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Progress in Group III nitride semiconductor electronic devices*

Hao Yue(郝跃)[1, †], Zhang Jinfeng(张金风)[1], Shen Bo(沈波)[2], and Liu Xinyu(刘新宇)[3]

[1]Key Laboratory of Wide Band Gap Semiconductor Materials and Devices, School of Microelectronics, Xidian University, Xi'an 710071, China
[2]School of Physics, Peking University, Beijing 100871, China
[3]Key Laboratory of Microwave Devices and Integrated Circuits, Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China

Abstract: Recently there has been a rapid domestic development in group III nitride semiconductor electronic materials and devices. This paper reviews the important progress in GaN-based wide bandgap microelectronic materials and devices in the Key Program of the National Natural Science Foundation of China, which focuses on the research of the fundamental physical mechanisms of group III nitride semiconductor electronic materials and devices with the aim to enhance the crystal quality and electric performance of GaN-based electronic materials, develop new GaN heterostructures, and eventually achieve high performance GaN microwave power devices. Some remarkable progresses achieved in the program will be introduced, including those in GaN high electron mobility transistors (HEMTs) and metal–oxide–semiconductor high electron mobility transistors (MOSHEMTs) with novel high-k gate insulators, and material growth, defect analysis and material properties of InAlN/GaN heterostructures and HEMT fabrication, and quantum transport and spintronic properties of GaN-based heterostructures, and high-electric-field electron transport properties of GaN material and GaN Gunn devices used in terahertz sources.

Key words: AlGaN/GaN; InAlN/GaN; HEMT; MOSHEMT; Gunn diode
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1. Introduction

Group III nitride semiconductor materials have shown great potential in the microwave power applications of wireless communication, radar, and automobile electronics. Its mainstream electronic device structure is the AlGaN/GaN high electron mobility transistor (HEMT), as shown in Fig. 1. The strong polar nature of nitride semiconductor materials makes it possible that a high density of two-dimensional electron gas (2DEG) with high mobility can be formed in an AlGaN/GaN heterostructure without intentional doping. It is the high electric conductivity of a 2DEG channel combined with the high breakdown field of AlGaN/GaN material that lays the physical foundations for GaN HEMT microwave power devices. The extremely strong power amplification capability of GaN HEMTs has been demonstrated by the reports of a total output power of over 200 W @ 2 GHz delivered by a single HEMT device[1] and a record high output power density of over 40 W/mm @ 4 GHz[2]. More recent efforts to expand the operation frequency of GaN HEMTs have realized W-band power amplification. In 2011, at the IEEE International Electron Devices Meeting, an AlN/GaN/AlGaN double heterostructure (DH) HEMT[3] with a current gain cutoff frequency f_T and a highest oscillation frequency f_{max} of 310 GHz and 364 GHz, respectively, and an AlGaN/GaN DH HEMT[4] with the achievement of a continuous wave (CW) output power of 1023 mW @ 95 GHz (W-band) and a power added efficiency (PAE) of 19.1% were reported. In GaN HEMTs without an AlGaN barrier layer, the most impressive one is the InAlN/GaN DH HEMT[5] with an f_T in the range of 290–300 GHz.

In China there is also an increasingly rapid development in group III nitride semiconductor electronic materials and devices. Since 2008, Xidian University, Peking University, and the Institute of Microelectronics of Chinese Academy of Sciences had undertaken a Key Program of the National Natural Science Foundation of China to research GaN wide bandgap microelectronic materials and devices, and a successful fulfillment of the program was achieved after four years of great efforts. Some main results will be briefly re-

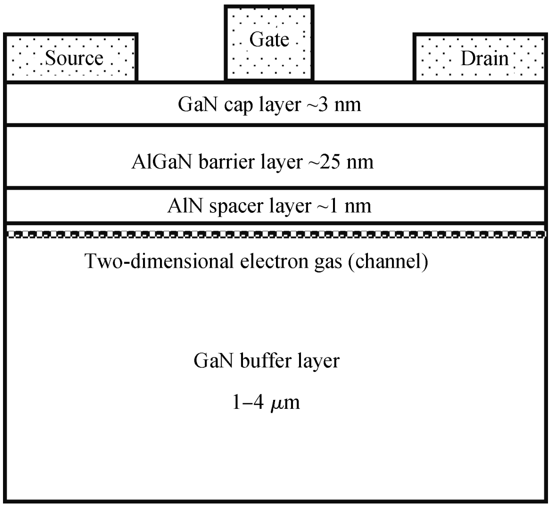

Fig. 1. Schematic cross section of AlGaN/GaN HEMT material.

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† Corresponding author. Email: yhao@xidian.edu.cn

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viewed, such as high performance GaN HEMTs and GaN metal–oxide–semiconductor high electron mobility transistor (MOSHEMTs) with novel high-*k* gate insulators, and material growth, defect analysis, and material properties of InAlN/GaN heterostructures and HEMT fabrication, and quantum transport and spintronic properties of GaN-based heterostructures, and high-electric-field transport properties of GaN material and GaN Gunn devices used in terahertz sources.

