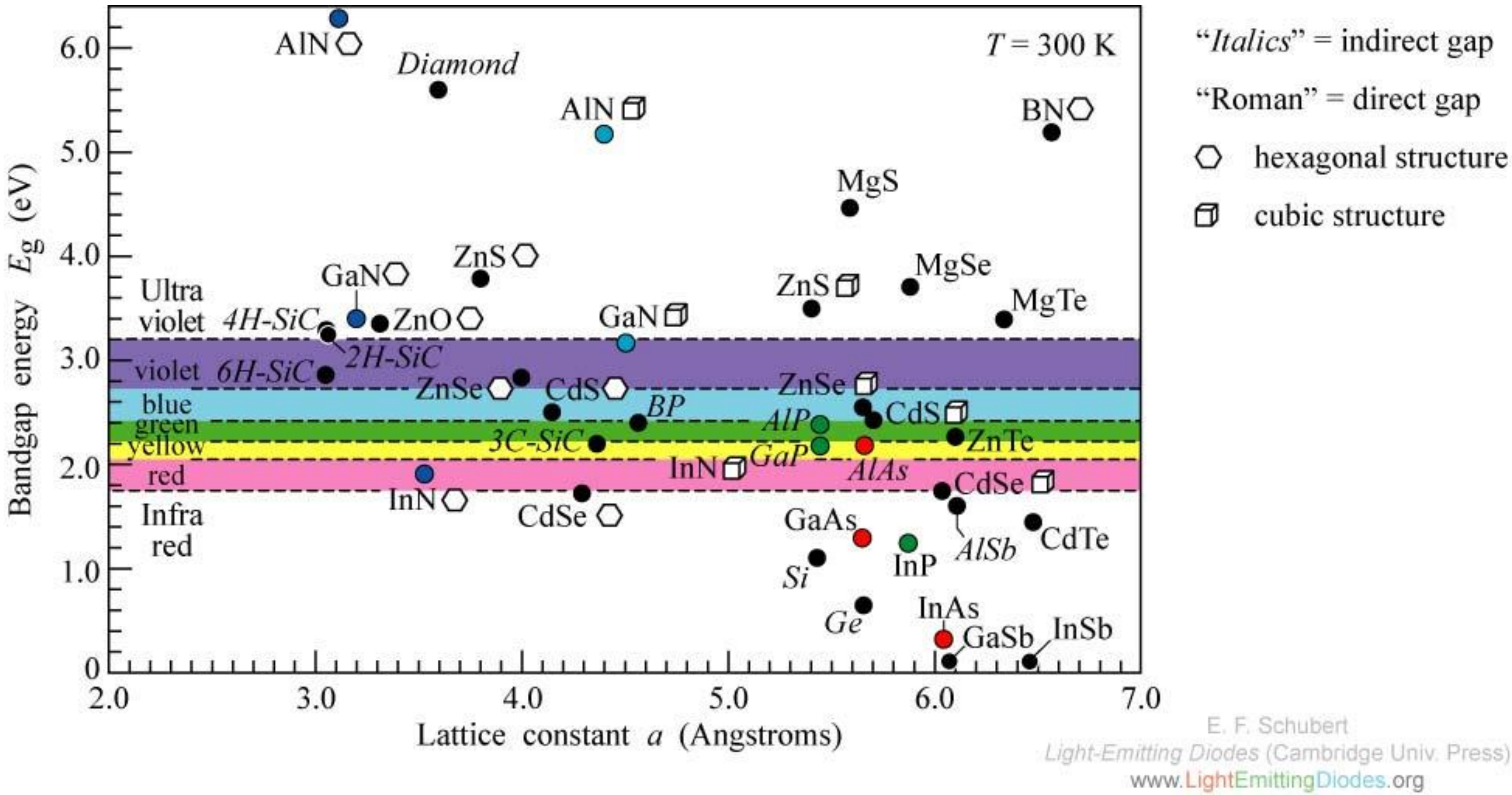
  InAlGaAs

  InGaAsP

  InAlGaP

  GaInNAs

Bandgap and Lattice Constant of Common Semiconductors



General Introduction to Semiconductor Electronics

Basic Equations for Semiconductor Device Operation

- The basic equations can be classified in four groups:
  - **Maxwell's Equations:** we will use mainly electrostatics (Poisson's equation)
  - **Current-Density Equations:** we will use the drift-diffusion approximation
  - **Continuity Equations** (conservation law)
  - **Quantum Mechanics**: we will refer to quantum mechanical principles but will not apply directly quantum models

