Dean&Francis

ISSN 2959-6157

Using the Characteristics of Existing Semiconductors to Predicted the Possible Direction of Future Semiconductor Development

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Abstract:

In today's scientific and technological development, the semiconductor industry is one of the key topics that can make its rapid development, whether it is a vehicle such as automobiles, aircraft or mobile phones, computers such as the daily need of electronic equipment, are inseparable from semiconductors. The research theme of this paper is to analyze the possible development direction of future semiconductors based on the characteristics of existing new semiconductors. The research method of this paper is to collect the structure and property data of GaN and SiC, and then compare these data with the previous Si semiconductors to find the reasons why GaN and SiC can replace the previous semiconductors. The study found that although GaN and SiC are respectively inferior to Si in some aspects, such as SiC's lower electron mobility than Si, they can both work in environments that Si cannot withstand and are better than Si as a whole.

Keywords: GaN; SiC; Si semiconductors; SiC polytypes

1. Introduction

Semiconductor is necessary for the development and application of today's technology because of the compactness, reliability, power efficiency, and low cost they have [1].

This paper will try to use the information mentioned below to analysis the possible future direction of semiconductor development. This paper first presented the properties, structures and types of semiconductors. Then the paper expanded on the properties and structure of GaN and SiC first, which are the representative of the third-generation semiconductor. After that the advantages and limitations of GaN and SiC have been presented. The comparisons among GaN and silicon and SiC are made in the paper to show that why GaN and SiC can replace the silicon. This paper also showed some application scenarios of GaN and SiC.

2. Fundamental analysis of semiconductor theory

2.1 Properties and structure

Semiconductor is a special substance which has a different electrical conductivity from that of either a conductor or an insulator. In the electronics industry, semiconductors are the basis for building various electronic devices and integrated circuits. Its electrical conductivity is low at room temperature, but it can be significantly improved with increasing temperature or changes in external conditions such as light. This property makes the semiconductor have important application value in electronic devices. The basic concepts of semiconductors can be understood in terms of their crystal structure and physical properties.

2.2 The type of semiconductor

Semiconductor can be divided into n-type and p-type. The semiconductor which the part of conducting electricity is mainly negative charged electrons is the n-type. These electrons come from “donor” impurities in the semiconductor. In the p-type, the conduction is mainly caused by positively charged holes, which come from “acceptor” impurities in the semiconductor. The p-n junction, which occurs when there is an abrupt change in impurity type from acceptors (p-type) to donors (n-type), occurs within a single crystal structure. The electrons are the dominant carriers on the n side, while the holes are the minority carriers. The depletion layer is a region near the junction that does not have any free charge carriers. This region has a very large electrical resistivity, because it is similar to the insulator. On the p side, the dominant carriers are constituted by holes, so they are called majority carriers. The minority carriers in p side are a few of thermally generated electrons exist there [1]. The structure of n-type and p-type semiconductor are shown in the Figure 1.

