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GaAs, GaN MATERIALS ON THE MODERN SEMICONDUCTOR MATERIALS MARKET

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The review paper examines the prospects of GaAs and GaN from the point of view of the latest technologies. The main areas of application of gallium arsenide are presented. The dynamics of the development of the market of materials based on gallium arsenide are considered. The possible development of events in the semiconductor market is analyzed, taking into account the growth of demand for high-performance radio frequency devices for advanced wireless communication systems, the expansion of 5G networks and telecommunications networks. A comparison of the advantages and disadvantages of modern semiconductor materials is made.

INTRODUCTION

The modern semiconductor materials market consists of many materials: Si, SiC, GaAs, GaN, InP, SiGe, etc. Each of them has its own advantages and disadvantages. Although silicon is one of the most common elements on Earth and has unique radioelectronic properties, its use becomes limited when the latest technologies come to the fore. In the modern world, electronic devices should be as small as possible, cheaper, and provide as much energy as possible while consuming less energy. Therefore, modern semiconductor materials such as GaAs, one of the promising materials, the methods of growing which can be improved, and GaN, as the most promising semiconductor material based on Ga today, come to the fore.

DEVELOPMENT OF GaAs MARKET

From the creation of the first optoelectronic devices based on GaAs in the mid-20th century to the creation of high-speed integrated circuits for military equipment control systems, the global market for devices based on gallium arsenide has experienced ups and downs. By the early 2000s, the areas of application of gallium arsenide single crystals had been determined, the main technologies for obtaining single crystals had been selected and mastered, and a developed industrial infrastructure for mass production had been created. There was a transition from the initial stage of obtaining a material with certain parameters, despite the cost, to the next stage of the transition to economically viable materials for mass production. Rapid growth in production began, with production volumes more than doubling over ten years (1990–1999). A group of companies was formed, accounting for about 90% of global gallium arsenide production: Litton Airtron, M/A-COM Inc., American Xtal Technology (AXT), Sumitomo Electric Industries (SEI), Hitachi Cable, Mitsubishi Chemical Corporation, Freiberger Compound Materials (FCM). In 2000–2001, the GaAs technology market experienced an overproduction crisis. At the beginning of 2000, the growth in GaAs sales was over 60%, and by the end of that year, actual consumption of gallium arsenide did not exceed 65% of sales, which led to the accumulation of huge inventories. As a result, by the end of 2001, gallium arsenide production had decreased by approximately 40%. The decline was observed until 2005 (Fig. 1). The main feature of the recovery and growth period, which lasted from 2005 to 2011, was the entry into the market of a number of new manufacturers, mainly Chinese. Chinese enterprises at that time were mainly focused on the production of gallium arsenide single crystals for optoelectronics as the fastest growing consumption segment [1].

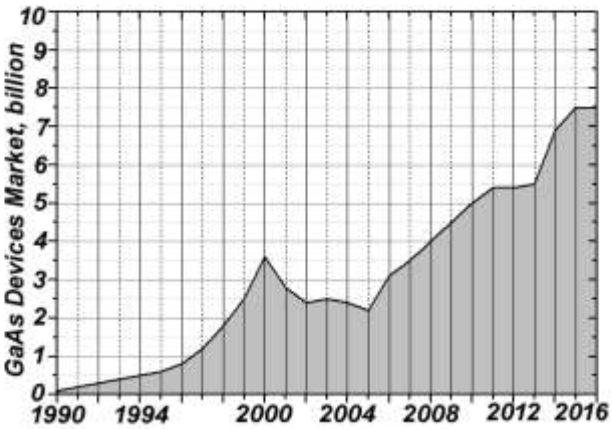

Fig. 1. Development of the GaAs-based device market in 1990–2016 (billion USD) Source: Strategy Analytics‘ Advanced Semiconductor Applications. 2017