Maxwell Equations for Homogeneous and Isotropic Materials

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = -\frac{\partial D}{\partial t} + J_{cond} = J_{total}$$

$$\nabla \bullet D = \rho(x,y,z)$$

$$\nabla \bullet B = 0$$

$$B = \mu_o H$$

$$D(r,t) = \int_{-\infty}^{t} \varepsilon_s(t - t')E(r,t')dt'$$

$$= \varepsilon E + P$$

E: electric field

D: electric displacement

B: magnetic field

H: magnetizing field

ε_s: permittivity

μ_o: permeability

ρ: total electric charge density

J_{cond}: the conduction current density

P: polarization density

$\times$: curl operator

$\bullet$: divergence operator

Electrostatics is what we use typically

Gauss Law

$$\nabla \bullet D = \rho$$

In one dimension: $\mathcal{E}(x) = -\dfrac{d\mathcal{V}(x)}{dx}$

$$D = \varepsilon \mathcal{E}$$

$$\mathcal{V}(x) = -\int \mathcal{E}(x)dx$$

Electric field

$$\mathcal{E} = -\nabla \mathcal{V}$$

Poisson Equation

$$\nabla \bullet D = \rho \rightarrow \nabla \bullet \mathcal{E} = \frac{\rho}{\varepsilon} \rightarrow \nabla^2 \mathcal{V} = -\frac{\rho}{\varepsilon}$$

$$\xrightarrow{1-D} \frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon} \rightarrow \frac{d^2\mathcal{V}}{dx^2} = -\frac{\rho}{\varepsilon}$$

Current-Density Equations

Drift ↓ Diffusion ↓

$$J_n = q\mu_n nE + qD_n \nabla n$$

$$J_p = q\mu_p pE - qD_p \nabla p$$

$$J_{cond} = J_n + J_p$$

- Two charge carriers
  - Electrons
  - Holes
- Drift caused by fields
- Diffusion by carrier concentration gradient