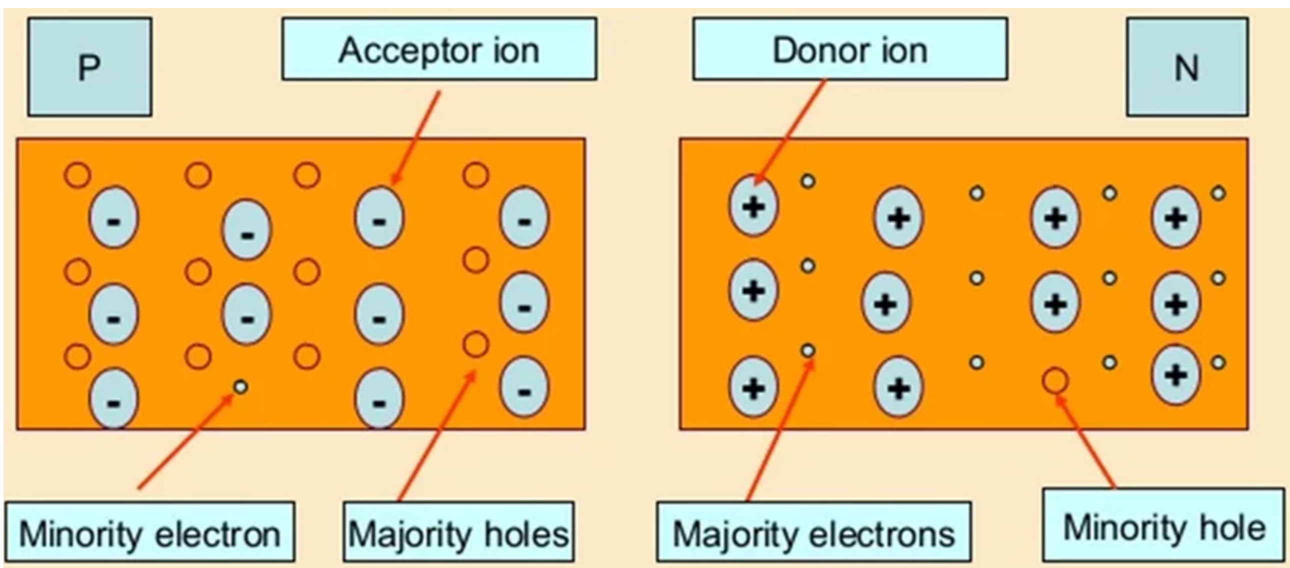

Figure 1. Structure of n-type and p-type semiconductors

2.2.1 The properties of silicon

Due to silicon is the second only to oxygen in quantity on Earth which make it easy to gain and inexpensive, it has been used as a semiconductor widely. It is suitable to use in the electrical applications, due to high melting point (1414°C) and the ability of withstanding high temperatures (up to 150°C) and currents it has. It needs less energy to release valence electrons in the crystal structure and produce charge carriers, because it has a relatively low band gap energy of 1.1 eV. When silicon is exposed in the air or water, a thin layer of silicon dioxide will be formed on the surface of silicon. This silicon dioxide layer is a good insulator which can prevent underlying silicon from pollution and corrosion. Moreover, silicon can be doped with different impurities to create n-type or p-type semiconductors, which are critical for forming p-n junctions and other devices [2].

But nowadays, it is more and more difficult to decrease the volume of the silicon devices and increase the density of silicon devices. Meanwhile, the design complexity, processing power, memory, energy consumption, density and heat dissipation of silicon devices have reached to their upper physical limits. Which means that silicon devices are not far from being obsolete [3].

2.2.2 The advantage of SiC

SiC has many different types. 4h-iC and 3c-SiC are the most common in electronic devices and 6h-SiC is usually used in industrial applications. 6h-SiC has a hexagonal crystal structure with six alternating making it very efficient for power electronics. The structure of 4h-SiC has similar to 6H-SiC but has a four-layer period and a more favorable electronic band structure for certain applications. 3c-SiC has cubic structure and is different from the hexagonal types. The structures of 6h-SiC, 4h-SiC and

ISSN 2959-6157

3C-SiC are shown in the Figure 2.

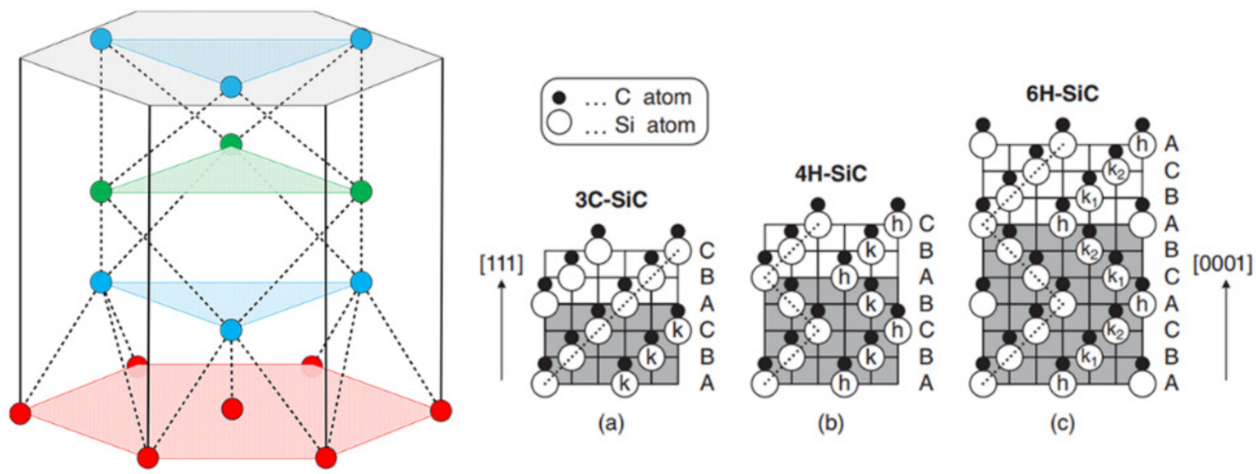

Figure 2. Structure of 6h-SiC, 4h-SiC, 3c-SiC

The stacking sequences of Si–C double layers are different in different SiC polytypes. Hence, the band gap of SiC typically fluctuates between 2.4 and 3.3 eV, with the 6H-SiC polytype exhibiting a medium value (3.0 eV). The 6H-SiC has the ability to let electrons in it moving more smoothly.