2. High performance GaN HEMTs and MOSHEMTs with novel high-*k* gate insulators

In order to realize a high performance microwave power GaN HEMT, systematic research efforts were put into AlGaN/GaN material optimization, fabrication process optimization, and the device physics of HEMT devices.

To realize a large output current, a high breakdown voltage, a high on/off ratio and the robust reliability of HEMT devices, AlGaN/GaN HEMT material is required to be of high crystal quality with a smooth AlGaN/GaN heterointerface and show high electric conductivity with low buffer leakage. These goal characteristics usually result from a multilayered structure including a high-resistance low-defect buffer layer, a high quality AlGaN barrier layer with optimized thickness and Al content, a thin AlN spacer layer inserted into the AlGaN/GaN heterointerface and a GaN cap layer on top of the AlGaN barrier layer.

Vicinal substrate and nucleation layer optimization are adopted to reduce the defects in the GaN buffer layer, and it is found that the dislocations in GaN grown on a vicinal substrate emerge in clusters and annihilate in batches. To realize a high resistance buffer layer, the so-call buried charge layer located on top of the nucleation layer, which comes into being as a result of the out-diffusion of oxygen from the sapphire substrate, must be eliminated, and meanwhile the unintentional background n-type doping of GaN material must be lowered as much as possible. High-resistance (HR) GaN is grown by using the metal-organic chemical vapor deposition (MOCVD) technique in a self-compensated way with stable growth repetition[6]. The room temperature (RT) sheet resistance is well above 10^{11} Ω/□, the detection limit of the measurement instrument, and the full width at half maximum (FWHM) of the X-ray rocking curve is 260 arcsec for (002) plane and 370 arcsec for (102) plane indicating the very good crystal quality of the HR GaN.

In the research of AlGaN barrier layer, achieving good electric conductivity of the AlGaN/GaN material is important, but keeping the initial strain of the AlGaN layer fairly small is also considered in order to constrain the inverse piezoelectric effect, a degradation mechanism widely supported as a severe detriment of GaN HEMT device reliability under high electric field. Therefore, a thin AlGaN layer with low Al content and thus low lattice mismatch with GaN is adopted, and at the same time the AlN spacer layer at the AlGaN/GaN heterointerface is optimized in its thickness and growth process. Quite high 2DEG density is maintained, the AlGaN/GaN heterointerface is smoothed and 2DEG mobility is improved. A GaN cap layer on top of AlGaN is also ascertained helpful in restraining the strain relaxation of AlGaN and enhancing the 2DEG transport characteristics[7]. A highly stable growth process of AlGaN/GaN HEMT material with RT mobility of over 1800 cm^2/(V·s) is established with quite wide process parameter window, and the 2DEG mobility as high as 2230 cm^2/(V·s) @ RT and 15000 cm^2/(V·s) @ 90 K is achieved.

