Beyond Silicon: Exploring Graphene, GaN, SiC and Organic Semiconductors for Advanced Electronics and 5G Communication

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Abstract. With the advent of integrated circuits, modern electronics place increasingly stringent demands on semiconductor performance—from higher carrier mobility and thermal conductivity to better stability under extreme temperatures and high-frequency conditions. Silicon semiconductors have long dominated the industry due to their mature fabrication processes and cost-effectiveness, but in-depth exploration reveals their inherent limitations: their relatively low bandgap restricts performance in high-power applications, and they struggle to meet the speed and heat dissipation requirements of advanced technologies like 5G and beyond (e.g., 6G). This research corroborates that non-silicon alternatives—graphene (with ultrahigh electron mobility), gallium nitride (excellent for high-power/high-frequency scenarios), silicon carbide (superior thermal stability), and organic semiconductors (flexible and low-cost)—can effectively break through these technological barriers. The unique advantages of each non-silicon semiconductor have been successively demonstrated through comparative tests. Based on this study, specific performance optimization directions (e.g., optimized bandgap alignment, enhanced thermal management) that mitigate constraints in emerging fields are proposed. Delving deeper into 5G communication scenarios, parametric analyses demonstrate how these non-silicon semiconductors improve radio frequency (RF) signal transmission efficiency, enhance the sensitivity of antenna array systems, and boost power amplifier (PA) output power—while reducing energy loss.

Keywords: Grahene, SiC, GaN, organic semiconductor, 5G communication, integrated circuit.

1. Introduction

On September 12, 1958, Jack Kilby demonstrated the first operating integrated circuit (IC) [1]. In 2014, 14-nm technology was introduced, and Intel even achieved 10-nm logic technology that enabled around 100 million transistors per square millimeter [1]. Currently, IC technology has significant impacts on laptops, smartphones, medical devices, industrial applications, the Internet of Things, and even automotive, consumer, and other electronic systems.

Traditional silicon semiconductors have been widely used in CPUs, diodes, transistors, and other electronics due to their high abundance in the Earth's crust (the second most abundant element) [2], ability to be highly purified (>99.99%) [3], and controllable doping (p- and n-type). Nevertheless, they have limitations that need to be addressed.

First, silicon semiconductors are extremely expensive to manufacture [4]. Second, they are brittle under stress due to their intrinsic structure. Third, they exhibit relatively low electron mobility, electrical conductivity, and thermal conductivity. Fourth, most notably, their narrow bandgap (≈1.11 eV) leads to unstable electrical properties [5]: (1) Under high temperatures or voltages, charge carriers in silicon semiconductors easily gain enough energy to cross the bandgap, making carrier density and conductivity unstable and prone to increase. This may accidentally trigger transistors to become conductive; (2) In reverse bias, narrow-bandgap silicon allows more electrons to cross the bandgap via thermal excitation, producing more minority carriers that form a reverse saturation current within the built-in electric field of the depletion region. This increased reverse saturation current raises power consumption and intensifies heating, which can sometimes damage electronic devices [6]; (3) Silicon is sensitive to photon absorption: even lower-energy photons (including part of the infrared spectrum and all visible light) can cause silicon's electrons to transition from the valence band (V_B) to the conduction band (C_B). This excites additional charge carriers, causing fluctuations in conductivity. Consequently, the resistance of silicon devices fluctuates with changes in photon wavelength and intensity, disturbing signals and causing false triggering in sensors; (4) Silicon's narrow bandgap requires a lower breakdown voltage, leading to power consumption, heating, and insulation failure. First, in silicon, charge carriers require only low kinetic energy to cause collisional ionization. As a result, under lower reverse bias voltages, charge carriers in silicon can easily accumulate sufficient energy to trigger avalanche breakdown—since a smaller depletion region creates a shorter, weaker critical electric field that still accelerates electrons enough to collide with lattice atoms, causing valence band electrons to transition to the conduction band. Second, due to the lower potential barrier caused by a smaller bandgap (E_g), Zener breakdown is more likely to occur. Thus, the critical tunneling electric field and breakdown voltage are lower [6] (requiring less driving force); (5) Silicon's smaller bandgap energy (E_g)—indicating a lower potential barrier for electrons to cross the bandgap and a higher probability of electron tunneling (directly pulling valence electrons of neutral atoms in the depletion region/barrier layer out of covalent bonds)—results in a larger tunneling current density [6], worsening electrical loss, heat accumulation, and insulation degradation.

Therefore, it is necessary to address these drawbacks by replacing silicon semiconductors with alternatives for specific applications where silicon's performance is constrained. The development of novel semiconductor materials and device structures (e.g., monolithic transistors, frequency quadruplers, and two-dimensional electron gas (2DEG)) has resolved some issues associated with Si-based semiconductor devices. However, one of these new materials—graphene—faces a zero-bandgap challenge that poses critical obstacles to its further development, and their solutions will be mentioned in a later section.

This research covers various advantageous non-silicon materials, including graphene, gallium nitride, silicon carbide, and organic semiconductors. By investigating the properties of these non-silicon alternatives, the study aims to address problems arising from silicon's limitations, such as high-power consumption, slow heat dissipation, instability under high-voltage and high-temperature conditions, and incompatibility with flexible displays. The research focuses on highlighting the advantages of non-silicon semiconductors and their applications in electronic devices and 5G communication. It reveals that these alternatives will be transformative in the future, gaining popularity and approaching universality.

2. Non-silicon Semiconductors

2.1. Graphene

2.1.1. Characteristics

Graphene, an allotrope of carbon, is a flat, single-atom-thick monolayer of carbon atoms arranged in a tight 2D hexagonal honeycomb lattice, as shown in Fig. 1 [7].

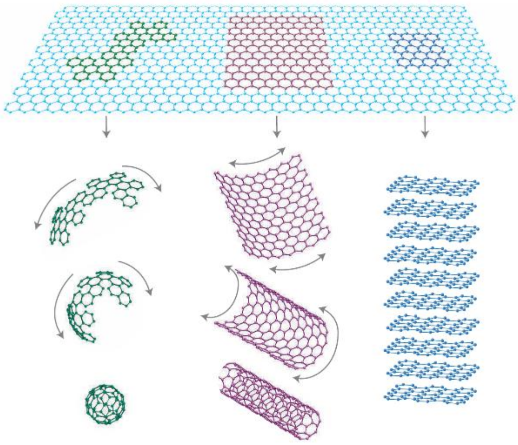

Fig. 1 Graphene can be shaped into different structures [7]

First, graphene has high flexibility. It can be wrapped, rolled, and stacked into other structures depicted in Fig. 1, enabling flexibility that silicon cannot match. Graphene also has a much higher thermal conductivity of 5000 W/m·K than silicon (148 W/m·K) [8, 9]. This allows heat to be transferred and dissipated faster (enhancing cooling) and contributes to high-temperature stability. Its fast heat dissipation and strong covalent bonds enable it to withstand higher current densities (as its structure is resistant to deformation), ensuring high current stability. Moreover, graphene exhibits high electrical conductivity [10], semi-metallic character, and excellent transparency [11], and it displays ambipolar behavior [10]—enabling it to conduct both electrons and holes simultaneously.

