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Systematic Analysis on The Developments of semiconductors beyond Silicon

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Abstract:

After the first discovery of silicon (Si), a revolutionary and innovative era for a brand-new class of materials, semiconductors, began to shine. Over decades, Si has become indispensable in various applications such as data storage and processing in computers and smartphones that are used frequently nowadays. With the increasing need for efficiency and colorful display, two new critical materials are synthesized, which are gallium nitride (GaN) and silicon carbide (SiC). These two materials have higher temperature endurance, excellent performance in high-frequency and high-voltage equipment such as electric vehicles and satellite communications, and are unprecedentedly suitable for light-emitting diode (LED) productions due to their nature of being direct bandgap semiconductors compared with Si, which is an indirect bandgap semiconductor. In this paper, the structures, applications, and limitations of the two new materials were discussed, and the principles behind these outstanding properties are explained. It traces the historical evolution of LEDs and the role of semiconductors in modern electronics, emphasizing the progression from Si to GaN and SiC to meet contemporary technological needs.

Keywords: Semiconductors, Si, GaN, SiC, bandgap

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1. Introduction

In the early 19th century, the first breakthrough blue light-emitting diode (LED) was invented by Shuji Nakamura in his own laboratory [1]. It symbolized the completion of the optical RGB full-light mode display. What makes it interesting is that what is widely used today was once a bold innovation at that time. Digging deep into the principle, the large field incorporating the LED was found. It is called semiconductors.

Semiconductors had a profound impact on modern electronic technology. One of the famous materials is Si, which, unlike any other substance, has profoundly transformed our world. The development of information and communication technologies would have been fundamentally different without the presence of silicon. The current generation of computers and mobile phones utilizes Si-based microprocessors, while critical files are stored in Si-made memory devices such as random-access memory (RAM) and flash memory, such as USB drives [2]. Therefore, according to its dominance nowadays, it is entirely justified to refer to the mid-19th century as the silicon era, like how previous eras were named after materials such as stone, copper, bronze, or iron, which were the primary materials associated with the accomplishments achieved during those times. As time passed by, the increasing need for optoelectronics shifted the hotspot to searching for new materials, as it turns out that some of the common semiconductors, including Si, are not suitable for making LEDs because they generate an abundance of heat when a large current is passed through, along with a vital breakdown of the device due to the leakage current [3]. On the other hand, the leakage current degenerates the device performance, as there was a trending challenge to produce smaller transistors to load more transistors on a chip to achieve a higher density of integration and a lower cost in the 1960s.

In modern days, electric vehicles such as Tesla play an important role in transportation, which also requires high frequency and high voltage to increase the efficiency of driving. Two outstanding compounds were found to have a wider bandgap and a higher charge carrier mobility than Si, which are GaN and SiC, making them more suitable in synthesizing high-frequency devices. In this report, to stress the importance of the two new materials, GaN and SiC, in modern applications, the comparison between typical silicon semiconductors and GaN and SiC will be discussed in terms of principles, limitations, and applications.

2. Structure and Principle of semiconductors

A semiconductor is a material with electrical conductivity that sits between a conductor and an insulator. It has valence bands and conduction bands that can determine its electrical conductivity. To vary electrical conductivity, doping techniques could be applied to intrinsic semiconductors to produce extrinsic semiconductors. By joining an n-type extrinsic semiconductor and a p-type extrinsic semiconductor, the P-N junction created could be used to create transistors, solar cells, and LEDs.

2.1 Energy bands

The valence band and the conduction band are the two main types of energy bands in semiconductors. At absolute zero, the temperature at which all electrons fill valence bands, the valence band is a collection of different energy levels that electrons can occupy. It contains the electrons that are in the covalent bonds between the two atoms and thus plays an important role in maintaining the material's stable structure. The valence band maximum (Ev) is the highest energy level occupied by electrons at absolute zero. The conduction band is the energy band located above the valence band. Excitation of electrons from the valence band to the conduction band allows them to freely move and contribute to electrical conduction. The lowest energy level in the conduction band is the conduction band minimum (Ec), and the bandgap energy (Eg) is the energy difference between Ev and Ec. As the temperature rises to a certain level, some electrons gain enough energy to overcome Eg and jump into the conduction band. The vacancies left behind are called holes. The excited electrons then enter the conduction band, promoting electrical conduction [4].

