# Lecture 1

# Introduction to Semiconductors and Semiconductor Devices A Background Equalization Lecture

**Reading:** 

Notes

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### **Sources of Information**

# **Reading: Notes are taken from a combined source of:**

# •Brennan – The Physics of Semiconductor Devices

- •Solymar and Walsh Electrical Properties of Materials
- •Neudeck and Pierret Advanced Semiconductor Fundamentals
- •Dimitrijev Understanding Semiconductor Devices
- •Mayer and Lau Electronic Materials Science
- •Colclaser and Diehl-Nagle Materials and Devices for electrical engineers and physicists
- •Tipler Physics for scientists and engineers V4.
- •Schubert Quantum Mechanics Applied to Semiconductor Devices

# Quantum Mechanics allows us to Understand and Design Complex Semiconductors and Devices

•The goal of this course is to teach the fundamentals of Quantum Mechanics, a modern approach to physics on the nano scale. Understanding of this important concept leads to the ability to:

•Understand and design custom semiconductor materials with optical and electrical properties tailored to specific needs

•Understand and design electrical and optical devices including advanced diodes, LEDs, LASER diodes, transistors (BJT and FET), and advanced device concepts such as microwave compound semiconductors and state of the art devices.

•Even silicon has entered the quantum mechanical domain!



Nakamura, S. *et al.*, "**High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes**," *Appl. Phys. Lett* **67**, 1868 (1995).

### **Devices Requiring Quantum Mechanics**

Heterojunction diodes, ballistic diodes, Schottky barrier diodes, Metal-Semiconductor Contacts, LEDs, Lasers, some Solar Cells, Photodetectors, some **BJTs**, HBT, some **MOSFETs**, MESFET, JFET, Polarization Based Devices (III-Nitrides HEMTs and Ferroelectric transistors), Microwave transistors, power transistors, some organic semiconductors.

# Modern amplifiers consist of extremely small devices – Small means Quantum Behavior



Figure 1-2 Scanning electron micrograph (SEM) of an IC circa mid 1980s. The visible lines correspond to Transistors in the above image are only a few microns (µm or 1e-6 meters) on a side.

Modern devices have lateral dimensions that are only fractions of a micron ( $\sim 0.1 \mu m$ ) and vertical dimensions that may be only a few atoms tall.

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# Famous Last Words: "I only want to design computers. I do not need to know about 'atoms and electrons' ". --- A Doomed Computer Engineer

#### Intel Develops World's Smallest, Fastest CMOS Transistor

SANTA CLARA, Calif., Dec. 11, 2000 - Intel Corporation researchers have achieved a significant breakthrough by building the world's smallest and fastest CMOS transistor. This breakthrough will allow Intel within the next five to 10 years to build microprocessors containing more than 400 million transistors, running at 10 gigahertz (10 billion cycles per second) and operating at less than one volt.

The transistors feature structures just <u>30 nanometers in size and three atomic layers thick.</u> (Note: A nanometer is onebillionth of a meter). Smaller transistors are faster, and fast transistors are the key building block for fast microprocessors, the brains of computers and countless other smart devices.

These new transistors, which act like switches controlling the flow of electrons inside a microchip, could complete 400 million calculations in the blink an eye or finish two million calculations in the time it takes a speeding bullet to travel one inch.

Scientists expect such powerful microprocessors to allow applications popular in science-fiction stories -- such as instantaneous, real-time voice translation -- to become an everyday reality.

Researchers from Intel Labs are disclosing the details of this advance today in San Francisco at the International Electron Devices Meeting, the premier technical conference for semiconductor engineers and scientists.

"This breakthrough will allow Intel to continue increasing the performance and reducing the cost of microprocessors well into the future," said Dr. Sunlin Chou, vice president and general manager of Intel's Technology and Manufacturing Group. "As our researchers venture into uncharted areas beyond the previously expected limits of silicon scaling, they find Moore's Law still intact."

