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PERSPECTIVE

Development trends of GaN-based wide bandgap semiconductors: from solid state lighting to power electronic devices

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1 Introduction

III-nitride wide bandgap semiconductors, such as GaN, InN, AlN and their ternary or quaternary alloy components, are wholly-component direct band gap materials with a full adjustable band gap (0.63 – 6.2 eV), strong polarization, high temperature resistant, anti-radiation, and can be achieved with low-dimensional quantum structures. Furthermore, it is the only one semiconductor material system that covers ultraviolet to infrared wavelength band. Therefore, a lot of attention has been paid to them. Through unremitting efforts, blue-green light-emitting diodes (LEDs) based on InGaN/GaN quantum well materials with low in composition have been developed and successfully industrialized. Their applications in the fields of the solid-state lighting and flat-panel displays are profoundly changing people’s lives. In addition, high power electron mobility transistor devices (HEMT) based on low Al content AlGaN/GaN heterostructure have significant applications in the fields of X-band radar and civilian communications, which is profoundly affecting the national security situation and the world’s strategic pattern.

2 GaN-based LED and semiconductor lighting

In 1989, the world's first GaN-based blue LED was developed by Shuji Nakamura from Nichia Corporation of Japan, and in 1991 commercial production of GaN-based blue LEDs was started. In 1994, the company approached the method of using blue LED to inspire yellow phosphor. Then they launched the world’s first white LED, and put forward the concept of semiconductor lighting, starting the lighting innovations from the traditional way to more efficient approach. Since then, focusing on how to achieve higher luminous efficiency and output power, a lot of researches have been done and remarkable results have been achieved. In April 2012, the Cree, Inc. used the SiC substrate technology to make a new laboratory record of high-power LED with the luminous efficiency of 254 lm/W and color temperature of 4408 K. In domestic, the white packaging closes to the international advanced level, and the industrial LED luminous efficiency reaches to 130 lm/W. With the continuous improvement of LED luminous efficiency and other characteristics, LEDs have a wider range of applications in the fields of lighting, backlighting, special display areas. This promotes a huge industrial chain, the upstream material growth and chips production, midstream packaging and module, and downstream lighting and display, and with it a revolutionary change in the lighting and display technology has been promoted as shown in Fig. 1.

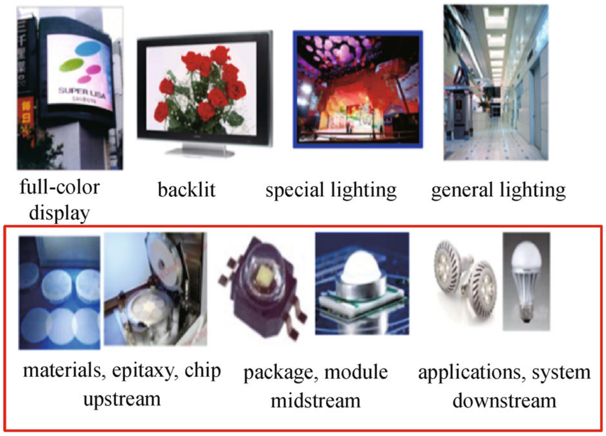

Fig. 1 Main application areas and industry chain of LED semiconductor lighting

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In recent years, LED semiconductor lighting industry has been developed rapidly at home and abroad. In 2011, the global sales market of GaN-based LED was \$ 12.5 billion, increased by 9.8% compared to that of 2010 with \$ 11.3 billion. Among them, the lighting market was increased by 44%, from \$ 1.2 to \$ 1.8 billion. The global market size of high brightness LEDs will be \$ 15.3 billion in 2015. High-power lighting and ultra-high power lighting markets continue to expand, and the market prospect is promising. At home, the LED lighting market is also developing developed steadily, from \$ 46 billion in 2010 to \$ 64.5 billion in 2012.