Charge carriers (e.g., electrons in materials like silicon and copper) follow the Schrödinger equation, whereas electrons in graphene are described by the Dirac equation (a result of graphene's crystal symmetry in this case [7])—a factor that explains its high carrier speed. Graphene grown via chemical vapor deposition (CVD: a process where carbon-containing gases decompose on a heated metal substrate, allowing carbon atoms to diffuse and self-assemble into a hexagonal lattice, forming a continuous graphene film [12]) has an extremely high mobility of approximately 100,000 $cm^2V^{-1}s^{-1}$ or higher [13], while silicon's mobility is only around 1000 $cm^2/V\cdot s$.

Graphene maintains high mobility even when chemically doped and under the highest electric-field-induced carrier concentrations [7]. Additionally, it can conduct electricity even at zero carrier density and zero electric field [7].

However, graphene has a zero bandgap, so it must be doped to modify its electronic properties. There are two main doping methods [14]: (1) Substituting carbon atoms with heteroatoms (e.g., boron and nitrogen) modulates charge carrier concentration, while the adsorption of dopant molecules alters the band structure; (2) Deep ultraviolet irradiation induces p-doping by dissociating two oxygen ions from O_2 molecules, forming C-O or C=O bonds.

2.1.2. Applications

In a monolithic transistor, silicon carbide (SiC) serves as the transistor channel, while epitaxial graphene (growing new crystal thin films on a substrate—in this case, the SiC itself) delivers high carrier mobility, electrical conductivity, current density, structural stability, temperature stability, and transparency (making it suitable for solar cells and displays).

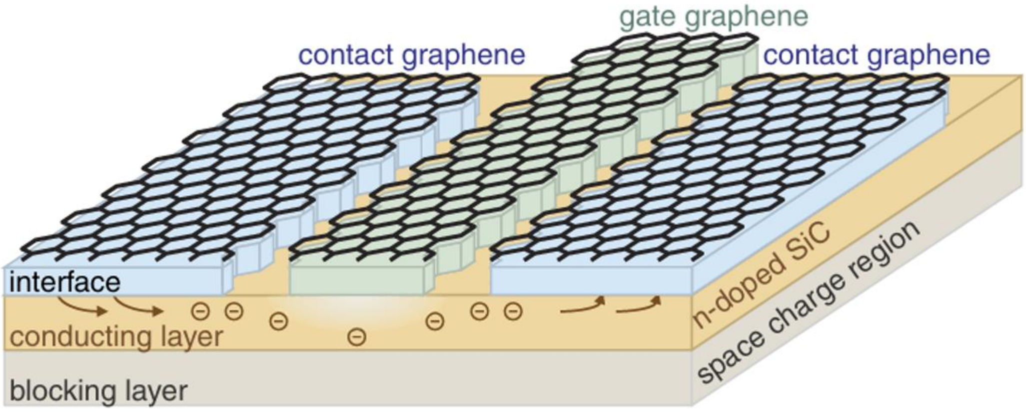

Fig. 2 Monolithic transistor with ohmic contact graphene for source and drain [11]

In a monolithic transistor as shown in Fig. 2, silicon carbide (SiC) serves as the transistor channel, while epitaxial graphene (growing new crystals in the form of thin films on the SiC substrate) on the SiC delivers high carrier mobility, electrical conductivity, current density, structural stability, temperature stability, and transparency—making it suitable for solar cells and displays.

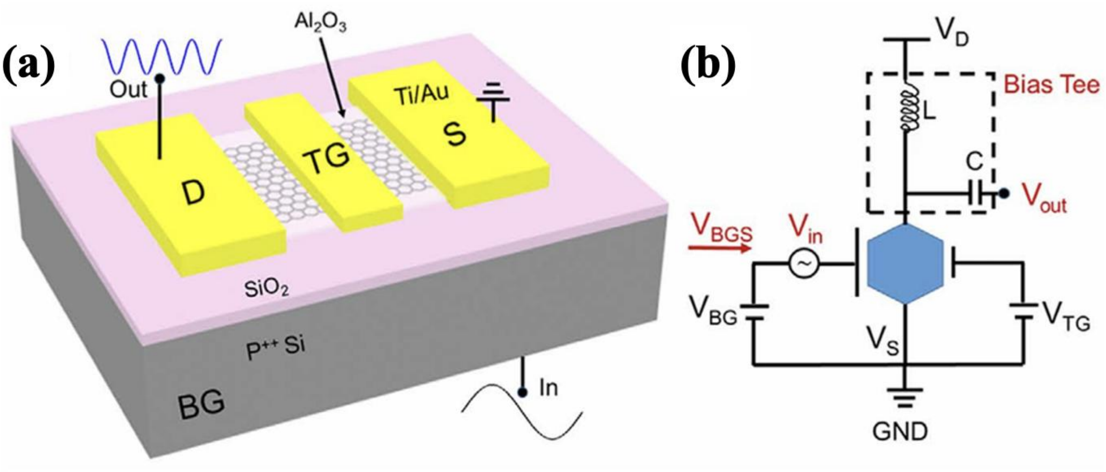

Fig. 3 A dual-gated GFET-based frequency quadrupler. (a) The three-dimensional layout of the basic device structure (b) Circuit schematic [10]

In this frequency quadrupler, graphene’s high carrier mobility and saturation velocity enable the complete and rapid transmission of high-frequency signals, as shown in Fig. 3. Its ambipolar behavior facilitates the proper operation of frequency multipliers, and its high electrical conductivity ensures low signal loss during transmission.

