Prospects for silicon being replaced by other materials in integrated circuit applications

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Abstract

Currently, silicon is the most widely used semiconductor material. However, in recent years, the development of integrated circuits has encountered more and more limitations, among which the physical characteristics of single-crystal silicon materials are an important reason. With the expansion of integrated circuit scale and the continuous reduction of manufacturing processes, silicon has gradually reached its physical limit. At the same time, silicon has a higher calorific value and a higher performance loss. Therefore, people are actively seeking alternatives to silicon in integrated circuits. This paper reviews the characteristics of three new semiconductor materials, graphene, silicon carbide, gallium nitride, and current research on their applications. Silicon carbide and gallium nitride materials have shown outstanding performance in power-integrated circuits, while graphene has many applications. However, they still have many defects before being used on a large scale. In short, in integrated circuit applications, when new materials replace silicon, many problems remain to be solved.

Keywords: Silicon; Sic; Graphene; GaN

I. Introduction

Graphene is a crystalline carbon material in a two-dimensional (2D) form. Carbon's graphitic structures have many parent forms, which include a honeycomb lattice constituted by nanographene or several doubled layers of graphene [1]. The arrangement of carbon atoms inside it is similar to that of graphite monolayers, forming bonds through sp2 hybrid orbitals, in which carbon atoms contain four valence electrons. The three of the electrons form sp2 bonds, meaning four unbound electrons located in the pz orbital are generated from the rest of the carbon atoms, whereas this electron can contribute to the π bond, which is in a half-filled state.

Silicon carbide (SiC) is a third-generation semiconductor material. It is often used to manufacture integrated circuits, especially power integrated circuits, in extreme environments such as high temperature, high voltage, and high frequency.

Silicon carbide is a wide bandgap semiconductor material. Compared to silicon, Its energy loss is relatively low [2]. Power Devices Made of Silicon Carbide as a Substrate Material can better meet the demand for high-power and high-frequency performance devices in emerging applications such as 5G base stations, electric vehicles, and high-speed railways.

Like silicon carbide, gallium nitride (GaN) materials have much higher bandgap energy than silicon. However, GaN has a more significant advantage in small and high-frequency devices than SiC. Therefore, the main application areas of GaN are lighting, RF communication, and low-voltage, high-frequency power devices. Meanwhile, GaN is usually used in conjunction with sic substrates to achieve better performance[3].

II. Graphene

The charge carriers, which are not vulnerable to temperature and chemical doping, especially in single-layer graphene, can achieve transport of ballistic carriers of submicron scale. Furthermore, the conductance measurements demonstrate that the mobility of electrons and holes in graphene is almost the same.

Since it has high carrier saturation velocity and the invulnerability of its electrical-transport behavior to temperature diversities, the potential of graphene in the IC industry has been explored expansively.[4]

Almost every application in energy storage devices involves the device of graphene because graphene can improve the performance, functionality, and durability of many applications.

Graphene is a representative of two-dimensional materials and the only material in the two-dimensional material family that has preliminarily solved stability and large-scale production problems. From the perspective of application direction, the application field of graphene is mainly concentrated in the field of conductive and thermal conductivity. Here are some examples of graphene devices.

A. Gate-controlled Schottky Barrier

A three-terminal active component, which is called graphene variable-barrier "barristor"(GB), can surmount the very few possibilities for traditional graphene transistors to achieve[5]. Because of its 2D properties[6], graphene's Fermi energy can be constituted by electrostatic gating. While graphene is metallic under ample Fermi energy, the doped material and semiconductor can generate a Schottky barrier (SB)[7-9]. However, SB differs from traditional metal semiconductor SB because it does not exist between graphene and a well-controlled semiconductor surface, such as hydrogen-terminated silicon.

SB at the silicon interface in contact with the drain is generated by mono graphene at the source electrode (Fig illustrates the structure of GB). Because the optimal process for graphene on silicon interfaces has been explored, charge trapping points can thus be reached by creating atomically sharp substrates (shown by Fig. 1c) using transmission electron microscopy to minimize the formation of atomic defects or silica. Typical Schottky diode characteristics of p-type GBs with optimized graphene/Si interfaces are shown in Fig. 1C. This low-bias forward characterization demonstrates a diode ideal factor hid ≈ 1:1 for the device. Thus, this confirms the high interface quality in the GBs.

