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Carrier mobility model for GaN

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Abstract

Simple analytical approximation has been obtained to describe the temperature and concentration dependencies of the low-field mobility in gallium nitride (GaN) in wide temperature ($50 \leqslant T \leqslant 1000$ K) and concentration ($10^{14} \leqslant N \leqslant 10^{19}$ cm^{-3}) ranges. The dependence of the temperature T_m at which the mobility μ is at a maximum on the doping level is also obtained. Results obtained can be directly used for computer simulation of GaN-based devices.

Keywords: Gallium nitride; Low-field mobility

1. Introduction

Gallium nitride (GaN) is one of the most promising materials for high-temperature, high frequency, and radiation hard applications. This material is in forefront of the semiconductor research. GaN-based ultraviolet visible–blind photodetectors, blue and violet light emitting diodes, lasers, rectifier diodes, bipolar transistors, field-effect transistors of different types, piezoelectric sensors have been successfully demonstrated. Further progress in the development, design and optimization of GaN-based devices necessarily requires a detailed computer simulation of GaN structures. It is well known that the effectiveness of a simulation is directly defined by the adequacy of approximations to the material parameters. For silicon, such approximations are well known (see, e.g., [1]). For GaN, however, there is the opposite situation, in particular, for such an important parameter of the material as carrier mobility. Experimental data on the dependence of mobility on temperature and doping level have been reported in many papers (see, [2–11]). However, to the best of our knowledge, no attempts have been made until now to propose adequate analytical approximations for these dependencies.

The aim of this paper is to provide analytical model for low-field carrier (electron and hole) mobility in wurtzite GaN in wide temperature and concentration ranges.

2. Results and discussion

A technique proposed in Ref. [12] and recently employed successfully for silicon carbide (SiC) [13] was used to analyze the low-field mobility in GaN. The first step of this technique consists in an adequate approximation of the doping level dependence of the mobility at room temperature on the base of the well known Caughey–Thomas approximation [14]:

$$\mu_i(N) = \mu_{\min,i} + \frac{\mu_{\max,i} - \mu_{\min,i}}{1 + \left(\frac{N}{N_{g,i}}\right)^{\gamma_i}} \tag{1}$$

where $i = \mathrm{n}, \mathrm{p}$ for electrons and holes respectively, model parameters $\mu_{\max,i}$, $\mu_{\min,i}$, N_g, i, and γ_i depend on

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the type of semiconductor material, and N is the doping concentration.

Analyzing the set of the experimental data reported in Refs. [2–11] we were able to find the values of parameters $\mu_{\max,i}$, $\mu_{\min,i}$, N_g, i, and γ_i providing the best approximation of the data reported for electron and hole mobility in wurtzite GaN. The values founded are listed in Table 1.

In Fig. 1 the dependence of the low-field electron mobility on doping level calculated according to Eq. (1) is compared with available experimental data on the room-temperature electron mobility in GaN. In Fig. 2, the analogous comparison has been made for hole low-field mobility. One can see that proposed approximations provide rather good agreement with available experimental data for wurtzite GaN either for hole or for electron mobility in very wide doping interval.

Table 1
The values of the parameters $\mu_{\max,i}$, $\mu_{\min,i}$, N_g, i, and γ_i providing the best fitting of the experimental results by Eq. (1)

Type of carriers	$\mu_{\max,i}$ ($cm^2 V^{-1} s^{-1}$)	$\mu_{\min,i}$ ($cm^2 V^{-1} s^{-1}$)	$N_{g,i}$ (cm^{-3})	γ_i
Electrons	1000	55	2×10^{17}	1.0
Holes	170	3	3×10^{17}	2.0