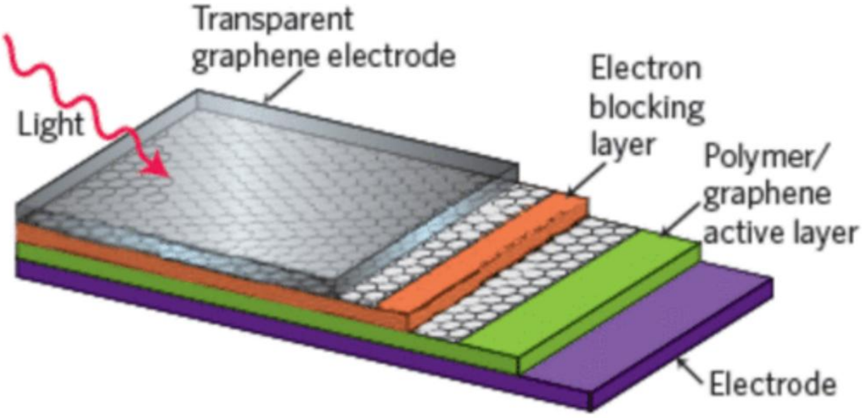

Fig. 4 Organic solar cell with graphene [8]

In the transparent electrode shown in Fig. 4, since organic solar cells are chemically reactive to the atmosphere and their materials may deteriorate, graphene electrodes can act as a barrier to stop the diffusion of air molecules into the layers. Graphene electrodes are transparent, so they let light pass through (their thin layer absorbs only a tiny portion of light) and allow solar cells to function well. They can replace indium-doped tin oxide (ITO) electrodes, which are a rare earth material, sensitive to extreme pH values, and brittle.

2.2. Gallium Nitride

2.2.1. Characteristics

Gallium nitride (GaN) has a wide bandgap of 3.39 eV, which is larger than that of silicon (1.12 eV) [15]. This property enables GaN to maintain stability under high temperatures, voltages, and power conditions, and limits leakage current—since fewer minority carriers are produced by thermal excitation. Second, GaN has a high breakdown field and excellent maximum electric field blocking capability—with a breakdown field (Emax) of 3.3 MV/cm, which is much higher than that of silicon (0.23 MV/cm) [15]. This further confirms that GaN can resist breakdown under high voltage. Third, GaN exhibits higher electron mobility (1500–2000 $cm^2/V\cdot s$) in the two-dimensional electron gas (2DEG) channel and a higher saturation velocity (2.5×10^7 cm/s) than silicon (1400 $cm^2/V\cdot s$ and 1×10^7

cm/s) [15], indicating faster switching and response speeds. Moreover, GaN is mechanically hard, with a Knoop hardness of 14.21 GPa [16]. It is harder than silicon and more mechanically robust. Finally, GaN has the wurtzite structure shown in Fig. 5.

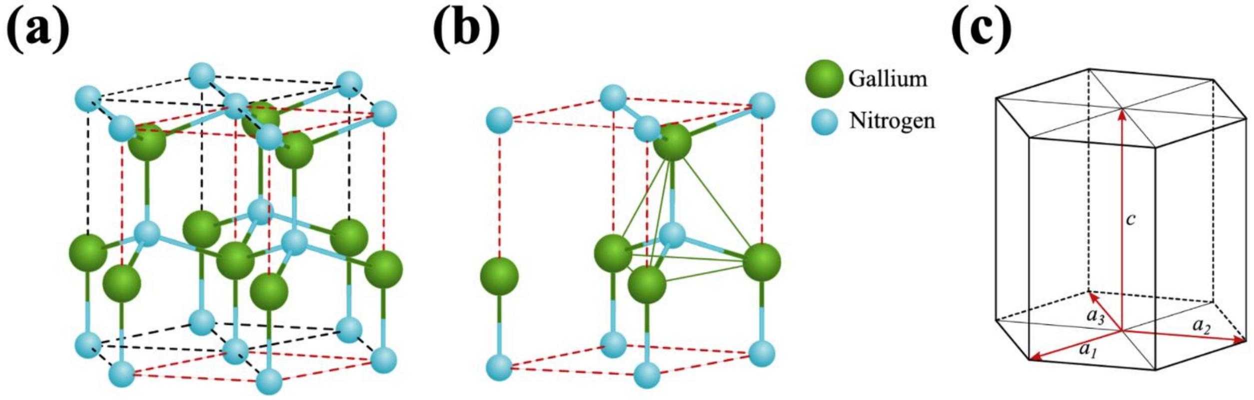

Fig. 5 (a) GaN's crystal structure of wurtzite (hexagonal α-ZnS structure) (b) Unit cell within wurtzite structure (c) Alignments of inversion symmetry [15]

GaN exhibits crystal inversion symmetry in the a_1, a_2, and a_3 directions (a result of its wurtzite structure) but no such symmetry in the c-direction. Consequently, it possesses spontaneous polarization (Psp). This spontaneous polarization (Psp) also occurs in AlGaN. Applied strain induces piezoelectric polarization (Ppz), as the bond angles and atomic distances of GaN and AlGaN change under this strain.

2.2.2. Applications

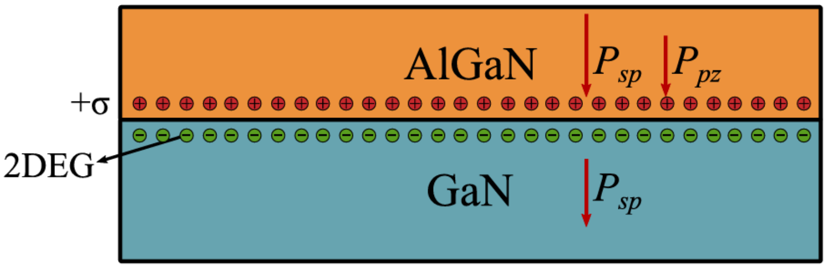

Fig. 6 GaN/AlGaN interface polarizations and 2DEG [15]

In Fig. 6, due to the combined effect of Psp (spontaneous polarization) and Ppz (piezoelectric polarization), a two-dimensional electron gas (2DEG)—which is highly conductive—forms an electron channel with high mobility and high density. By adding three terminals to this structure, a high electron mobility transistor (HEMT) is obtained. Electrons require significant energy to escape from the two-dimensional space, so they are confined within it [15].

2.3. Silicon Carbide

Although these values (for SiC) are lower than those of GaN, silicon carbide (SiC) still outperforms silicon in the following aspects: bandgap (Eg) = 3.23 eV, breakdown field = 2.5 MV/cm, electron mobility = 950 $cm^2/V \cdot s$, and saturation velocity = 2×10^7 cm/s, as shown in Fig. 7 [17]. This means SiC has a stronger ability to operate under higher voltages and temperatures and enables faster signal transmission than silicon. The thermal conductivity of 4H-SiC is 3.7 W/cm·K [18], which is much higher than that of silicon and GaN—allowing efficient heat dissipation.