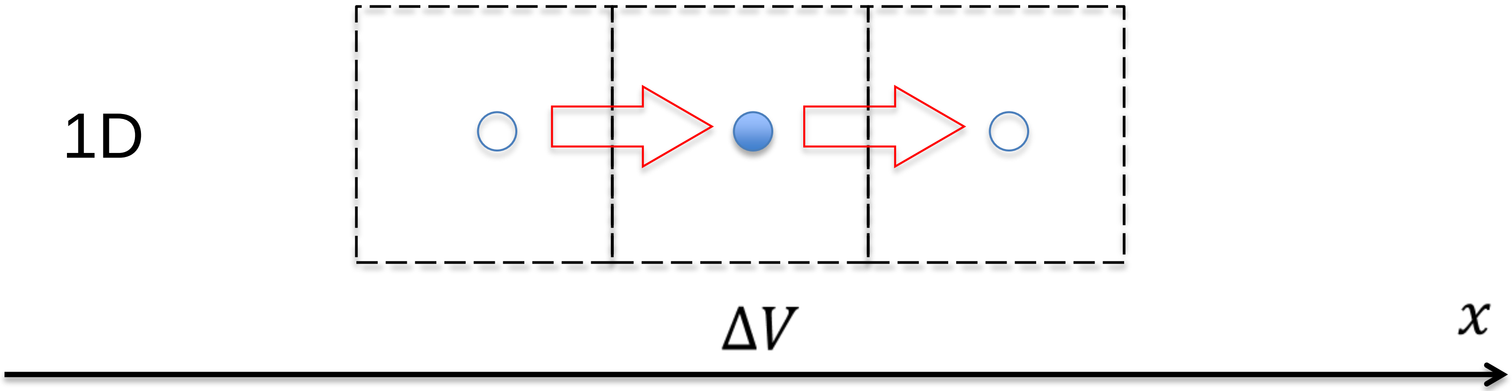
Continuity Equations

Conservation of charge

$$\frac{\partial n}{\partial t} = G_n - U_n + \frac{1}{q} \nabla \bullet J_n$$

$$\frac{\partial p}{\partial t} = G_p - U_p - \frac{1}{q} \nabla \bullet J_p$$

1D



Quantum Mechanics

Schrodinger's Equation :

$$-\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi = -\frac{\hbar}{j}\frac{\partial\Psi}{\partial t}$$

(Kinetic Energy + Potential Energy = Total Energy)

Could be used to study the behavior of a single particle
Not suitable for device simulation

$\Psi(x, y, z, t)$ = wave function

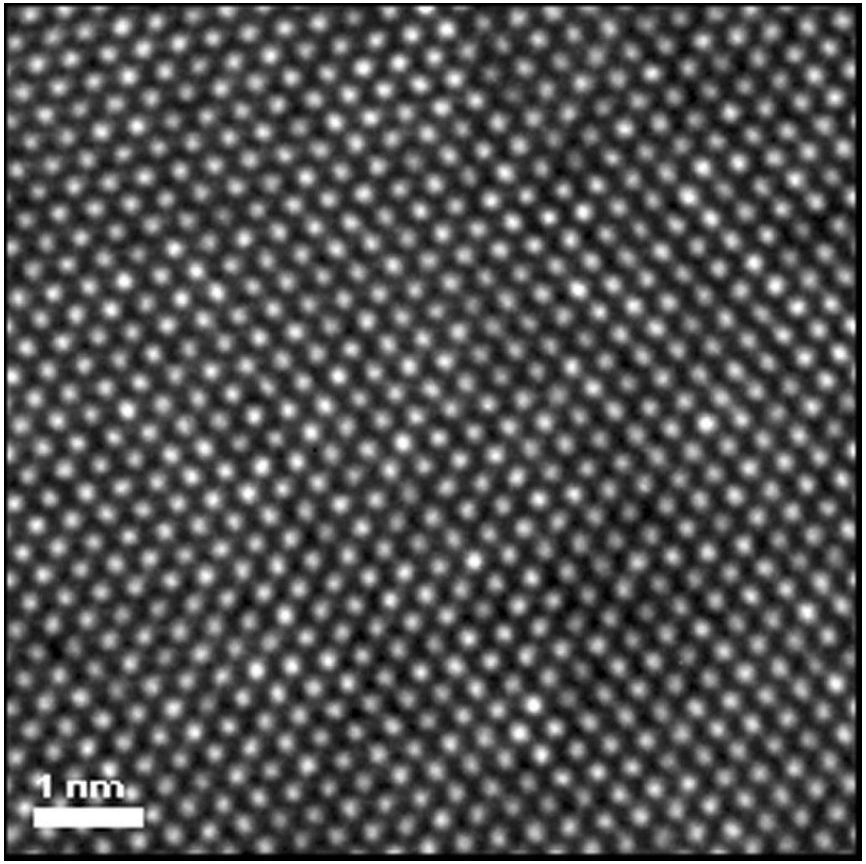
The probability of finding a particle with wave function Ψ is $\Psi^*\Psi$

The particle is somewhere, so $\int_{-\infty}^{\infty} \Psi^*\Psi \, dxdydz = 1$

Lattices and Crystal Structures

Types of Solids (1) Crystalline

Ki-Bum Kim, Seoul National University (2008)