Today, the market trends for gallium arsenide-based materials have changed. The growing demand for high-performance RF devices for advanced wireless communication systems has led to the development and production of more efficient GaAs RF semiconductors. The expansion of 5G networks and telecommunications networks has begun to require high-speed, low-latency RF semiconductors, in which GaAs outperforms traditional silicon-based alternatives. The wider adoption of GaAs technology in the aerospace and defense industries has made radars, satellite communications, and electronic warfare systems more efficient, contributing to the expansion of this market. It is also worth noting the growing use of GaAs in consumer electronics. GaAs RF components are being integrated into smartphones and tablets to improve performance and battery efficiency. Innovations in manufacturing technologies are making GaAs semiconductors more economical and accessible for wider industrial applications.

The gallium arsenide (GaAs) RF device market was valued at USD 11.3 billion in 2021 and is projected to reach USD 18.8 billion by 2030, at an average annual growth rate of 6.1% (Fig. 2). During the forecast period, technological advancements in emerging economies and growing applications in the automotive and power industries will create a promising future for the GaAs RF semiconductor market.

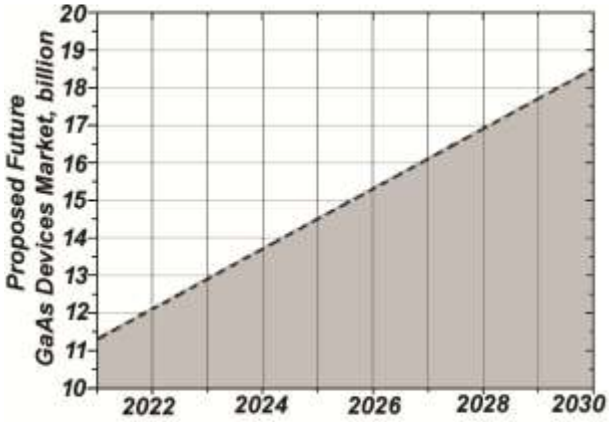

Fig. 2. Forecasted market for GaAs-based devices (Global Gallium Arsenide (GaAs) RF Devices Market. www.extrapolate.com)

The Strategy Analytics Advanced Semiconductor Applications (ASA) report, "RF GaAs Device Technology and Forecast: 2021–2026," indicates that the entry of GaAs-based devices into the aerospace and defense market is likely to continue to be a major application. The growing use of GaAs and GaN devices in this segment will lead to strong growth in RF semiconductor revenues.

RF GaN MARKET ANALYSIS

The RF GaN market size was estimated at US$1.7 billion in 2024 and is expected to reach US$4.03 billion by 2029, with a average annual growth rate of 18.76% during the forecast period (2024–2029) [2].

With the ever-evolving GaN technology, gallium nitride-based materials are enabling higher frequencies in more demanding applications such as radar and base stations for cable television (CATV), very small aperture terminals (VSAT), and defense communications. RF GaN plays a key role in wireless infrastructure, improving efficiency and expanding bandwidth to support ever-increasing data rates. The RF GaN market is primarily driven by the increasing adoption of 5G and advances in wireless communications. Telecom operators are also successfully using power GaN transistors. The widespread adoption of RF GaN in electric vehicles is also one of the major factors driving the demand in this market. Development of the required infrastructure for autonomous vehicles and drones is another factor boosting the demand for RF GaN technologies. Thus, the increasing development and adoption of autonomous vehicles and drones for various applications, especially in military and defense, is expected to further increase the adoption of RF GaN devices.

The inherent advantages of GaN are associated with some manufacturing challenges, including cost and optimization of device processing and packaging. Although significant improvements have been achieved in GaN-based RF devices, there are still some obstacles preventing gallium nitride on silicon carbide (GaN-on-SiC) from entering mainstream applications (e.g., wireless base stations or cable television). The COVID-19 pandemic has impacted supply chains and the telecommunications industry. This has significantly complicated the penetration of 5G in the telecommunications sector. Rapidly increasing data consumption has led to the growth of commercial networks and has forced network providers to implement next-generation networks such as 5G. Organizations around the world are introducing new products and expanding their businesses. For example, in June 2022, Integra, a provider of innovative RF and microwave power solutions, announced the availability of its revolutionary GaN RF 100 V technology to customers in the US and Europe. The company also announced the expansion of its GaN RF 100 V product portfolio with seven new products for the avionics, directed energy, electronic warfare, radar and research market segments, and delivering power levels up to 5 kW per transistor [2].