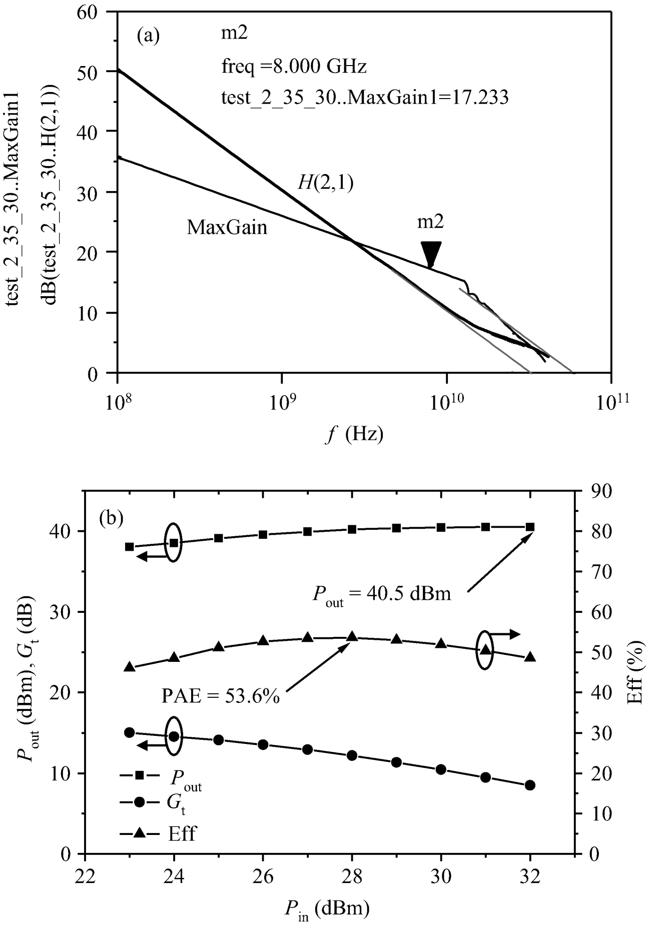
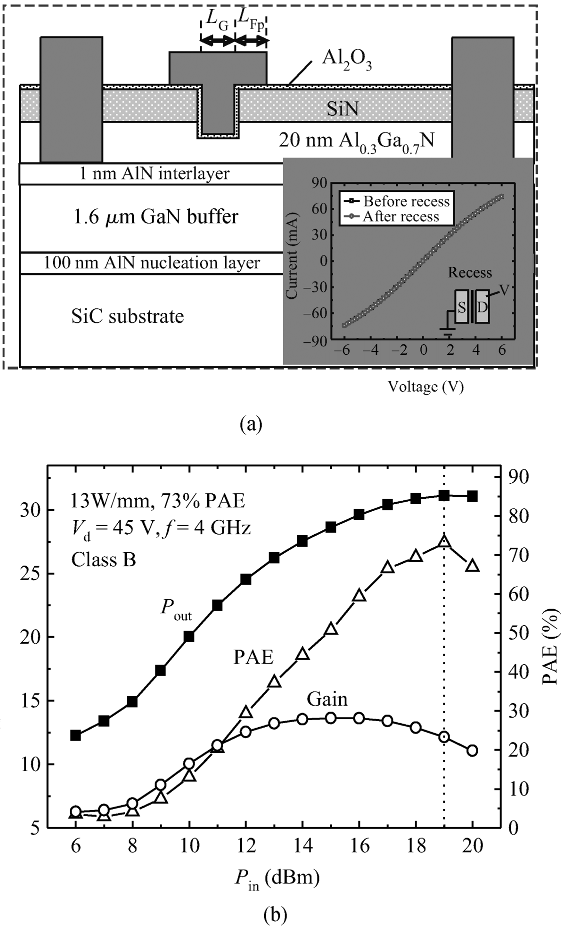


Fig. 2. X-band GaN HEMT device performance. (a) Frequency performance with $f_{\rm T} \geqslant 37$ GHz and $f_{\max} \geqslant 60$ GHz. (b) Microwave power performance @ 8 GHz with PAE of 53.6% and CW output power of 40.5 dBm when biased at $V_{\rm ds} = 45$ V and $V_{\rm gs} = -3$ V, which translates into a power density of 11.22 W/mm.

As for the fabrication process and device physics of GaN HEMT devices, the critical process techniques to expand device frequency characteristics are broken through such as formation of low resistance ohmic contacts, T-gate process, low damage etching of the gate trench, backside via hole formation in SiC substrate, etc. At the same time, the field plate design is optimized to improve the device breakdown voltage, and the surface passivation process is investigated to suppress current collapse and improve device reliability. All these efforts result in the independent establishment of a complete GaN HEMT device fabrication process line. High performance X-band GaN HEMTs are realized with an output current of 1.25 A/mm, transconductance of over 350 mS/mm, $f_{\rm T}$ of 37 GHz and $f_{\max}$ of 60 GHz, as shown in Fig. 2. The CW output power density reaches 11.22 W/mm @ 8 GHz with a PAE of 53.6%. Some progress has also been made in microwave power GaN HEMTs of higher frequency bands. Typical Ku-band devices



(a)

(b)

Fig. 3. High performance microwave gate-recessed AlGaN/AlN/GaN MOSHEMT[11] with (a) its schematic cross section, where the inset indicates that the low damage gate recess process causes no degradation of the source-to-drain current, and (b) the microwave power characteristics with CW power density of 13 W/mm @ 4 GHz, PAE = 73%, and Gain = 12 dB.

deliver a power density of 6.2 W/mm @ 14 GHz when biased at V_{ds} = 30 V and V_{gs} = −1 V, and the maximum gain is 12.93 dB. The Ka-band devices yield a power density of 1.19 W/mm @ 30 GHz when biased at V_{ds} = 20 V and V_{gs} = −1 V, and the maximum gain is 8 dB, though the power performance of Ka-band devices is not saturated because of the limitation of the load-pull power measurement system.

