**Understanding Semiconductors – A Technical Guide for Non-Technical People**

**Your Personal Semiconductor Awareness Test**

**Chapter 1 Semiconductor Basics**

1. Define electricity and conductivity. How do they related to current and voltage?
2. What is the most important semiconductor and why?
3. Which two inventions are responsible for the modern semiconductor industry? Why were these innovations so important?
4. After fabrication and manufacturing, what step in the SC value chain is necessary before system integration? Can you name all six?
5. What does PPAC stand for? Can you name which key design factor is missing?

**Chapter 2 Circuit Building Blocks**

1. Name the five types of discrete components we covered in this chapter. What function does each one perform? What are their differences?
2. Describe how a transistor in structure. What are its major components and how do they work?
3. What is the difference between a MOSFET and a FinFET transistor?
4. What is CMOS and what can it refer to?
5. How do logic gates work? What kind of logic do they use?

**Chapter 3 Building a System**

1. What five levels of electronics did we cover? On which level are all higher levels built?
2. Can you name each stage of the IC design flow? How does each step relate to a construction analogy?
3. What are the differences between emulation, functional, and formal verification? Pros and cons for each?
4. Which stage of the silicon design flow represents the transition between front- and back-end design? What happens at this stage?
5. How do EDA tools help hardware designers build better systems?

**Chapter 4 Semiconductor Manufacturing**

1. What are the four kinds of processes used for wafer fabrication?
2. Which core process technology is seen as a bottleneck to the rest of the industry? Why?
3. Can you tell the difference between front-end-of-the-line (FEOL) and back-end-of-the-line (BEOL)? How does this differ from front-end and back-end manufacturing?
4. Why is yield such an important metric? What is it used for?
5. What are the five core steps in the assembly and testing process?

**Chapter 5 Tying the System Together**

1. What are interconnects and what makes them so important?
2. What is the difference between wire bonding and flip-chip bonding? How do these impact the number of interconnects and transmission speed of a system?
3. Why do signal integrity engineers exist? What kinds of interfaces and transmission methods might they encounter?
4. In a chipset, why are the CPU, the northbridge, and southbridge arranged the way they are? What do each of these bridges handle and how are they different?
5. Describe the four main stages of power flow in an electronic system. Which components or modules handle each stage? Can you related each of them to similar components in a water utility system?

**Chapter 6 Common Circuits and System Components**

1. Compare and contrast analog and digital signals.
2. In the SIA Framework, what is the difference between Micro Components and Logic?
3. Which memory type sits closest to the CPU in the memory hierarchy? Why?
4. What makes MEMS similar and different from integrated circuits? If you were to categorized MEMS devices, which SIA component family would you choose?
5. Why are analog components well suited for wireless communications? Why not digital components?

**Chapter 7 RF and Wireless Technologies**

1. What do we mean when we say “RF”? Which key characteristics set one RF signal apart from another?
2. How does the FCC manage shared frequency bandwidths? What technologies are used to fit more information into a given amount of bandwidth? How does each technology accomplish this task?
3. Name the five key base components to any transmitter or receiver. Which component is number six and what makes it special?
4. Why is the physical layer so important in the OSI model? What are the other six layers and how do they function?
5. What makes each generation of telecommunications technology unique? How have these advancements enable the growth and success of cloud computing?

**Chapter 8 System Architecture and Integration**

1. What is the key difference between macro- and micro- level architecture? Where do ISAs fit in?
2. Which theoretical advantages does Harvard Architecture have over Von Neumann? Why does this not play out in real life?
3. Name four key differences between CISC and RISC.
4. Which ISA strategy is the most advantageous across the most design- and market-based constraints? What are its shortcomings?
5. Why are cost advantages not so straightforward between monolithic and heterogeneous integration? How do these factors relate to performance?

**Chapter 9 The Semiconductor Industry – Past, Present, and Future**

1. How have burgeoning design and manufacturing costs shaped the evolution of the semiconductor industry?
2. Make the case of IDMs. What are some competitive advantages they may have that fabless companies do not? Do you think these are sustainable?
3. List three key current industry trends. Which do you think is most important?
4. What are core drivers of consolidation? Can you think of any drawbacks to being too big (think IDMs)?
5. Describe the distribution of global value chain activities and consumption across the United States and Asia. Which surprising factor is responsible for much of Asia’s manufacturing cost advantages?

**Chapter 10 The Future of Semiconductors and Electronic Systems**

1. What advantages does stacking have over traditional “two-dimensional” ICs? Disadvantages?
2. Compare and contrast the structure of planar, FinFET, and GAA transistors. What gives GAA an advantage?
3. Name three promising channel materials. What are these materials so important?
4. Describe the difference between a bit and a qubit. Which applications might quantum computers be well suited for over traditional digit devices?
5. What questions do geometric scaling and functional scaling ask us? Classify each of the technologies covered in this chapter as more geometrically oriented or functionally oriented in nature.

