Carrier mobility in the channel of AlGaN/(AlN)/GaN and InAlN/(AlN)/GaN heterostructures, limited by different scattering mechanisms: experiment and calculation

D S Arteev¹, A V Sakharov¹, W V Lundin¹, D A Zakheim¹, E E Zavarin¹ and A F Tsatsulnikov²

¹Ioffe Institute, 26 Politekhnicheskaya, 194021 St. Petersburg, Russia
²Submicron Heterostructures for Microelectronics, Research & Engineering Center, RAS, 26 Politekhnicheskaya, 194021 St. Petersburg, Russia

E-mail: ArteevDS@mail.ioffe.ru

Abstract. Calculational analysis of different scattering mechanisms of two-dimensional electron gas in AlGaN/(AlN)/GaN and InAlN/(AlN)/GaN high-electron mobility transistors was carried out. It was found that the mobility of AlGaN-based structures at room temperature is mainly limited by inherent scattering mechanisms (namely, optical and acoustic phonon scattering), while the mobility in our InAlN-based structures is limited by the interface roughness scattering. The low-temperature mobility is found to be limited by the interface roughness scattering for both AlGaN- and InAlN-based structures.

1. Introduction

Gallium nitride (GaN) is gaining increasing interest over the last decades. Its unique properties, namely wide band gap, high electron saturation velocity and high breakdown voltages, make it a prospective material for high-frequency and high-power electronics [1]. The ability to form alloys with indium nitride (InN) and aluminium nitride (AlN) in the entire composition ranges is a huge advantage over the other wide-bandgap materials. The polar nature of wurtzite III-nitride materials and large conduction band offset in III-N heterostructures enable to fabricate high electron mobility transistors (HEMT) with two-dimensional electron gas (2DEG) density of 1-3×10¹⁵ cm⁻² and mobility up to 2200 cm²V⁻¹s⁻¹ at room temperature [2] even without intentional doping. High power densities in frequency ranges of tens to hundreds GHz previously unattainable for semiconductor devices, based on other material systems, were achieved using III-N heterostructures [3, 4, 5]. Furthermore, there is a prospect of using III-nitride based HEMT-like heterostructures as efficient and low-cost terahertz emitters [6].

There are two main parameters determining the performance of the HEMT: the density and mobility of 2DEG. The first depends more on the design of the heterostructure (i.e. the thickness and composition of the layers). The second is affected by scattering caused by different mechanisms, such as scattering by phonons, impurities, interface roughness, etc. Therefore, an in-depth understanding of the scattering mechanisms and their influence on the carrier mobility is required to enable fabrication of the devices with better performance.

In this paper, we present the calculational analysis of the mobility-limiting scattering mechanisms in AlGaN/(AlN)/GaN and InAlN/(AlN)/GaN HEMT heterostructures, depending on different
parameters, and comparison with large sets of experimental data. Some tentative ways to improve the performance of our heterostructures were identified based on the analysis.

2. Experimental details

The large set of samples was grown by metal-organic chemical vapor deposition (MOCVD) on c-face (0001) sapphire substrates in our in-house Dragon-125 epitaxial system with horizontal reactor. Conventional precursors, i.e. trimethylgallium, trimethylindium, trimethylalanuminum and ammonia were utilized. The intentional doping of AlGaN, AlN and InAlN barrier layers was not used. The growth conditions described in details in [7].

The mobility and sheet concentration of 2D electrons were extracted from the conductivity and the Hall effect measurements made by the Van der Pauw method. The thickness and composition of the layers were obtained from the growth calibrations and verified through XRD analysis. The surface morphology of some samples was analyzed by means of Atomic Force Microscopy (AFM).

3. Mobility-limiting scattering mechanisms

Scattering mechanisms of two-dimensional electron gas in III-V heterostructures are well established nowadays. Both Monte Carlo simulation and analytical approaches were developed and successfully used for scattering analysis and mobility calculation in different material systems [8, 9, 10, 11, 12].