2.2 Intrinsic semiconductors

Intrinsic semiconductors are undoped pure semiconductors without any significant dopant species present in the structure. One of the most common examples is Si. The electrical conductivity depends on the charge carrier concentrations, including electron concentration (n) in the conduction band above Ec and hole concentration (p) in the valence band below Ev. At the thermal equilibrium, n=p=n_i, where n_i is the intrinsic carrier concentration at thermal equilibrium when the material is kept in the dark with no external electrical bias applied and the only source of energy is due to the ambient temperature [5]. N_i is directly proportional to T^3/2*e^-Eg/2k_bT, where T is the temperature and k_b is the Boltzmann constant of approximately 1.38^10^-23JK^-1, and for Si, n_i is approximately 1.05*10^10 charge carriers per meter cube (ccm^-3) at 300K [5].

2.3 Extrinsic semiconductors

If the structure of a pure semiconductor needs to be altered, the doping process is introduced to synthesize extrinsic semiconductors. Doping is the intentional way to vary and control the electrical conductivity of the material and implant impurity atoms into an intrinsic semiconductor because the charge carrier concentration in intrinsic semiconductors is too low for most practical electronic applications. The two primary types of doping are n-type and p-type doping. For the n-type doping, atoms with more valency electrons than those in the current intrinsic semiconductor are implanted into the lattice. When these dopant atoms provide extra electrons into the system, electrical conductivity is significantly increased. Additionally, the band structure of the new semiconductor is also varied to have a smaller band gap that makes electron transition much easier [4]. On the other hand, atoms that have fewer valence electrons than atoms inside the intrinsic semiconductor are commonly used in p-type doping

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as it creates additional holes, facilitating conduction by allowing electrons from neighboring atoms to move into the vacancies created by the absence of electrons. Like n-type, the band structure is also altered. Directly above the valence band, the creation of additional holes enables electrons in the valence band to fill these vacancies more effectively, facilitating enhanced conductivity as the holes move throughout the lattice.

2.4 The P-N junction

P-N junction is a critical structure in diodes, transistors, and solar cells. It is created after an n-type and a p-type material are joined together. The recombination of electrons and holes takes place afterwards, emitting photons with a specified wavelength. The properties of the P-N junction come from the action of holes from the p-type semiconductor and electrons in the n-type semiconductor.

2.4.1 Depletion region

Due to the dramatic concentration gradient, the diffusion of charge carriers occurs instantaneously after joining the two types of semiconductors, resulting in the formation of a depletion area empty of free charge carriers that acts as an insulating barrier. Holes from the p-type semiconductor diffuse into the n-type region and recombine with electrons. The lack of holes results in a net negative charge in the p-type zone. Similarly, a net positive charge in the n-type area is created when more electrons in the p-type region diffuse into it, followed by the same recombination process [6]. Diffusion stops when the electric field repulsion from the depletion region overcomes the concentration gradient. The built-in potential is the voltage generated by this electric potential barrier at this established equilibrium, in the absence of an external electric field and net current flow.

2.4.2 Forward biased P-N junction

After connecting the positive terminal to the p-type side and the negative terminal to the n-type side, holes and electrons will move toward the middle of the junction and produce a contracted forward-biased p-n junction. The built-in potential then falls, and more majority carriers flow across the junction. As a result, resistance falls, electrons move from the n-side to the p-side, and holes move in the opposite direction.

2.4.3 Reverse biased P-N junction

When a positive voltage is applied to the positive terminal and a negative voltage is applied to the negative one, electrons are attracted to the positive pole while holes are drawn to the other side. The flow of majority carriers across the junction is then restricted as the junction expands to a greater width that has a higher built-in potential as well as the resistance. The minority carriers, which are thermally generated electrons in the n-type semiconductor and holes in the p-type semiconductor, contribute to a small amount of leakage current flowing across the junction [6].

3. Properties and applications of GaN and SiC semiconductors

3.1 GaN semiconductors

In the 1930s, GaN was synthesized by reacting metallic gallium with ammonia gas at a temperature of approximately 1000 °C [7]. GaN has a hexagonal P63mc wurtzite crystal structure at atmospheric pressure with an extremely high level of hardness, and it has strong chemical stability and a melting point reaching up to 1700 °C [8].