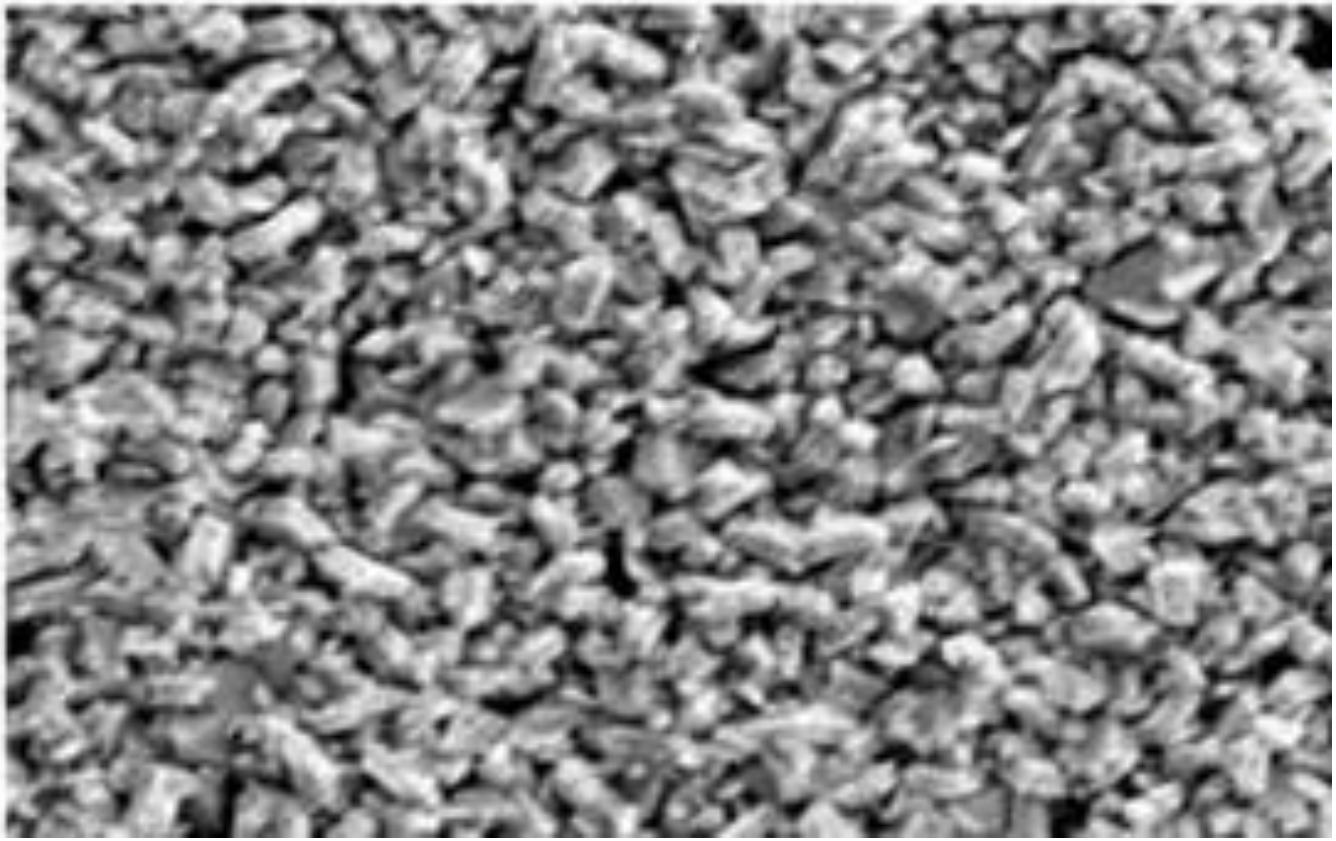


HRTEM image of a silicon (Si) [110] crystallographic zone axis.