The calculations are based on several assumptions: (1) screening is determined only by electrons in the lowest subband; (2) electron statistics is degenerate; (3) the exact Hartree-Fock wave function is approximated by the analytical Fang-Howard variational wave function [13]. The total 2DEG inverse mobility $\mu^{-1}$ is calculated through the Matthiessen’s rule (1) from the component inverse mobilities $\mu_i^{-1}$, limited by each individual scattering mechanism:

$$\mu^{-1} = \sum_i \mu_i^{-1}$$  \hspace{1cm} (1)

The individual mobilities are calculated in the momentum relaxation approximation:

$$\mu_i = \frac{e \cdot \tau_i}{m^*},$$  \hspace{1cm} (2)

where $\tau_i$ is the momentum relaxation time, $e$ is the elementary charge, and $m^*$ is the effective electron mass. The analytical expressions for the individual scattering $\tau_i^{-1}$ rates are briefly summarized below, and the relevant material parameters are listed in Table 1.

3.1. Acoustic phonon scattering

At high and intermediate temperatures, we consider elastic scattering of electrons by acoustic phonons via deformation potential and piezoelectric scattering. The deformation potential scattering rate is expressed as [14]:

$$\tau_{DP}^{-1} = \frac{3m^*e^2a^2k_BT}{16\rho V_L h^2} b,$$  \hspace{1cm} (3)

where $b$ is a variational parameter of Fang-Howard function:

$$b = \left(\frac{33m^*e^2n_{2DEG}}{8\hbar^2\varepsilon_0\varepsilon_s}\right)^{1/3}.$$  \hspace{1cm} (4)
Table 1. The relevant material parameters used in calculations.

| Parameter | Symbol (unit) | GaN | AlN | InN |
|-----------|---------------|-----|-----|-----|
| Band gap  | \(E_g\) (eV)  | 3.437\(^{[15]}\) | 6.158\(^{[15]}\) | 0.642\(^{[15]}\) |
| Band gap bowing | \(b\) (eV) | 0.7\(^{[15]}\) | 3.4\(^{[15]}\) |
| Conduction band offset | \(CBO\) (eV) | 0.7\(\Delta E_g\)^\(^{[15]}\) |
| Static dielectric constant | \(\varepsilon_s\) | 9.5\(^{[16]}\) | 8.5\(^{[16]}\) | 15.3\(^{[16]}\) |
| High-frequency dielectric constant | \(\varepsilon_\infty\) | 5.35\(^{[15]}\) | - | - |
| Lattice constant | \(a\) (Å) | 3.189\(^{[16]}\) | 3.112\(^{[16]}\) | 3.540\(^{[16]}\) |
| Lattice constant | \(c\) (Å) | 5.186\(^{[16]}\) | 4.982\(^{[16]}\) | 5.703\(^{[16]}\) |
| Spontaneous polarization | \(P_{sp}\) (C m\(^{-2}\)) | -0.029\(^{[16]}\) | -0.081\(^{[16]}\) | -0.032\(^{[16]}\) |
| Elastic constant | \(C_{13}\) (GPa) | 103\(^{[16]}\) | 108\(^{[16]}\) | 92\(^{[16]}\) |
| Elastic constant | \(C_{33}\) (GPa) | 405\(^{[15]}\) | 373\(^{[16]}\) | 224\(^{[16]}\) |
| Piezoelectric constant | \(e_{33}\) (C m\(^{-2}\)) | 0.73\(^{[16]}\) | 1.55\(^{[16]}\) | 0.97\(^{[16]}\) |
| Piezoelectric constant | \(e_{31}\) (C m\(^{-2}\)) | -0.49\(^{[16]}\) | -0.58\(^{[16]}\) | -0.57\(^{[16]}\) |
| Electron effective mass | \(m^*/m_0\) | 0.20\(^{[15]}\) | 0.30\(^{[15]}\) | 0.07\(^{[15]}\) |
| Acoustic deformation potential | \(a_c\) (eV) | 8.3\(^{[15]}\) | - | - |
| Mass density | \(\rho\) (g cm\(^{-3}\)) | 6.15\(^{[15]}\) | - | - |
| Longitudinal acoustic phonon speed | \(u_k\) (m s\(^{-1}\)) | 8.10\(^{[12]}\) | - | - |
| Electromechanical coupling coefficient | \(M\) | 0.039\(^{[12]}\) | - | - |
| LO phonon energy | \(h\omega_{LO}\) (meV) | 91.2\(^{[16]}\) | - | - |
| Dislocation filling factor | \(f\) | 0.5\(^{[12]}\) | - | - |
| Alloy scattering potential | \(\delta V\) (eV) | \(CBO \cdot (E^{AlN}_{g} - E^{GaN}_{g})\) | \(CBO \cdot (E^{AlN}_{g} - E^{InN}_{g})\) |
| Electron rest mass | \(m_0\) (kg) | 9.1×10\(^{-31}\) | - | - |
| Boltzmann constant | \(k_B\) (K\(^{-1}\)) | 1.38×10\(^{-23}\) | - | - |
| Elementary charge | \(e\) (C) | 1.6×10\(^{-19}\) | - | - |
| Vacuum permittivity | \(\varepsilon_0\) (F m\(^{-1}\)) | 8.854×10\(^{-19}\) | - | - |