**Scientific Underpinnings**

Human advancement is characterized by our ability to harness and control forces. SCs have been the key to harnessing the power of electrical energy. The basics of electricity and conductivity is key to understanding how this works.

**Electricity and Conductivity**

***Electricity*** describes the relationship between charge and current. Electric charge is a fundamental property of matter stemming from protons and electrons that are held together by a balance between two forces – ***electromagnetic force*** (opposite charges attract, similar charges repel; protons attract orbiting electrons; lends mobility to electrons between atoms) and ***strong force*** (holds neutrons and protons together). In some ***elements***, electrons stay close to the atom’s nucleus (***insulators***) while in others, electrons are constantly bouncing around to other nearby atoms (***conductors***).

In a neutral state, electrons move from atom to atom randomly but in aggregate the collective charge of an object remains neutral. ***Electric current***, measured in ***amperes*** (the number of electrons that flow past a given point in one second), results when electrons collectively flow in the same direction across a wire at nearly the speed of light (individual electrons themselves travel only a few millimeters a second). Current transfers energy from the atoms at the front of a conductor to the atoms at back analogous to how a physical moving object carrying **kinetic energy** transmits its kinetic energy to other objects upon contact.

By creating a **charge differential** (**electric potential,** **voltage, electromotive force, potential difference**) between two regions, we can initiate a chain reaction of electron movement by connecting the regions via a conductive material. A **circuit** is any closed loop between a source of voltage (e.g. a **battery**), a conductive wire, and other electrical elements. A circuit can also be formed by placing two regions in direct contact. The potential difference describes the amount of **work** required to displace a positive charge in an electric field (positive regions are at higher potential than negative regions). Electrons flow from low to high potential while “conventional” current flows from high to low potential. The greater the charge difference between the regions, the greater the voltage. ***Electrons cannot flow without voltage***.

Rather than depending on potential difference in nature, **batteries** work by separating charge and therefore creating a potential difference, in the form of chemical energy, between its cathode (+) and anode (-). Current will not stop flowing until all of the surplus negative charges at the anode have flowed to the cathode thus depleting the battery. The battery’s stored chemical energy is converted into electric energy by completing the circuit.

Current and voltage tell us how electricity works in principle, but **power**, measured in **watts** (amount of work done, in Joules, when one amp is pushed through one volt), is the key to understanding how electricity can be used to do productive things. Power describes the work done when electric current is converted into some other form of energy such as motion, light, heat, or sound.

This relationship is called **Joule’s Law**, named after the **James Prescott Joule** who discovered it in 1840. The challenge with electricity and power is to figure out how to optimally harness current to do something useful. This is where conductive materials come into play. Conductivity measures of how easily current passes through a material and thus manipulating conductivity allowing current to flow in some cases and restricting it in others. Materials fall into three main types:

**Conductors**, like copper, have high conductivity and low electrical resistance measured in **Ohms**.

**Insulators**, like plastics, have low conductivity and high electrical resistance.

**Semiconductors** can act like conductors and insulators and our ability to control exactly when SCs conduct and when SCs insulate is the key to the electronics revolution.

**Silicon – The Crucial Semiconductor**

There is a large variety of SC materials – each with varying levels of conductivity – such as Germanium and Gallium Arsenide. Silicon is the most prevalent SC material because it has numerous advantages including beneficial mechanical and thermal properties, cheap, and abundant – comprising 30% of the Earth’s crust, Silicon is the second most abundant element on Earth and is found in sand, rocks, clays, and soils.

Electronic devices are built using some combination of **discrete components**:

1. **Transistor** – function like electronic switches. By stringing many transistors together, transistor switches can form patterns that can represent and manipulate information. This is the basis for the **binary computer language** used in **digital electronics** and serves as the core foundation **for modern computing**.
2. **Resistor** – impedes the flow of electricity through a circuit thus controlling voltage and current.
3. **Capacitor** – stores electrical energy.
4. **Inductor** – uses magnetic fields to control the flow of electricity. Found in power supplies that convert a battery or **Alternating Current** (**AC**) wall power supply into low voltage **Direct Current** (**DC**). Capacitors and inductors regulate and stabilize voltages.
5. **Diode** – like transistors except that they the direction of electron flow thus acting as a one-way gate or valve for electricity.

These discrete components vary wide in shape and size and are used in different combinations to manipulate the flow of electricity. They can either be discrete (manufactured separately, non-integrated) or integrated (manufactured on the same substrate).

**FinFET versus MOSFET Transistors and CMOS**

There are two primary transistor types – BJT and FET. BJTs are used for a limited set of applications like power management and signal amplification for wireless and audio devices. FETs are used in most modern computing devices with MOSFET being the most popular configuration. MOSFET has served as the bedrock for microelectronic design and manufacturing for decades. In MOSFETs, a metal oxide separates the gate from the channel. When an electric field is applied at the gate, a channel between the source and drain forms through which electrons flow.

