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REVIEWS

Progress of power field effect transistor based on ultra-wide bandgap Ga_2O_3 semiconductor material

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Abstract: As a promising ultra-wide bandgap semiconductor, gallium oxide (Ga_2O_3) has attracted increasing attention in recent years. The high theoretical breakdown electrical field (8 MV/cm), ultra-wide bandgap (~ 4.8 eV) and large Baliga's figure of merit (BFOM) of Ga_2O_3 make it a potential candidate material for next generation high-power electronics, including diode and field effect transistor (FET). In this paper, we introduce the basic physical properties of Ga_2O_3 single crystal, and review the recent research process of Ga_2O_3 based field effect transistors. Furthermore, various structures of FETs have been summarized and compared, and the potential of Ga_2O_3 is preliminary revealed. Finally, the prospect of the Ga_2O_3 based FET for power electronics application is analyzed.

Key words: gallium oxide (Ga_2O_3); ultra-wide bandgap semiconductor; power device; field effect transistor (FET)

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1. Introduction

The development of power electronics technology is closely related to the performance of power devices. The emergence of new-generation power devices and power integrated circuits has greatly improved the efficiency and power density of power electronic systems[1]. However, plenty of scientific and technical problems of power semiconductor electronics have to be settled urgently due to continuous development requirements including high operation voltage, large current density, fast switching speed, low energy loss etc.[2]. The range of power semiconductor has been extended from silicon to wide bandgap semiconductor (such as SiC, GaN, etc.), recently to ultra-wide bandgap semiconductor (such as Ga_2O_3, diamond, etc.)[3–6]. New semiconductor materials provide new development opportunities for power electronics technology.

As a promising ultra-wide band gap semiconductor, Ga_2O_3 has an enormous potential for the next-generation power electronic application due to its large bandgap (~4.8 eV), high breakdown field (8 MV/cm), adjustable n-type doping concentration (10^{15}–10^{19} cm^{-3}) and availability of high quality large area native substrate from low cost melt-based growth methods[7–10]. As shown in Table 1, owing to its advantages, the Ga_2O_3 material is very suitable for fabricating high power devices, including Schottky barrier diode (SBD) and field effect transistor (FET)[11–20]. In this case, there is an increasing number of papers that report the substrate and epitaxial growth technology, doping and defect properties, and devices fabrication in the last several years.

As well-known, field effect transistor is a significant component of power electronics for high voltage and high frequency applications, such as inverters, amplifiers and power switches. In this paper, we firstly review the physical properties of Ga_2O_3 semiconductor, and then summarize the recent development of Ga_2O_3 based FETs through comparing the device performances including breakdown voltage (V_{br}), transconductance (g_m), maximum current density (J_{max}) and on/off ratio, as well as device structures. Though the investigation on Ga_2O_3 based FET is still in the early stage, the material potential has been preliminarily revealed. Therefore, an overview is beneficial for the further development of Ga_2O_3 based power electronics.

2. Basic properties of gallium oxide semiconductor material

Though Ga_2O_3 single crystal growth technology is developed recently, its compound has a relatively long research history. As early as 1952, the investigation on the phase equilibria in the Al_2O_3-Ga_2O_3-H_2O system was carried out and various polymorphs were determined by Roy *et al.*[21]. In 1965, Tippins *et al.* observed the optical absorption and photoconductivity of β-Ga_2O_3 and confirmed its band gap of 4.7 eV[22], which is in good agreement with recent absorption and angle-resolved photoemission spectroscopy measurements[23–25]. Since the 1990s, plenty of bulk growth and epitaxy growth technologies of single crystal Ga_2O_3 have been developed, especially in last five years, an increasing number of researchers paying their attention on ultra-wide bandgap Ga_2O_3.

In fact, there have been five phases of Ga_2O_3, all of which

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Table 1. Comparison of the physical properties of Si, GaN, SiC and β-Ga_2O_3 semiconductor[6].

Semiconductor material	Si	GaN	4H-SiC	β-Ga_2O_3
Bandgap E_g (eV)	1.1	3.4	3.3	4.7–4.9
Electron mobility μ ($cm^2 \cdot V^{-1} \cdot s^{-1}$)	1400	1200	1000	300
Breakdown electric field E_b (MV/cm)	0.3	3.3	2.5	8
Baliga's FOM ($\varepsilon \mu E_b^3$)	1	870	340	3444
Thermal conductivity λ ($W \cdot cm^{-1} \cdot K^{-1}$)	1.5	2.1	2.7	0.11

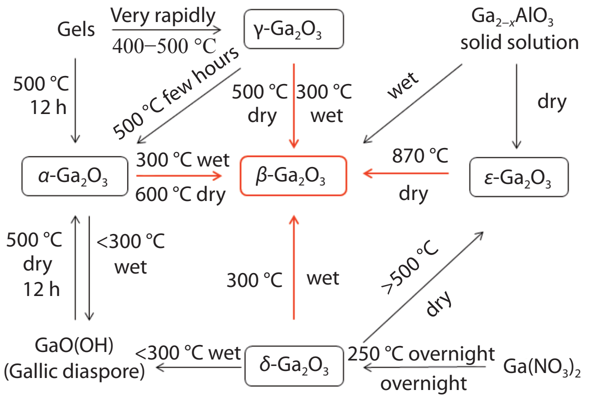

Fig. 1. (Color online) Transformation relationships among Ga_2O_3 in different crystalline phases and their hydrates[21].