Due to the negative effects on the phenomenon of polytypism for SiC, 6H-SiC polytype is one of the most easily formed than other polytypes [4].

Compared with devices made by Si, SiC devices have better temperature characteristics, higher frequencies of working and it will consume less energy during transmission. In the applications such as high temperature, high voltage, high power and high frequency, SiC devices have more advantages, which can improve efficiency of system effectively and reduce consumption of energy, making the device smaller and lighter, thereby making the system more reliable, power electronic devices are developing in this main direction. Comparison of performance between silicon and SiC devices is shown in table 1.

Table 1. Comparison of performance between silicon and SiC devices

Characteristics	4h-SiC	Si
Crystal	Hexagon	Diamond
Band gap width	3.26	1.12
Hole mobility	100	600
Electron mobility	900	1400
Breakdown field strength	3	0.3
Electron saturation drift velocity	2.7	1
Thermal conductivity	4.9	1.5
Relative permittivity	9.7	11.8

4H-SiC is a power device due to the properties it has, to let electrons inside of it moving more smoothly and the lower ionization of doping, become the most popular material in the production of these devices. In the table 1, a comparison between characteristics in physics of Si and SiC materials are made. The differences of characteristics between SiC and Si materials can be found and the advantages of SiC are shown below:

High temperature resistance: The crystal structure of SiC materials are more stable, which give them a forbidden band width three times wider than silicon materials. The strength of valence electrons, can be shown by the forbidden band width. Which means that SiC can be used to work in the environment with high temperature steadily. However, because of the limitation of technology on packaging, the SiC power devices on the market are only capable of working at a maximum temperature of 175°C. But with the development in packaging, the highest temperature that packaging technology withstand can be even higher in the future.

Switching at a high speed: In a strong electric field, the maximum drift velocity of the whole electron affects the switching speed of the power device. When there is a strong electric field, it can also be increased by having a higher maximum drift velocity of the whole electron. And the maximum drift velocity of the whole electron in a strong electric field of SiC is almost triple that of Si.
Good thermal conductivity: SiC has much higher thermal conductivity and better ability to decrease the heat it has than silicon. Under the same condition of operating, the needing of releasing heat of SiC power devices are not as much as those for Si power devices. The measure of how much power can be handled in a given space can be increased, the size of devices and the costs of product manufacturing can be reduced by using SiC power devices.
Low loss: The SiC device always let electrons inside of it moving less smoothly and lower hole mobility when it compares with Si device, and the obstruction of the current in the circuit of power device is determined by the the obstruction of the current in the circuit of the drift layer, which is why the unit area is turned on in the SiC device [5].

2.2.3 The advantage of GaN

The minimum distance between the energy levels of valence band and conduction band of wurtzite GaN is large in momentum space occurs at the same momentum value. This material has a high critical value of the insulating properties under specified conditions. Wurtzite GaN has tetrahedral-coordinated structure. In regards to the GaN that has a tetrahedral coordination, when the structure and electrons change because of the change of dimensionality, different properties and even different uses of the materials will be produced. The decrease of efficiency and the heat emitted or absorbed in the devices of light emitting diodes (LEDs) can be reduced by the crystals or films of 3D GaN which own a direct wide bandgap of 3.4 eV. Meanwhile, 3D GaN crystals of that type can also increase the current spreading. 3D GaN's characteristics make it an ideal choice for high electron mobility transistors (HEMTs), high-frequency microwave communications, and terahertz detectors at high temperature. Because it can transfer heat quickly, and it will not react with other substance easily, and it can keep its properties in the intense radiation. However, the deposited substrates causing 3D GaN to have high dislocation densities and strong interfacial effects are not ideal for electronic devices. Whereas, the new characteristics showed by low dimensional GaN can be used to overcome the problems existed in 3D GaN. The applications of GaN have been expanded [6]. The structure of GaN is exhibited in the Figure 3.

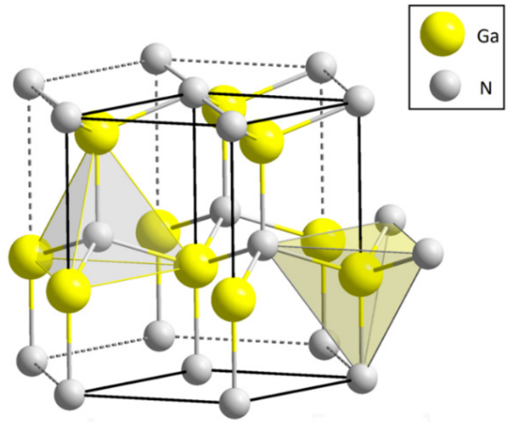

Figure 3. The structure of GaN

Meanwhile, at the same maximum voltage that can cut off the flow of current reliably, GaN HEMTs have lower resistance between drain and source and gate drain capacitance, enabling switching operation with higher frequency. They have shown potential to surpass the properties which below to SI-based power devices and compare with their SiC counterparts, they are more cost effective [7].