Although the LED industry is successful, there are still some problems and challenges, which are the focuses of the scientific and industry community. 1) LED luminous efficiency droop at large current injected (Droop effect); 2) light extraction efficiency; 3) only the blue light is thriving among the whole band; 4) micro and nano-LEDs; 5) GaN-based LED on Si substrate. From the current situation, the development of LED shows the following trends: turning from light efficiency drive to cost-driven and quality-driven, from blue chips to green and UV chips, from traditional lighting to intelligent lighting, from optical illumination to beyond lighting. Figure 2 shows some applications of intelligent LED lighting.

Fig. 2 LED semiconductor intelligent lighting

3 Physical basis of GaN-based electronic devices

The usual applied III-nitride materials are hexagonal wurtzite structures, and grown along the c-plane (001), which does not have a center of symmetry. Therefore, a strong spontaneous polarization with the polarization coefficient of $-0.029\,\mathrm{C/cm^2}$ (GaN) and $-0.081\,\mathrm{C/cm^2}$ (AlN) is presented along this direction, resulting in a strong polarization electric field existing at the interface of c-plane AlGaN/GaN heterojunction. In addition, the conduction band offset is large for AlGaN material system, reaching 2.8 eV in AlN/GaN, which results in a deep quantum well and strong confinement for electrons. Strong polarization effects and large conduction band offset enable a high-density two-dimensional electron gas in AlGaN/GaN heterostructures (surface density up to $10^{13}\,\mathrm{cm^{-2}}$), making AlGaN/GaN heterostructures one of the ideal materials to prepare high power HEMTs. Figure 3 shows the advantages of GaN over Si and GaAs in terms of preparing high-power HEMTs. Because of this characteristic, GaN-based HEMTs have wide applications in microwave power devices and power electronic devices.

4 GaN-based microwave power devices

Since Khan successfully prepared the first AlGaN/GaN heterostructure HEMT devices in 1993, many scholars have studied the current collapse effect, the roles of the passivation layer and the role of field plate, making power density of GaN-based HEMT devices gradually increased and eventually reached 41.4 W/mm. This progress promotes the application of HEMTs in civilian communication and military radar, but also makes industrialization of GaN-based HEMT devices into reality. Figure 4 shows several international companies that successfully industrialize HEMT devices. These companies are mainly from the United States, South Korea and Japan. With the drive of markets, GaN-based HEMTs develop towards microwave amplifiers and ultra-high speed devices.

5 GaN-based power electronic devices

Power electronic devices have been widely used in photovoltaic power generation, power switch, electric cars, electric locomotives, and so on. As shown in Fig. 5, since the first transistors was prepared in 1904, power electronics devices have been transformed from the vacuum power electronic devices to solid state power electronic devices. Hereafter, with the advancement of epitaxial technology, solid-state power electronic devices have been developed from Si material to the third generation wide band gap semiconductor materials.

GaN-based III-nitride materials have many advantages, such as wide band gap, large saturation mobility, high two-dimensional electron gas density, high critical field, and so on. Therefore, power electronic devices based on GaN-based materials have high temperature performance, fast switching speed, low on-state resistance, high breakdown characteristics, and so on. So the power electronic devices based on GaN-based materials have low requirements for the cooling system, small capacitance and inductance, small energy loss, and high output power. Thus, GaN-

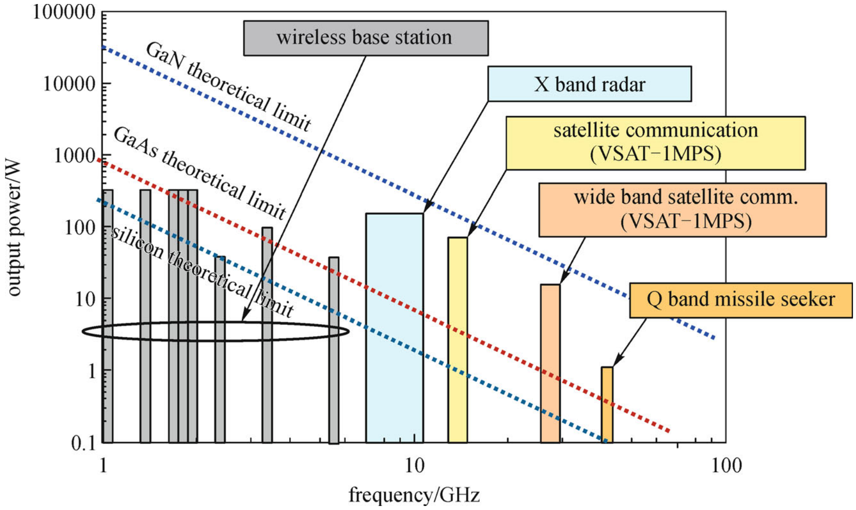

Fig. 3 Theoretical limit power of three generations of semiconductor materials HEMTs