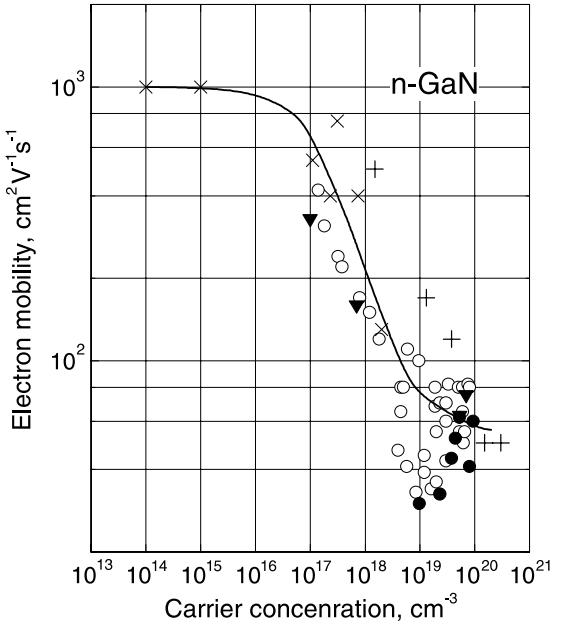

Fig. 1. Low-field electron mobility as a function of doping concentration in GaN at room temperature. Curve represents the best approximation according to Eq. (1) and data presented in Table 1. Experimental data are taken from different references: (×, ○, ▼, ●) data for wurtzite GaN from Refs. [2–5]; (+) data for zink blende GaN from Ref. [10].

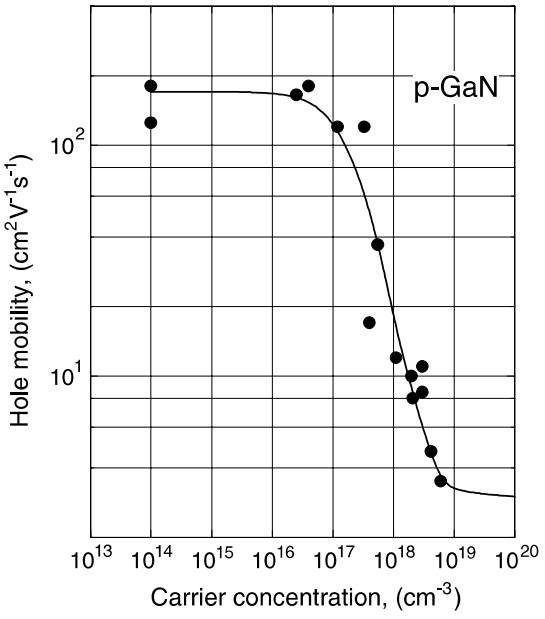

Fig. 2. Low-field hole mobility as a function of doping concentration in wurtzite GaN at room temperature. Curve represents the best approximation according to Eq. (1) and data presented in Table 1. Experimental data are taken from Ref. [9].

Note that appreciable scatter of the experimental data has been observed especially at high doping level. This scattering is mainly caused by different degree compensation, which is not controlled in the majority of experimental studies. It is worth noting that just the same scatter of the experimental data on low-field mobility has been observed in GaAs, InP [15] and virtually all semiconductor materials with the exception of Si and Ge. Careful control of the degree of compensation and step-by-step decrease in GaN compensation will make it possible to reduce the scatter of the experimental data and refine the values of the parameters listed in Table 1.

It is also worth noting that the most part of available experimental data corresponds to wurtzite GaN and only a minor part of data refers to zink blende GaN. As seen in Fig. 1 (where data for zink blende GaN have been marked by crosses), the model proposed can be applied to estimate the electron mobility in zink blende GaN as well with reasonable accuracy.

The second step in development of the model under consideration consists in approximation of the temperature dependencies of the low-field mobility. At low doping level and room temperature phonon scattering is the main mechanism of scattering. In this case it directly follows from Eq. (1) that:

$$\mu_{\max,i} = \mu_{L,i} \tag{2}$$

where $\mu_{L,I}$ is the lattice (phonon) mobility component. Taking the temperature dependence of the phonon mobility to be $\mu_L = \mu_L(T_0)(T/T_0)^{-\alpha}$, we have from Eq. (2):

$$\mu_{\max,i} = \mu_{\max,i}(T_0)(T/T_0)^{-\alpha_i} \tag{3}$$

where $T_0 = 300$ K.