GaN is used in RF applications for several reasons such as high breakdown field, high saturation velocity and reliable thermal properties as they play an important role in transmitting signals over long distances or at high power levels. The application of gallium nitride is segmented by application: military industry, telecommunications infrastructure, satellite communication, wired broadband, commercial radar and avionics, RF power, materials (GaN-on-Sic and GaN-on-Silicon). The leaders of the RF gallium nitride market today are Mitsubishi Electric Corporation, STMicroelectronics NV, Qorvo Inc., Analog Devices Inc., Raytheon Technologies.

MAIN APPLICATIONS OF GaAs

GaAs is the third most widely used semiconductor material in industry after silicon and germanium. This semiconductor has high conversion efficiency, high electron mobility, a direct band gap, and low noise. Gallium arsenide is widely used worldwide in areas such as wireless applications, optoelectronics, and solar cells. GaAs is used to make microwave integrated circuits (MICs), monolithic microwave integrated circuits (MMICs) [3, 4], discrete microwave (ultra-high frequency) transistors [5], light-emitting diodes (LEDs) [6], laser diodes [7], Gunn diodes [8, 9], tunnel diodes [10], photodetectors [11], and nuclear detectors [12, 13]. Currently, various types of materials based on GaAs single crystals are used in the semiconductor industry. Semi-insulating GaAs with high resistivity is used in the manufacture of high-frequency power integrated circuits and discrete microwave transistors. In addition to high resistivity, GaAs single crystals must have high carrier mobility values and high macro and microscopic uniformity of the distribution of properties both in the cross section and along the length of the grown ingots, and have a fairly perfect crystal structure. GaAs is also used in optoelectronics for the manufacture of injection lasers, light-emitting and photodiodes, photocathodes, serves as a material for microwave oscillation generators, and is used for the manufacture of tunnel diodes. Table 1 lists the main areas of application of gallium arsenide, its composition and properties.

Modern production of devices based on gallium arsenide is clearly structured by application and type of material used. The main areas of application of gallium arsenide: microwave microelectronics devices (microwave integrated circuits (MIC), monolithic microwave integrated circuits (MMIC), discrete field-effect transistors and Gunn diodes); optoelectronic devices (light-emitting diodes, photodetectors and lasers in the infrared and red spectral ranges); production of optics (windows, lenses, etc.) for lasers.

Currently, the following growth methods are used in the production of GaAs single crystals: the Czochralski method with liquid encapsulation of the melt with a layer of boric anhydride (Liquid Encapsulat Czochralski (LEC)), the Bridgman horizontal directional crystallization method (Horizontal Bridgman (HB)), the crystallization method in a moving gradient (Horizontal Gradient Freeze (HGF)), and the vertical directional crystallization method in two variants (Vertical Bridgman (VB) and Vertical Gradient Freeze (VGF)) [14–17].