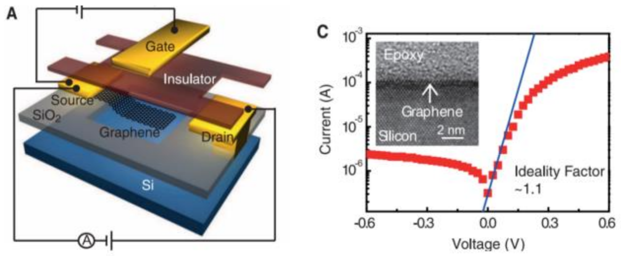

Fig. 1. Graphene barristor.

B. Graphene gate-controlled p-n junction.

GGraphene is an ideal material for application in bipolar nanoelectronics, as its unique band structure allows for reconfigurable electric field control of parameters such as carrier type and density. Therefore, the carrier type and density in two adjacent regions can be locally controlled through electrostatic gating to obtain a single graphene p-n junction.

Due to the above properties, single-layer graphene can also be a zero-gap semiconductor and has a linear energy-momentum relationship near the intersection of valence and conduction bands. The characteristic of local gate doping allows for generating graphene-based bipolar technologies, including junctions between hole-like and electron-like regions, p-n junctions, etc.

The transport measurements under zero vertical magnetic field and quantum Hall (QH) states indicate that alumina (Al2O3) separated from graphene and the top gate does not fully mix in this layer and does not affect its low-frequency transmission characteristics[10-11].

C. Gate-Controlled Superconducting Proximity Effect Carbon Nanotube

A. F. Morpurgo used a gate-adjusted transparency of niobium nanotubes to form a superconducting proximity effect in single-walled carbon nanotubes attached to niobium electrodes. At a temperature of 4.2 Kelvin, a decrease in low bias resistance was observed at higher transparency, indicating the proximity effect mediated by Andreev reflection.

When the transparency was tuned to a lower level, the Andreev reflection property disappeared, and only tunneling conduction was observed. The fabrication of nanotubes is based on chemical vapor deposition (CVD), which uses flowing methane gas and catalysts to incubate the growth of individual single-walled carbon nanotubes [12]. Using electron beam lithography and stripping technology, the separation range is 0.3 to 3 μm on thermal silicon oxide wafers five μm multiplied by five μm catalyst graph island.

III. Sic in integrated circuits

Currently, using it as a power device is the most effective way to leverage the advantages of SiC.

Compared to silicon, SiC materials have a wider energy band gap and, therefore, a smaller intrinsic carrier concentration. From the perspective of blocking stability, this characteristic endows silicon carbide materials with the ability to achieve high-temperature operation[13].

Various commercial solar power devices are currently available, such as diodes, MOSFET, JFET, BJT, and so on. This section will review some commercial and experimental SIC power devices.

A. Diodes

SiC diodes are divided into three types: Schottky, junction barrier Schottky (JBS) diodes, and PIN diodes. Their basic structure is shown in Figure 2 [14].

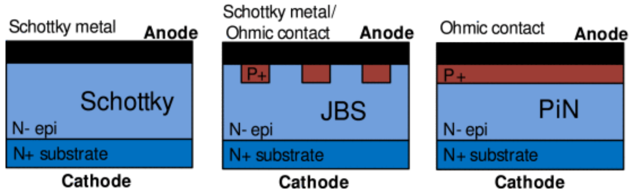

Fig. 2. Three basic SiC diode structures.

