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The Application of Third Generation Semiconductor in Power Industry

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Abstract. With the rapid development of technologies, the third generation semiconductor is being studied, as it is leading to the significant change in industry like the manufacture of PC, mobile devices, lighting etc. Till now, due to its irreplaceable physical characteristics, third generation semiconductor is applied to lots of fields. This paper analyzes the application of third generation semiconductor, namely, GaN and SiC. Their characteristics including advantages as well as disadvantages will be discussed through reviewing the result of relevant researches. Meanwhile, comparison between the third generation semiconductors and the second as well as the first generation semiconductors is made in this paper. Through the comparison of physical characteristics, recent marketing, production and limitations, the advantages and disadvantages of each semiconductor is analyzed and the suggestion of how to avoid the disadvantage through application is proposed. At last, the future development is predicted. According to the analysis result of this paper, silicon poses more merits. Silicon is not only cheaper but also performs better making it a preference of GaAs, and GaN in the domain of IC. The second generation semiconductor, GaAs, is widely used in the circuits and photoelectric integration. Furthermore, the third semiconductor material GaN is a promising material for power switching and communication and has the great possibility to play a crucial role in market.

1 Introduction

During the development of semiconductor industry, silicon (Si), and germanium (Ge) are called the first generation of semiconductors. Gallium arsenide (GaAs) and aluminum arsenide (GaSi) represent the second generation of semiconductors. And nowadays, the third generation of semiconductors, materials with energy band over than 2.3eV, has emerged in daily life like gallium nitride (GaN), and silicon carbide (SiC). Electron mobility determines the working performance under low pressure, performance under high pressure is decided by saturated electron velocity. Energy bandgap determines the wavelength of light emitted-higher energy gap leads to shorter wavelength[1].There is a considerable number of papers and works of research that have ventured on the study this new dormain with a special focus on gallium nitride. Studies not only describe advantages and disadvantages associated with wide bandgap devices but also take a deeper look into its characteristics[7]. Findings from the studies show that heat is generated mainly from the width of bandgap as seen in power amplifiers, diodes and power switching. This study will focus on different characteristics of three representative materials—Si, GaAs and GaN. Additionally, the study will scrutinize recent developments and designs of devices that incorporate gallium nitride. Based each material's characteristic and a comparison of applications, the study will evaluate the merits of using Si, GaAs and GaN. This study is based mainly on the related research result. And through reviewing the literature, this study will drawn the conclusion on, which material has the most advantages in which area. At last, the future development will also be predicted. Besides, several suggestions are also given.

2 Physical characteristics of Si and related applications

Physical characteristics. As compared to GaAs, and GaN, Silicon is relatively cheaper and has excellent thermal and mechanical properties. Additionally, it is easier for silicon to expand in size and has got high-purity crystal. Incorporating the required technology alongside the standard development stage has seen silicon play a critical role in electronic information industry. More than 99 percent of integrated circuits (IC) are made of silicon[5]. Table 1 shows the material properties of Si, Sic and GaN. Because GaN has higher electron mobility than Si and SiC, it is more suitable for high-frequency devices. In comparison to the other two, SiC has higher thermal conductivity, so it has the advantage of working at higher power. The different physical characteristics allow them being applied in different ways.

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Tab 1. Material Properties of Si, SiC and GaN

Table I. Material properties of Si, SiC and GaN[7,8]

Material property	Si	4H-SiC	GaN
Bandgap (eV)	1.12	3.26	3.4
Critical field (10^6 V/cm)	0.3	3.5	3.3
Carrier mobility ($cm^2/V \times sec$)	1500	650	990, 2000[a]
Electron saturation velocity(10^6 cm/sec)	10	20	25
Thermal conductivity ($W/cm^2 \times K$)	1.5	5	1.3

[a]In bulk GaN/2D electron gas region of GaN/AlGaN HEMT, respectively.