can exist stably under normal condition and will convert into other phases at high pressures or high temperatures, as shown in Fig. 1[21]. From this figure, we can observe that the β phase is the most stable one and other phases will translate into it under high temperature and high moisture. The ε phase is the second-most stable phase of Ga_2O_3[26, 27], and this phase will keep it steady until 870 °C. The bandgap of ε-Ga_2O_3 is also approximately 4.9 eV, and it has the same hexagonal structure as the common wide bandgap semiconductors GaN and SiC[28, 29]. The α phase is the third stable single crystal of Ga_2O_3, and its highest stable temperature is 600 °C under dry condition, which drops to 300 °C under wet condition. The α phase have the same corundum crystal structure as α-Al_2O_3, leading to the possibility of epitaxial growth of high quality Ga_2O_3 layer on sapphires. In addition, the melting point of β-Ga_2O_3 is about 1793 °C[30]. Therefore, only β-Ga_2O_3 can be grown through melting methods, while others not due to phase transition, which is the major reason for the rapid development of β-Ga_2O_3. What's more, the β phase has the lowest volume expansion and bulk moduli through theoretical calculation[31]. In this paper, we mainly review the research progress on β-Ga_2O_3 and its power FET devices.

β-Ga_2O_3 belongs to monoclinic system, C2/m space group, and its lattice constants are $a = 1.22$ nm, $b = 0.3$ nm, $c = 0.58$ nm, and $\beta = 103.83°$. The lattice constant value in the direction of (100) is much larger than those in (001) and (010), which means that it is easy to exfoliate the ultra-thin film from its (100) direction for device preparation. For the crystal structure, the double chain composed of [GaO_6] octahedron is arranged along the b axis, and the chains are connected by [GaO_4] tetrahedron. Ga atoms exists in the crystal in two kinds of forms of four and six ligands, as shown in Fig. 2[32]. The crystalline structure of β-Ga_2O_3 is helpful for the movement of free carriers. However, the conductivity of Ga_2O_3 is limited by its ultra-wide bandgap (4.7–4.9 eV). In fact, the intrinsic electrical conduction of β-Ga_2O_3 originates from the free electrons led by the point defects in the crystal, which is the same as ZnO[33]. As a kind of oxide crystal, oxygen vacancies are pervasive in β-Ga_2O_3, and plenty of theoretical and experimental studies indicate that the oxygen vacancies play the key role in the electrical conduction[34–36]. It's worth mentioning that it is the oxygen vacancies in Ga_2O_3 crystal that drive many researches on gas sensors, because they can easily adsorb certain gases, such as H_2, CH_4, CO, O_2.etc, and will change the resistivity upon adsorption[37–40].

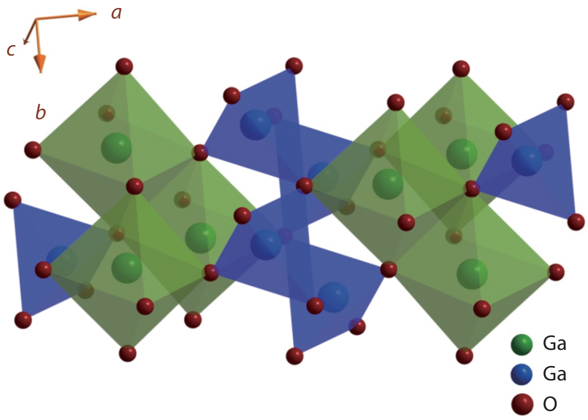

Fig. 2. (Color online) Crystal structure of β-Ga_2O_3[32].

β-Ga_2O_3 has a large bandgap of approximately 4.8 eV and corresponding large estimated critical electric field strength of about 8 MV/cm, about twice that of SiC and GaN. The large bandgap of β-Ga_2O_3 allows its high temperature operation and the large critical field can sustain high voltage operation. However, the poor thermal conductivity of 0.1–0.3 $W \cdot cm^{-1} \cdot K^{-1}$ will limit high temperature capability of Ga_2O_3 based power devices and thermal management will be especially significant[41–43]. In order to assess the appropriateness of various semiconductors for power electronics application, there are different figures-of-merit (FOM), such as Baliaga's figure of merit (BFOM) for dc conduction losses, Huang's material figure of merit (HMFOM) for dynamic switching losses, etc, most of which involve breakdown field strength[44, 45]. Through calculation, we find that the BFOM for β-Ga_2O_3 is four times larger than GaN and ten times larger than SiC. Except for its high voltage capability, β-Ga_2O_3 has a predicted high theoretical electron velocity of 2×10^7 cm/s and a measured mobility of 100 $cm^2/(V \cdot s)$[46, 47]. These properties are beneficial for low power under high frequency switching in the radio frequency regime, where its power density would be limited by the low thermal conductivity.