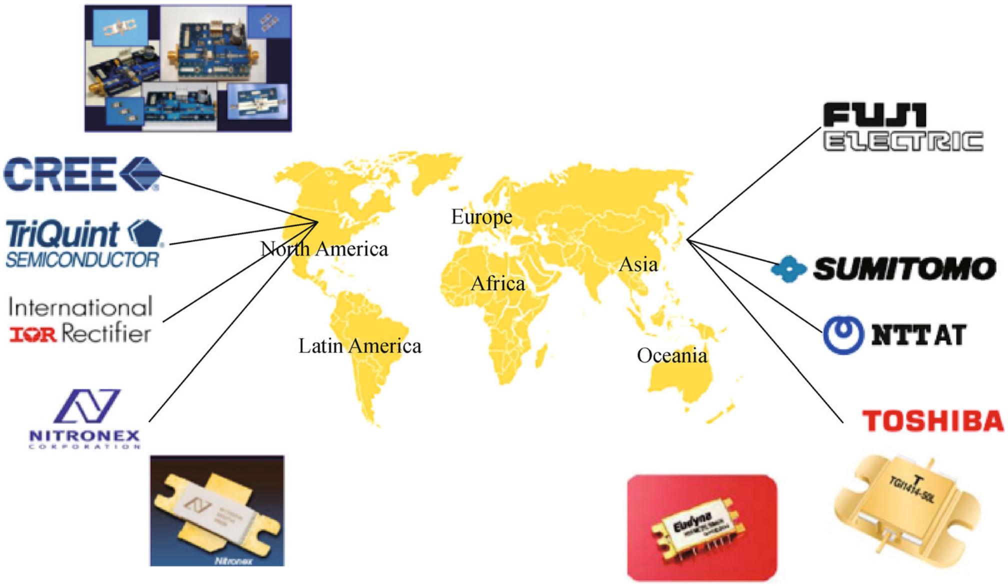

Fig. 4 Several companies that relatively successful industrialized GaN-based HEMT

based power electronic devices have certain advantages. As can be seen from Fig. 6, the operate voltage of GaN-based power electronic device is higher than that of the Si-based power electronic device, belonging to middle withstand voltage devices and having important applications in industrial motors, electric railways drive and other fields.

Currently, the U.S. International Rectifier (IR) Corporation reported GaN-based power electronic devices whose volume is 1/4 of that of Si-based power electronic devices while the efficiency is increased 4.5% when the current is 30 A. But for now, GaN-based power electronic devices still exist the following key scientific and technological issues: 1) the laws of controlling warping and cracking during the growth of large size Si-based GaN heterostructure materials; 2) defects in Si substrate GaN induced degradation of breakdown characteristics and high-field transport property and the solution of this problem; 3) the key technology to compatible with Si semiconductor technology; 4) to realize a high threshold voltage and normally-off function. Thus, there are a lot of work can be done to research GaN-based power electronic devices.