Recent Marketing. As mentioned above, nowadays, Si is widely used in diodes, integrated circuits (personal computers, electric devices, mobile phones), and rectifiers[3]. Due to the plenty storage and increasing sophisticated process, as well as the worldwide utilization of silicon, other burgeoning materials like GaAs and GaN are not strong enough to shake silicon's dominance in a short time. In addition, Si is the basement of integrated circuits industry--98% of semiconductors are Si, and over 90% large-scale integration (LSI), very large scale integration (VLSI), ultra large scale integration (ULSI) are founded on polished silicon wafers and epitaxial silicon wafer[4]. One crucial reason is the low price and mature technology of Si production. According to the research done by Lux Company, tile 2024, silicon production may still own 87% market share[2].

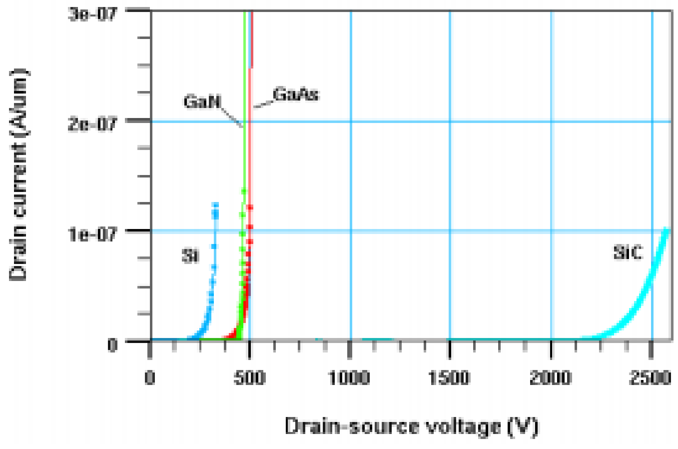

Fig. 1. Comparison of predicted hold-off voltages for the Si, GaAs, SiC, and GaN devices (GaN JFET was obtained at Vgs= -25V)

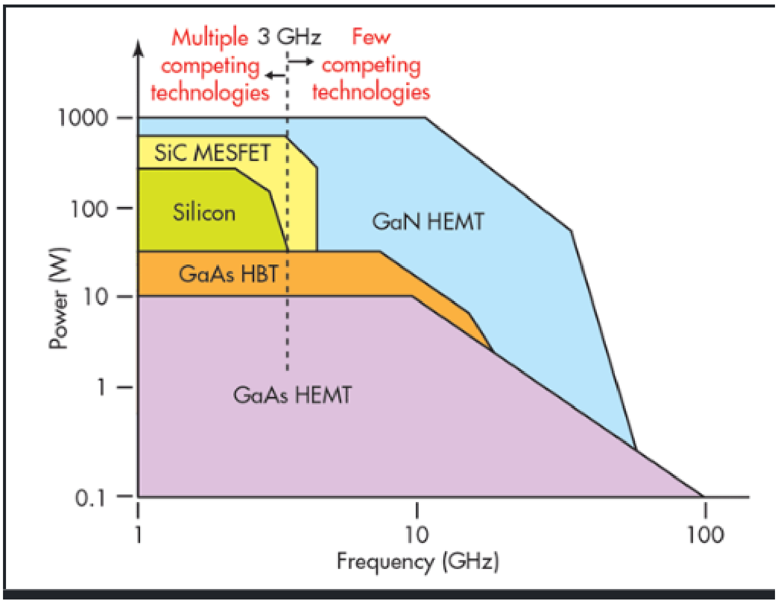

Fig. 2. Level of electron mobility in Si, GaAs, and GaN

3 Physical characteristics of GaAs and related applications

Special advantages of GaAs. Gallium arsenide has over 6 times electron mobility higher than silicon,according to the table, and owns high frequency, high speed and excellent optoelectronic properties which silicon doesn't have. The ability of simultaneously processing photoelectric signals on the same chip makes gallium arsenide an outstanding material[6].

Current main applications. It has become the fastest developing and most widely used semiconductor materials after silicon. With higher saturated electron velocity and temperature resistance than silicon, GaAs owns the unique advantages in the area of circuits and photoelectric integration[5].