The expression for the piezoelectric scattering rate is [17]:

\[
\tau_{PE}^{-1} = \frac{e^2 M k_B T m^*}{4 \pi \varepsilon_0 \varepsilon_s h^3 k_F^2} \int_0^{2k_F} \frac{F(q) q^3}{(q + q_{TF} F(q))^2} \sqrt{1 - \left(\frac{q}{2k_F}\right)^2} dq, \tag{5}
\]

where \(k_F = \sqrt{2m_{2DEG}}\) is the Fermi wave vector, \(q = 2k_F \sin \left(\frac{\theta}{2}\right)\), \(\theta e (0, \pi)\) is the difference of the wave vectors between the initial state and the final state in scattering, \(q_{TF} = m^* e^2 / (2\pi \varepsilon_0 h^2)\) is the Thomas-Fermi wave vector, reflecting the screening length of 2DEG; \(F(q) = n^2\) with \(n = b/(b + q)\) is the form factor of ground state Fang-Howard wave function [13].

3.2. Optical phonon scattering

Optical phonon scattering in highly inelastic due to high LO phonon energy in GaN, and relaxation-time approximation does not work. But as the polar optical phonon scattering becomes dominant at temperatures ~250K and higher, it should be taken into account in RT mobility calculation. An accurate description of optical phonon scattering requires numerical methods, but some analytical approximated equations exist. We found that commonly used equation for polar optical-phonon
scattering in 2DEG from [18] tends to underestimate the total mobility at RT. So we used the equation (6) from [19] for optical-phonon-limited mobility, since it gave better agreement with our experimental data.

\[
\mu_{LO} = \frac{137e}{2m^*} \sqrt{\frac{m^*e_{light}^2}{2h\omega_{LO}}} \exp\left(\frac{\hbar\omega_{LO}}{k_BT}\right) \exp\left(\frac{1}{\varepsilon_{0}\varepsilon_{\infty}} - \frac{1}{\varepsilon_{0}\varepsilon_{s}}\right) \omega_{LO}
\]

(6)

3.3. Background and surface donor scattering

A large number of experiments shows, that despite of non-using the n-type doping, GaN layers nearly always have weak n-type conductivity, representing the presence of unintentional background donors. The ionized background donor scattering rate is expressed as [14]:

\[
\tau_{BD}^{-1} = N_{DB} \frac{m^*}{2\pi\hbar^3k_F^2} \left(\frac{e^2}{2\varepsilon_0\varepsilon_s}\right)^2 \int_0^{2k_F} \frac{F(q)^2 q}{\left(q + q_{TF}G(q)\right)^2 \sqrt{1 - \left(q\frac{q}{2k_F}\right)^2}} dq,
\]

(7)

where \(G(q) = (2\eta^3 + 3\eta^2 + 3\eta)/8\) is screening form factor of Fang-Howard wave function, \(N_{DB}\) is the ionized background donor density.