After combining its Schottky diode structure with silicon carbide material produces a silicon carbide Schottky barrier diode (SBD), an ideal substitute for silicon-based diodes. In the forward state, current conduction is mainly achieved by the flow of most charge carriers (electrons) from the anode to the cathode. The N-layer Schottky resistance and barrier height determine the conduction voltage drop, typically between 0.7 and 0.9V [14]. Most carrier conduction mechanisms result in devices quickly switching state bodies while generating almost no reverse current. The only current that needs to be reversed is the current that charges the junction capacitor. This characteristic is the most significant advantage of silicon carbide diodes compared to Si PIN diodes. While improving potential efficiency, the low reverse current characteristic can also reduce electromagnetic interference (EMI) issues during diode cutoff.

B. SiC switch based on direct drive JFET

Sic is also commonly used as a switching device, with SiC MOSFET being the most popular choice for this kind of switch.

Compared with ordinary silicon IGBT, it relies on its unique majority carrier conduction mechanism to reduce switching losses. SiC MOSFET structures are divided into planar MOSFETs and groove MOSFETs, as shown in Fig. 3 [15].

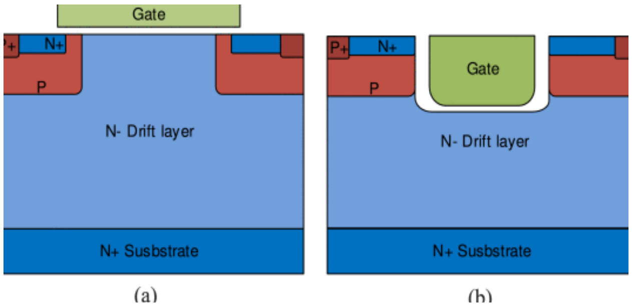

Fig. 3. Two typical SiC MOSFET structures: (a) planar and (b) trench.

Although commercially available SiC diodes have been around for many years, the type of active bandgap switch is still lacking. To address this defect, 1200 V SiC JFET was introduced as a commercial silicon carbide power switch [16]. As a normally open power switch device, SiC JEFT has excellent performance. The concept of directly driving JFET is proposed as an alternative to using JEFT to achieve normally closed behavior. It combines normally open JFET devices with normally closed silicon MOSFET devices at low voltage and develops a complete intelligent driver solution to fully utilize the performance of JFET. The proposed direct drive JEFT circuit structure is shown in Fig.4 [17].

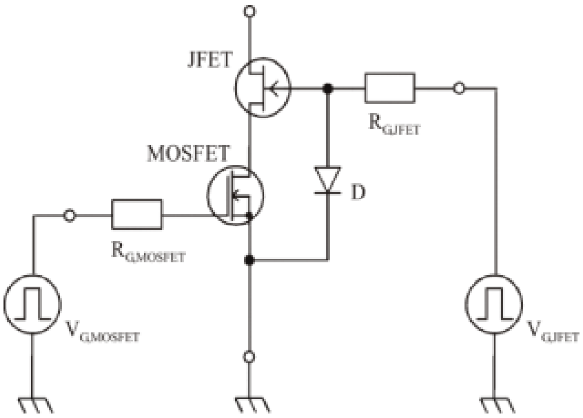

Fig. 4: Schematic of the proposed direct-driven JFET

IX. Device in digital integrated circuits

In addition to the above, existing research also focuses on the application of silicon carbide in digital circuits in extreme environments.

In theory, semiconductor integrated circuits composed of broadband gap semiconductors can adapt to working environments with temperatures hundreds of degrees Celsius(℃) higher than traditional integrated circuits using silicon. The development of silicon carbide and III-NIC with T ≥ 500C is reviewed. Recently, 4H SiC junction field-effect transistor (JFET) integrated circuits with two-stage interconnection structures have begun to exhibit sustained normal operating times of 1000 hours or more at 500 ℃. Its microstructure photo is shown in Fig.5[19].

