Quantum corrections to the electrical conduction in an AlGaN/GaN heterostructure

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Received: 27 November 2000/Accepted: 18 December 2000/Published online: 3 April 2001 – © Springer-Verlag 2001

Abstract. A new method for magneto-transport characterisation of semiconductor heterostructures is presented. The classical model of mixed conduction, modified by corrections resulting from quantum effects, has been used in the analysis of the conductivity-tensor components, magnetoresistance, and Hall coefficient in n-type Alₐ₀.₃₅Gaₐ₀.₆₅N/GaN in magnetic fields up to 12 T, in the temperature range from 2 to 295 K. The mixed conduction is due to high-mobility carriers in the conduction band in the interface and to low-mobility carriers in the conduction band in the GaN layer and in an impurity band. The corrections to the conduction of high-mobility carriers result from quantum effects: negative magnetoresistance, extraordinary Hall effect, and freeze-out of electrons. Negative magnetoresistance is due to localisation of electrons and to increasing tunnel coupling between electron states in different minima of a random potential, due to interface roughness. The extraordinary Hall effect has been explained by interaction of electrons with magnetic moments of dislocations in the interface. Decreasing concentration of electrons is probably due to Landau quantisation of the conduction band in the interface of the heterostructure.

PACS: 72; 72.20; 72.60; 73.40

The analysis of the electrical conduction in a magnetic field (the conductivity and the Hall coefficient) provides substantial information on the transport phenomena in heterostructures and is used for characterisation of optoelectronic and microelectronic devices [1]. For some purposes, the electrical conduction in heterostructures can be analysed by using a simple single-carrier approximation [2]. However, more information can be obtained by using multicarrier analysis of the electrical conduction. The contributions of all bands and layers to the electrical conduction can be separated if the mobilities of all groups of carriers are noticeably different. The multicarrier analysis can be carried out either by using the mobility-spectrum technique [3–6] or by the standard fitting procedure [7]. The concentrations and mobilities versus temperature, estimated from multicarrier analysis, have been analysed in AlGaN/GaN [5] and InAs/GaAs [6, 8] heterostructures.

The problem is more difficult if quantum effects modify the electrical conduction. In that case, in the analysis we must first specify a model different from the classical one and consider quantum correction in the analysis of the transport properties. The negative magnetoresistance, observed in an InGaAs/InP heterostructure, has been described by introducing a magnetic-field dependence of the mobility, originating from quantum effects [6]. Anomalous behaviour of the Hall coefficient in an InAs/GaAs heterostructure has been explained as the extraordinary Hall effect [8]. Those examples show that quantum corrections in classical multicarrier expressions are necessary to describe precisely the electrical conduction in some heterostructures.

The negative magnetoresistance has been observed in AlGaN/GaN heterostructures [2, 9–11] and in many semiconductors and semiconductor structures [6, 8, 12, 13]. Negative magnetoresistance has been usually explained as due to localisation [2]. However, other possibilities have also been considered in the analysis of the negative magnetoresistance [6, 12–15]. Anomalous behaviour of the Hall coefficient may be noticed in the magnetic-field dependence of the Hall coefficient in a low magnetic field in GaAs/AlGaAs [16] and has been recently reported in p-Ge/GeSi [17] heterostructures. Anomalous behaviour of the Hall coefficient in InAs/GaAs heterostructures has been investigated in our previous work and explained as due to interaction of electrons with misfit dislocations [8]. We have also seen a similar effect in InGaAs/InP heterostructures [18]. It is possible that the anomalous behaviour of the Hall coefficient due to the extraordinary Hall effect can be observed in other heterostructures with a high concentration of misfit dislocations.

In the present paper we investigate the electrical conduction in the Alₐ₀.₃₅Gaₐ₀.₆₅N/GaN heterostructure, similar to heterostructures investigated in our previous paper [5]. In the
sample investigated here we see the negative magnetoresistance and the anomalous magnetic-field dependence of the Hall coefficient, in a wide range of temperatures. The negative magnetoresistance and the anomalous magnetic-field dependence of the Hall coefficient have been explained as due to quantum effects. We present a consistent, semi-quantitative description of the electrical conduction in an AlGaN/GaN heterostructure, taking into account the quantum corrections in the multicharrier conduction. The details of fitting many parameters used in our model describing the field dependence of the conductivity-tensor components, the Hall coefficient, and the magnetoresistance, are described in the appendix.

1 Preparation of the sample and experimental results

An Al$_{0.85}$Ga$_{0.15}$N/GaN structure has been grown on c-plane sapphire, like the previously investigated sample-1 and sample-2 [5]. The sample-3, investigated in the present paper, has been grown by metal–organic chemical-vapour deposition (MOCVD) at the Department of Electrical and Computer Engineering, University of California, Santa Barbara. In this sample a thin, 0.3 µm, GaN layer has been doped by Si to concentration $n = 1 \times 10^{17}$ cm$^{-3}$ and a 300 Å Al$_{0.85}$Ga$_{0.15}$N epilayer has not been doped. The Hall effect and conductivity have been measured in the van der Pauw configuration at temperatures from 2 K up to 300 K, in a magnetic-field range from 0.01 to 12 T. Experimental Hall data at temperature 4.2 K in the form of a coefficient $r_H(B) = (V_H(B) - V_H(0))/IB$ ($V_H$ – voltage in Hall configuration; $I$ – electric current; $B$ – magnetic field) are presented in Fig. 1. The anomalous magnetic-field dependence of the Hall data is seen as the characteristic sharp increase of $r_H$ with increasing magnetic field in fields below 1 T. Magnetoresistance, $\Delta \rho/\rho_0$, relative Hall coefficient, $\Delta R/R_0$, and conductivity-tensor components, $\sigma_{xx}$, $\sigma_{xy}$, are shown at selected temperatures in Figs. 2 and 3. Negative magnetoresistance at low temperatures and a positive one at high temperatures are seen in Fig. 2a. The anomalously increasing Hall coefficient in low magnetic fields is seen in Fig. 2b.

2 Model of the electrical conduction

In the analysis we have considered the mixed conduction of two groups of carriers, $\sigma = \sigma_n + \sigma_{\text{LMC}}$ [5]. The sheet conductivity, $\sigma_n$, describes the electrical conduction of a two-