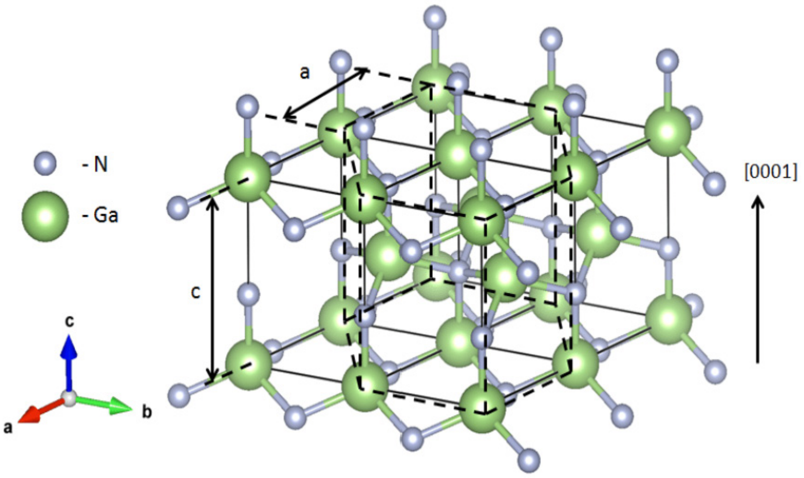

Figure 1. Crystal structure of solid GaN [9]

It is a direct bandgap semiconductor that has a wide energy gap of approximately 3.4 electron volts (eV) [10]. This allows GaN-based devices to perform well in high temperature, high voltage, and high frequency environments. These exceptional properties prove its dominance in industrial production. In display technology, GaN is a commonly used material in producing low-wavelength blue and ultraviolet LEDs, lasers, and photodetectors [1, 7]. GaN has a great thermal conductivity of 2.0 Wm−1K−1. This makes it a good amplifier for spreading signals over a large area in 5G base stations and satellite communications over the earth. It can work as a transistor at high power and switching frequency and send data with little interference and loss of information [11].

3.2 SiC semiconductors

The synthesis of SiC was completed decades ago, in 1891, by American inventor Edward Goodrich Acheson during an experiment using electric current and a mixture of silica and carbon [12]. It was initially used as an abrasive in grinding and cutting operations due to its outstanding hardness and thermal stability of the material. In addition, SiC is the only compound semiconductor that is capable of being thermally oxidized to form SiO2 that has high quality. Mechanical importance was prevalent until recent times, during which the potential for becoming a semiconductor has been developed. SiC has been discovered to have more than 200 polytypes, which is the phenomenon of adopting various crystal structures in one-dimensional variation while maintaining identical chemical composition [13]. The polytypes are defined according to the quantity of stacked Si-C layers within a unit cell and the corresponding crystal system (C for cubic and H for hexagonal) [13]. The three most important polytypes of SiC are in 3C, 4H, and 6H forms [14]. The A, B, and C in Figure 2. are the sites of occupation in a hexagonal, close-packed structure [13].