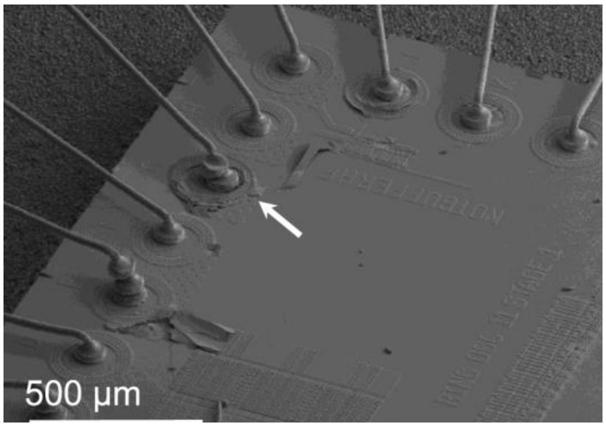

Fig. 4. Electron micrograph of the Test # 1 chip cross-section tested at 966 ° C. Most wires maintain functional integrity, as do chip connections and packaging. The damage to the metal trace in the above image is related to the oxide damage that begins during the wire bonding to the solder pad represented by the arrow.

IX. Gan in integrated circuits

Gan is also a wide bandgap material with better high-frequency applicability than SiC. Gan is widely used in high-frequency communication and miniaturized equipment.

A. Power adapters

With the rapid market-oriented application of fast charging and USB-PD standards, improving power density of power adapters is becoming increasingly important. Any design that reduces size through innovative packaging or high-frequency switches must be accompanied by efficiency improvements to maintain low component and adapter housing temperatures in fully enclosed adapters. This also brings new challenges to the design of power adapters.

Due to their excellent inherent characteristics, gallium nitride transistors have lower resistance performance and faster switching speeds than silicon transistors [20-22]. Gan-based power adapters have become a strong competitor in the power adapter market [23]. Many technologies for gallium nitride power adapters are also being developed. Rahil Samani et al. used the finite element method to analyze the effects of a single and multiple heat sources on gallium nitride adapters. The temperature rise in gallium nitride transistors is mainly caused by three significant parameters: heat from the gallium nitride transistor, heat from adjacent components, and cooling and thermal superposition conditions [23]. Therefore, controlling the transistor's temperature is also an important part of controlling the temperature of the power adapter.

With the increasing demand for higher power and lighter power adapters, the increasingly developed GaN charging technology can also meet the demand.

Integrated Power Stage (IPS) is a system in package-based conceptual solution for GaN devices. IPS includes GaN driver circuits and switches. Compared to discrete GaN solutions, gallium nitride IPS has significant advantages when applied in power supplies in the range of 45W-1kW. It further reduces the size of the converter and the Bill Of Material (BOM) count, making it easier to use and shortening development time. When operating under high-frequency zero voltage switching conditions, GaN devices and IPS can significantly increase the energy density of the power supply, thereby improving power efficiency. In topology structures such as Active Clamp Flyback (ACF) and hybrid inversion, high-frequency design can be achieved [24-26].

Robert Vartanian et al. described an ACF topology 65W charger device based on GaN IPS. Table 1 shows the efficiency performance of this kind of power adapter under different load conditions. In each case, the average efficiency of the four tested points is above 88%, which meets the CoC level 2 requirements [27].

Table 1 ACF Prototype Efficiency Performance

Parameter	Input Voltage		
	90 60Hz	120 60Hz	240 50Hz
Efficiency at 100% load(%)	92.5	93.6	92.9
Efficiency at 75% load(%)	92.6	93.1	91.1
Efficiency at 50% load(%)	92.0	91.8	88.7
Efficiency at 25% load(%)	89.4	88.6	83.3
Efficiency at 10% load(%)	89.8	89.4	80.4
Four-point average efficiency(%)	91.6	91.8	89.0

B. Power amplifier for High-frequency communication technology

From the 2G era to the current 5G era, the communication frequency has gradually increased during the development of modern technology. Hence, the requirements for high-frequency performance of RF devices in base stations and communication equipment are also constantly improving. In this context, GaN devices, especially GaN power amplifiers, will inevitably become a core component of advanced communication equipment with their unique high-frequency characteristics, ultra-high power density, and superior integration.

Kelvin Yuk et al. summarized the frequency band and voltage characteristics of a series of related production technologies for gallium nitride devices, including silicon or silicon carbide substrates. Some of the products are shown in Table 2. GaN technology has been commercially used for many years and has rapidly developed in applications such as RF and microwave industries [28].