It is known that the MOSHEMT structure is a powerful competitor to improve GaN microwave power device performance and reliability as compared with the HEMT structure. To further enhance the frequency performance of MOSHEMT devices, a high-k gate insulator is used instead of SiO_2 and SiN, and the insulator film, which is generally thinner than 10 nm but uniform and compact and can be used as a surface passivation layer at the same time, is realized by using the atomic layer deposition (ALD) process. Yue *et al.* reported a novel AlGaN/GaN MOSHEMT using an ALD grown stack gate HfO_2/Al_2O_3 structure[8]. The gate leakage current is at least six orders of magnitude lower than that of the reference HEMT at a positive gate bias, and the devices with 1-μm gate length exhibit f_{max} of 34 GHz. The synchronously pulsed current–voltage (I–V) measurement similar to microwave power measurement shows that current collapse in the MOSHEMT devices is significantly reduced due to the good passivation effect of ALD-grown insulator films and therefore the MOSHEMTs are superior to conventional HEMTs in terms of device reliability[9]. A composite gate insulator NbAlO grown by the introduction of Nb into Al_2O_3 is used in GaN MOSHEMTs showing largely improved permittivity with very good high temperature stability[10]. Yang *et al.* realized for the first time a high performance microwave gate-recessed AlGaN/AlN/GaN MOSHEMT with a PAE as high as 73%, as shown in Fig. 3[11]. The device with a 5 nm thick Al_2O_3 gate insulator and a gate length of 0.6 μm exhibits a maximum drain current density of 1.59 A/mm, and f_T of 19 GHz, and f_{max} of 50 GHz are deduced from S-parameter measurements. The CW output power density is 13 W/mm at 4 GHz and 45 V drain bias.

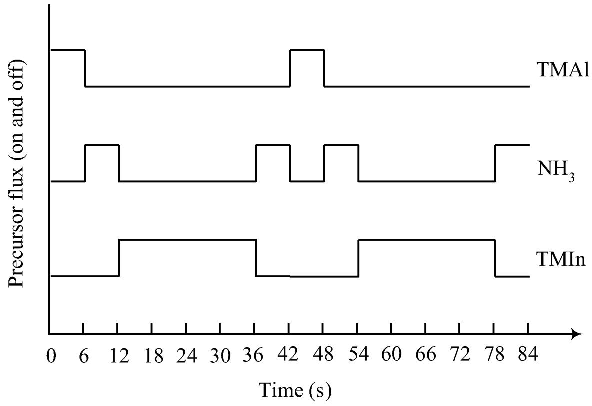


Fig. 4. Growth sequence of PMOCVD pulses for an InAlN barrier layer[14].

3. Material growth, defect analysis, and material properties of InAlN/GaN heterostructures and HEMT fabrication

Strain-free InAlN/GaN heterostructures with an Al content of about 0.83 have been a competitive GaN HEMT material compared with conventional AlGaN/GaN heterostructures. There are even stronger polarization induced electric fields and higher conduction band offsets (0.65 eV) at an InAlN/GaN heterointerface. An unintentional doped InAlN barrier layer as thin as 5–20 nm on top of GaN could induce a 2DEG with a sheet density of over 2.5×10^{13} cm^{-2} and thus bring a sheet resistance of lower than 220 $\Omega/\square$[12]. As a result, InAlN/GaN HEMT bears great current driving capability and natural superiority in scaled down device design[5]. In terms of device reliability, a strain-free InAlN/GaN HEMT is immune to the inverse piezoelectric effect from which AlGaN/GaN HEMTs widely suffer[13]. However, the growth process parameters of AlN and InN contradict each other, and so it is quite hard to grow high quality InAlN crystal and the research on growth and properties of InAlN/GaN material is far less mature as compared with AlGaN/GaN material.

Xue and Hao *et al.* proposed to grow InAlN by pulsed MOCVD (PMOCVD). As shown in Fig. 4[14], the approach of PMOCVD cyclically transports ammonia and metal-organic

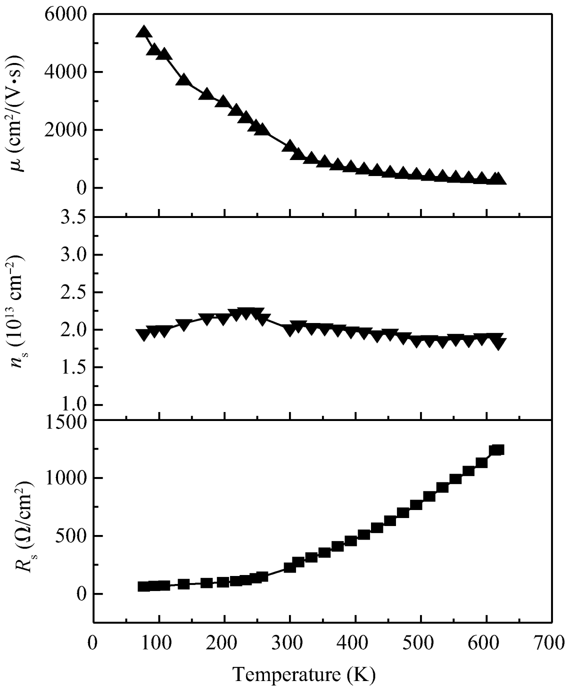


Fig. 5. Hall mobility (μ), sheet carrier density (n_S), and sheet resistance (R_S) of a PMOCVD-grown InAlN/GaN heterostructure as a function of temperature[14].