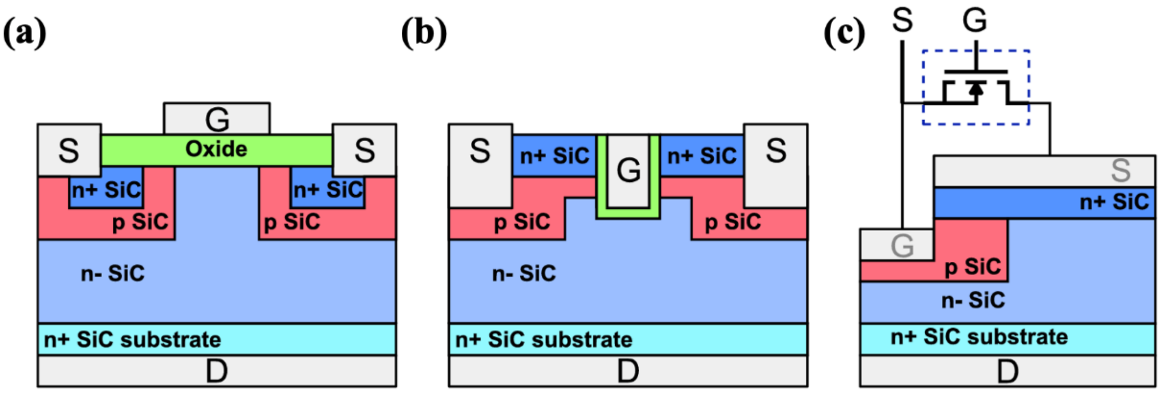

Fig. 7 Schematic representation of the different semiconductor struc tures used in commercial SiC and GaN power transistors. (a) SiC vertical planar-gate depletion MOSFET (b) SiC vertical double trench MOSFET (c) SiC vertical cascode JFET [17]

SiC is utilized in high-voltage-oriented power transistors (covering 650V, 900V, 1000V, 1200V, and 1700V) [17]. SiC is commonly used in high voltage applications above 400V, as shown in Fig. 8.

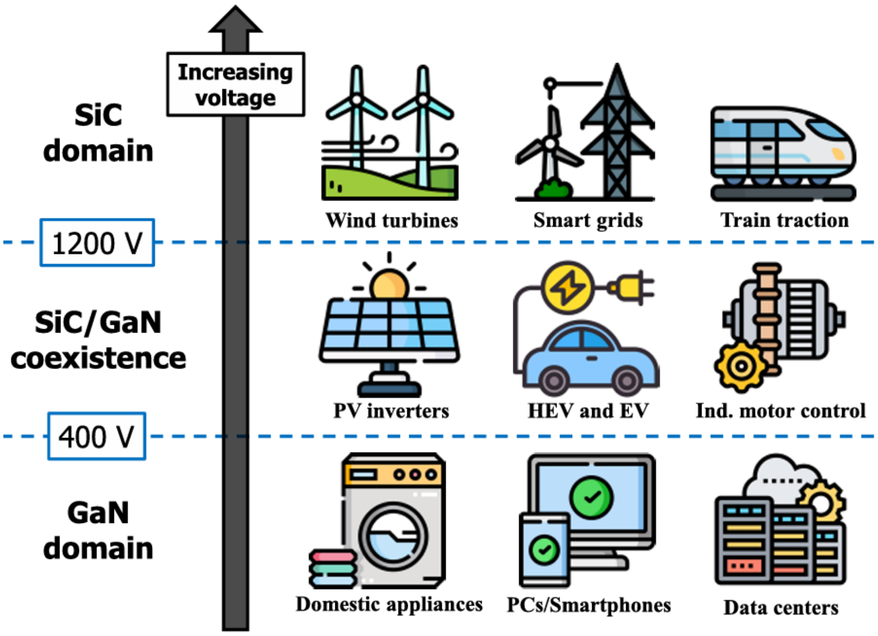

Fig. 8 Current and future fields of interest for GaN and SiC power devices [17]

2.4. Organic Semiconductor

2.4.1. Characteristics

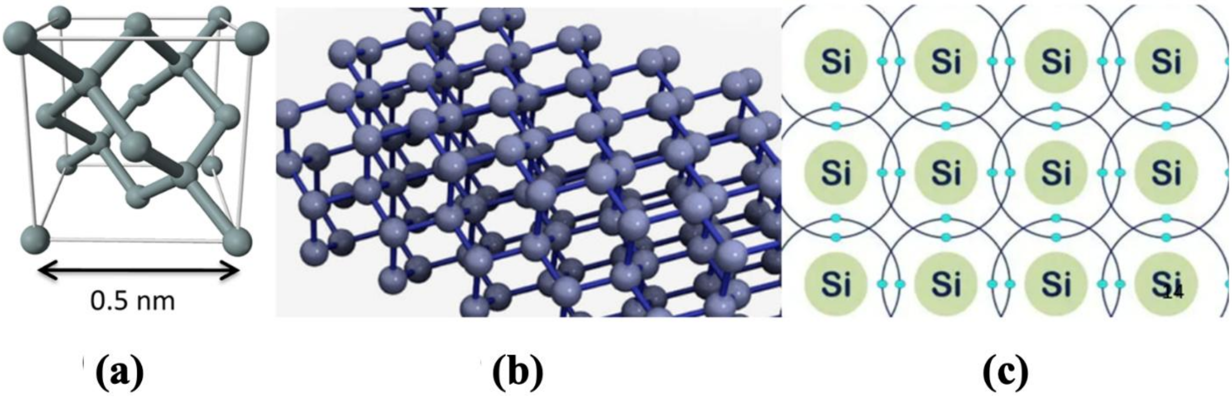

Fig. 9 The make-up of silicon. (a) Face-centered cubic (FCC) unit cell (b) FCC structure in combination of FCC unit cells (c) Covalent bonds within silicon [19]

In terms of the structure, traditional silicon, with tight, organized face-center cubic structure and strong covalent bonds, is brittle under stress because molecules are fixed in place, they can’t slip, as shown in Fig. 9.

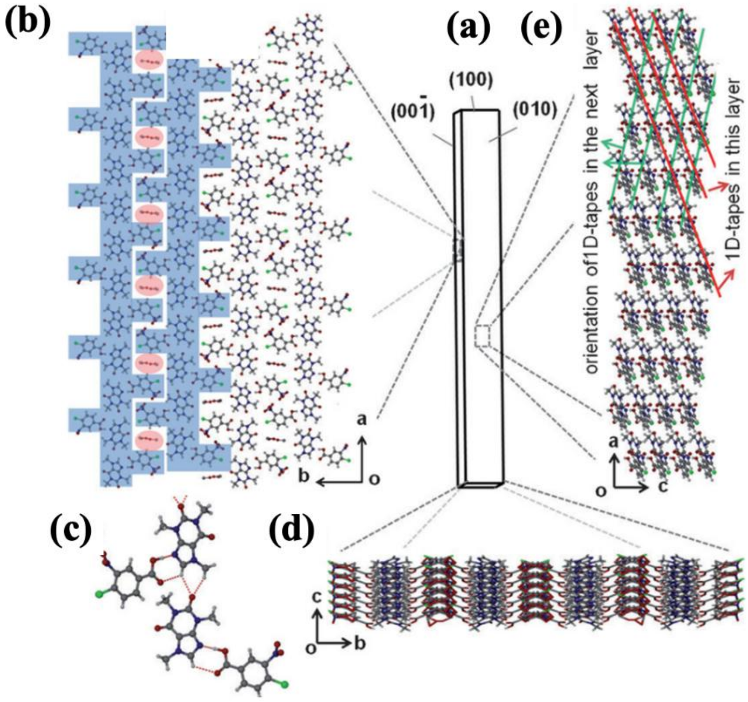

Fig. 10 Classic organic material structure. (a) Crystal morphology with face indices (b) Interlocking of the comblike 2D sheets (blue) and the formation of channels (red) (c) Formation of dimers (d) Miller Indices of (100) (e) The 2D layers in Miller Indices of (010) [19]

However, organic materials have weak bonds like hydrogen bonds here. According to Fig. 10, they also have loose, interlaced layers that sometimes form angles in between, allowing slippage, elasticity, and bendability for flexible displays.