The contribution from impurity scattering can be obtained subtracting the phonon contribution from the total mobility described by Eq. (1):

$$\mu_{I,i} = \mu_{\max,i}\left[\frac{\mu_{\max,i}}{\mu_{\max,i}-\mu_{\min,i}}\frac{1+\left(\frac{N}{N_g,i}\right)^{\gamma_i}}{\left(\frac{N}{N_g,i}\right)^{\gamma_i}} - 1\right] \tag{4}$$

Then, combining Eqs. (2) and (4) we have:

$$\frac{\mu_{\max,i}-\mu_{\min,i}}{1+\left(\frac{N}{N_g,i}\right)^{\gamma_i}}\left(\frac{N}{N_g,i}\right)^{\gamma_i} = \frac{\mu_{L,i}}{1+\frac{\mu_{I,i}}{\mu_{L,i}}} \tag{5}$$

Substituting (5) in (1) and taking into account that $\mu_L = \mu_L(T_0)(T/T_0)^{-\alpha}$ and $\mu_I = \mu_I(T_0)(T/T_0)^{\beta}$ [16], relation (1) can be written in the following form:

$$\mu_i(N,T) = \mu_{\max,i}(T_0)\frac{B_i(N)\left(\frac{T}{T_0}\right)^{\beta_i}}{1+B_i(N)\left(\frac{T}{T_0}\right)^{\alpha_i+\beta_i}} \tag{6}$$

where

$$B_i(N) = \left[\frac{\mu_{\min,i}+\mu_{\max,i}\left(\frac{N_g,i}{N}\right)^{\gamma_i}}{\mu_{\max,i}-\mu_{\min,i}}\right]\Bigg|_{T=T_0} \tag{7}$$

It can be seen that expressions (6) and (7) describe correctly the temperature dependence of mobility in the limiting cases of low and very high doping. At specified doping level, Eq. (6) describes the non-monotonic temperature dependence of the mobility. The α_i and β_i values providing the best approximation to the experimental data for wurtzite GaN are given in Table 2. Because of the lack of adequate experimental data on the hole mobility, the value β_p cannot be indicated in this table. The α_i and β_i values indicated in Table 2 differ from the theoretical values obtained in terms of the simple semiconductor band structure (see, e.g., [16]). It worth noting that just the same situation is characteristic of many other semiconductor materials: Ge ($\alpha_n = 1.66$, $\alpha_p = 2.33$), Si ($\alpha_n = 2.42$, $\alpha_p = 2.2$), GaAs ($\alpha_n = 1.0$, $\alpha_p = 2.1$).

Table 2
The values of the parameters α_i and β_i providing the best fitting of experimental data by Eqs. (6) and (8)

Type of carriers	α_i	β_i
Electrons	2.0	0.7
Holes	5.0	–

Figs. 3 and 4 present the temperature dependencies of mobility in wurtzite GaN for electrons (Fig. 3) and holes (Fig. 4) calculated using Eqs. (6) and (7) with the parameter values listed in Tables 1 and 2. The calculated curves are compared with available experimental data.

As seen in Fig. 3, at low temperatures, with the main contribution to electron scattering coming from ionized impurities, the mobility grows with increasing temperature. By contrast, at high-temperatures, where the scattering is effected by phonons, the mobility decreases with increasing temperature. The dependence of the temperature T_m at which the mobility μ is at a maximum ($d\mu/dT = 0$) on the doping level can be obtained from Eqs. (6) and (7):

$$T_{im} = T_0\left[\frac{\beta_i}{\alpha_i}\frac{1}{B_i(N)}\right]^{\frac{1}{(\alpha_i+\beta_i)}} \tag{8}$$

It is easily seen that established Eqs. (6)–(8) provide rather well agreement with experimental data. Note that at $T = T_0$, Eq. (6) transforms immediately into Eq. (1).