As the same as other wide bandgap materials, it is significant for β-Ga_2O_3 to control its electrical conductivity by doping or reduce defects in crystal. The n-type doping technology has been widely used in substrate, and epitaxial layer growth. Ion implantation has been used to reduce the contact resistance. Several common n-type dopants, such as Si, Ge and Sn, are proved to have low activation energy and can be effectively activated at room temperature. In addition, doping concentration can be flexibly modulated in the range of 10^{15}–10^{19} cm^{-3}, with the highest value of 10^{20} cm^{-3} reported[48]. As for p-type doping, similar to other wide-band semiconductors, it is difficult to obtain low activation energy of acceptors in β-Ga_2O_3.

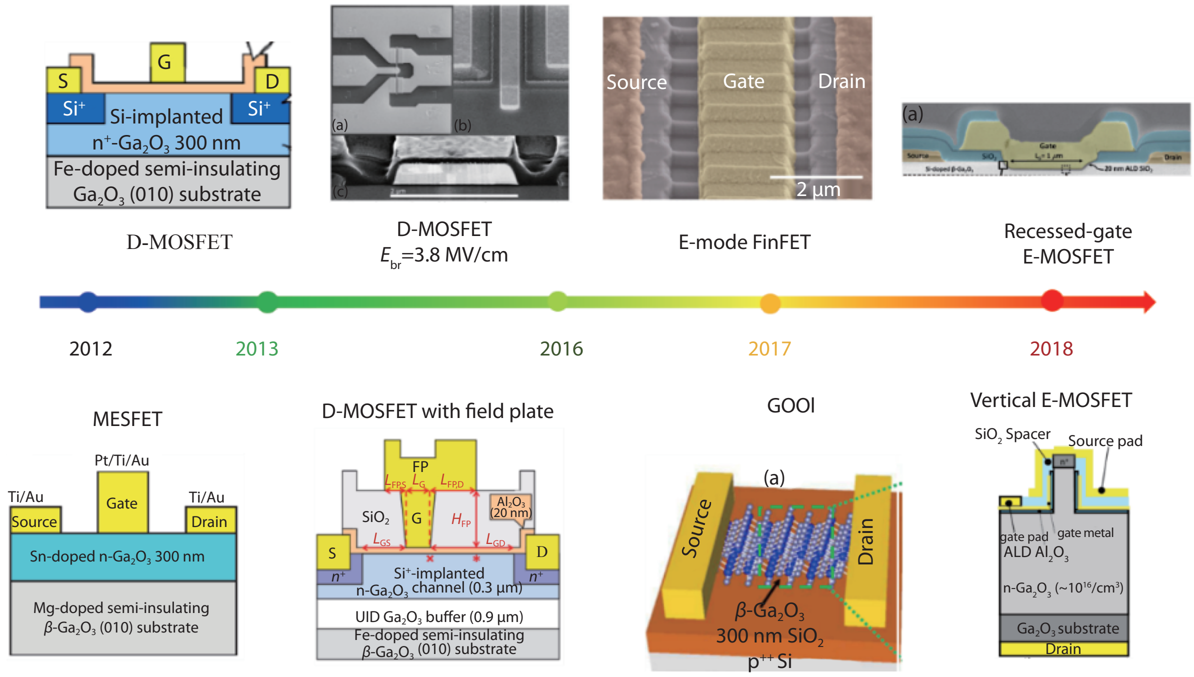

Fig. 3. (Color online) The development of β-Ga_2O_3 transistor in recent years.

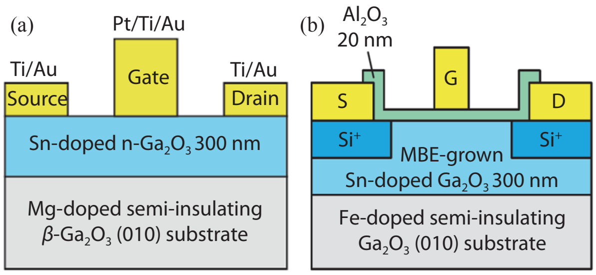

Fig. 4. (Color online) Schematic cross-section of β-Ga_2O_3 (a) MESFET[12] and (b) MOSFET[11].

Though Na, Mg, Ca, Cu, Ag, Zn, Cd, etc are likely to be potential candidates for usable p-type dopants[49], there still have been no breakthrough reported. In addition, the results from theoretical prediction and calculation indicate that the electron effective mass is $0.34m_0$ (here m_0 is the free electron mass), while the hole effective mass is rather large due to local lattice distortions[50, 51].

Additionally, it's worth noting that the future development of β-Ga_2O_3 needs to overcome the following two difficulties. (1) Develop effective p-type doping process, which determines the destiny of β-Ga_2O_3 based power electronics to some extent. It's well-known that carrier inversion is the unique characteristic of semiconductor and reverse p-n junction can effectively undertake high voltage to give full play to the material advantages of β-Ga_2O_3. (2) Severe self-heating effects caused by the relatively low thermal conductivity of β-Ga_2O_3 must be mitigated in high voltage and high frequency application, though ultra-wide bandgap of β-Ga_2O_3 improve electronics thermal tolerance. What's more, the mobility of carrier will also be reduced due to anabatic scatterings[46], and will lower switch speed.