Intel researchers were able to build these ultra-small transistors by aggressively reducing all of their dimensions. The gate oxides used to build these transistors are just three atomic layers thick. More than 100,000 of these gates would need to be stacked to achieve the thickness of a sheet of paper. Also significant is that these experimental transistors, while featuring capabilities that are generations beyond the most advanced technologies used in manufacturing today, were built using the same physical structure as in today's computer chips.

"Many experts thought it would be impossible to build CMOS transistors this small because of electrical leakage problems," noted Dr. Gerald Marcyk, director of Intel's Components Research Lab, Technology and Manufacturing Group. "Our research proves that these smaller transistors behave in the same way as today's devices and shows there are no fundamental barriers to producing these devices in high volume in the future. The most important thing about these 30 nanometer transistors is that they are simultaneously small and fast, and work at low voltage. Typically you can achieve two of the three, but delivering on all facets is a significant accomplishment."

"It's discoveries like these that make me excited about the future," added Chou. "It's one thing to achieve a great technological breakthrough. It's another to have one that is practical and will change everyone's lives. With Intel's 30 nanometer transistor, we have both."

For more information on Intel Silicon Technology Research, please reference Intel's new Silicon Showcase at www.intel.com/research/silicon. Intel, the world's largest chip maker, is also a leading manufacturer of computer, networking and communications products. Additional information about Intel is available at <a href="https://www.intel.com/pressroom">www.intel.com/pressroom</a>. Source: Intel Web Page.

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# What is a Semiconductor? - Control of Conductivity is the Key to Modern Electronic Devices

•Conductivity,  $\sigma$ , is the ease with which a given material conducts electricity.

•Ohms Law: V=IR or J= $\sigma$ E where J is current density and E is electric field.

•Metals: High conductivity

•Insulators: Low Conductivity

•Semiconductors: Conductivity can be varied by several orders of magnitude.

•It is the ability to control conductivity that make semiconductors useful as "current/voltage control elements". "Current/Voltage control" is the key to switches (digital logic including microprocessors etc...), amplifiers, LEDs, LASERs, photodetectors, etc...

#### What is a Semiconductor Energy Bandgap?



For metals, the electrons can jump from the valence orbits (outermost core energy levels of the atom) to any position within the crystal (free to move throughout the crystal) with no "extra energy needed to be supplied"
For insulators, it is VERY DIFFICULT for the electrons to jump from the valence orbits and requires a huge amount of energy to "free the electron" from the atomic core.

•For semiconductors, the electrons can jump from the valence orbits but does require a small amount of energy to "free the electron" from the atomic core.

#### What is a Semiconductor Energy Bandgap?



•Semiconductor materials are a sub-class of materials distinguished by the existence of a range of disallowed energies between the energies of the valence electrons (outermost core electrons) and the energies of electrons free to move throughout the material.

•The energy difference (<u>energy gap or bandgap</u>) between the states in which the electron is bound to the atom and when it is free to conduct throughout the crystal is related to the bonding strength of the material, it's density, the degree of ionicity of the bond, and the chemistry related to the valence of bonding.

•High bond strength materials (diamond, SiC, AlN, GaN etc...) tend to have large energy bandgaps.

•Lower bond strength materials (Si, Ge, etc...) tend to have smaller energy bandgaps.

#### What is a Semiconductor Energy Bandgap?

•More formally, the energy gap is derived from the *Pauli exclusion principle*, where no two electrons occupying the same space, can have the same energy. Thus, as atoms are brought closer towards one another and begin to bond together, their energy levels must split into bands of discrete levels so closely spaced in energy, they can be considered a continuum of allowed energy.

•Strongly bonded materials tend to have small interatomic distances between atoms. Thus, the strongly bonded materials can have larger energy bandgaps than do weakly bonded materials.





Two hydrogen atoms: (a) noninteracting and (b) interacting. Splitting of e nergy levels is illustrated for (b).