As for temperature dependence of the hole mobility (Fig. 4) the predictions of the model can be compared

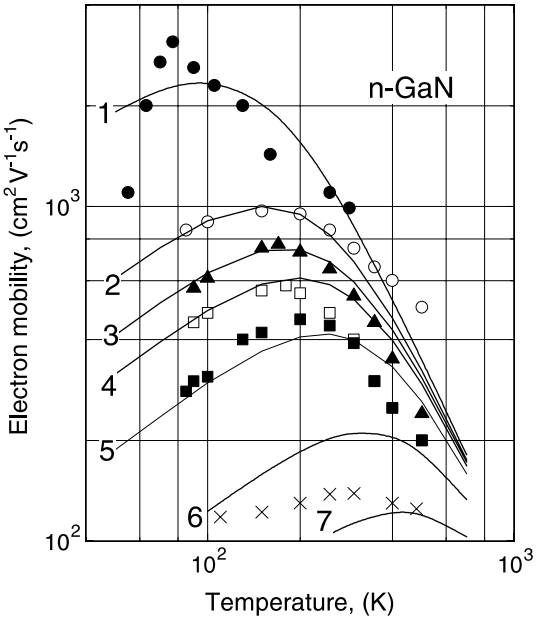

Fig. 3. Temperature dependencies of low-field electron mobility in wurtzite GaN at different values of doping concentration. Curves represent the best approximation according to Eqs. (6) and (7) and parameter values listed in Tables 1 and 2: 1—$N = 3 \times 10^{16}$ cm^{-3}, 2—$N = 10^{17}$ cm^{-3}, 3—$N = 1.5 \times 10^{17}$ cm^{-3}, 4—$N = 2 \times 10^{17}$ cm^{-3}, 5—$N = 3.5 \times 10^{17}$ cm^{-3}, 6—$N = 10^{18}$ cm^{-3}, 7—$N = 3 \times 10^{18}$ cm^{-3}. Experimental data are taken from Ref. [5].

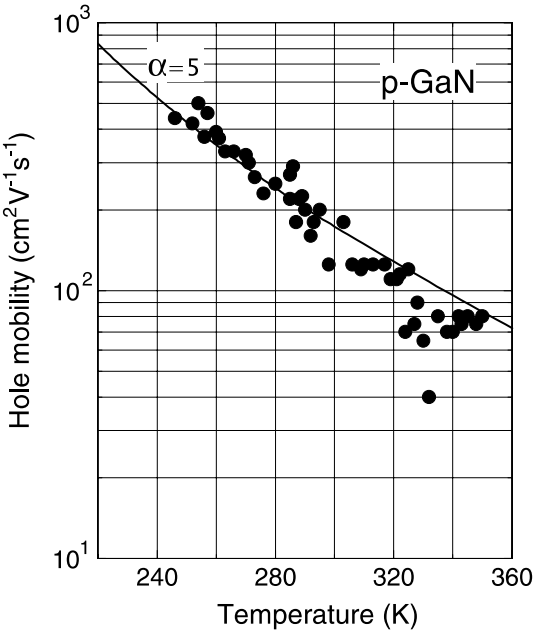

Fig. 4. Temperature dependencies of low-field hole mobility in wurtzite GaN. Curve represents the best approximation according to Eqs. (6) and (7) and data listed in Tables 1 and 2. Experimental data are taken from Ref. [8].

with experimental data only in a limited temperature range due to the lack of data for holes in GaN. The above account indicates a need for additional experimental investigation of the hole mobility in GaN.

It is worth noting that the use of Eqs. (6) and (7) implies that the given mobility μ at $T = 300$ K is single-valued function of doping level N. Meanwhile, as seen from Figs. 1 and 2, the experimental values of μ at given N at room temperature exhibit appreciable scatter. (As mentioned above this scattering is mainly caused by not controlled degree compensation.) To overcome this difficulty, for every experimental value of mobility μ (300 K), N_0 was calculated using Eq. (1). Next, for the N_0 value obtained, the temperature dependence $\mu(N_0, T)$ was calculated.

3. Conclusion

A simple semi-empirical analytical model has been proposed to describe experimental data on low-field mobility in wurtzite GaN in wide temperature range and doping level diapason. Analytical expressions obtained describe well experimental data in the temperature range from approximately 50 to 1000 K at widely varying doping level 10^{14} cm$^{-3} \leqslant N \leqslant 10^{19}$ cm^{-3}. These expressions can be used to simulate the characteristics of GaN devices with the layers of different doping level in very wide temperature range.

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