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Low-Field Electron Mobility Models for Bulk GaN and AlGaN/GaN 2DEGs

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1. Introduction

Recently FETs based on wurtzite GaN attracted considerable attention. AlGaN HEMTs showing record output power densities in excess of 30W/mm and frequency limits f_T and f_{max} (cutoff frequency and maximum frequency of oscillation) above 100GHz, as well as GaN MESFETs showing the capability of GHz operation have been reported (see, e.g. [1-3]). Given the importance of GaN-based transistors, GaN mobility models are urgently needed for transistor simulation and simulation-based transistor optimization. Although experimental mobility data is available in the technical literature, there is a serious lack of reliable mobility models suited for device simulation. For the simulation of GaN MESFETs a mobility model for bulk GaN is necessary, while for AlGaN HEMTs a mobility model for the two-dimensional electron gas (2DEG) channel is needed.

The aim of the present work is to fill the gap mentioned above and to provide reliable electron mobility models for bulk GaN and for AlGaN/GaN 2DEGs. Experimental mobility data collected from the literature serve as the basis for our model development [4].

2. Electron Mobility Model for Bulk GaN

So far, two bulk GaN electron mobility models for use in device simulators have been reported [5-6]. In this section, a new mobility model will be presented that in general shows similar trends as the models from [5-6] but fits recently published experimental mobilities more correctly.

The low-field electron mobility for bulk materials depends on the electron density n and can be modeled using the Caughey-Thomas expression

$$\mu_0 = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(n / n_{ref}\right)} \qquad (1)$$

where μ_{min}, μ_{max}, n_{ref}, and α are fitting parameters. Figure 1 shows the experimental low-field mobilities used for the model development as a function of electron concentration. Different symbols are used for the data published by the end of 1996 and for those reported since early 1997 to demonstrate the progress obtained in the quality of epitaxially grown GaN during the last few years.

Two sets of fitting parameters have been elaborated. The first set together with eq. (1) results in what we call the representative fit. It models the typical mobilities expected from GaN samples, while the second set fits the best mobilities reported so far. The parameters determined for the representative fit are

$$\mu_{min} = 80\text{cm}^2/\text{Vs} \qquad \mu_{max} = 1405\text{cm}^2/\text{Vs}$$
$$n_{ref} = 7.78\times10^{16}\text{cm}^{-3} \qquad \alpha = 0.71$$

and the parameters for the upper limit fit are

$$\mu_{min} = 100\text{cm}^2/\text{Vs} \qquad \mu_{max} = 1410\text{cm}^2/\text{Vs}$$
$$n_{ref} = 1.66\times10^{17}\text{cm}^{-3} \qquad \alpha = 0.691.$$

The resulting dependences $\mu_0 = f(n)$ are shown in Fig. 1. Also included are the fits obtained using the mobility models from [5-6].

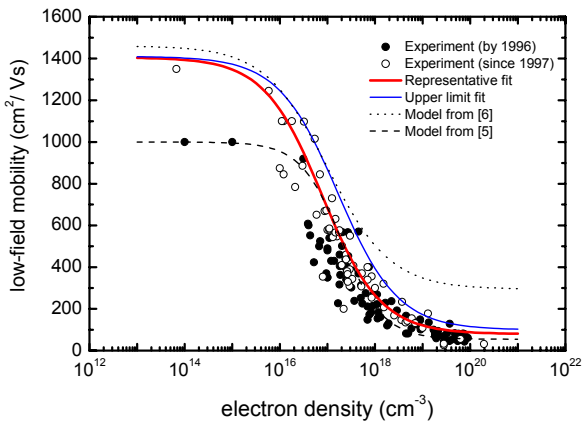

Fig. 1 Experimental electron low-field mobility in bulk GaN vs. electron concentration together with the mobilities.

3. 2DEG Electron Mobility Model for AlGaN/GaN

2DEG low-field mobilities, $\mu_{0\text{-}2DEG}$, can not be modeled with an expression like eq. (1). The mobility in 2DEGs depends on the vertical electric field (perpendicular to the direction of carrier transport) in the 2DEG. This is true for 2DEGs in MOS inversion channels as well as for 2DEGs at AlGaN/GaN interfaces. For AlGaN/GaN heterostructures, commonly experimental $\mu_{0\text{-}2DEG}$ data is reported not for the vertical field in the 2DEG but rather for the existing 2DEG sheet density n_S. However, the vertical field can easily be related to the sheet density (and vice versa). Therefore, we decided to elaborate a fit of the form $\mu_{0\text{-}2DEG} = f(n_S)$.