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# **Consider the case of the group 4 elements, all covalently bonded**

Element	Atomic Radius			
(How closely spaced are the atoms?)				
С	0.91/3.5	6 Angstroms	5.47 eV	
Si	1.46/5.4	-3 Angstroms	1.12 eV	EMPERATIS Intel Fabracie Industry Market Fabracie Industry Market Fabracie Industry Industry Conference Industry Ind
Ge	1.52/5.6	5 Angstroms	0.66 eV	Andreas scattering 10° v, face and them include linebox as the provide of the model of degree as schools of the provide and the model of degree as schools of the provide and the model of degree as schools of the provide and the model of degree as schools of the provide and the model of the school of the school of the off degree and the school of the school of the school of the off degree and the school of the school of the school of the off degree and the school of the school of the school of the off degree and the school of the
α-Sn	1.72/6.4	9 Angstroms	~0.08 eV*	10.0 6 12.011 7 14.0007 8 15.9999 9 15.999403 10 20179 B 222 C 1.391 N 16.991 0 16.999403 10 20179 222 C 1.391 N 16.991 0 16.999403 10 20179 222 C 1.391 N 16.991 0 16.999403 10 20179 223 C 1.391 N 16.991 0 16.99140 10 20179 234 0 16.9914 0 16.9914 0 16.9914 0 16.9914 0 16.9914 0 16.9914 0 16.9914 0 16.9914 0 16.9914 0 16.99140 1000000000000000000000000000000000
Pb	1.81/**	Angstroms	Metal	Al and Since Phase Since Since Ar Phase Since Since Ar Phase Since
*Only has a measurable bandgap near OK **Different bonding/Crystal Structure due to unfilled higher orbital states		1         2         C         0	Алектрани         <	

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#### **Classifications of Semiconductors**

Types of Semiconductors:

•Elemental: Silicon or Germanium (Si or Ge)

•Compound: Gallium Arsenide (GaAs), Indium Phosphide (InP), Silicon Carbide (SiC), CdS and many others

•Note that the sum of the valence adds to 8, a complete outer shell. I.E. 4+4, 3+5, 2+6, etc... **PERIODIC TABLE OF THE ELEMENTS** 



# **Classifications of Electronic Materials**

Compound Semiconductors: Offer high performance (optical characteristics, higher frequency, higher power) than elemental semiconductors and greater device design flexibility due to mixing of materials.

Binary: GaAs, SiC, etc...

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Ternary: Al_xGa_{1-x}As, In_xGa_{1-x}N where 0 \le x \le 1
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Quaternary:  $In_xGa_{1-x}As_yP_{1-y}$  where  $0 \le x \le 1$  and  $0 \le y \le 1$ 

Half the total number of atoms must come from group III (Column III) and the other half the atoms must come from group V (Column V) (or more precisely, IV/IV, III/V, or II/VI combinations) leading to the above "reduced semiconductor notation.

Example: Assume a compound semiconductor has 25% "atomic" concentrations of Ga, 25% "atomic" In and 50% "atomic" of N. The chemical formula would be:

$$Ga_{0.25}In_{0.25}N_{0.5}$$

But the correct reduced semiconductor formula would be:

```
Ga<sub>0.5</sub>In<sub>0.5</sub>N
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# **Classifications of Electronic Materials**

Compound Semiconductors allow us to perform "Bandgap Engineering" by changing the energy bandgap as a function of position. This allows the electrons to see "engineered potentials" that "guide" electrons/holes in specific directions or even "trap" them in specific regions of devices designed by the electrical engineer.

Example: Consider the simplified band diagram of a GaN/  $Ga_{0.75}In_{0.25}N/GaN$ LED structure. Electrons and holes can be "localized" (trapped) in a very small region – enhancing the chance they will interact (recombine). This is great for light emitters!



### **Classifications of Electronic Materials**

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Example: Consider the band Diagram of a GaAs MODFET. Electrons in the "transistor channel" can be confined in a very thin (50-100 Angstroms) sheet known as a 2 dimensional electron gas (2DEG). This thin layer is very quickly (easily) depleted (emptied of electrons) by application of a gate voltage (repelling electrons) making such transistors very fast. This technology enables high speed communications, modern RADAR and similar applications.



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# How do we produce these Energy Engineered Structures and Devices?

# **Epitaxial Semiconductor and Dielectric deposition Techniques:**

•"Epitaxial" is derived from the Greek word for skin, more specifically "thin skin". Thin layers of materials are deposited on a substrate

•Temperature and substrate determines the physical structure of the deposited films:

•Low Temperatures or non-crystalline substrate:

•End up with amorphous or polycrystalline materials

•High Temperature AND Crystalline substrate

•Need to have an existing crystalline wafer so as to "seed" the crystallization process.

•Films that retain the substrates basic crystal structure are "Epitaxial"

# **Epitaxy**

#### **Single Crystal Semiconductors (Epitaxy)**

We can grow\* crystalline semiconductors by raising the temperature to allow more surface migration and by using a crystalline substrate (Si, GaAs, InP wafer, etc...)

===> Single crystal material mimicking the crystal structure of the layers below it.



**Figure 14-32** A microscopic view of a semiconductor surface during MBE growth or evaporation.

\*Instead of the word deposit, we use "grow" to describe the tendency of the deposited material to mimic the crystal structure of crystalline substrate material.

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# **Molecular Beam Epitaxy (MBE)**

#### **Molecular Beam Epitaxy (MBE)**

Dominates III-V electronic market and strong competitor in upper end LASER market Offers the highest purity material (due to UHV conditions) and the best layer control (almost any fraction of an atomic layer can be deposited and layers can be sequenced one layer at a time (for example Ga then As then Ga etc...).

•In an UHV chamber, ultra high purity materials are evaporated.

Because of the very low pressure, the mean free path is very long (can be hundreds of meters). Thus, the evaporated material travels in a straight line (a molecular beam) toward a hot substrate resulting in highly efficient raw materials usage.
Once on the substrate, the atom or molecule moves around until it finds an atomic site to chemically bond to.

•Shutters can be used to turn the beam flux on and off

•The flux of atoms/molecules is controlled by the temperature of the "effusion cell" (evaporation source).



# **Molecular Beam Epitaxy (MBE)**



Ga

# **Molecular Beam Epitaxy (MBE)**



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•Repeating a crystalline structure by the atom by atom addition.

•Chemistry controls the epitaxy to insure that, for example, Ga bonds only to N and not Ga-Ga or N-N bonds\*.





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# **Commercial Veeco® MBE**







### **Alternative Methods: MOCVD**

Primarily used for II-VI, and III-V semiconductors, special metallic oxides and metals.

Metal Organic Chemical Vapor Deposition (MOCVD)

Many materials that we wish to deposit have very low vapor pressures and thus are difficult to transport via gases.
One solution is to chemically attach the metal (Ga, Al, Cu, etc...) to an organic compound that has a very high vapor pressure. Organic compounds often have very high vapor pressure (for example, alcohol has a strong odor).

•The organic-metal bond is very weak and can be broken via thermal means on wafer, depositing the metal with the high vapor pressure organic being pumped away.

•Care must be taken to insure little of the organic byproducts are incorporated. Carbon contamination and unintentional Hydrogen incorporation are sometimes a problem.

Human Hazard: As the human body absorbs organic compounds very easily, the metal organics are very easily absorbed by humans. Once in the body, the weak metal-organic bond is easily broken, thus, poisoning the body with heavy metals that often can not be easily removed by normal bodily functions. In extreme cases, blood transfusion is the only solution (if caught in time). "Luckily", such poisoning is rare as the pyrophoric (flammable in air) nature of most metal organic means the "victim" is burned severely before he/she can be contaminated.



Figure 14-19 Examples of common organometallics used in MOCVD include (from top to bottom): trimethylgallium, tetrabutylarsine, and triethylgallium.

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### **Commercial Thomas Swan® MOCVD**



# **Engineered Energy Behavior in Compound Semiconductors**

The potential distributions we will use in this class are all possible/common in device structures. Some may represent "grown in potentials" (quantum wells, etc...) or naturally occurring potentials (parabolic potentials often occur in nature – lattice vibrations for example) including periodic potentials such as lattice atoms.



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So much for the introduction. Now on to the meat of the course.

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