3. Application scenario analysis

Kachi et al. discussed reliabilities of GaN power devices in the application of automotives [8]. Because the structure of device comes from HEMT, most of the GaN devices which is developing, are produced in lateral device structure. GaN device is usually used in high frequency operation. The on-resistance of the GaN lateral device using in nowadays has reached the limit of the 4H-SiC device. GaN lateral device is usually applied in both systems with middle and low power in the electric vehicle (EV) and a hybrid vehicle (HV). It has higher cost performance than the Si power MOSFET used in HV or EV.
Keshmiri et al. compared GaN HEMTs and SiC HEMTs in different ranges of using [9]. Table 2 shows that GaN has higher breakdown electric field, wider energy gap and can let electrons in it moving more smoothly than Si and SiC. GaN has less heat transfer ability than Si and SiC which means that GaN device has a poor heat conduction property. Therefore, the heat propagates from the junction to the case and heatsink in GaN device is poor. The poor heat transfer ability of GaN results in higher thermal resistance which means that under the same dissipated power, GaN devices will withstand higher operation temperatures. The GaN has similar saturation drift velocity to SiC.

ISSN 2959-6157

Table 2. Comparison of Si, SiC and GaN parameters

Parameter	SiC	GaN	Si
Energy gap (eV)	3.26	3.5	1.12
Thermal conductivity (W/cm*K)	4.9	1.3	1.5
Breakdown electric field (MV/cm)	3	3.3	0.3
Mobility of electron (cm^2/V*s)	900	1800	1400
Saturation drift velocity (Mcm/s)	27	27	10

One of the challenges of More Electric Aircraft (MEA) facing is how to control and cool converters and power generators down, which results a higher demand in electrical power. The properties such as low consuming of energy, high temperature operating capability and high switching capability belong by GaN and SiC are helpful to address this challenge.

Kayser et al. presented that SiC MOSFET can be switched to zero voltage by utilizing separate gate signal switching patterns [10]. The energy losses caused by the turn-on and turn-off circuit in Si IGBTs can be reduced by the concept of hybrid-switch. 1.7 kV chips are used to complete the research.

With the use of a fast-switching Si IGBT, the maximum speed allowed of switching can be gained by the fast hybrid switch at turn-off. Although there is almost no tail current can be seen, a good damping with a few slight oscillations is provided by enough charge in the switch. Slightly damped oscillations with bigger amplitude are the only things encountered by the unipolar full-SiC switch, which is different with the fast-switching Si IGBT. The amount of MOSFET chips used by the full-SiC switch is twice that the hybrid switch has. It will lead the current drop to be doubled when the voltage slope is raising, because an increasing in the overall unintentional capacitance in electronic devices and circuits of the switch. When the full-SiC switch and the fast hybrid are working under the worst-case operating conditions, an active clamping circuit can be used to keep them in the same maximum overvoltage. Under normal condition, a higher overvoltage is still owed by the full-SiC switch.

Both full-SiC MOSFET and fast hybrid reduce more than half of overall switching losses than full-Si. A sharp reduction on turn-off losses happens because the speed of switching is increased and the tail current is reduced. The reverse-recovery charge and losses can be reduced because a fast turn-on is allowed by the SiC MOSFET. At low load currents, the switching losses is in a low point. Not only increase the turn-off speed, but also remove the disproportionally high energy losses during the state in which a diode flows a reverse current after the current has crossed zero of the Si diodes. The lowest switching losses is still owned by the full-SiC MOSFET. Although energy losses during the state in which a diode flows a reverse current after the current has crossed zero are increased, they are still very low, because the area of the SiC chip is twice the area of hybrid switch

4. Conclusion

GaN and SiC still have some challenges. GaN has strong thermal conductivity. Joule heat generation will produce a self-heating effect and lead the temperature to increase sharply when the transistor channels are passed through current flows. The channel temperature increasing not only cause substantial lifetime reductions, but also reduce the speed of electrons and holes moving as a whole in a semiconductor and cause a shift in the threshold voltage, resulting a large decrease in performance. That's the reason why although GaN-based HEMTs have showed high output power potential in radio frequency, they still work at a low power. And the manufacturing process of SiC is complex, so the cost is high. These problems may become the future research direction of the semiconductor industry.

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