3. Field effect transistor based on β-Ga_2O_3

Summing up the above discussion, the physical properties suggest that β-Ga_2O_3 has a broad prospect in high voltage and high frequency power devices. At present, due to the absence of p-type doping, researchers focus on two kinds of unipolar devices, i.e. Schottky barrier diode (SBD) and field effect transistor (FET). FET is the conventional power switch device in which the resistance between source and drain electrodes is modulated by gate electrical field, and it is mainly used in converters and inverters.

The researching process of β-Ga_2O_3 based field effect transistors is shown in Fig. 3. Transistors develop from MESFET[12, 52] to planar MOSFET, then to well-performance devices with termination structure as well as vertical ones. Most early transistors work in depletion mode due to the absence of inversion layer in β-Ga_2O_3. Afterwards, researchers take advantage of depletion layer from interface states to realize enhancement mode devices. Recently, vertical transistor with a breakdown voltage of 1 kV have been reported[14]. Some typical works on transistors will be introduced in the following parts.

In 2012, Higashiwaki *et al.* (from the National Institute of Information and Communications Technology (NICT)) manufactured a metal semiconductor field effect transistor (MESFET) on molecular-beam (MBE) epitaxial layer with Sn doping (7.0×10^{17} cm^{-3}) on (010) oriental β-Ga_2O_3, as shown in Fig. 4(a)[12]. This transistor's breakdown voltage reaches 250 V with Pt/Ga_2O_3 Schottky barrier as gate structure, and serious off-state leakage current of 3 μA, leading to an on/off ratio of 10^4. Therefore, in 2013, 20 nm Al_2O_3 is used as the gate dielectrics to solve this problem, as Fig. 4(b) shows [11], and the source and drain regions are highly doped (5.0×10^{19} cm^{-3}) by Si to improve Ohmic contact. The device doesn't breakdown until 370 V, and the on/off ratio reaches 10^{10}.

Depletion-mode MOSFET with V_{br} of 750 V was fabricated on MBE epitaxial (010) β-Ga_2O_3 layer with Sn doping of 3.0×10^{17} cm^{-3} by Wong *et al.* (from Novel Crystal Technology Inc.) in 2016, as shown in Fig. 5(a)[16]. The highly resistive uninten-

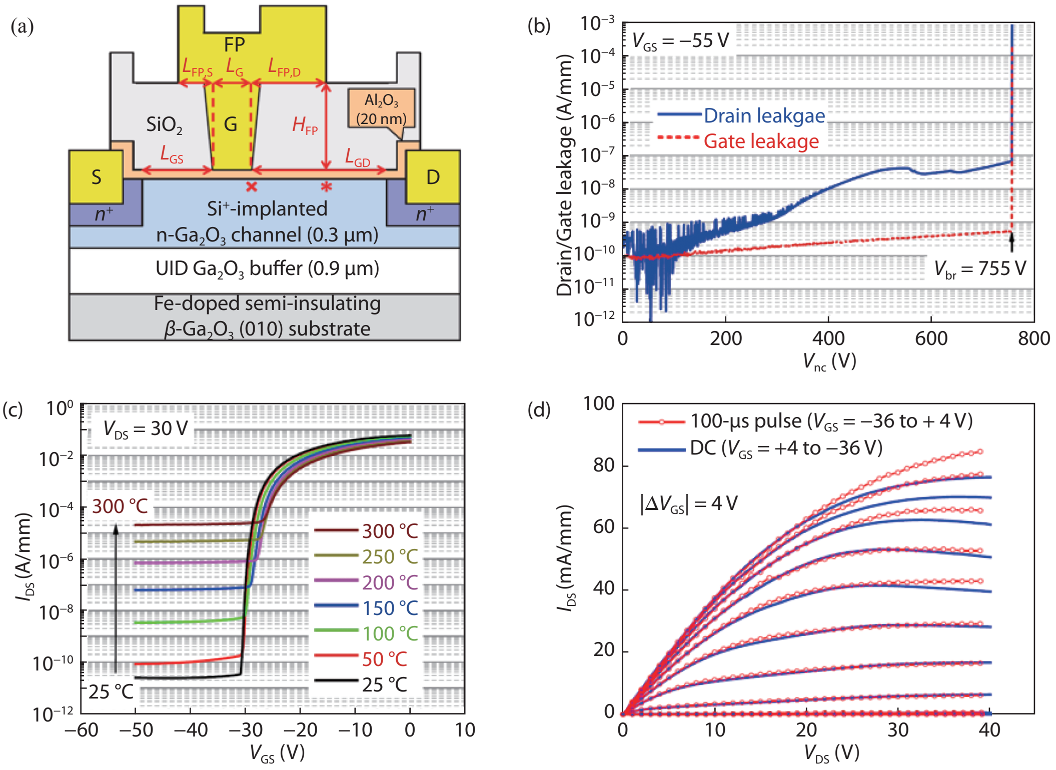

Fig. 5. (Color online) (a) Schematic cross-section, (b) the off-state drain/gate leakage and breakdown curves, (c) temperature-dependent transfer characteristics at V_{ds} = 30 V, and (d) DC and pulsed output curves of the β-Ga_2O_3 FP-MOSFET[16].