Table 2 Commercially available gan foundry services[28]

Foundry Service			Discretes
Process	Bias (V)	Freq (GHz)	
0.25μm GaN-on-SiC	28-40	18	Y
0.40μm GaN-on-SiC	28,50	8	
0.25μm GaN-on-Si	N/A	N/A	N
0.50μm GaN-on-Si	N/A	N/A	
0.50μm GaN-on-SiC	N/A	N/A	

Foundry Service			Discretes
Process	Bias (V)	Freq (GHz)	
0.20μm GaN 4-in	N/A	60	Y
0.10μm	N/A	>70	N
0.25μm GaN-on-SiC 100mm	40	18	Y
0.25μm GaN-on-SiC 100mm	48	10	
0.15μm GaN-on-SiC 100mm	28	40	
0.50μm GaN-on-SiC 100mm	65	10	
0.50μm GaN-on-SiC 3-in-E-mode	N/A	N/A	N
0.15μm GaN-on-SiC 3-in	N/A	Ka-band	
0.50μm GaN-on-SiC 3-in	40	X-band	
0.25μm GaN-on-SiC	N/A	30	Y

So far, multiple ku band HPAs have been developed for single carrier satellite communication applications, and the offset frequencies within 5MHz have been optimized accordingly(Δ f). Yoshioka Takagi et al. described a 70-W Ku band internally matched high-power gallium nitride amplifier (HPA) for multi-carrier satellite communication with a wide offset frequency of up to 400MHz [29].

Fig.7 shows the development trend of GaN HPA in the Ka-band. With the development of satellite communication services, progress has been made in the development of Ka-band gallium nitride PA to meet the growing demand for high data rates, high capacity, and high availability.

To ensure high efficiency during high-power operation, the phase difference between the standing waves of the RF gate voltage waveform connected to the gate in the transistor must be considered in the ka band. The reverse node and node of the standing wave must be located outside and inside the fingers, respectively, so that the RF gate voltage between each finger is different. Therefore, under the influence of the phase difference between the gate RF voltages, the output power density will decrease, decreasing energy conversion efficiency. As shown in Fig. 6, in the design scheme of this ka band GaN PA, a unit effect FET large model is adopted while considering the phase difference of the gate RF voltage and the thermal effect during operation. Using this model, the gate pitch length of the unit cell FET was designed, and the maximum output of the MMIC amplifier was obtained under continuous wave operation [30-31].

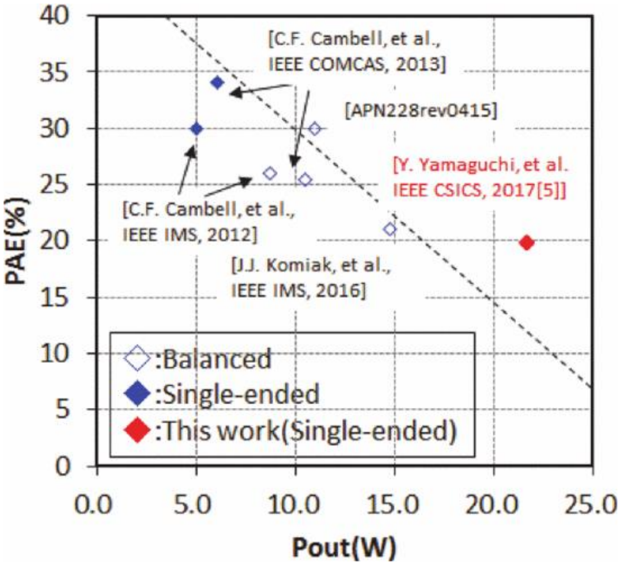

Fig. 6 Trend of ka-band GaN PA.[18]

Conclusion

In summary, these new-generation semiconductor materials, such as graphene, SiC, and GaN, have shown significant advantages in their respective fields. SiC is commonly used in power devices in high-temperature scenarios, GaN is commonly used in high-frequency devices, and graphene has strong conductivity and thermal conductivity. In the future, with the maturity of technology and commerce, These materials are expected to be applied in more and more fields.