Surface donor states on the top of the III-N-based HEMTs are generally accepted as the source of the 2DEG [20, 21]. The influence of these donor states could be taken into account with [14]:

\[
\tau_{SD}^{-1} = N_{SD} \frac{m^*}{2\pi\hbar^3k_F^2} \left(\frac{e^2}{2\varepsilon_0\varepsilon_s}\right)^2 \int_0^{2k_F} \frac{F(q)^2 \exp(-2qd) q^2}{\left(q + q_{TF}G(q)\right)^2 \sqrt{1 - \left(q\frac{q}{2k_F}\right)^2}} dq,
\]

(8)

where \(N_{SD}\) can be assumed to be equal to \(n_{2DEG}\), and \(d\) is the thickness of AlGaN/(AlN) or InAlN/(AlN) barrier.

3.4. Dislocation scattering

Unfortunately, free-standing GaN substrates for homoepitaxy are still very expensive, so the most of the III-N-based structures are grown on the lower-cost foreign substrates (e.g. sapphire, SiC or Si), leading to high threading dislocation densities (typically \(10^7-10^9\) cm\(^{-2}\)). The dislocation scattering rate is expressed as [22]:

\[
\tau_{D}^{-1} = N_{dis}\frac{m^*e^4f^2}{4\pi\hbar^2\varepsilon_0^2\varepsilon_s^2} \int_0^1 \frac{du}{\left(u + \frac{q_{TF}G(q)}{2k_F}\right)^2 \sqrt{1 - u^2}}
\]

(9)

where \(N_{dis}\) is 2D density of threading dislocations, \(f\) is the occupancy of the states in the energy gap introduced by the dislocation and \(u = q/(2k_F)\).

3.5. Alloy disorder scattering

It is known that microscopic compositional fluctuations (disorder) in semiconductor alloys induces fluctuations of potential, so electrons can be scattered by this potential. The alloy disorder scattering rate can be calculated as [23]:
\[
\tau_{AB}^{-1} = \frac{m' \Omega(x) \delta V^2 x(1-x)}{\hbar^3} \int_{-\infty}^{z_0} \psi^4(z) dz,
\]  
(10)

where \(\Omega(x) = \frac{\sqrt{3}}{2} c_0(x) a_0^3(x)\) is the volume of the unit cell of the AlGaN or InAlN layer, \(\delta V\) is the alloy scattering potential, \(\psi(z)\) is the modified Fang-Howard wave function \([24]\). Here, the upper limit of integration \(z_0\) corresponds to the interface between the ternary alloy barrier (AlGaN or InAlN) and binary material (GaN or AlN).

3.6. Interface roughness

The quality of the interface between semiconductor layers has a strong impact on the properties of the heterostructures, especially for the ones with quantum-size layers, where interface roughness can lead to a large fluctuation in the electron energies. The interface roughness scattering rate is given by \([24]\):

\[
\tau_{IFR}^{-1} = \frac{\Delta^2 L^2 e^4 m^*}{2(\varepsilon_s \varepsilon_0)^2 \hbar^3} \left( \frac{1}{2 n_{2DEG}} \right)^2 \int_0^1 \frac{u^4 \exp(-k_F^2 Lu^2)}{u + G(q \frac{q_F}{2k_F} \sqrt{1 - u^2})} du,
\]

(11)

where \(\Delta\) is the root-mean-square roughness, and \(L\) is the correlation length. The detailed analysis of the influence of these parameters can be found in \([12]\).

4. Results and discussion

The GaN-based HEMT heterostructures with different composition of Al\(_x\)Ga\(_{1-x}\)N and In\(_x\)Al\(_{1-x}\)N barrier layer with 1 nm AlN interlayer were first simulated by solving Poisson and Schrödinger equations self-consistently. Piezoelectric and spontaneous polarization induced charges were taken into account. The following figures 1 and 2 show the calculated 2DEG density as a function of the barrier thickness. As one can see, the calculation gives rather good agreement with the experimental data. Additionally, the heterostructures with 0.25 nm (~ 1 monolayer) AlN interlayer and without it were simulated. It was found that electron wave function penetrated deeply into the barrier in the absence of AlN interlayer (figure 3a). This penetration would result in significant alloy disorder scattering. But even 0.25 nm of AlN considerably reduced the probability \(I^2\) of finding electron in the ternary alloy barrier region (figure 3b), and it vanished in the case of 1 nm AlN interlayer (figure 3c), so we could exclude alloy disorder scattering from calculation when analyzing the heterostructure with AlN interlayer.

