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Alternative Semiconductor Materials to Silicon

The majority of the content of our ECE 3110 class has considered the use of silicon in semiconductor devices, but silicon is not the only semiconductor material available. Through the course of this paper I will consider the other types of semiconductor materials that are used commonly, how and why they're used, and their differences when compared with silicon. Semiconductor devices have changed the way our world works, and further developments are constantly being researched in an attempt to find devices that can do more for less energy used. The uses of semiconductor devices extend far beyond computation devices such as computer processors. The robust utility of semiconductors means that they've found their way into just about every electronic device we see today, and the magic behind a semiconductor lies in the fact they possess properties of both a conductor and an insulator.

The discovery of these electrical properties of semiconductors can be attributed to many people and began over 150 years ago. The very first instances of discovering semiconductor properties in materials can even date back to Faraday's observations regarding electrical conductivity in relation to temperature. This study dates back to the year 1833, but it would be a long time before people began thinking of semiconductors as such extremely useful devices. Another important discovery in the early development of semiconductor thought includes the experiment of Alexandre-Edmond Becquerel. When he experimented with the electrical properties of electrolytes, he one day ”noted that, if one of the electrodes was illuminated with sunlight, the emf generated between the electrodes increased.” (Jenkins). These first discoveries of semiconductor properties opened the gateway to many new ways to experiment with electricity. Doors were opened and discoveries began to poor in. Other important discoveries in the timeline of semiconductors include observations from Willoughby Smith and Heinrich Hertz, who had similar findings regarding photoconductivity in the late 1800s, and another late 1800s discovery regarding rectification in the contacts between metals and some oxides and sulfides. Discoveries like these poured out over the course of several decades and led to increased thought and innovation in the area.

Moving forward to the 1920s and '30s, there was a significant increase in demand for radar and other forms of communication due to the impending war. Under this pressure, and with the recent discovery of bipolar conduction in semiconductors (being the flow of current due to both electrons and holes moving), the scientific scene was ready for heavy increase in the development of semiconductor devices. The two primary material subjects of semiconductor research were silicon and germanium, though many materials possess the desired qualities in semiconductor behavior. Discoveries surrounding the p-n junction and its manufacture paved the way to new applications of diodes that could support more current flow. This eventually led to the discovery of transistors. In 1950, Gordon Teal and his team grew a single crystal of germanium that contained regions of both p-type and n-type materials. After some more processing, ”[this] crystal was cut into n-p-n rods and contacts applied to the three regions of doping. The electrical properties of the transistor thus made were largely consistent with Shockley's proposed junction transistor. This transistor was more reliable than the point contact version, generated less noise and could handle higher powers" (Jenkins).

The advent of transistors led the way to many new technologies, and silicon quickly became the favorite material for semiconductor development. The main reasons that silicon is used in integrated circuits today are plenty. Silicon is one of the most abundant resources found here on Earth, meaning that it is relatively cheap and was more readily available for experimentation and testing. More important than cost, though, was the material properties and electrical properties that made it so special. Silicon boasts amazing reliability in diverse conditions, and has shown the ability to operate as intended in extreme weather and temperature conditions. As silicon was adopted in the industry, manufacturers would decide to make devices out of silicon so that they could be compatible with already built devices, and so that the manufacturing processes could source from others as well.

The current methods for manufacturing silicon chips have been through many renditions and revisions to get where they are today. Each manufacturing company may have their own processes to build the chips, but the process roughly follows this same outline. Silicon chips are cut from wafers of silicon. After a purification process to find produce a raw crystal of silicon, thin wafers are sliced from a large ingot. They are then cleansed and polished to make sure that the surface is free and defect free. Any small defects in the wafer now can prevent operation in the integrated chip once it's done. Once they've produced a clean silicon wafer it undergoes a process that produces an oxidized SiO_2 layer on top of the silicon which acts as an insulating material. The insulated silicon wafer then undergoes a photolithography stage which defines the patterns for the various components on the integrated circuit. After an etching process, the silicon wafer undergoes what is possibly the most important step when considering the use of semiconductors. This is the doping stage, where impurities are introduced into the silicon and modify its electrical properties. Creating separate regions of p-type and n-type concentrated areas allows the semiconductor silicon to act as diodes and transistors. These produce the computational logic of the chip and allow it to work as intended. Often times, a silicon wafer undergoes lithography, etching, doping and deposition multiple times to correctly build the proper design on the silicon chip.