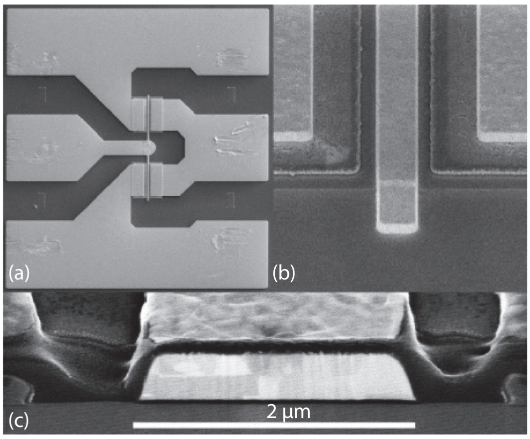

Fig. 6. Top–down SEM image of the two-finger MOSFET on (100) β-Ga_2O_3[55].

tionally-doped (UID) Ga_2O_3 was implemented to isolate the planar devices successfully. Fig. 5(b) shows that the off-state current primarily comes from drain leakage current with gate leakage being 1–2 orders of magnitude lower. The on/off ratio decreases from 10^9 to 10^3 with rising temperature, as shown in Fig. 5(c), which indicates the transistor can operate stably against thermal stress up to at least 300 °C. In addition, current collapse phenomenon caused by self-heating effect is observed in output curves measured in DC and pulse condition as shown in Fig. 5(d). Therefore, heat management is significant for devices on Ga_2O_3 with relatively low thermal conductivity. The characterization of channel temperature and radiation hardness against gamma ray irradiation of similar devices were also tested and analyzed[53, 54].

In 2016, Green *et al.* (from Wright-Patterson Air Force Base of USA) fabricated a depletion mode transistor on Sn doping (1.7 × 10^{18} cm^{-3}) epitaxial layer of (100) oriental β-Ga_2O_3, which was grown via metal-organic vapor phase epitaxy (MOVPE). The transistor has a tremendous breakdown voltage of 230 V with a small gate-drain distance of 0.6 μm[55]. The experimentally measured breakdown electrical field of 3.8 MV/cm is the highest reported value for Ga_2O_3 transistors, surpassing SiC and GaN theoretical limits, though this value is far smaller than Ga_2O_3's theoretical value of 8 MV/cm. The representative two-finger structure is adopted, as shown in Fig. 6. This achievement strongly inspired the researchers to make further effort to exploit the advantages of Ga_2O_3.

Though depletion-mode transistors show an excellent performance, including high current density, high breakdown voltage, low on-resistance etc, amounts of researches on enhancement-mode transistors have been also reported due to its unique advantages in application.

In 2016, a wrap-gate fin field-effect transistor operated on enhancement-mode was fabricated on (100) β-Ga_2O_3 by Chabak *et al.* (from Air Force Research Laboratory of USA). Fin array channels are beneficial for depletion by interface states to turn off without gate bias, but on current is limited to ~1 mA/mm[15]. The device achieved a three-terminal breakdown voltage exceeding 600 V with 21 μm gate-drain spacing. In December 2017, they reported another recessed-gate enhancement-mode β-Ga_2O_3 MOSFETs, as shown in Fig. 7(a). In this device, the gate recess is self-aligned to the gate region, so the partially removed region is fully depleted by interface state and the channel for normally-off operation is formed. As a result, the on current is promoted to 40 mA/mm with on/off ratio of ~10^9 and V_{br} of 505 V. From the breakdown current curves in Fig. 7(b), it can be observed that the breakdown per-

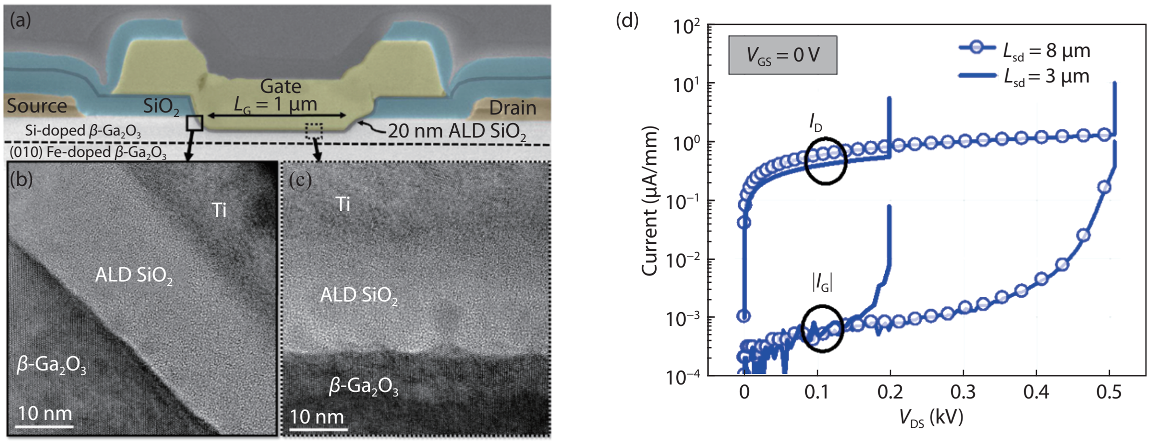

Fig. 7. (Color online) (a) SEM false-colored cross-section view of recessed-gate MOSFETs and HR-TEM of (b) its sidewall and (c) bottom facets of the gate-recess contact, (d) its gate-source and drain-source breakdown curves of both source-drain distances[15].