precursors into a growth chamber in pulses at different times, and so material defects caused by pre-reaction are reduced, surface migration of Al atoms is enhanced, and a monoatomic smooth layer of InAlN thin film is formed. The enhancement of surface reaction also allows the reduction of the growth temperature, and hence indium incorporation is significantly increased. Strain-free InAlN/GaN heterostructures formed by InAlN directly deposited on GaN grown by conventional MOCVD or MBE usually suffer an electron mobility which is as low as 70–500 cm^2/(V·s) at RT and changes with temperature in a bulk-electron-like way, i.e., it rises to a maximum point and then falls when temperature goes down from RT to the liquid nitrogen point or lower. In contrast, the strain-free InAlN/GaN heterostructure grown by PMOCVD, whose Hall electron mobility is 949 and 2032 cm^2/(V·s) at RT and 77 K, respectively[15], exhibits a typical 2DEG-type electric conductance indicating the high quality of InAlN barrier layer achieved by PMOCVD. Introduction of an AlN spacer layer into the InAlN/GaN heterointerface leads to a 50 mm InAlN/GaN heterostructure wafer with a mobility of 1402 cm^2/(V·s), an average sheet resistance of 234 Ω/□ and a sheet resistance nonuniformity of 1.22%, as shown in Fig. 5[14]. To further reduce the sheet resistance of InAlN/GaN material, or to reduce the parasitic access resistance which deteriorates the linearity and maximum frequency of operation of HEMT devices, Xue *et al.* investigated InAlN/GaN double channel heterostructures and in 2012 reported their results with a high electron mobility of 1414 cm^2/(V·s) and a very low sheet resistance of 172 Ω/□[16]. This is the first double-channel nitride heterostructure containing only InAlN (with 1 nm AlN spacer) barrier layers, and the RT sheet resistance data approach the lowest value of sheet resistance reported for nitride heterostructures.

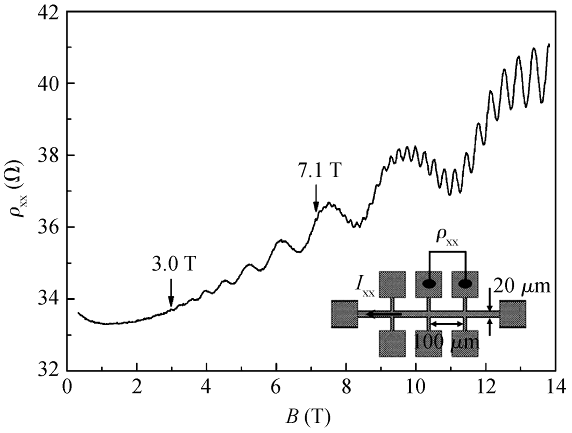
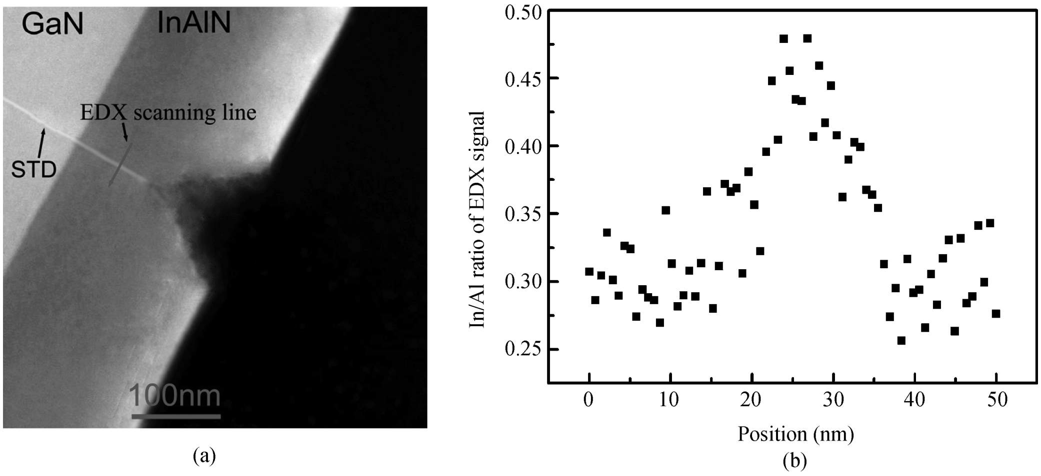


Fig. 6. Magnetotransport measurement of In$_{0.18}$Al$_{0.82}$N/AlN/GaN heterostructures at 1.5 K demonstrating 2DEG population in two subbands[17].