These manufacturing techniques have been developed over years of experimentation with silicon chips, thus, silicon quickly became king of the semiconductor field. The discoveries, developments, and innovations in the realm of electronics have increased greatly in this era of silicon dominated semiconductor materials, but, as we saw from years of electronic research and experimentation, silicon isn't alone in its electrical properties. Other materials are commonly used as semiconductors in electronics today, including germanium, gallium arsenide, gallium nitride, and others. Their strengths are separate from those of silicon, thus they find their own place in the world of semiconductor use. Many semiconductors, including the ones just previously listed, are made of alloys consisted of Group III and Group V elements on the periodic table. Gallium belongs to Group III and has been paired in experimentation with several Group V elements and found to have unique properties that make it especially useful in specific areas, such as the area of optoelectronics.

Gallium arsenide (GaAs) has been found very useful in the area of optoelectronics. It has a higher electron mobility than silicon, which makes it useful in high frequency applications, such as radar systems, satellite communication devices, etc. Research is currently being done in the realm of building computer processors out of GaAs because of its strengths in these areas which could allow it to overcome some shortcomings of silicon-based semiconductor devices. The major roadblocks that keep silicon in the spotlight when it comes to semiconductor devices, is the cost of materials and manufacturing. One of the most common processes required for the manufacturing of GaAs semiconductor devices is the use of molecular beam epitaxy.

Molecular beam epitaxy (MBE) isn't just a process used for the creation of GaAs semiconductor devices, it can also be used for other Group III-V semiconductor materials. The MBE process must be completed in an ultra-high vacuum (UHV) environment, which is one of the leading factors in how expensive the process is. However, without a UHV environment, the process would allow impurities into the semiconductor material, and it would result in a poor outcome, so it is essential. Similar to silicon wafers, after a crystal structure is made from the semiconductor material, thin wafers are cut from the crystal and prepared for processing. Once the wafers of material are prepared, the effusion cells are heated, evaporating the materials that will be deposited on the surface of the wafer. This forms molecular beams which are then directed toward the wafer in a very controlled manner, and eventually growth of the material is developed on the substrate. "[An evaporated material] is deposited by Atomic Layer Deposition (ALD) process for advantages like high quality and purity" (Nikte). While MBE is very expensive, one of the advantages is the precision in the manufacturing process. Well-designed MBE processes can have enough control to allow the process to be specific to each atomic layer of growth on the substrate. Often, these steps are repeated multiple times to ensure that the process is done well and completely. As previously stated, one of the contributing factors to the increased cost in the MBE manufacturing process is the necessity of an ultra-high vacuum environment. Another contributing factor to the elevated cost is the amount of time it takes to grow the layers. It is often a timely process, and that doesn't make it cheap.

Each development in the semiconductor world has its own strengths. Another realm of semiconductors being researched now is the use of carbon nanotubes. These small nanotubes, constructed almost entirely out of carbon, are used to make flexible electronic circuit devices, and have shown excellent properties when it comes to conductivity. By changing the way that the tubes are shaped and aligned, one can moderate the electrical properties of the nanotubes. This means that they can be used in electronic devices as well as semiconductor devices. Some of the defining features of carbon nanotubes that make them desirable to use are their absolutely tiny size. As Moore's law comes to a close in recent years, it's getting more difficult to build silicon chips with even smaller transistors, and carbon nanotubes can allow for even smaller transistor networks and circuits. Another interesting thing about carbon nanotubes is their exceptional mechanical strength. Robust electronic devices that are built to withstand flexible designs are possible with carbon nanotube circuits. Being made of carbon means that it resists chemical changes as well, and it is more resilient to environmental factors that could damage semiconductors made from other materials.

Just as with other alternatives to silicon in the semiconductor world, these benefits also come with costs. The materials for building carbon nanotubes, including the carbon resources as well as catalysts that aid in the manufacturing process, are more scarce and thus more expensive. The lack of development in the space also means that manufacturing processes are more expensive. These costs result in fewer resources available to create devices with carbon nanotubes, and thus it lacks the economies of scale that silicon devices benefit from. The most common practice in manufacturing carbon nanotube devices is known as chemical vapor deposition.

In chemical vapor deposition (CVD), a process which is used in the manufacturing of several types of semiconductor devices, a thin film or coating is put onto a substrate by evaporating several materials, including methane, ethylene, and some hydrocarbons, in a chamber and then allowing those gases to collect on a substrate in thin layers. Once the layers are collected on the substrate, they undergo chemical reactions that produce the desired film on the substrate. All of these processes result in some undesirable byproducts that need to be removed at the end of the process. By specifically controlling each element of the CVD process, carbon nanotubes can be created and designed to very specific parameters. This amount of control is expensive, but allows for the specific design and application of carbon nanotubes in different use cases, including semiconductor devices, especially those which are flexible.