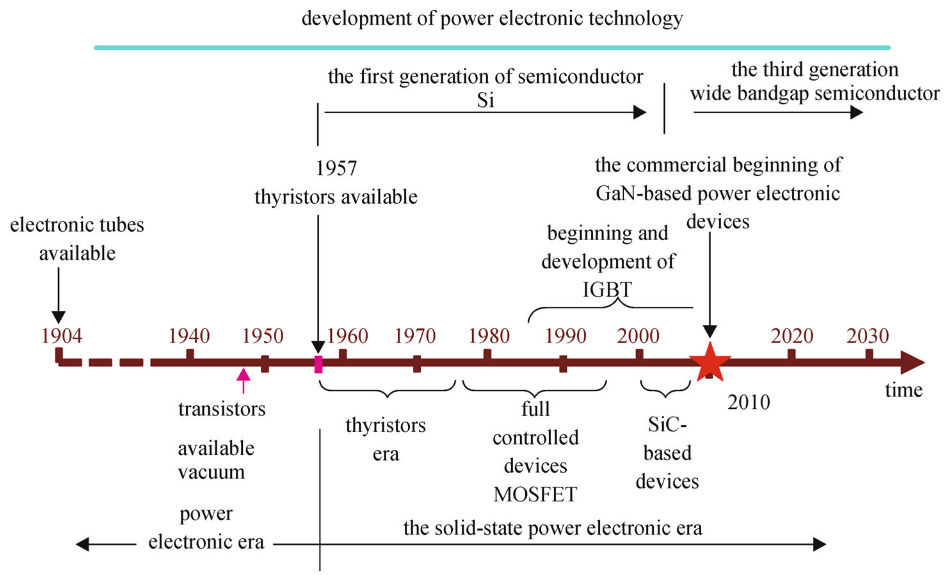

Fig. 5 Development of power electronic devices

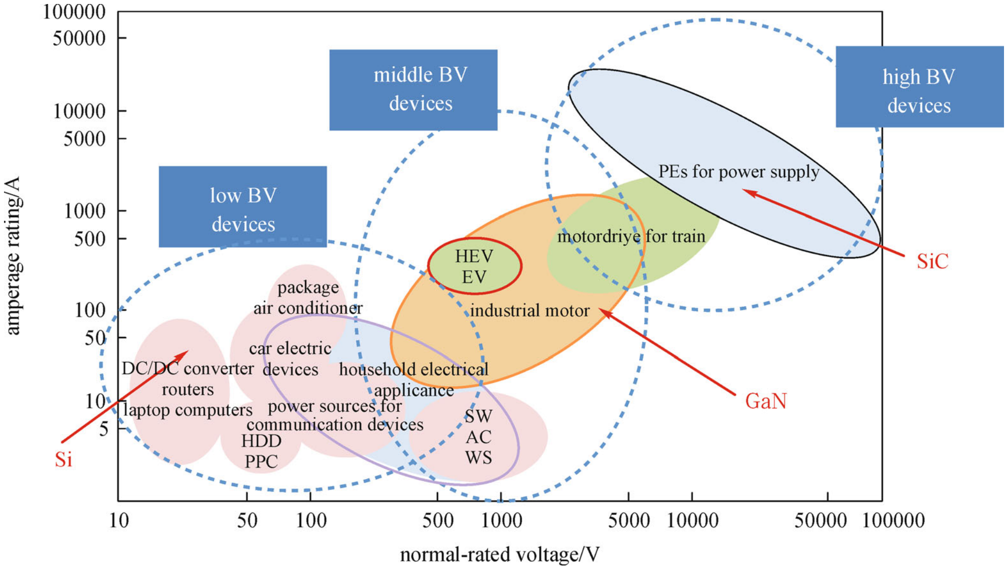

Fig. 6 Performance comparisons of power electronic devices

6 Conclusions

Owing to a series of excellent physical and chemical properties, III-nitride semiconductor is the optimal material system to develop semiconductor lighting chips and power electronic devices. In the past 20 years, semiconductor lighting has become a huge high-tech industry, which is currently being transformed from light effects-driven to cost and quality-driven. Moreover, intelligent lighting and beyond lighting are developing rapidly. GaN-based microwave power devices have also made a series of key breakthroughs and been used in military radar currently, which will be widely used in 4G ~ 5G mobile communication base stations in the near future. Now, the current work is mainly to improve the reliability and high-frequency device characteristics. GaN-based power electronic device is the current hot topics, whose market is large and in the future the industry may keep pace with semiconductor lighting. But the market has just started, there are a series of key scientific and technical issues need to be overcome and the production costs need to be reduced significantly.

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