4 Physical characteristics of GaN and related applications

Brief introduction of GaN. GaN is the basis of group III nitride and is also studied deeply. Generally, the electrical properties of GaN are the main factors that determine the performance of devices made of them. Due to the wider bandgap than gallium arsenide and silicon, devices based on GaN contribute to high-frequency, high-efficiency power electronics. They can have thinner drift regions, which means the devices will have lower specific on-resistance so that they will experience less losses than a Si device with comparable voltage and current capabilities.[1](Review of commercial) Its inherent high breakdown strength with high saturation electron velocity indicate the bright future of GaN devices. The unintentionally doped GaN based on sapphire substrate had high n-type intrinsic carrier concentration, which can be seen as a feedback for this material; fortunately, nowadays, some better specimens can make it lower to be around $10^{18}/cm^3$[3]. By applying the method of IEEBI to dope GaN into p-type with Mg, recent technology may prepare p-type GaN materials owing carrier concentration in the range of 10^{11}-$10^{20}/cm^3$[1].

Production condition. As a new merging material, GaN power devices are recently put into applications commercially. GaN, a very stable compound, with high melting pointaround 1700 degrees, has excellent ability to equip with high electronic density. Consequently, it is widely applied to power factor correction, power system design of DC-DC, power adapter, photovoltaic converter and solar converter devices[5]. Its atomic volume is about half the size of GaAs. Comparing with the first two generations of semiconductors, GaN has a larger potential area to explore, especially in electrical and electronic engineering. The market of electronic devices formed formally in 2016, with the scale of twenty million dollars to thirty million dollars. According to the data from IC insights, the occupied rate of GaN devices has reached nearly 2%. Meanwhile, Yole predicts that the compound increase rate per year of power switching based on GaN will reach 86% (2016-2021)[6].

Challenges of GaN. However, there are still lots of challenges of GaN devices. Theoretically, due to the structure of its energy band, the capability of transformation is poor so that the electric field mobility is low and high frequency performances are not ideal. The selection of substrate materials will significantly affect GaN's heteroepitaxy, properties and reliability. One of the biggest challenges is thelacking of suitable substrate materials for matching the thermal compatibility with GaN. Recently, sapphire and SiC are widely used as substrates, which may have large dislocation--the dislocation density can reach 10^8-$10^{10}/cm^2$. The level of doping is at a low level (mainly with Mg), and specifically, the hole concentration is only 10^{17}-$10^{18}/cm^3$, and the electron mobility is less than 10^2V.S. More importantly, the efficiency of doping is only 0.1%-1%. Another drawback is the much higher cost of the whole producing process than Si and GaAs, including the cost of substrate materials.

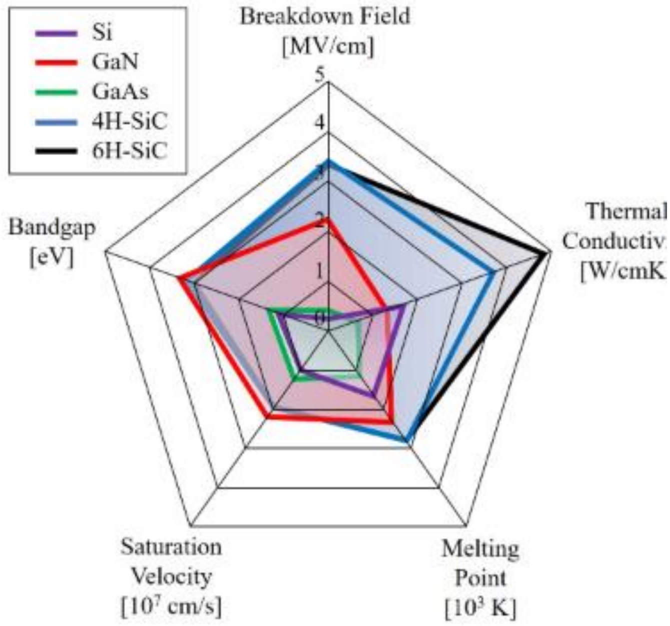

Fig. 3. Material properties of Si (violet), GaN (red), GaAs (green)

5 Literally analysis

Despite Silicon being the most popular semi-conductor, GaAs devices amassed popularity for RF thus replacing silicon in MOSFETs application. GaN however has been the latest market's favourite over the last decade due to high frequency traits possess as seen in table 1. This section features performance analysis based on related works from researchers. HEMTs have been the greatest interest of many researchers when it comes to gauging the efficiency of the three materials. Several numerical studies related to HEMTs have been carried out with an aim of analysing how internal-physical mechanisms affect HEMTs. Yoshida et al used a 2 dimensional numerical analysis for simulation of device performance[8]. Their analysis of HEMTs featured Anderson's model where equations of band-edges alongside Boltzmann statistics are evaluated. Yoshida et al method commonly applied what is commonly referred to as drift-diffusion model which detects thermal effects in complex structured HEMTs.The impact is less experienced in GaN than GaAs and Si.