In the CRYSTALLINE state the atoms are ordered into a well-defined lattice that extends over very long distances

Types of Solids (2) Amorphous

Rajathi and Berchmans, www.nature.com/scientificreports (2019)

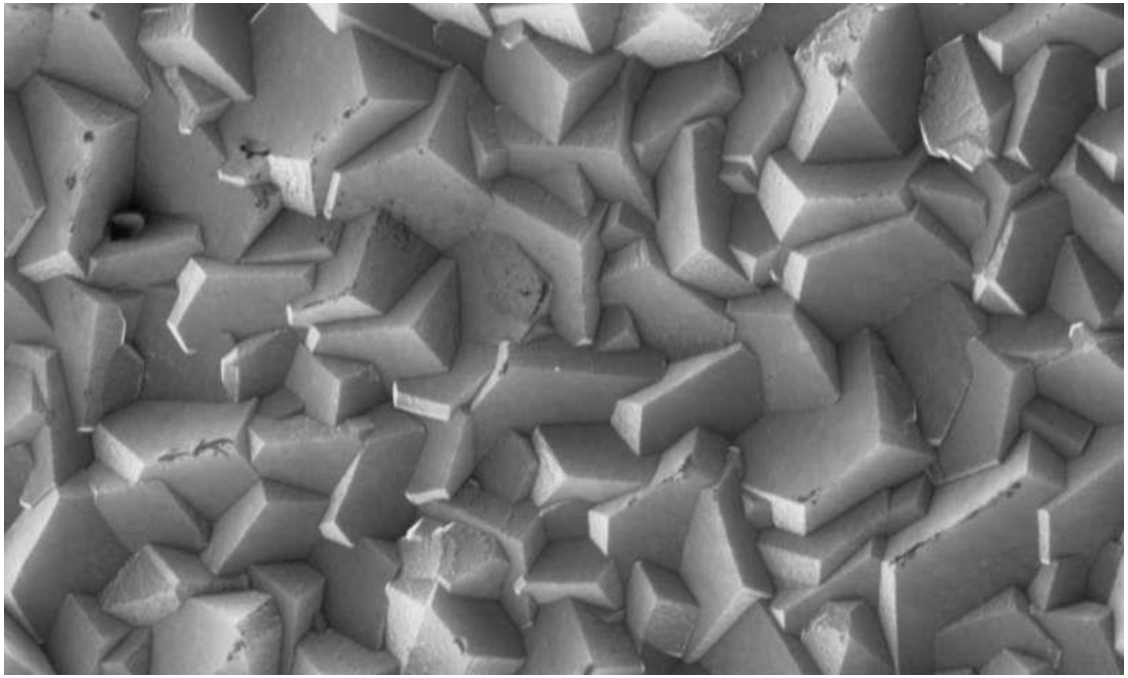


Glassy Palladium

In the AMORPHOUS state there is little or no evidence for long-range crystalline order

Types of Solids (3) Polycrystalline

Tomsk Polytechnic University (2017)



Polycrystalline diamond film

POLYCRYSTALLINE materials consist of small crystallites that are embedded in AMORPHOUS regions of material

Crystal Lattice

- **Lattice:** Periodic arrangement of a substance or "**basis**"
  - Atom, atomic pair, group of atoms, molecule, etc.
- **Unit Cell:** Contains a region which is representative of the lattice which can be regularly repeated to recreate the entire lattice
- **Primitive Cell:** The smallest unit cell that can be repeated in integral steps to produce the lattice
  - Contains a single lattice point
  - The Primitive Cell is a special form of the Unit Cell
- **Primitive Vectors:** **a, b, c**
  - (1 dimension) $r = p\,\mathbf{a}$
  - (2 dimension) $r = p\,\mathbf{a} + q\,\mathbf{b}$
  - (3 dimension) $r = p\,\mathbf{a} + q\,\mathbf{b} + r\,\mathbf{c}$
- **Basis Vectors**: Similar to primitive vectors, but used to replicate the lattice through the translation of a unit cell