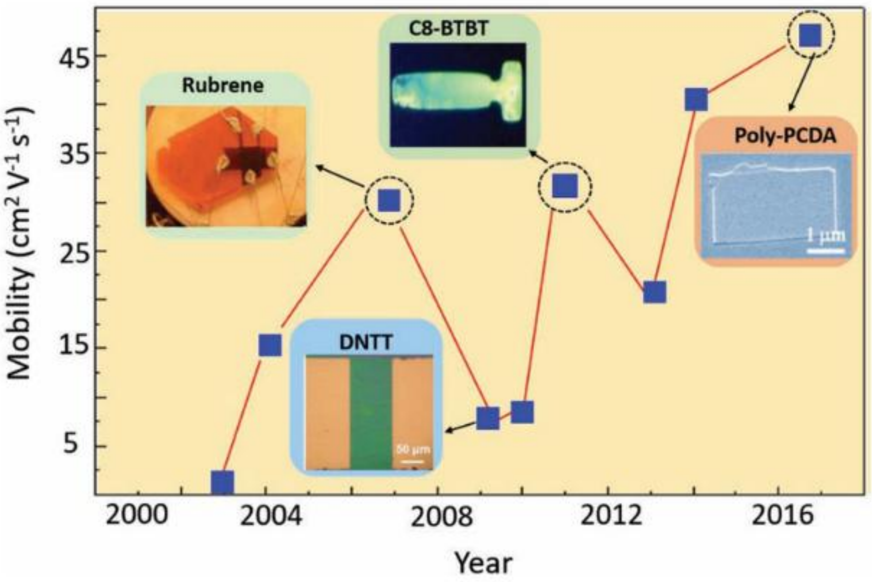

Fig. 11 Overview of the organic mobility growing trend [20]

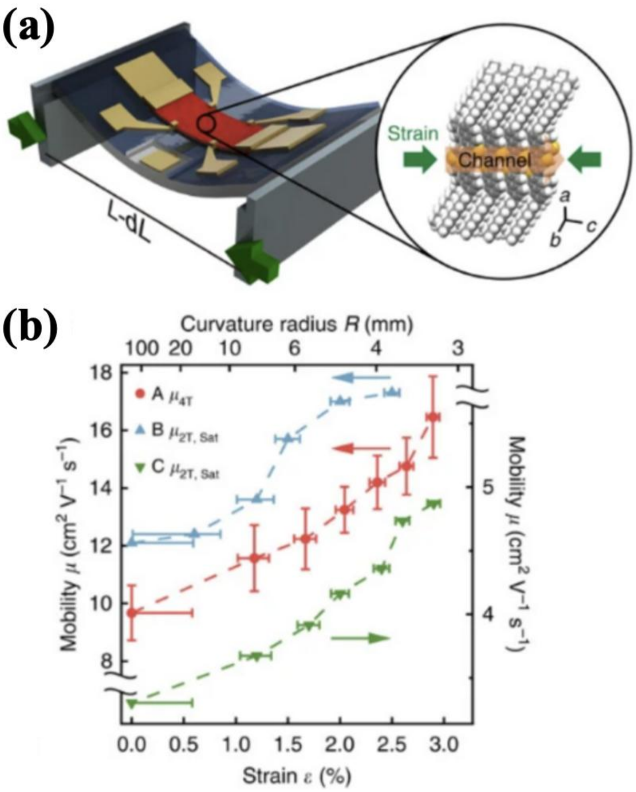

Fig. 12 Improvement in mobility. (a) Schematics on how uniaxial strain was applied (b) Evolution of the mobility under compressive strain [21]

As shown in Fig. 11, though less organized and initially lower in mobility than silicon, organic semiconductors have improved mobility over years. Bending organic materials also produces an adjustment that increases mobility for two reasons: First, enhanced orbital overlap transforms discrete energy levels into continuous bands, enabling freer carrier movement; Second, bending brings molecules closer together, reducing scattering and molecular vibration—closer molecular distances lead to higher potential energy and lower kinetic energy, which decreases vibration amplitude. These two factors significantly enhance mobility, as shown in Fig. 12.

2.4.2. Application in Manufacture

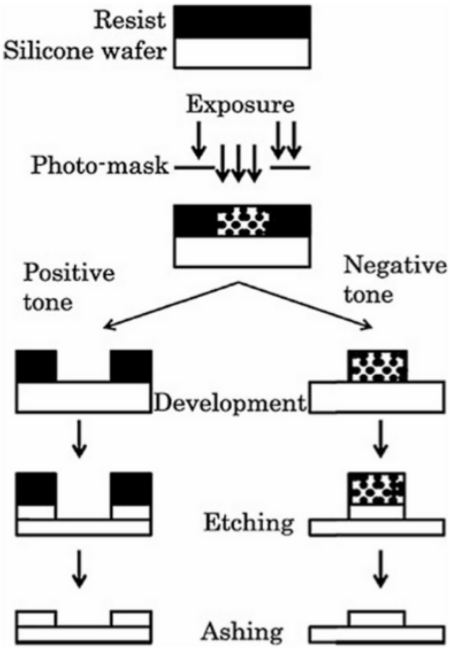

Fig. 13 Process of photolithography [22]

As shown in Fig. 13, silicon semiconductors rely on traditional photolithography, which works as follows: a mask is placed over the resist to block part of the ultraviolet (UV) rays; the exposed positive resist undergoes bond cleavage and becomes soluble in solvent, while the exposed reactive negative resist becomes insoluble; the substrate is then chemically etched according to the pattern, and the remaining resist is finally removed. Traditional photolithography requires costly lithographic tools and masks [4], whereas organic semiconductors can be processed using more economical methods. The key mechanism enabling organic semiconductors to be integrated into integrated circuits via various methods is their ability to dissolve in organic solvents.