FinFETs are structurally different from MOSFETs. By raising the source and drain to surround the gate on three sides, FinFETs allow more efficient control of current through the transistor and also consume less power and reduce leakage current. However, FinFETs are more difficult to manufacture than MOSFET.

Making high-performance ICs at scale is challenging and expensive especially as transistors achieve smaller size (**geometric scaling** – e.g. a 7nm node refers to a gate length of 7nm or equivalently source to drain distance). Geometric scaling is fundamental to the realization of Moore’s Law. Most chips today use CMOS (complementary metal-oxide semiconductor, p- and n-channel transistor on the same substrate). CMOS may be used to refer to the circuitry itself, but can also refer to the design methodology and processes that are used to manufacture ICs. CMOS has long been the dominant IC design and fabrication technology and enjoys a competitive advantage in power consumption, area requirements, and cost over more specialized alternatives like BJT manufacturing.

Geometric scaling has been so impactful in the evolution of SCs that engineers have not had to squeeze as much efficiency out of their designs at each process node (**functional scaling**). In recent years, however, the pace of geometric scaling has slowed as the physical limitations and the manufacturing economics of smaller transistor size are being challenged with each successive generation of SCM, called a **technology node** or **process node** that are driven by a mix of equipment, materials, and process improvements. Functional scaling will start playing a more significant role since it aims to increase performance by maximizing utilization at existing nodes by way of application-specific design, tighter system integration, and new packaging and interconnect technologies.

***Signal Processing Systems – Putting Components Together***

It’s useful to think of electronic systems as signal processing devices. Let’s use the example of a music producer using a laptop to record and mix music using the five different components from the SIA Framework.

1. A microphone records an analog audio signal that is input and converted by ADCs to a digital representation in the laptop.
2. The ADC then feeds that signal to a DSP (micro component), which accepts the incoming digital stream and can apply some simple signal processing alogorithms.
3. After that, the newly converted digital signal is sent to the central processor, in this case a CPU, that runs the mixing software the producer uses for editing.
4. The central “system” processor (logic) may use volatile memory to store the collection of sound signals temporarily while it performs other tasks as directed by the mixing program.
5. Once the producer is done, she can tell the central processor to store the finished track for later using the system’s non-volatile memory, like NAND flash.
6. When the producer is ready to play the finished song, the digital signal is sent to another DSP followed by a DAC that converts the digital signal to an analog signal.
7. The analog signal is then sent to an analog processor or simply an amplifier that amplifies it out into the real world through the laptop’s speakers as music.
8. Through the system, various discrete components perform functions like system timing and power management that enable the device to run properly.

**Thoughts and Questions**

“*If I had asked people what they wanted, they would have said faster horses*” – Henry Ford.

How to discover and assess new industries? How to understand the evolution of existing industries and the impact of this evolution of SCs? How to assess the growth of existing industries?

How critical is product differentiation in the relevant product’s market? How critical is SCs in the product differentiation strategies of companies in these markets?

Deposition methods include atomic layer deposition, molecular beam epitaxy, physical vapor deposition, electrochemical deposition, and other methods.

Intel made huge investment in EUV starting in the 1980s.

What are all of the scientific, manufacturing, utilization, and other benefits for realizing Moore’s Law? What are the risks of realizing Moore’s Law particularly in today’s SCI?

How do you account for technological obsolescence in this product development and manufacturing dynamics (in context to ASIC vs. FPGA)?

**Memory Hierarchy**: CPU registers 🡪 Cache (L1 and L2, volatile) 🡪 RAM, DRAM, and SDRAM (volatile, quick access, transient, low capacity) 🡪 ROM (non-volatile, slow, long-term, high capacity).

What is the distribution (company, geography) of direct jobs? What industries are associated with indirect jobs? Bonus if you can identify companies and geographies of indirect jobs.

Make a list of elements that are insulators and conductors in order of degree of insularity and conductivity.

What are the pros and cons of wire molding versus flip-chip technology?

Why is removal processing such a big slice?

Can you put packaging options on a spectrum across various manufacturing parameters and see how this lends itself to competitive advantage and valuation?

Can this be the basis for making a valuation trade based on the slowing of Moore’s Law and geometric scale with a shift toward functional scaling? Is there any economic proof that such a valuation shift has or is taking place?

What of objective ways to measure signal integrity as a function of transistor size and density?

The market across these five systems components is led by memory -> micro components -> logic -> OSAD -> analog components.

Communication architecture that enable different parts of an SoC to talk to one another (Arteris).

Out of this cycle sprang **SC IP companies (SCIPC)** that used upfront licensing fees, per-product royalties, and library access subscriptions.

Figure 9.19, page 208, shows the forecasted trajectories of US and Chinese chip manufacturing market share according to BCG and SIA’s report on Government Incentives and US Competitiveness in Semiconductor Manufacturing (Varas et al., 2020).