Simple Lattices and Unit Cells

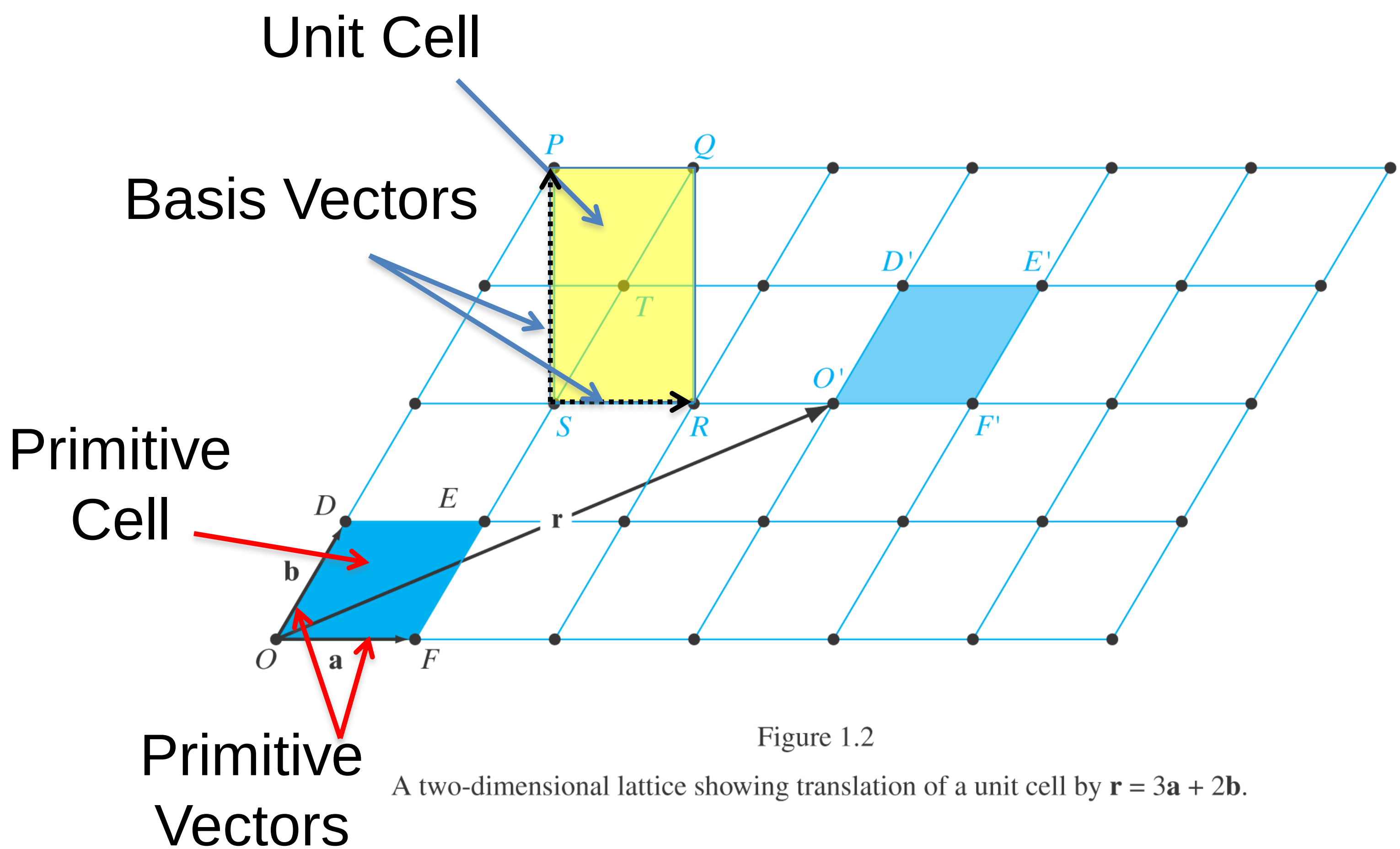


Figure 1.2

A two-dimensional lattice showing translation of a unit cell by **r** = 3**a** + 2**b**.

From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.