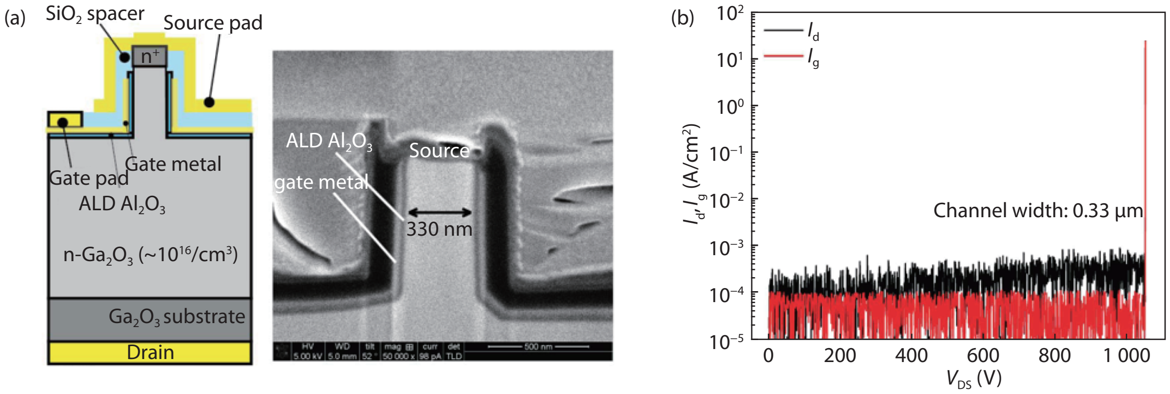

Fig. 8. (Color online) (a) Schematic cross-section and SEM image, and (b) three-terminal off-state breakdown curves of vertical β-Ga_2O_3 Fin-MISFET[14].

formance is limited by gate dielectric failure.

In March 2017, Wong *et al.* (from NICT) took advantage of fully depleted unintentionally doping (010) β-Ga_2O_3 (with a background carrier concentration of 4×10^{14} cm^{-3}) to realize transistor's operation in enhancement mode[56]. In addition, box-like ion implantation of 5×10^{19} cm^{-3} was applied to decrease contact resistance in source and drain regions. As a consequence, transistors have a maximum saturation current of 1.4 mA/mm when V_{gs} = 38 V and V_{ds} = 15 V, and on/off ratio near 10^6. The peak extrinsic transconductance of 0.38 mS/mm is imputed to charge trapping of unoptimized ALD interface.

From the above, we can conclude that effective p-type doping is very significant for investigation of transistors. Without p–n junction structure, the thick gate dielectric is required to undertake too high voltage to excavate the excellent property of Ga_2O_3. In order to enhance breakdown voltage, vertical field effect transistor is a promising option.

In 2017, Wong *et al.* (from NICT) fabricated a vertical β-Ga_2O_3 MOSFET, and a buried current blocking layer (CBL) was used to electrically isolate the source and drain electrodes[57]. However, the device has a large source-drain leakage current due to the difficulty in activating p-type dopants in CBL.

In 2017, Hu *et al.* (from Cornell University) attempted to fabricate vertical fin transistor, and though the device has an on/off ratio of 10^9, the field crowding near the bottom of the column limited V_{br} to 185 V[58]. Whereafter, in June 2018, they reported a high-voltage (over 1 kV) vertical β-Ga_2O_3 MISFET, distinguished from conventional p-n junction based MOSFET due to no p-region in this device. As shown in Fig. 8(a)[14], the MISFET was fabricated on halide vapor phase epitaxial (HVPE) layers with low charge concentration of ~10^{16} cm^{-3} on bulk β-Ga_2O_3 (001) substrates, and has a nano bar structure to realize enhancement operation with a threshold voltage of ~1.2–2.2 V, and a current on/off ratio of ~10^8, which demonstrate the well gate modulation of transistor. In addition, an on-resistance of ~13–18 mΩ·cm^2 and an output current of over 300 A/cm^2 were also extracted. Fig. 8(b) shows the three-terminal off-state breakdown curves and indicates that both the drain and gate leakage currents remain low until the hard breakdown near 1057 V. Field plate and ion implantation edge termination techniques are expected to further increase the breakdown voltage. To sum up, this is the first high-breakdown voltage vertical transistor reported and is a milestone for the application of β-Ga_2O_3 based power electronics.

In addition to high voltage, high theoretical electron velocity and high breakdown electrical field make β-Ga_2O_3 a potentially useful material in radio frequency (RF) and mm-wave region, and its power density at high frequency would not be limited by the low thermal conductivity. Therefore, some works in this direction have been reported in succession.