Another interesting branch of semiconductor materials are those labelled as *organic* semiconductors. You may have heard of the newer TV display technologies featuring *organic* LEDs (or OLEDs). These are devices made from organic compounds that allow for unique semiconductor properties. OLEDs have desirable qualities in their own right. While organic semiconductors don't have the best properties when it comes to processing power and other high-speed or high-frequency use cases, they can be found in consumer electronics because of their use in displays. OLEDs show very dynamic colors and allow displays to have more contrast as well. The reason that they don't showcase lots of speed is because the electron mobility is often reduced in organic semiconductor materials. Organic semiconductors aren't only used in OLEDs, they have some other use cases as well. Some are used in organic solar cells, and photodetectors. In this way they differ from silicon because silicon has poor optoelectronic qualities.

A large realm of electronics that heavily utilizes semiconductors is the realm of optoelectronics. There are many facets of optoelectronics that make it such a widely influential area in our world. Optoelectronics present a way that we are able to directly interact with electronic circuits. As humans, we receive the majority of the information we process through our eyes, so optoelectronics has always been a large priority for the development of any industry, including that of electronics. The first optoelectronic devices to be developed were light emitting diodes (LEDs) which were made with silicon carbide point contact diodes in 1923 by Oleg Losev. The LEDs were weak, as were the solar cells of the time, and progress was slow in the development and discovery within the field, but it moved on. Discoveries continued within the field for several decades, and ”[the] realization of the wide-gap window effect was very important for photodetectors, solar cells, and LED applications. It permitted us to broaden considerably and to control precisely the spectral region in solar cells and photodetectors and to improve drastically the efficiency for LEDs" (Alferov). These significant differences in the train of thought led to many more innovations in the realm of optoelectronics.

Silicon isn't often used in optoelectronic devices because of its poor ability to produce or receive light. This is because of its indirect bandgap. The amount of energy required for an electron to move from the valence band to the conduction band isn't correlated with the energy of a photon that it can absorb or emit. Because it has limitations in this aspect, other materials are often used in its stead for optoelectronic devices. Some of these other semiconductor materials include germanium, GaAs, indium phosphide (InP), other III-V semiconductor materials, and even some II-VI semiconductors such as cadmium selenide. When it comes to optoelectronic devices and their requirements, there often isn't a clear choice because each material has specific properties that will react differently in these conditions. Different materials can result in different wavelengths of light absorbed or emitted. This can mean that separate materials, when used to produce LEDs, will make different colors of light. It was a surprise to me to find that the white LED was discovered in the late ’90s, when experimentation with LEDs dates all the way back to the ’20s.

One of the most currently demanding areas of optoelectronic devices is the creation and use of solar cells used in solar panels. Photovoltaic cells allow us to transfer the energy of light into electricity and power other electronic devices that require energy. Studies and manufacturing within this field have shown that converting from sunlight to energy is not a trivial task. Despite silicon’s indirect bandgap and limited efficiency in the optoelectronic world, it is still the most widely used material in optoelectronic devices. This is largely because of the large infrastructure built around silicon devices, and because it is often reliable in extreme conditions. Reliability is certainly important as solar cells placed indoors are worthless in energy production. This is often where other photovoltaic cells are lacking, such as Perovskite solar cells. These solar cells are made with a material that has been shown to rival silicon in efficiency, and boast lower manufacturing costs, but the relative stability in real world cases makes it very difficult to justify in real world instances. Perovskite solar cells are unique because they are made from perovskite crystal structures such as methylammonium lead iodide, ($CH_3NH_3PbI_3$). Other concerns with these materials include their toxicity, which would especially prove to be a problem if they aren’t reliable and would have to be disposed of often.

Because of its abundance and manufacturing infrastructure, silicon remains the first choice for many semiconductor applications today. We are tasked with whether silicon will remain the future of semiconductor devices. Because of its infrastructure and current development in the field, it will always play a role in the world of electronics, but in some areas it is limited. It has relatively low electron mobility when compared with some other semiconductor materials, and is rather rigid, making it difficult to use in flexible devices. It has an indirect bandgap which limits its use in optoelectronic devices such as LEDs and lasers. Despite these limitations, there is no clear replacement for silicon in the current electronic landscape. Situations may arise that demand more from our semiconductor devices, and in those situations there may be discoveries and innovations that lead to materials that can outperform silicon in each task, but silicon will likely remain the favorite material for so many applications.

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