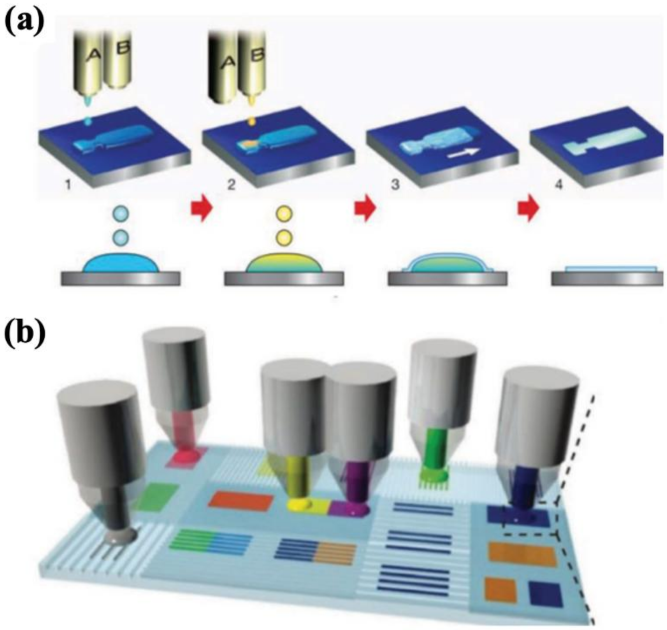

Fig. 14 Inkjet method. (a) Schematic of inkjet printing with solvent–antisolvent crystallization process (b) Schematic illustration of the fabrication process of 1D OSCC patterns by combination of inkjet printing and nanochannel mold [20]

First, large-area inkjet method simply prints the organic solvent which contains organic semiconductors onto the substrate and leaves organic semiconductor after evaporation (though it reduces mobility via misaligned large grains), as shown in Fig. 14.

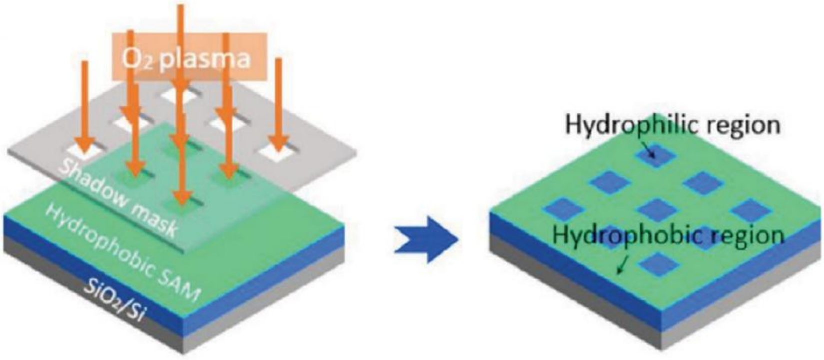

Fig. 15 Schematic representation of shadow masking approach for the self-assembled monolayer (SAM) patterns [20]

For the second method, a masked hydrophobic plate with holes is treated with oxygen plasma (which imparts hydrophilicity) to create hydrophilic regions. Water films form and remain in these hydrophilic regions, so the hydrophobic solvent that contains dissolved organic semiconductors is repelled into the hydrophobic regions—leaving the organic semiconductors deposited there after the solvent evaporates, as shown in Fig. 15.

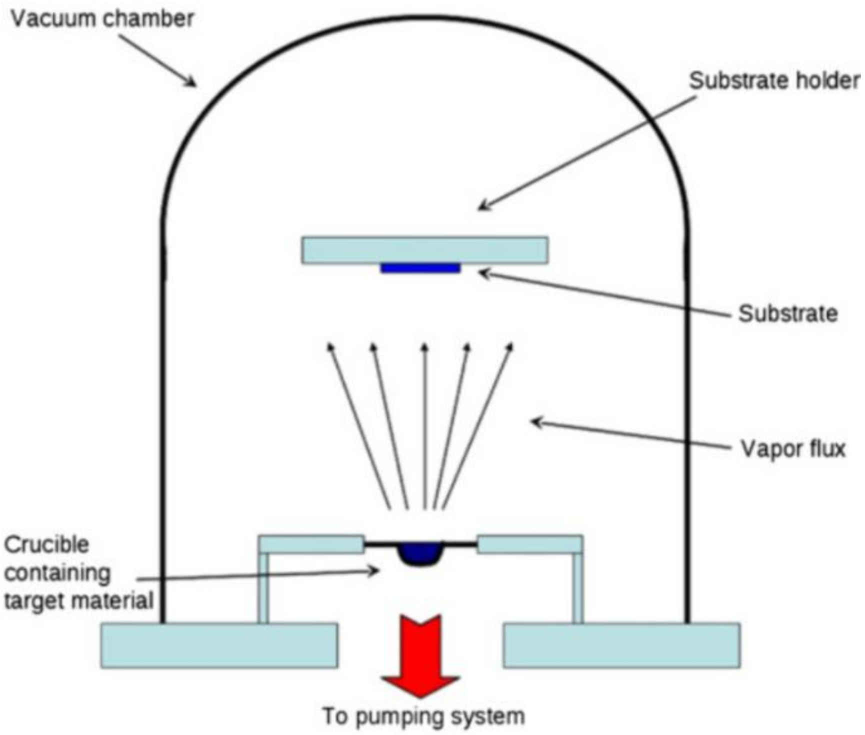

Fig. 16 Schematic of thermal evaporation method [23]

As illustrated in Fig. 16, thermal evaporation works by heating organic semiconductors to form a vapor, which then deposits on the substrate. After cooling, the vapor condenses back into a solid film on the substrate. This process enhances crystallinity and carrier mobility because it is performed in a vacuum environment—an environment that minimizes contamination and particle scattering, thereby improving material quality.

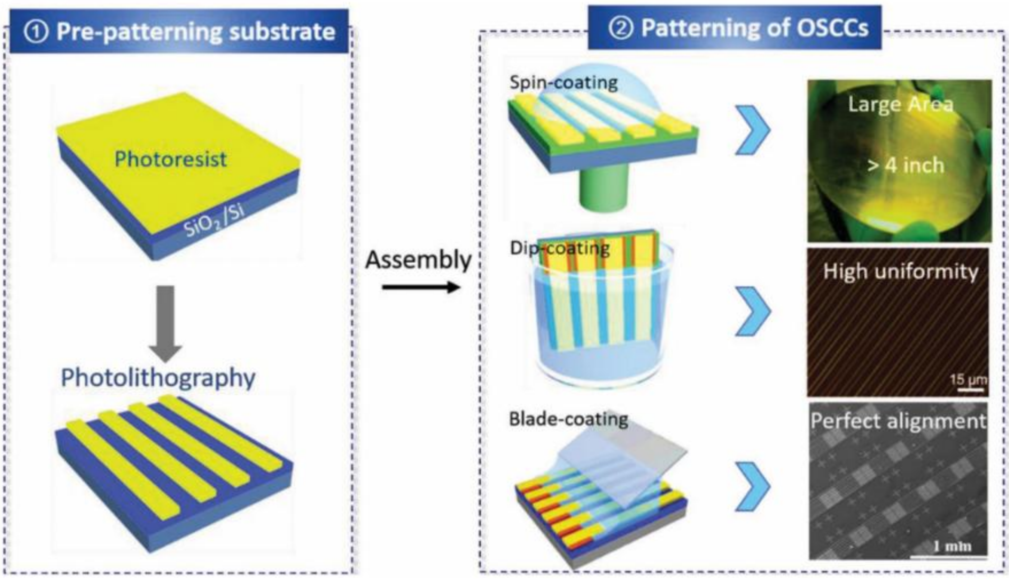

Fig. 17 Other methods for organic semiconductor manufacture [20]