Table 1

Main applications of gallium arsenide, composition, properties and production

<table>
<tr><th>Application</th><th>Composition and Properties</th><th>Production</th></tr>
<tr><td>Monolithic microwave integrated circuits</td><td rowspan="2">Semi-insulating GaAs
Specific resistance 10^7 Ω·cm
High values of charge carrier mobility
High macro- and microscopic homogeneity</td><td rowspan="2">Low dislocation density single crystals with a diameter of 100…150 mm
Various methods of growing crystals: the Czochralski methods, gradient crystallization methods, the Bridgman methods</td></tr>
<tr><td>Discrete parts of microelectronic devices</td></tr>
<tr><td>LEDs</td><td>GaAs single crystals of n-type conductivity with low dislocation strength, heavily doped with silicon ($10^{17}…10^{18}$ cm^{-3})
High conductivity
Perfect crystalline structure
Dislocation density
$N_D < 10^4$ cm^{-2}</td><td>Small plate areas up to 10 mm
Complex layered GaAs structures are produced using molecular beam epitaxy (MBE)
or Metalorganic Vapor Phase Epitaxy</td></tr>
<tr><td>Laser diodes</td><td rowspan="3">Dislocation density $N_D < 2 \cdot 10^3$ cm^{-2}</td><td rowspan="6">Metal-organic chemical vapor deposition (MOCVD)

A feature of the production of optoelectronic devices is the use of plates with a diameter of up to 2 inches in large volumes. The main part of the cost is the division of the structure into separate chips</td></tr>
<tr><td>Gunn Diodes</td></tr>
<tr><td>Tunnel diodes</td></tr>
<tr><td>Photodetectors
Nuclear radiation detectors</td><td>High purity n-GaAs grown by liquid phase epitaxial process</td></tr>
<tr><td>Infrared optics</td><td>Chromium doped GaAs single crystals</td></tr>
<tr><td>Optoelectronic devices</td><td>Gallium arsenide single crystals doped with zinc or tellurium</td></tr>
</table>

The main manufacturers of GaAs-based semiconductor products are Qorvo (the company was created as a result of the merger of TriQuint Semiconductor and RF Micro Devices), Freiberger Compound Materials, Broadcom, Sumitomo Electric Industries (SEI), Sony, Panasonic, Mitsubishi Electric, Win Semiconductor (Taiwan), Skyworks, AXT, China Crystal Technologies, Shenzhou Crystal Technology, Tianjin Jingming Electronic Materials, Wafer Technology.

APPLICATION OF SEMICONDUCTORS IN ELECTRONICS

The operating frequencies for microwave integrated circuits differ for different technologies. The most popular devices for broadband microwave amplifiers at one time were field-effect transistors with homogeneous doping based on gallium arsenide (GaAs MESFET) [1]. They were distinguished by high reliability and linearity of transmission. The operating temperatures of the crystal are up to 175 °C, the specific output power is 0.4…0.6 W/mm. Later they were replaced by GaAs pseudomorphic heterostructure field-effect transistors (GaAs pHEMT (high-electron mobility transistor (HEMT)), with better characteristics of the frequency range, efficiency and amplification. The technology of GaAs heterostructure field-effect transistors (HFET) provides a high breakdown voltage (22…25 V), efficiency (up to 55%) and good linearity of the transfer characteristic. Today, GaAs pseudomorphic heterostructure field-effect transistors (GaAs pHEMT) have become the most widespread. As the industrial development of technological processes for processing wafers with a diameter of up to 150 mm has decreased, the cost of pHEMT devices with a gate length of 0.1…0.25 μm has decreased, which has stimulated their spread to all areas of application: from mobile phones and base stations to radars and millimeter-wave communication systems. pHEMT technology has become standard, its use has allowed the serial production of amplifiers in ranges up to 32 GHz with powers up to 4…7 W [1].

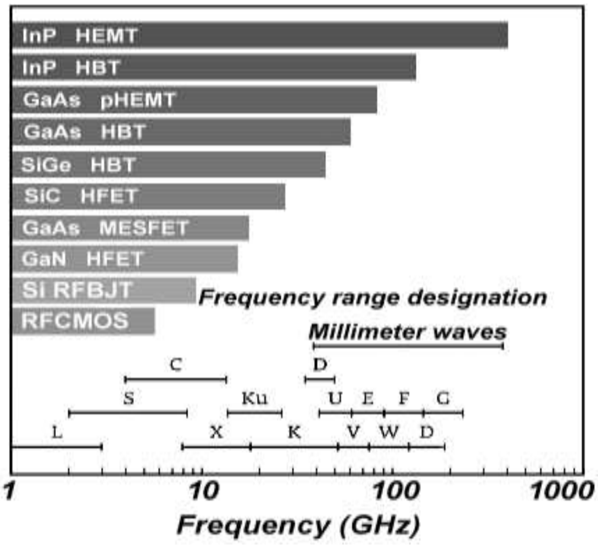

Fig. 3. Operating frequency of microwave integrated circuits for different technologies [1]