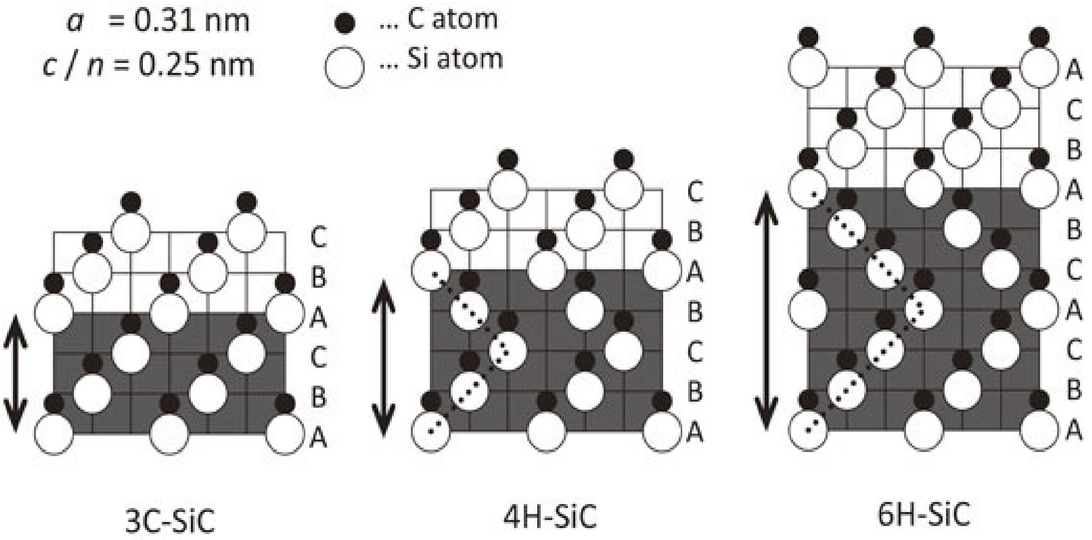

Figure 2. Crystal structures of 3C-SiC, 4H-SiC and 6H-SiC [13]

In general, 3C-SiC appears to stably exist at low temperatures, while the two hexagonal forms are stable at high temperatures. The wide bandgap of approximately 3.0 eV means that it has a high thermal conductivity that can facilitate the heat dissipation to prevent the breakdown of the material, and its high breakdown field strength makes it suitable for high-voltage devices like an MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) [14]. For the 3C-SiC, it has the form of zinc blende and has a better optical property, which enables it to make LEDs better than the two hexagonal SiCs [15]. Due to their structures, the two hexagonal SiCs have a higher breakdown voltage than the cubic one, allowing for better construction of high-power transformers and circuit breakers. SiC is particularly useful for battery recharging, both on board and in charging stations, and it also significantly reduced the size of the battery, which increases the efficiency and symbolizes its dominance in the EV industry [4].

3.3 Structure imperfections and traps

Holes and electrons can be trapped or emitted from defects and imperfections known as traps in the crystal structure. These trap states act as energy levels inside the semiconductor's energy gap. Traps close to the valence or conduction band are called shallow traps, which are usually created by doping impurity atoms intentionally to synthesize LEDs [16]. In contrast, deep traps are caused by unexpected defects in the crystal lattice after growing on a wafer with bad matching or introducing unwanted atoms by accident. The deep ones have negative effects on the performance of devices because they can prevent charge carriers from passing through the material [16].

3.4 Cost

For GaN, compared with Si, Ga is much rarer in the earth crust and is much harder to locate and exploit, which makes it take more time and labor to collect the same amount as Si. Moreover, to grow high-quality GaN to prevent lattice mismatch with defects present that brings the problem of having a low voltage performance and an easier thermal runaway, the substrates must be chosen to be crystals of sapphire or SiC, which are much more expensive than using typical Si wafers [17].

3.5 Reliability

Even though GaN has excellent thermal stability and high-voltage performances, the long-term reliability under real-world operational conditions is still being examined because, on real occasions, the voltage requirement of the device may be higher than the threshold breakdown voltage of the two materials that will bring vital safety issues to the public. The concerns such as gate leakage currents, thermal runaway, and serious circuit failure under high-frequency operation need rigorous testing repetitively to reach the safety level. The industry is becoming more familiar with GaN technology, but further theoretical studies and tests are required for different applications to ensure consistent and dependable performance overall.

4. Analysis of the advantage of GaN and SiC semiconductors over Si semiconductors.

4.1 Charge carrier mobility

Charge carriers, or electrons and holes, feel the force of an electric field and accelerate when it is applied across a semiconductor material. Charge carrier mobility is the rate at which charge carriers flow through a semiconductor material in response to an electric field. It is computed as the charge carrier drift velocity divided by the applied electric field, which stands for v_d=μE, where v_d is the drift velocity and μ is the charge carrier mobility, with E implying the strength of the electric field applied [18]. High-frequency gadgets need to change states very quickly. This is directly impacted by how quickly charge carriers react to shifting electric fields. For instance, high mobility carriers in a high-speed transistor will rapidly attain their saturation drift velocity in the presence of an electric field, enabling the transistor to transition states more quickly and achieve a huge operating frequency.