For other methods, such as spin-coating, dip-coating, and blade-coating, the film uniformity improves in the order of spin-coating, dip-coating, and blade-coating—with carrier mobility increasing correspondingly, as shown in Fig. 17. These three methods require minimal selective photolithography to create grooves. Spin-coating is a special case: it works over large areas and controls the thickness of the organic semiconductor film by adjusting the spin rate. However, spin-coating tends to reduce carrier mobility due to the disorganized arrangement of organic semiconductor molecules.

3. 5G Communication

Currently, wireless communication is ubiquitous worldwide. 5G communication—one of the most advanced and mature technologies available today—relies on electronic components, particularly semiconductors. All the non-silicon semiconductors mentioned above offer significant merits for 5G communication.

Graphene can be used to construct nanoantennas and transceivers. It is suitable for extremely high frequencies, and a single graphene monolayer can multiply the frequency from gigahertz (GHz) to terahertz (THz) for further directional radiation [24]. For graphene antennas, hybrid integration at 5G and even 6G frequency bands enables tunable resonant frequencies, gain improvements, and a wide impedance bandwidth. When a DC bias or resistance is applied and adjusted, the antenna's efficiency is increased. Owing to graphene's tunable properties, the antenna's main beam direction, beam pattern, and radiation pattern can be controlled by adjusting the chemical potential through a DC bias or tuning the surface impedance [25]. Graphene is the thinnest two-dimensional (2D) layer of carbon atoms and the material with the highest carrier mobility compared to other semiconductor materials. Under a DC voltage, it achieves switching and tunable characteristics. Graphene has a zero bandgap, so its valence band (VB) and conduction band (CB) meet at the K points of the Brillouin zone (i.e., the Dirac point)—a feature that enables devices to remain continuously switched on. Thus, it can be applied in radio frequency (RF) components and antennas [26].

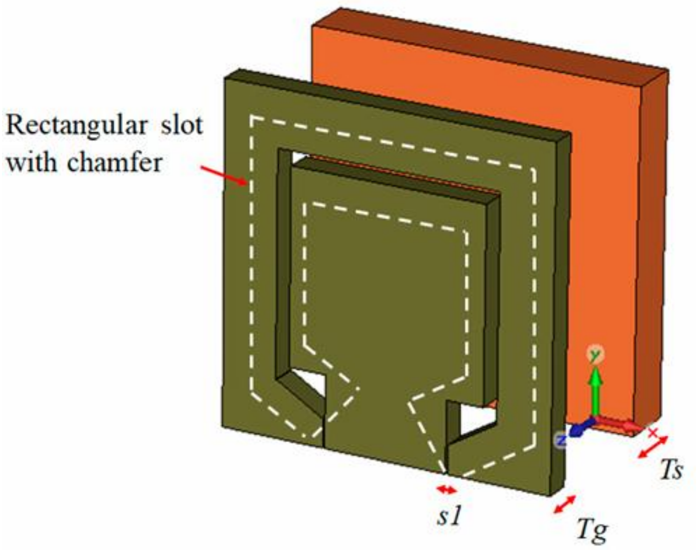

Fig. 18 Printed graphene antenna with rectangular slot [26]

Graphene antennas are printed using graphene ink on a Kapton polyimide film substrate with a relative permittivity (ε_r) of 3.5. Specifically, graphene ink enhances the antenna's conductivity, while a rectangular slot with chamfers is incorporated to achieve impedance matching and the required resonance frequency. Additionally, the slot effectively reduces near-field coupling through a defected ground structure (DGS), preventing energy leakage to adjacent units, as shown in Fig. 18 [26]. Due to the rectangular slot architecture, the mutual coupling is reduced by around 4.66 dB as shown in Fig. 19 [26].

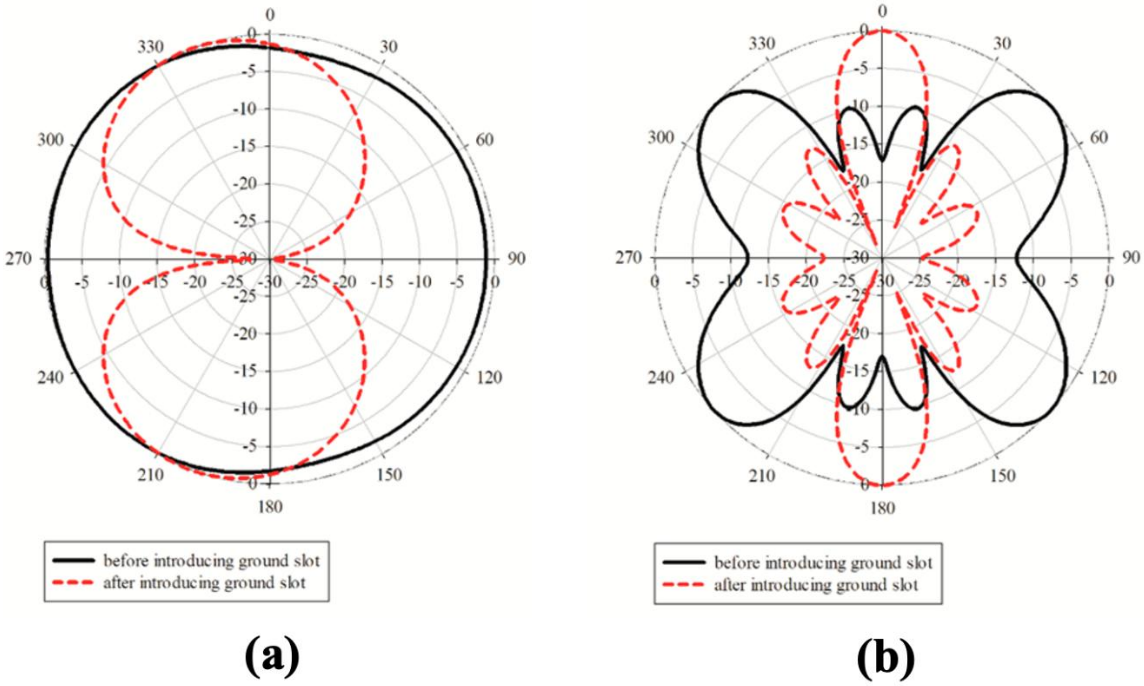

Fig. 19 Radiation patterns of the printed graphene antenna array before and after introducing the rectangular slot within (a) E-plane and (b) H-plane [26]