Fig. 3 shows the frequency characteristics of microwave integrated circuits of field-effect transistors with heterojunction based on SiC, GaN (heterojunction field-effect transistor (HFET)); heterojunction bipolar transistor (HBT)) based on InP, GaAs, SiGe; integrated circuits of metal-oxide-semiconductor on RF CMOS technology (metal–oxide–semiconductor (MOS) integrated circuit (IC) radio-frequency (RF)), which combines radio-frequency, analog and digital electronics on a CMOS RF chip with mixed signals.

The paper [18] examines the current state of the art in GaN Ku-band high-electron mass transistors (HEMTs) and high-power amplifiers (HPAs), which are critical for satellite communications, unmanned aerial vehicles, and military radars. It is noted that the demand for high-power high-frequency amplifiers is increasing, driven by the global expansion of high-speed data transmission and increased national security requirements.

The frequency bands used for satellite communication are mainly divided into C-band, X-band, Ku-band and Ka-band. Among them, Ku-band and Ka-band have advantages such as supporting large data transmission, providing high-resolution and wide-band services, and enabling miniaturization of antennas due to their short wavelength. Due to the high operating frequency, the performance of transceiver modules used in towers and ground stations has been limited, which has made further development difficult. However, the remaining technological advances in gallium conductors based on complementary metal-oxide-semiconductor (CMOS) and gallium nitride (GaN) with high electron fragility (HEMT) encouraged their commercialization. The Ku-band is currently being used not only for satellite communication, but also in transmitter and receiver modules (TRM) for communicating with UAVs, which are increasingly being used in conjunction with their satellites. advances in miniaturization and data throughput [19].

Fig. 4 shows the breakdown voltage characteristics depending on the frequency across different conductor technologies [18, 20]. As can be seen from Fig. 4, GaN HEMT conductors can be widely used as high-frequency power conductors due to high voltage breakdown and extreme fragility of electronics, resulting in wide energetic fenced zone.

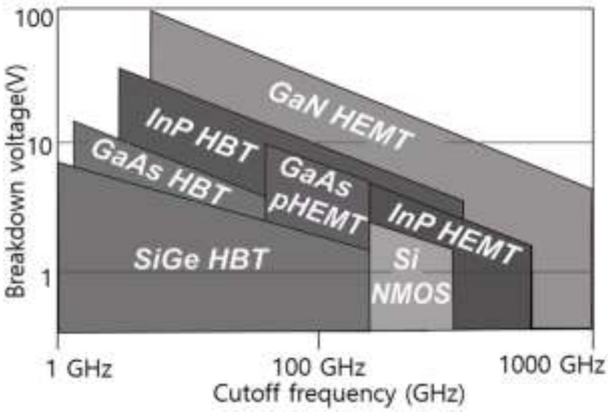

Fig. 4. Comparison of breakdown voltage and cutoff frequency among for different high-speed semiconductor devices [18, 20]

Transistors fabricated using gallium nitride technology can operate at much higher temperatures and voltages. In [21], GaN HEMT devices with an output power of 176 W, an operating voltage of 63 V and an efficiency of 54.8% with a gain of 12.9 dB at a frequency of 2.1 GHz, as well as with a specific power of 32.2 W/mm and an operating voltage of 120 V at a frequency of 4 GHz are considered [22].

ADVANTAGES AND DISADVANTAGES OF Si, GaAs, GaN

Some electronic properties of GaAs are superior to those of silicon. Gallium arsenide has a higher electron mobility, which allows devices to operate at frequencies up to 250 GHz. Table 2 lists the electrical properties of the main semiconductor materials [23].