In 2017, Green *et al.* (from the Wright-Patterson Air Force Base of USA) used a highly doped cap layer to decrease con-

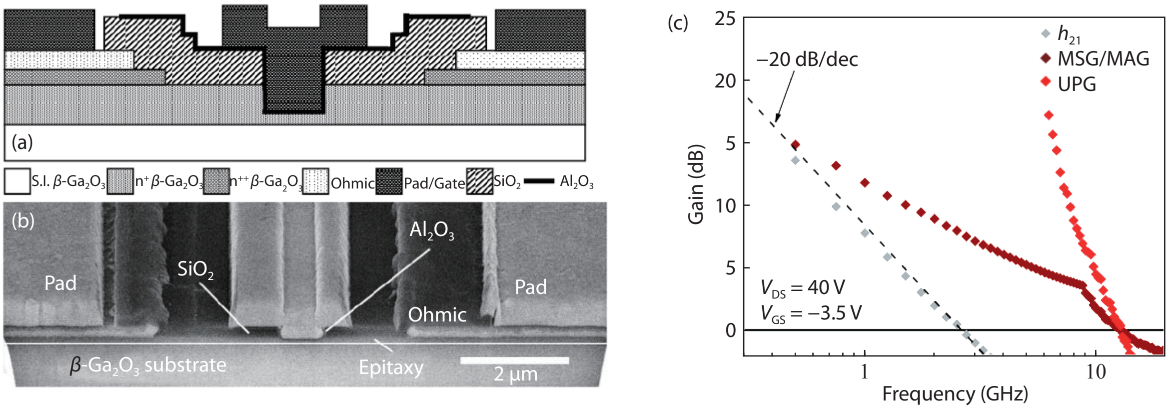

Fig. 9. (Color online) (a) Cross section schematic, (b) focused ion beam (FIB) cross sectional image, and (c) extrinsic small signal RF gain performance of RF β-Ga_2O_3 MOSFET[59].

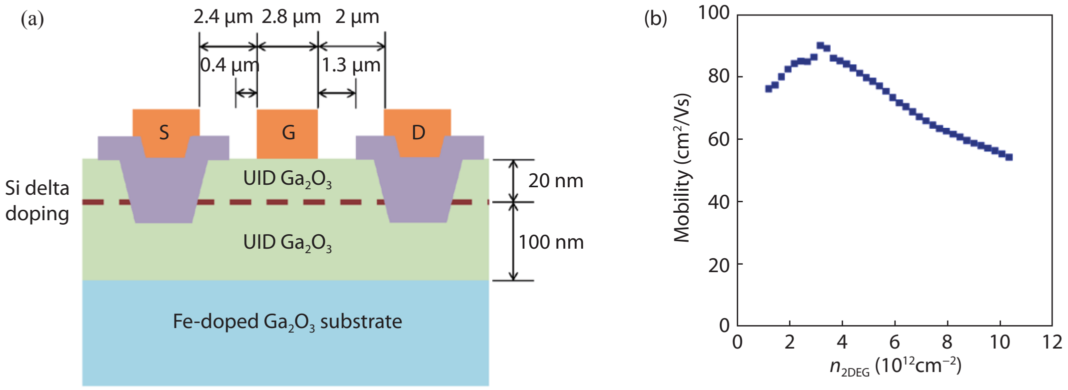

Fig. 10. (Color online) (a) Schematic and (b) density-dependent field effect mobility of Silicon delta-doped β-Ga_2O_3 MESFET.

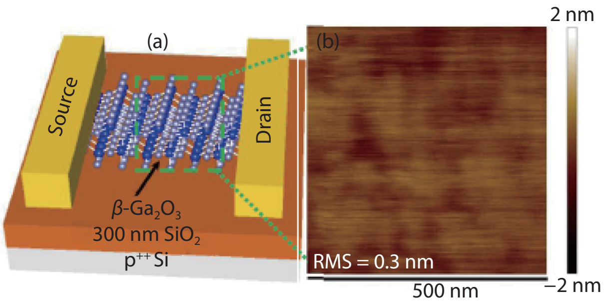

Fig. 11. (Color online) Depletion/enhancement-mode β-Ga_2O_3 on insulator (GOOI) FETs[17].

tact resistance, and an incompletely depleted sub-micro gate recess to form modulation channel and attained a RF Ga_2O_3 transistor, as shown in Figs. 9(a) and 9(b)[59]. A transconductance (g_m) of 21 mS/mm, extrinsic cutoff frequency (f_T) of 3.3 GHz, and maximum oscillating frequency (f_{max}) of 12.9 GHz are measured experimentally, as shown in Fig. 9(c). With a passive source and load tuning at 800 MHz, RF performances including P_{out} of 0.23 W/mm, power gain of 5.1 dB, and power-added efficiency of 6.3%, were confirmed in detail. All results preliminarily suggest that Ga_2O_3 has a potential in applications for power switch and RF electronics.