To gauge on transport of energy Bout applied a two-dimensional simulator that entailed numerical analysis of preceding 3 moments of Boltzmann equation. The method, commonly referred to as energy-transport model has often been used to evaluate GaAs HEMTs performance. Unlike Widiger's energy model Bout's method does not omit conduction factors in AlGaAs layer. Based on Bout's findings,GaAs is suitable in operations where thermal capacities are available[8]. Temperature therefore is a key factor when determine which material best suits the operation at hand. This is due to the shear stress effect that is brought about by inverse piezoelectric effect. Findings prove that Shear stress usually results to slip which in affects the structures of the GaN crystal. Si, however, has abilities to expand and maintain clear crystals when subjected to temperatures. As such, it would be wiser to use them in arrears where GaN proves futile.

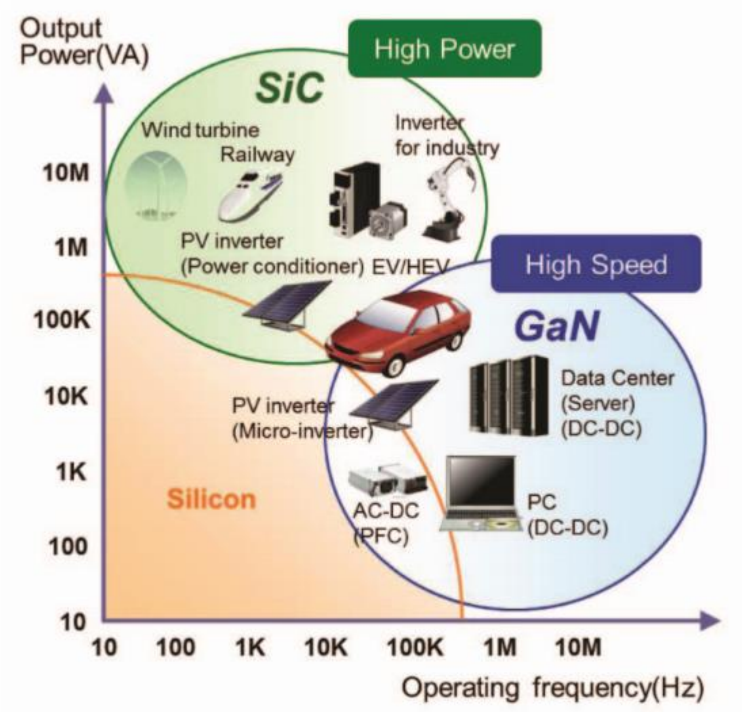

Fig 4. Potential applications of GaN and SiC power switching transistors[9].

6 Conclusion

In conclusion, this paper analyzes the application of third generation semiconductor, namely, GaN and SiC. Their characteristics including advantages as well as disadvantages are discussed through reviewing the result of relevant researches. Meanwhile, comparison between the third generation semiconductors and the second as well as the first generation semiconductors is made in this paper. Through the comparison of physical characteristics, recent marketing, production and limitations, the advantages and disadvantages of each semiconductor is analyzed and the suggestion of how to avoid the disadvantage through application is proposed. At last, the future development is predicted. Based on the descriptions and analysis discussed, it is evident that Silicon poses more merits. Silicon is not only cheaper but also performs better making it a preference of GaAs, and GaN in the domain of IC. The second generation semiconductor, GaAs, is widely used in the circuits and photoelectric integration. While the third semiconductor material GaN, a promising material for power switching and communication has the great possibility to play a crucial role in market. Resolving the challenges and limitations mentioned, the study of GaN may have a great development in the future.

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