In the investigation of material properties and defects of InAlN/GaN heterostructures, Miao *et al.*[17] reported the first observation of strong Shubnikov–de Haas (SdH) oscillations of In$_{0.18}$Al$_{0.82}$N/AlN/GaN heterostructures demonstrating 2DEG population in two subbands, as shown in Fig. 6. The energy separation between the two subbands is as high as 191 meV and much larger than that in conventional AlGaN/GaN heterostructures, and the quantum scattering time of the first subband is much smaller than that of the second subband. Analysis indicates that the stronger 2DEG confinement in the triangular quantum well in InAlN/GaN heterostructure is due to the strong spontaneous polarization of the InAlN layer, and the large difference of quantum scattering time of the 2DEG in the two subbands originates from interface roughness scattering, which is very sensitive to the distance of 2DEG from the interface. To figure out the cause of the generally much higher reverse-bias leakage current of Ni/Au Schottky contacts on InAlN/GaN heterostructures than that on AlGaN/GaN ones, Song *et al.* investigated the correlation between microstructures and Schottky leakage of strain-free InAlN/GaN heterostructures by means of current-voltage measurements, conductive atom force microscopy, and transmission electron microscopy (TEM). It is revealed that indium segregation is formed around screw- and mixed-type threading dislocations, which could reduce the local Schottky barrier height to form highly conductive leakage current channels, as shown in Fig. 7[18]. Further research shows thermal oxidation at 700 degrees centigrade leads to a six-order-of-magnitude reduction of the reverse-bias leakage current of Ni/Au Schottky contacts on InAlN/GaN heterostructures. Since the leakage current flow is mainly formed by the emission of electrons from trapped states near the metal–InAlN interface into states associated with conductive dislocations, it is suggested that after thermal oxidation a thin oxidation layer forms on the InAlN surface and increases the barrier height for electron emission from trapped states, and thus reduces the Schottky leakage of InAlN/GaN heterostructures.

Xue *et al.* realized high performance InAlN/GaN HEMTs on SiC grown by PMOCVD[19]. The gate diode leakage current density is lower than 2×10^{-3} A/cm^2 at $V_{GS} = -20$ V even though it is without a gate insulating layer or GaN cap



(a)

(b)

Fig. 7. Cross-section TEM observation shows that indium segregation is formed around screw- and mixed-type threading dislocations in InAlN material[18].

layer or post thermal oxidation process, which indicates that the PMOCVD approach significantly improves the quality of the epitaxial InAlN barrier layer and reduces the surface defects related to the gate leakage current. The HEMT device with a gate length of 0.5 μm exhibits f_t and f_{max} of 18 and 39 GHz, respectively, and shows the potential of InAlN/GaN heterostructures to be used in millimeter wave devices.

4. Quantum transport and spintronic properties of GaN-based heterostructures

The quantum transport properties of GaN-based heterostructures reflect the detailed energy band structure of 2DEG with the transport property of each subband, and thus correlate closely with the electric properties of the material. Tang *et al.* investigated systematically the transport property of 2DEG in AlGaN/GaN heterostructures in low magnetic field, such as weak localization, weak antilocalization, electron–electron interaction, etc., and measured related transport parameters. The SdH oscillation measurements of gated Hall bar AlGaN/GaN heterostructure devices indicate that 2DEG properties can be adjusted efficiently by gate voltage. An increase of gate voltage would cause a decrease of 2DEG density in subbands and a linear reduction of electron mobility. Meanwhile, it is found that the zero-field spin splitting (ZFSS) energy of the 2DEG is also sensitive to gate voltage.

In the research on the spintronic properties of GaN-based heterostructures, He *et al.* reported the first observation of an anomalous circular photogalvanic effect (CPGE) current in AlGaN/GaN heterostructures produced by a radial spin current of 2DEG via the reciprocal spin Hall effect (RSHE) under normal incidence of circularly polarized light at room temperature, as shown in Fig. 8[20]. Analysis shows that Rashba spin splitting (intrinsic) combined with impurity scattering (extrinsic) causes the transverse displacements of spin polarization electrons, and converts a radial spin current into a swirly charge current. The spin transverse force acting on a single electron is estimated to be about 10^{-19} N. It suggests a new way to research the reciprocal spin Hall effect and spin current on the macroscopic scale and at room temperature. Yin *et al.* investigated the ratios of Rashba and Dresselhaus spin-orbit coupling coefficients (R/D ratios) in $Al_xGa_{1-x}N$/GaN heterostructures with various Al compositions by means of CPGE experiments under uniaxial strain[21]. It is found that the R/D ratio increases from 4.1 to 19.8 with the Al composition of the $Al_xGa_{1-x}N$ barrier varied from 15% to 36% indicating that the spin splitting in GaN-based heterostructures can be modulated effectively by the polarization-induced electric fields. The Dresselhaus coefficient of bulk GaN is experimentally obtained to be 0.4 eV·Å^3. Tang *et al.* investigated the ZFSS in $Al_xGa_{1-x}N$/GaN heterostructures with various Al compositions at low temperatures and high magnetic fields[22], and obtained the ZFSS energy and the spin-orbit coupling (SOC) parameter. It is found that the SOC parameter can be tuned by the polarization-induced electric field, and a large SOC parameter can be obtained in the $Al_xGa_{1-x}N$/GaN heterostructure with high Al composition.