Table 2

Comparison of electrical properties of basic semiconductor materials [18, 23]

Property	Si	GaAs	SiC	GaN
Energy Bandgap, eV	1.11	1.43	3.2	3,4
Critical Electric Field, MV/cm	0,3	0.5	3.0	3.5
Charge Density, $\times 10^{13}$/cm^2	0,3	0,3	0.4	1
Mobility, cm^2/(V·s)	1350	8000	900	1500
Saturation Velocity, $\times 10^7$cm/V	1	1.4	2	2.7

Semiconductor devices based on GaAs generate less noise than silicon devices at the same frequency. Due to the higher breakdown electric field strength in GaAs compared to Si, gallium arsenide devices can operate at higher power. These properties make GaAs widely used in semiconductor lasers, some radar systems. Semiconductor devices based on gallium arsenide have higher radiation resistance than silicon, which makes them suitable for use in radiation-exposed environments (e.g., solar cells operating in space). GaAs is a direct-gap semiconductor, which is also its advantage.

Unlike silicon-based materials, GaAs also has high electron mobility, thermal stability, low noise, a wide temperature range, and can also be used in space applications. It is worth noting a number of disadvantages: GaAs has a higher production cost, does not contain a natural oxide, is more fragile, small ingots can be obtained, gallium is less common, and arsenic is toxic. In turn, GaN-based devices can operate at significantly higher power without emitting much heat, and, therefore, can be smaller for the same given power. The thermal conductivity of GaN, much higher than that of GaAs, but slightly lower than that of Si, is especially important for applications where space is limited and cooling solutions need to be minimized. The larger band gap of GaN allows it to be used at higher voltages. As a result, GaN is not only able to deliver more power, but also to do so at higher voltages, while maintaining higher efficiency. The high electron mobility also allows GaN to be used at higher frequencies. However, silicon is slightly better than GaN in terms of thermal conductivity, meaning that GaN devices have higher thermal requirements than silicon devices.

GaN chips, with their higher speed, lower resistance, lower manufacturing cost, and smaller form factor, contribute to lower power consumption, a key factor for carbon reduction initiatives, and provide improved performance compared to traditional silicon-based semiconductors.

CONCLUSIONS

The use of GaAs and GaN from the point of view of the latest technologies is very promising. Although at the beginning of the two thousandths the market for materials based on gallium arsenide experienced a decline, at present the main areas of application of GaAs are expanding and improving. Given the growing demand for high-performance radio frequency devices for advanced wireless communication systems, the expansion of 5G networks and telecommunications networks, the market for GaAs and GaN semiconductors will only grow. The paper analyzes the advantages and disadvantages of using each material. It should be noted that the entry of GaAs and GaN-based devices into the aerospace and defense market has led to the creation and production of more efficient radio frequency semiconductors that outperform traditional silicon-based alternatives. Although the overall profit from the sale of radio frequency semiconductors will only continue to grow, the production of GaAs-based devices will not be the main factor in this growth. The possible growth of the semiconductor materials market will continue to be ensured by the active introduction of gallium nitride.

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МАТЕРІАЛИ GaAs, GaN НА СУЧАСНОМУ РИНКУ НАПІВПРОВІДНИКОВИХ МАТЕРІАЛІВ

О.А. Даценко

Розглянуто перспективи GaAs та GaN із погляду новітніх технологій. Приведено основні сфери застосування арсеніду галію. Розглянуто динаміку розвитку ринку матеріалів на основі арсеніду галію. Проаналізовано можливий розвиток подій на ринку напівпровідників з урахуванням зростання попиту на високопродуктивні радіочастотні пристрої для передових систем бездротового зв'язку, розширення мереж 5G та телекомунікаційних. Зроблено порівняння переваг та недоліків сучасних напівпровідникових матеріалів.