4.2 High-temperature performance

The covalent bonds in silicon vibrate more at high temperatures. With a narrow band gap, the electrons will be readily thermally generated and result in a process known as avalanche breakdown, in which electrons crash with other atoms to produce additional free charge carriers that contribute to the uncontrollable current that could harm the gadget [19]. Leakage current then increases dramatically, which raises the temperature further and increases the risk of catastrophic circuit failure.

4.3 Bandgap type

For GaN's E-k band diagram, it has the feature of being a direct bandgap semiconductor, which indicates that the valence band maximum and the conduction band lowest in a direct bandgap semiconductor happen at the same momentum value (k-value) [20]. As a result, extra momentum is not required for the electron and hole to recombine. This makes it appropriate for the manufacturing of LEDs by enabling the efficient emission of a particular photon wavelength. For Si, it belongs to the indirect bandgap semiconductor, where the valence band maximum and the conduction band minimum in an indirect bandgap semiconductor happen at different k-values [21]. For electron transitions, both a change in momentum and energy are needed because there is an imbalance in velocity between these bands, which prevents recombination from occurring vertically easily. A phonon, a quantum of lattice vibration, is needed to supply the momentum required to satisfy the conservation of momentum during the transition. By enabling the electron to collect or release energy in the form of lattice vibrations, the phonons aid in the transition [21]. As a result, the silicon chip internally produces a lot of heat. Because it might not always match well with the phonon interactions required during the transition, more phonons are likely to be created, which increases the likelihood of heat generation and breakdown. The efficiency of this process is also lower than that of direct bandgap semiconductors.

4.4 Bandgap energy

Since GaN and SiC have wider bandgaps than Si, more energy is needed to excite electrons from the valence band to the conduction band across the band gap so they can resist stronger electric fields without breaking down than Si. Leakage currents can therefore come from fewer thermally produced carriers, avoiding thermal runaway. This makes GaN and SiC more reliable than Si for high-voltage, high-frequency applications because they can resist higher electric fields without breaking down.

4.5 Comparison

The result of comparison of three type of semiconductors are shown in table 1.

Table 1. Comparison of Si, GaN and SiC semiconductors [10, 13, 14, 16]

	Si	GaN	SiC (4H)
Bandgap energy	1.12	3.39	3.26
Electron mobility (cm^2/Vs)	1350-1450	1000	950-1000
Saturation velocity	1	2	2
Thermal conductivity	1.5	1.3	4.9
Breakdown field strength	0.2-0.3	3.3	3.0-3.3

From Table 1, GaN and SiC have the overall best performance among the three materials, with SiC having the highest thermal conductivity, enabling it to make high-temperature diodes and transistors. GaN has the highest bandgap, which makes it suitable for making high-frequency, high-voltage devices. GaN and SiC both have a lower electron mobility than Si, which limits the performance on high switching rate devices such as transistors. However, the wide bandgap allows them to overcome this shortcoming by handling high-voltage devices better than Si. Even though Si has a mature production line and merged with real-life applications better than GaN and SiC, it can’t replace GaN and SiC in various aspects, including EV production and satellite telecommunications, which are equally important in people’s daily lives.

5. Conclusion

After the first discovery of Si and an extended period of advancement, semiconductors remain a global research focus. Researchers introduced the doping process to modify the electrical conductivity of an intrinsic semiconductor and produce various extrinsic semiconductors. Soon, researchers discovered that combining a p-type and an n-type semiconductor created a P-N junction, which acted as a fundamental element in the production of transistors, solar cells, and LEDs. After technological advancement, two new materials emerged: GaN and SiC. Due to their direct bandgap and higher bandgap energy, GaN and SiC outperform Si, an indirect bandgap material with a narrower bandgap. This advantage allows them to perform better in high-voltage, high-power, high-frequency devices like high-frequency transistors in electric vehicles and remote communications between space and Earth. Additionally, GaN and SiC are better suited for optoelectronic applications such as LED and laser production at specific light frequencies. However, we cannot overlook the drawbacks of these two materials, which include significant trap imperfections, high production costs, and the possibility of device malfunction in actual use. It is not advisable to overlook the significance of Si’s functions as microprocessors in today’s computers and smartphones, as well as the fact that most memory devices in computers, such as RAM and flash memory components, are silicon-based.

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