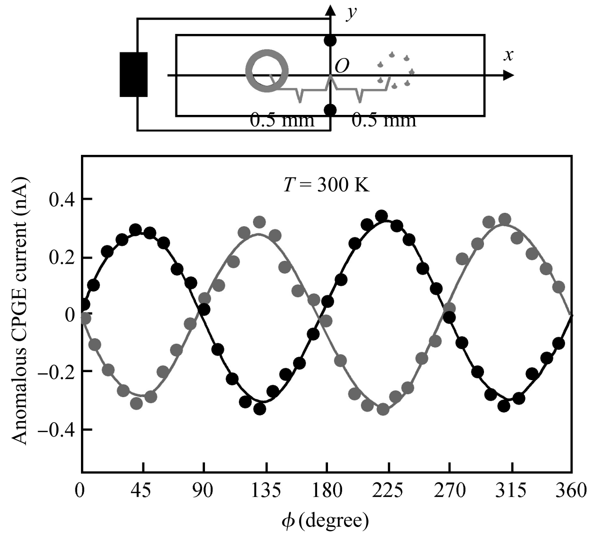


Fig. 8. Anomalous circular photogalvanic effect (CPGE) current as a function of the phase angle, which is related to the polarization direction of incident light[20].

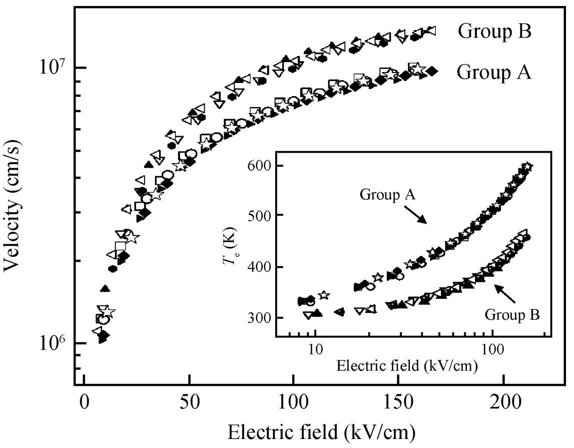


Fig. 9. Size-effect of high-electric-field drift velocity of electrons in n-type GaN[23]. Group A consists of wide channel (> 20 μm) samples and group B consists of narrow channel (< 5 μm) ones. The inset shows the estimated electron temperature (T_e) in these channels.

5. High-electric-field transport properties of GaN material and GaN Gunn devices used in terahertz sources

There are many interesting issues worthy of investigation when the high-electric-field transport behavior of bulk electron in GaN is involved, such as energy relaxation, momentum relaxation, negative differential resistance (NDR), etc. Ma *et al.* observed in the high-field electron transport measurements of n-type GaN epilayers that the electrons in narrow channels drift much faster than those in wide channels, as shown in Fig. 9. This discrepancy is attributed to the boundary-enhanced momentum relaxation of longitudinal optical (LO) phonons, which increases the electron drift velocity through enhancing the electron energy dissipation while weakening the momentum relaxation. Such a size effect leads to fast but not "hot" electrons and is beneficial to microwave power devices. Ma *et al.* also observed in the pulsed current–voltage characteristics of n-type GaN epilayers during high-field carrier transport measurement that when the electric field is beyond the threshold electric field of the Gunn effect (about 400 kV/cm), the current–voltage characteristics changed from voltage-controlled NDR to current-controlled NDR in tens of nanoseconds, as shown in Fig. 10[24]. This is ascribed to the Gunn-type instability in n-type GaN and takes the early electric breakdown of the GaN epilayers in charge.

The high threshold electric field of the NDR characteristics allows nitride NDR devices to work under high bias and produce high output power, and meanwhile the high electron saturation drift velocity of nitrides significantly improve the operation frequency. Consequently, group III nitride material is promising in terahertz power devices. Yang *et al.* proposed to use AlGaN in the notch region of the GaN Gunn diode structure used in terahertz sources, as shown in Fig. 11[25]. Compared with the conventional doping notch structure used in Gunn diodes, the novel GaN/AlGaN notch/launcher structure with nonuniform doping and polarization effects could significantly improve the electron energy injected into the transit region, and increase the stability of self-excitation oscillation of dipole domains. Theoretic simulations show that the diode with a two-step-graded AlGaN launcher structure can yield the maximal RF power of 1.95 W and DC/RF conversion efficiency of 1.72% at the fundamental oscillation frequency of around 215 GHz. It is established an improved negative differential mobility model for GaN and $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ ($0<x<1$) to simulate GaN Gunn diodes at terahertz frequencies with Al-composition-related coefficient and random-alloy-potential-related factor introduced[26]. The AlGaN/GaN sub-micrometer Gunn diode with tristep-graded Al composition AlGaN as the hot electron injector is simulated by using the improved mobility model at different temperatures[27]. It indicates that the oscillation mode of a Gunn diode gradually shifts from the dipole domain mode toward the accumulation mode when temperature increases, and the mode shift closely depends on the thickness of the AlGaN injector layer. In 2012 the experimental optimization of material structure and crystal quality of terahertz GaN Gunn diodes was reported for the first time[28].