---

**Figure 1.** Calculated 2DEG density in AlGaN/AlN/GaN structure as a function of barrier thickness. Scatters are experimental data.

**Figure 2.** Calculated 2DEG density in InAlN/AlN/GaN structure as a function of barrier thickness. Scatters are experimental data.

**Figure 3.** Penetration of the 2DEG into the barrier. Solid line is conduction band energy; dashed line is the square of the wave function.
Next, we calculated the scattering rates and mobility of two our typical HEMT structures: 
Al$_{0.23}$Ga$_{0.77}$N/AlN/GaN with 25 nm barrier and $n_{2DEG}=1.1\times10^{13} \text{ cm}^{-2}$ and In$_{0.12}$Al$_{0.88}$N/AlN/GaN with 5 nm barrier and $n_{2DEG}=2.67\times10^{13} \text{ cm}^{-2}$. Additionally, in order to analyze the impact of alloy scattering the mobility in two structures without AlN interlayer were also calculated (barrier layers were adjusted to 35 nm Al$_{0.30}$Ga$_{0.70}$N and 10 nm In$_{0.12}$Al$_{0.88}$N according to our simulations to keep $n_{2DEG}$ unchanged). The values of the threading dislocation density $N_{\text{disl}}=5\times10^{8} \text{ cm}^{-2}$ with filling factor $f=0.5$, background donor density $N_{DB}=1\times10^{16} \text{ cm}^{-3}$ and correlation length $L=3 \text{ nm}$ were used in these and subsequent calculations. The calculated component mobilities as a function of temperature are shown in figure 4. The best fitting was achieved with RMS roughness $\Delta$ of 0.41 nm and 0.8 nm for AlGaN and InAlN structures, respectively. As one can see, at room temperature the mobility is mainly limited by optical phonon scattering (LO); interface roughness scattering (IFR) and acoustic phonon scattering (PE and DP) also make a significant contribution to mobility. At low temperatures the main limiting mechanisms are IFR, DP and PE scattering. In the case of InAlN barrier surface donor scattering also has an impact on the mobility, as the surface is much closer to the 2DEG channel than in the case of AlGaN barrier. In the absence of AlN interlayer, alloy disorder scattering leads to ~30% and ~20% low temperature mobility reduction for AlGaN and InAlN structures, respectively. The room temperature mobility is reduced by ~10% for both structures.

![Figure 4](image)

**Figure 4.** Calculated 2DEG mobility and component mobilities of individual scattering processes as a function of temperature for the structures with AlGaN (a) and InAlN (b) barrier. Scatters are experimental data. The insets show the total mobilities of the structures with and without AlN interlayer in linear scale.

Since the threading dislocation and interface roughness scattering mechanisms are both temperature-independent, it is very difficult to distinguish the impact of each mechanism. In order to estimate the influence of the dislocation density on the total mobility we calculated the mobility taking into account optical phonon, deformation potential, piezoelectric and threading dislocation scattering with various densities of dislocations. In figure 5, the values of the total mobility for the typical threading dislocation densities ($10^2$-$10^5 \text{ cm}^{-2}$) are shown in solid lines, while the dashed lines represent highly-dislocated GaN cases. The low-temperature mobility changes insignificantly for the typical dislocation densities. It is reduced by ~12-16% in the case of AlGaN barrier and ~3-8% in the case of InAlN barrier when dislocation densities increases from $10^3 \text{ cm}^{-2}$ to $10^6 \text{ cm}^{-2}$. The influence on the room-temperature mobility is negligible for both InAlN and AlGaN structures. Further reduction of dislocation density to below $10^5 \text{ cm}^{-2}$ does not lead to an increase in total mobility. When other scattering mechanisms are additionally taken into account, the influence of the dislocation scattering becomes weaker. Similarly, it was found that ionized background donor scattering had a negligible
impact on the total mobility in a very wide concentration range of $10^{14}$ to $10^{17}$ cm$^{-3}$. Therefore, the uncertainty of the exact values of the threading dislocation density and background donor concentration does not lead to a significant error in the estimations of contribution of individual scattering mechanisms.