In 5G electronics, GaN exhibits high stability and efficiency. Its hexagonal wurtzite structure makes it a hard material with a high melting point of approximately 1700 °C. GaN's wide bandgap makes it more resistant to radiation, high temperatures, and high voltages—since electrons require more energy to be excited and cross the bandgap. This resistance to high voltages results in a high breakdown electric field, which means the distance between the terminals of transistors can be reduced (based on the formula V = -E·d: the higher the breakdown field, the shorter the distance). A shorter distance then further leads to faster operating speeds and higher working frequencies. Furthermore, a shorter distance translates to lower energy loss, and GaN's high mobility and high carrier concentration decrease resistivity [27].

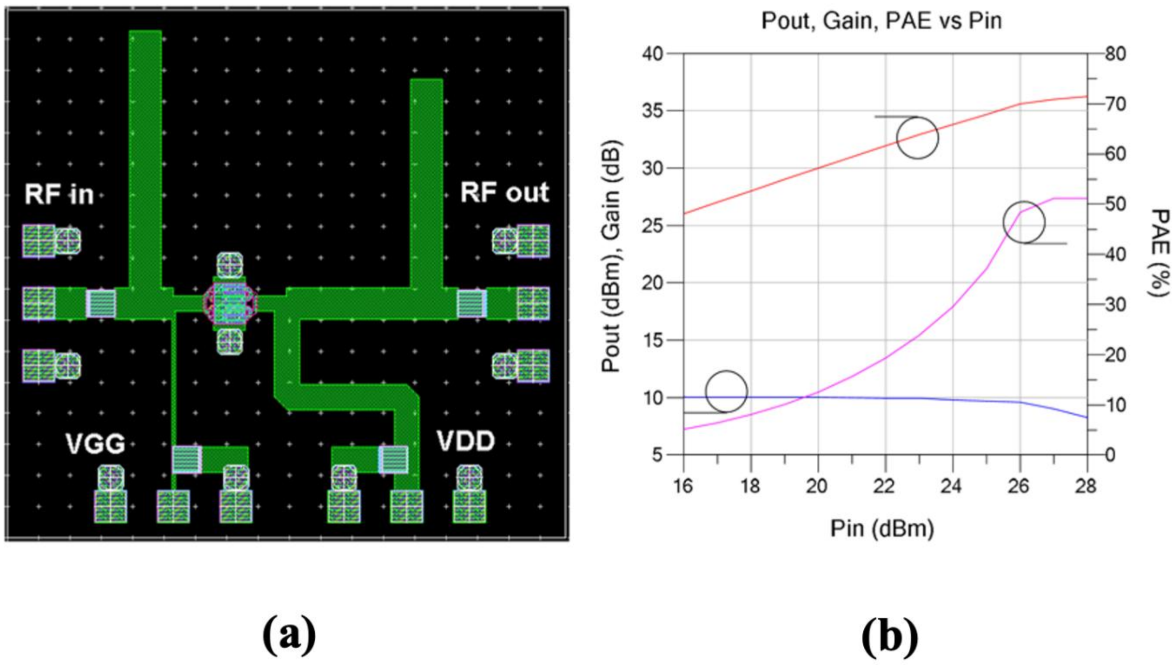

Fig. 20 5G PA using a 0.20 µm GaN 8×100µm FET. (a) Monolithic microwave integrated circuit (MMIC) (b) Chart of gain and PAE [28]

Power amplifiers (PA) use GaN for the sake of its high saturation velocity, breakdown voltage, and thermal conductivity. It enables high output power density and high power-added efficiency (PAE) at microwave frequencies, as well as resistance to thermal stress, as shown in Fig. 20 [28]. SiC-based MOSFETs, IGBTs, RF devices, and monolithic microwave integrated circuits (MMICs) are well-suited for 5G infrastructure and communication systems. Parallel to GaN, SiC enables high frequencies, compact designs in 5G hardware with a small footprint, durability under high voltages, and a reduction in power loss. Organic semiconductors are manufactured using various solvent-based processes, thus requiring lower costs. Their intrinsic flexibility facilitates the deployment of electrical hardware. Antennas that adhere to curved surfaces are no longer a fantasy. These semiconductors make more 5G devices affordable and foldable.

4. Conclusion & Future Prospect

This research discusses the drawbacks of silicon semiconductors: high costs, brittleness, and intrinsic electrical instability due to its narrow bandgap. It explores non-silicon alternatives (graphene, GaN, SiC, and organic semiconductors) with distinct strengths. Graphene exhibits ultra-high mobility, flexibility, and thermal and electrical conductivity, though it requires bandgap engineering. GaN, with its wide bandgap, high breakdown field, and the formation of 2DEG via polarization effects, is suitable for use in HEMTs. SiC excels in thermal conductivity and maintains voltage tolerance, making it suitable for high-voltage power transistors. Organic semiconductors offer flexibility, low-cost manufacturing, and tunable mobility via bending. These non-silicon options overcome silicon’s limitations, driving innovation in high-performance, flexible, and cost-effective electronics.

In terms of 5G communication, graphene stands out for its ultra-thin 2D structure, high carrier mobility, and tunable properties. It enables the fabrication of nanoantennas and transceivers suitable for 5G/6G frequency bands. Additionally, its optimized rectangular slot design reduces mutual coupling and energy leakage, ensuring stable directional radiation and impedance matching. GaN excels in its hexagonal wurtzite structure, wide bandgap, high breakdown electric field, and high stability under high temperatures and voltages—making it ideal for 5G power amplifiers (PAs) with high power-added efficiency (PAE). Moreover, both SiC and GaN enable the miniaturization of 5G infrastructure components and reduce power loss. Finally, organic semiconductors meet 5G’s needs for flexible and low-cost deployment.

Collectively, these alternatives overcome the bottlenecks of silicon-based ICs and antenna systems in high-frequency signal transmission and efficiency under harsh conditions. Future research could focus on optimizing the long-term stability of organic semiconductors (to prevent oxidation) and enhancing their carrier drift velocity. It is expected that these non-silicon semiconductors, and potentially others, will unlock further potential in 5G and beyond.

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