Figure 2 shows the collected experimental $\mu_{0\text{-}2DEG}$ data as a function of n_S. The data scatters considerably and a distinct trend cannot be observed. To get a more clear impression we first convert $\mu_{0\text{-}2DEG}$ to the 2DEG sheet resistance R_{sh} by the relation $R_{sh} = 1/(q\times\mu_{0\text{-}2DEG}\times n_S)$. The result is shown in Fig. 3. At low sheet densities the sheet resistance decreases rapidly for increasing n_S, while at higher

sheet densities the decrease of R_{sh} becomes weaker. All R_{sh}-n_S pairs are within the shaded area and the two bent curves are the empirical lower and upper limits of R_{sh}. Next, from the upper R_{sh} limit a lower $\mu_{0\text{-}2DEG}$ limit and from the lower R_{sh} limit an upper $\mu_{0\text{-}2DEG}$ limit is calculated. These lower and upper $\mu_{0\text{-}2DEG}$ limit curves are then plotted together with the experimental $\mu_{0\text{-}2DEG}$-n_S pairs in one diagram as shown in Fig. 4. Now, with the help of the lower and upper mobility limits, a clear trend of the $\mu_{0\text{-}2DEG}$-n_S dependence becomes obvious. For low sheet densities, the mobility increases with increasing n_S, then reaches a maximum (below an n_S of 10^{13}cm^{-2}), and finally decreases continuously towards higher n_S.

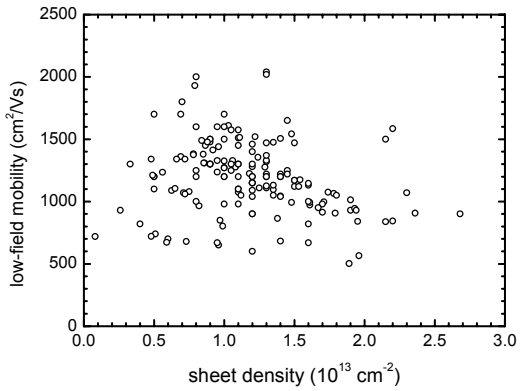

Fig. 2 Experimental 2DEG mobility as a function of 2DEG sheet density.

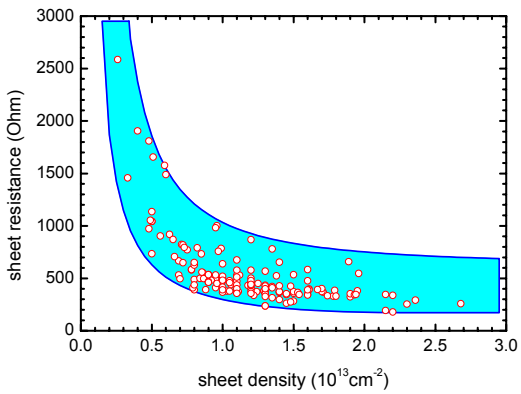

Fig. 3 2DEG sheet resistance R_{sh} as a function of sheet density. The symbols are related to experimental mobility data and the full lines show the lower and upper R_{sh} limits.

For the fitting we assume that the overall 2DEG mobility contains the two components μ_1 and μ_2. The former component combines all scattering mechanisms whose effectivity decreases with increasing n_S, such as impurity and phonon scattering, and is expressed as $a \times n_S^b$. The component μ_2 describes the effect of interface scattering which increases with increasing n_S and is expressed as $c \times n_S^d$. Applying the Matthiessen rule, from the mobility components μ_1 and μ_2 the overall 2DEG mobility is obtained. The parameters a, b, c, and d are determined by fitting using the final expression

$$\mu_{0-2DEG} = \left(\frac{1}{a\, n_S^b} + \frac{1}{c\, n_S^d} \right)^{-1} \qquad (2)$$

In eq. (2), the 2DEG sheet density is in units of 10^{13}cm^{-2}, the parameters a, b, c, and d are dimensionless, and the 2DEG mobility is in cm^2/Vs. Again, two sets of fitting parameters have been elaborated. The first set (a = 1663, b = 0.2608, c = 7433, and d = -1.903) is the representative mobility fit shown in Fig. 4 and describes the typical mobility expected in AlGaN/GaN 2DEGs. The second set (using a = 2013, b = 0.2375, c = 12950, and d = -1.997) predicts the 2DEG mobility in high-quality AlGaN/GaN structures.

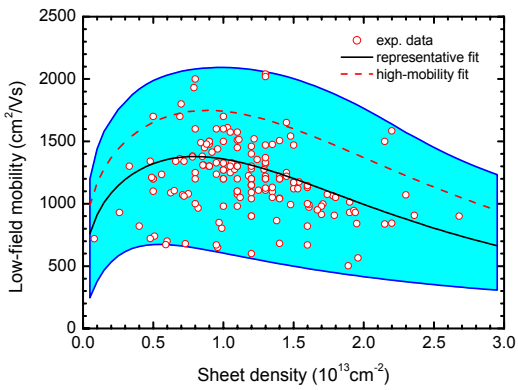

Fig. 4 Experimental 2DEG mobility and the two mobility fits as a function of 2DEG sheet density.

4. Conclusions

Low-field electron mobility models for bulk GaN and AlGaN/GaN 2DEGs have been presented. The models describe the trends of measured bulk and 2DEG mobilities very good. The model equations are simple and can easily be incorporated in device simulators. The next steps are to include the temperature dependence of the mobility in the model and to develop models for the high-field mobility in bulk GaN and AlGaN/GaN 2DEGs. First results have been obtained recently [7].

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