The Ohio State University devoted themselves to utilize 2-dimensinal electron gas from silicon delta-doped β-Ga_2O_3 to fabricate high frequency transistors. In 2017, a delta-doping β-Ga_2O_3 MOSFET with integrated sheet charge of 2.4×10^{17} cm^{-2}, mobility of 83 $cm^2V^{-1}s^{-1}$, was manufactured by Krishnamoorthy *et al.*, and drain current I_{max} of 236 mA/mm and transconducance g_m of 26 mS/mm were obtained[60]. In 2018, Xia *et al.* from the same department fabricated a silicon delta-doped MESFETS with low regrown source/drain contact resistance and UID Ga_2O_3 as gate insulator, as shown in Fig. 10(a)[61]. The turn-off voltage of 4 V, a peak drain current of 140 mA/mm, g_m of 34 mS/mm and V_{br} of 170 V are obtained. Fig. 10(b) shows the correlation between mobility and 2-D electron gas density. The detailed scattering mechanisms that limit 2DEG mobility is required to further analyze theoretically. Though high frequency parameters weren't reported in the literature, the results indicate that delta doping can be a potential process of the scaled Ga_2O_3 high frequency field effect transistors.

In addition, as mentioned above, β-Ga_2O_3 belongs to monoclinic system with the lattice of a axis longer than other two ones, and nano membrane can be acquired mechanically the same as 2-D materials[13, 17, 62–65]. Therefore, plenty of film transistors are reported for power application. For instance, in January 2017, the back-gate transistor fabricated by Zhou *et al.* from Purdue University has a high record drain current of 600/450 mA/mm, a high on/off ratio of 10^{10} in depletion/enhancement modes, as shown in Fig. 11[17]. An average breakdown electric field of 2 MV/cm was realized in E-mode devices with a breakdown voltage of 185 V, which shows the great promise of FETs based on β-Ga_2O_3 on insulator for power electronics.

4. Conclusion and future outlook

In conclusion, early researches on transistors mainly focus

Table 2. Development of Ga_2O_3 FETs and the corresponding performances.

Device type	Substrateorientation	Gate dielectrics	V_{br} (V)	J_{max} (mA/mm)	On/off ratio	g_m (mS/mm)	Reference
D-MESFET	(010) β-Ga_2O_3	—	250	—	10^4	1.4	[12]
D-MOSFET	(010) β-Ga_2O_3	Al_2O_3	370	39	10^{10}	—	[11]
E-Fin FET	(100) β-Ga_2O_3	Al_2O_3	600	-	10^5	—	[15]
Two-finger D-MOSFET	(100) β-Ga_2O_3	Al_2O_3	230	60	10^7	1.1	[55]
Field plate D-MOSFET	(010) β-Ga_2O_3	Al_2O_3	750	78	10^9	3.4	[16]
Recessed-gate D-MOSFET	(100) β-Ga_2O_3	Al_2O_3	—	150	10^6	21.2	[59]
E-MOSFET	(010) β-Ga_2O_3	Al_2O_3	—	1.4	10^6	0.38	[56]
D-MOSFET	(010) β-Ga_2O_3	HfO_2	400	45	10^8	—	[74]
Vertical trench D-MOSFET	(001) β-Ga_2O_3	HfO_2	—	—	10^3	—	[75]
Vertical Fin D-MOSFET	(-201) β-Ga_2O_3	Al_2O_3	185	1 kA/cm^2	10^9	—	[58]
D-MOSFET	β-Ga_2O_3	SiO_2	382	40	10^8	1.23	[76]
Recessed-gate E-MOSFET	(010) β-Ga_2O_3	SiO_2	505	40	10^9	7	[15]
Vertical Fin E-MISFET	(001) β-Ga_2O_3	Al_2O_3	1057	300–500 kA/cm^2	10^8	—	[14]
Delta doped D-MOSFET	(010) β-Ga_2O_3	—	170	140	10^6	34	[61]

on realizing gate modulation and high breakdown voltage no matter planar and vertical structures. Up to now, the material properties of Ga_2O_3 have not been fully demonstrated experimentally, more investigations on p-type doping and device fabrications are in demand. In addition, low carrier mobility and self-heating effect are also research hotspots. There is no doubt that all efforts taken in FET will be beneficial for future improvement of Ga_2O_3 FET. Table 2 shows the basic performance parameters of some typical β-Ga_2O_3 based FETs reported up to now and apparently indicates their gradual improvement in performances. Based on the available achievements reported, we can summary that

(1) Al_2O_3 and SiO_2 are widely used as gate insulators due to their larger conduction band offset with β-Ga_2O_3 and can effectively prevent gate leakage current. In addition, interfacial property in gate channel region affect the performance of FET, such as gate control ability and switch speed. Therefore, there are many studies focusing on evaluating and improving the interfacial property[66–72].

(2) High doping by ion implantation, spin-on-glass, or regrown layer are common methods to reduce contact resistance, and annealing can further improve Ohmic contact. Titanium is proved to be the best ohmic electrode metal directly contacting with β-Ga_2O_3[73].

(3) Depletion-mode transistors have been realized earlier. As for the enhancement-mode, either a low unintentional doping channel or a thin depletion layer by gate region interface states is proved to be effective solution when p-type doping is absent.

(4) The thermal damage should be unswervingly considered as the significant issue in β-Ga_2O_3 based power devices due to its relatively low thermal conductivity.

(5) The large theoretical breakdown electrical field of β-Ga_2O_3 can make a tradeoff between mobility and power loss during the high voltage and high frequency operation. In order to exert the advantages of β-Ga_2O_3, it's necessary to scale down the gate length for high frequency application, and to develop vertical FETs for high voltage application.

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