![Figure 5](image)

**Figure 5.** The influence of the threading dislocation density on the total mobility at 77 K (a) and RT (b).

As shown in [12], there are infinite sets of RMS roughness $\Delta$ and correlation length $L$ which give the same value of interface roughness scattering limited mobility through the equation (11), therefore we cannot precisely extract both of them. But if we fix $L$ (the value of 3 nm was chosen), we can roughly evaluate the RMS roughness from the comparison between the experimental data and calculated values of the total mobility for different $\Delta$ and estimate the “quality” of the interface. Figure 6 shows the distribution of the obtained RMS roughness. It is clear that the values for InAlN barrier are shifted to higher numbers, indicating the poorer quality of InAlN/GaN interface. A little discrepancy between room- and low-temperature distributions may be explained by the tendency underestimate the RT mobility and/or smaller set of experimental data of low-temperature mobility compared to RT mobility set. However, despite the using the same value of $L$ used in all calculations, the obtained values of the RMS interface roughness correlate with the experimental values of the RMS roughness of the surface. All the above-mentioned prompts the conclusion, that the huge difference between the mobilities of our structures with AlGaN and InAlN barriers resulted from the insufficient quality of the InAlN/GaN interface compared to the AlGaN/GaN one. It appears that despite the fact that growth conditions of GaN channel and AlN interlayer can generally be the same for both structures, the consequent lowering the temperature, required for the InAlN barrier layer growth, has the strong impact even on the previously grown layers and their quality.

![Figure 6](image)

**Figure 6.** The RMS interface roughness, estimated from comparison between calculated and experimental mobilities at room temperature (a) and 77K (b). Scatters are the RMS roughness of the surface, measured by AFM (each scatter refers to one sample, not the distribution). The lines are guided for eyes.
5. Conclusion
The calculational analysis of the different scattering mechanisms of 2DEG in AlGaN/(AlN)/GaN and InAlN/(AlN)/GaN HEMT heterostructures was carried out. It was confirmed that the main inherent mechanisms limiting the mobility at room temperature were optical and acoustic phonon scattering. The interface roughness scattering also influences the RT mobility and is the main limiting mechanism at lower temperatures. Additionally, the alloy disorder scattering has a strong impact on the mobility, and it may be vanished by the insertion of the thin AlN interlayer between the GaN channel and the barrier layer. The detailed analysis of the different scattering mechanisms and comparison with the large set of experimental data showed that the main reason of the relatively low mobility of our HEMTs with InAlN barrier layer was insufficient quality of the AlN/GaN interface, caused by lower growth temperature required during InAlN growth. The mobility at lower temperature is limited by the interface roughness scattering for both AlGaN and InAlN structures. Therefore, the first priority to increase the mobility and improve the performance of the devices (especially the InAlN-based ones) is to find better growth conditions to obtain smoother 2DEG channel interface.

Acknowledgements
This work was supported by the Russian Foundation for Basic Research (grant 18-02-00848).