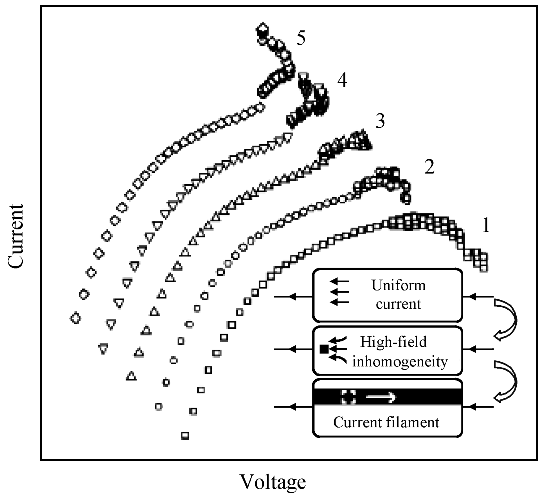


Fig. 10. Transition of the current–voltage characteristics from voltage-controlled NDR to current-controlled NDR due to the Gunn-type instability in n-type GaN[24]. The serial numbers of the curves denote the time sequence. The time interval between adjacent curves is several nanoseconds. The inset shows the formation process of a current filament.

6. Summary

Research developments are reviewed, including those in GaN HEMTs and MOSHEMTs with novel high-*k* gate insulators, and material growth, defect analysis and material properties of InAlN/GaN heterostructures and HEMT fabrication, and quantum transport and spintronic properties of GaN-based heterostructures, and the high-electric-field transport properties of GaN material and GaN Gunn devices used in terahertz sources. Many fundamental physical mechanisms in the field of group-III nitride semiconductor electron devices are now far better understood. In the future, domestic development of higher level high frequency power GaN HEMT devices will continue independently and GaN HEMT device reliability will be investigated intensively. New research focuses and opportunities will emerge in but not limited to N-face nitride electronic devices, enhancement/depletion HEMT circuit modules and

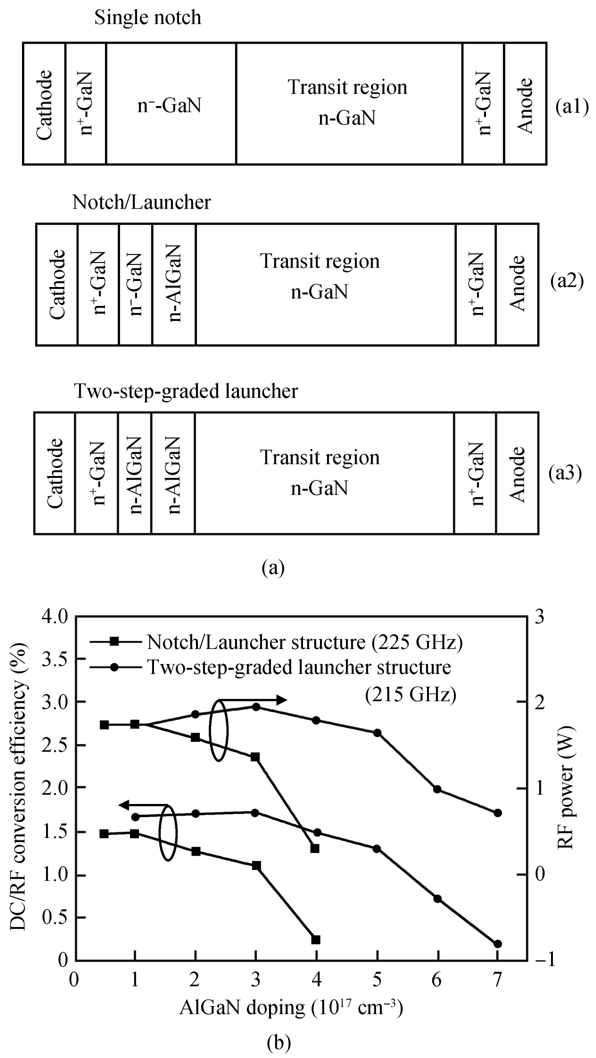


Fig. 11. GaN/AlGaN heterostructure Gunn diode used in a terahertz source[25] with (a) schematic cross section of device structure and (b) simulated device performance demonstrating a maximal RF power of 1.95 W at 215 GHz.

nitride electronic materials and devices on silicon substrates.

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