References
[1] Mishra U K, Parikh P and Wu Y-F 2002 AlGaN/GaN HEMTs-an overview of device operation and applications Proceedings of the IEEE 90 1022–31
[2] Chen J-T, Persson I, Nilsson D, Hsu C-W, Palisaitis J, Forsberg U, Persson P O Å and Janzén E 2015 Room-temperature mobility above 2200 cm²/V·s of two-dimensional electron gas in a sharp-interface AlGaN/GaN heterostructure Appl. Phys. Lett. 106 251601
[3] Chung J, Hoke W, Chumbe E and Palacios T 2010 AlGaN/GaN HEMT With 300-GHz fmax IEEE Electron Device Lett. 31 195–7
[4] Yue Y et al. 2012 InAlN/AlN/GaN HEMTs with regrown ohmic contacts and fr of 370 GHz IEEE Electron Device Lett. 33 988–90
[5] Sarazin N, Morvan E, Poisson M D F, Oualli M, Gaquiere C, Jardel O, Drisse O, Tordjman M, Magis M and Delage S 2010 AlInN/AlN/GaN HEMT Technology on SiC with 10-W/mm and 50% PAE at 10 GHz IEEE Electron Device Lett. 31 11–3
[6] Shalygin V A, Vorobjev L E, Firsov D A, Sofronov A N, Melentyev G A, Lundin W V, Nikolaev A E, Sakharov A V and Tsatsulnikov A F 2011 Blackbody-like emission of terahertz radiation from AlGaN/GaN heterostructure under electron heating in lateral electric field J. Appl. Phys. 109 073108
[7] Tsatsulnikov A F et al. 2016 Effect of the parameters of AlN/GaN/AlGaN and AlN/GaN/InAlN heterostructures with a two-dimensional electron gas on their electrical properties and the characteristics of transistors on their basis Semiconductors 50 1383–9
[8] Ridley B K 1982 The electron-phonon interaction in quasi-two-dimensional semiconductor quantum-well structures J. Phys. C: Solid State Phys. 15 5899–917
[9] Polyakov V M and Schwierz F 2007 Monte Carlo calculation of two-dimensional electron gas mobility in InN-based heterostructures J. Appl. Phys. 101 033703
[10] Gold A 1989 Mobility of the two-dimensional electron gas in AlGaAs/GaAs heterostructures at low electron densities Appl. Phys. Lett. 54 2100–2
[11] Quang D N, Tuan L and Tien N T 2008 Electron mobility in Gaussian heavily doped ZnO surface quantum wells Phys. Rev. B 77 125326
[12] Jin-Feng Z, Wei M, Jin-Cheng Z and Yue H 2008 The low-temperature mobility of two-dimensional electron gas in AlGaN/GaN heterostructures Chin. Phys. B 17 2689–95
[13] Fang F F and Howard W E 1966 Negative field-effect mobility on (100) Si surfaces Phys. Rev. Lett. 16 797–9
[14] Davies J H 1998 Two-dimensional electron gas The Physics of Low-Dimensional Semiconductors (New York: Cambridge University Press) pp 356-65

[15] Vurgaftman I and Meyer J R 2007 Electron bandstructure parameters Nitride Semiconductor Devices: Principles and Simulation ed J Piprek (Berlin: Wiley-vch) p 24

[16] Quay R 2008 Gallium Nitride Electronics (Springer Series in Materials Science vol 96) ed R Hull et al (Berlin: Springer Science & Business Media) pp 21 and 30-3

[17] Zanato D, Gokden S, Balkan N, Ridley B K and Schaff W J 2004 The effect of interface-roughness and dislocation scattering on low temperature mobility of 2D electron gas inGaN/AlGaN Semicond. Sci. Technol. 19 427–32

[18] Gelmont B L, Shur M and Stroscio M 1995 Polar optical-phonon scattering in three- and two-dimensional electron gases J. Appl. Phys. 77 657–60

[19] Grundmann M 2010 The Physics of Semiconductors (Berlin: Springer) p 262

[20] Koley G and Spencer M G 2005 On the origin of the two-dimensional electron gas at the AlGaN/GaN heterostructure interface Appl. Phys. Lett. 86 042107

[21] Bakeroort B, You S, Wu T-L, Hu J, Hove M V, Jaeger B D, Geens K, Stoffels S and Decoutere S 2014 On the origin of the two-dimensional electron gas at AlGaN/GaN heterojunctions and its influence on recessed-gate metal-insulator-semiconductor high-electron mobility transistors J. Appl. Phys. 116 134506

[22] Jena D, Gossard A C and Mishra U K 2000 Dislocation scattering in a two-dimensional electron gas Appl. Phys. Lett. 76 1707–9

[23] Bastard G 1983 Energy levels and alloy scattering in InP-In (Ga)As heterojunctions Appl. Phys. Lett. 43 591–3

[24] Jena D 2008 Polarization effects on low-field transport & mobility in III-V nitride HEMTs Polarization Effects in Semiconductors: From Ab Initio Theory to Device Applications ed C Wood and D Jena (New-York: Springer Science & Business Media) pp 175-9