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High temperature electrical transport study of Si-doped AlN

Sylvie Contreras [a, *], Leszek Konczewicz [a], Jaweb Ben Messaoud [a], Hervé Peyre [a], Mohamed Al Khalfioui [b], Samuel Matta [b], Mathieu Leroux [b], Benjamin Damilano [b], Julien Brault [b]

[a] Laboratoire Charles Coulomb (L2C), UMR 5221 CNRS-Université de Montpellier, CC 074, Montpellier, FR-34095, France
[b] CRHEA-CNRS, Centre de Recherche sur l'Hétéro-Epitaxie et ses Applications, CNRS, Rue B. Grégory, Valbonne, FR-06560, France

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ABSTRACT

Electrical transport (resistivity and Hall Effect) have been studied in silicon doped aluminum nitride (AlN) thick epitaxial layers from 250 K up to 1000 K. The investigated samples, grown by molecular beam epitaxy were characterized by n-type conduction with an ambient temperature free carrier concentration of about ˜ 1×10^{15} cm^{-3}. The donor level, situated about 250 meV below the conduction band edge, was found to be responsible for the experimentally observed increase of free carrier concentration with temperature. The temperature dependence of carrier mobility has been analyzed in the framework of a multimode scattering model. In the investigated samples the main scattering mechanism is supposed to be dislocation scattering.

1. Introduction

Nitride-based materials have emerged as the leading technology for a wide range of optoelectronic applications, (in particular in the visible range, with blue light emitting diodes (LEDs)). A next step, which represents one of the most important challenges for nitride light emitting devices, is to replicate in the ultra-violet (UV) range, the performances obtained in the blue. In order to obtain an emission below 360 nm, it is necessary to use the ternary $Al_xGa_{1-x}N$ compounds, which offer the possibility to cover a wide spectral region in the UV, i.e. from 360 nm (for GaN) down to 210 nm (for AlN) by adjusting the Al concentration. The possibility of both n-type and p-type doping in AlN has allowed demonstrating an AlN pin (p-type/intrinsic/n-type) homojunction LED with an emission wavelength of 210 nm [1]. Moreover AlN is widely used as a buffer layer for UV devices and AlN bulk substrates should play an increasing role for the fabrication of high-quality $Al_xGa_{1-x}N$ materials with low dislocation density ($<5 \times 10^8$ cm^{-2}) and as consequence, of efficient deep-UV LEDs. Despite this technological importance, some properties of AlN are still relatively unknown. In particular, there still are large discrepancies on the effective electron mass value of AlN. From the correlation between the effective masses of direct-gap semiconductors and their band gaps energies, it was estimated to be about $0.48m_o$ [2]. On the other hand, theoretical band structure models predict lower values, i.e. $0.27m_o$ [3] or $0.35m_o$ [4]. To obtain n-type conductivity silicon (Si) is widely used as a dopant. Situated between period III (Al) and period V (N) elements it can act as both donor and acceptor depending on which atom it substitutes. Substitution of Al is more preferential and it is considered that Si creates a donor level below the conduction band, but the problem of self-compensation remains important for high doping levels. The broad scatter of the Si donor activation

* Corresponding author.
E-mail address: Sylvie.Contreras@umontpellier.fr (S. Contreras).

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energy between 60 meV and 570 meV [1,5–19] is awaiting a convincing explanation. Simultaneously the question of the DX (negative U) character of Si donors in AlN is still under discussion [5–9]. The 6.1 eV energy bandgap and the defective nature of the host material make the electrical characterization complicated due to lack of well-conductive material. Only a few papers provide mobility values at room temperature that are generally of the order of few cm^2/Vs [11–16]. Concerning the temperature dependence of the electron mobility in AlN, the experimental data are extremely limited [12–14]. In the present paper the electrical transport (resistivity and Hall Effect) have been studied in AlN thick epitaxial layers doped with Si as a function of temperature in the range 250 K–1000 K. The measured increase of free electron concentration with temperature is related to the ionization of donors and the temperature dependence of carrier mobility has been analyzed in the framework of a multimode scattering model.

2. Experimental methods

The structures under study were grown on 2-inch c-plane sapphire substrates by molecular beam epitaxy (MBE) in a Riber 32 MBE system. Effusion cells were used for Al and Si and ammonia (NH_3) as the nitrogen source. The surface was initially nitridated with ammonia at ~950 °C for 10 min. Then a 30 nm GaN nucleation layer was grown at low temperature [20], followed by the growth of 1 μm-thick Si doped AlN at a temperature of 920 °C and with a growth rate of 0.15 μm/h. Finally, to avoid the oxidation of AlN, a 3 nm GaN cover layer was deposited. The samples were cut into 5×5 mm^2 squares size and electrical contacts have been deposed in van der Pauw configuration in the corners of the sample. The ohmic contacts were obtained by the evaporation of Ti(30 nm)/Al(180 nm)/Ni(40 nm)/Au(150 nm) electrodes and subsequent annealing in N_2 ambient. For high temperature measurements the sample holder was installed inside a furnace in a quartz tube to keep during the high temperature experiments a vacuum lower then 10^{-6} bar. The temperature was measured with a platinum (Pt) resistor and stabilized with a precision better than 1 K. The measurements of resistivity ρ and Hall coefficient R_H were performed using the van der Pauw method, taking the average of all current configurations. For each temperature, in order to improve the signal to noise ratio, the Hall measurements were done as a function of magnetic field and the carrier concentration was determined from the slope of the Hall resistance ρ_{Hall} versus magnetic field B: $\beta = d\rho_{Hall}/dB$. Typical results are presented in Fig. 1, where the Hall Effect in sample B at T = 988 K is shown. During all the measurements, the current through the samples was kept adequately low to ensure ohmic conditions.

3. Experimental results and analysis

The room temperature electrical characteristics of the Si-doped AlN layers under study are presented in Table 1. The electron concentration and mobility were extracted by assuming a Hall factor $r_H = <\tau^2>/<\tau>^2$ of unity (τ is the carrier scattering relaxation time). Fig. 2 shows, for both samples, the resistivity as a function of the inverse of temperature. A typical behaviour of a thermally activated conduction process is observed: as the temperature increases, the sample resistivity decreases exponentially and saturates at the highest temperatures.

Fig. 3 shows the Hall concentration as a function of the inverse of temperature for sample A and B. As well as for the resistivity measurements, the thermally activated process is observed: as the temperature increased, the Hall electron concentration n_H increased exponentially and saturated at highest temperatures. The experimental temperature

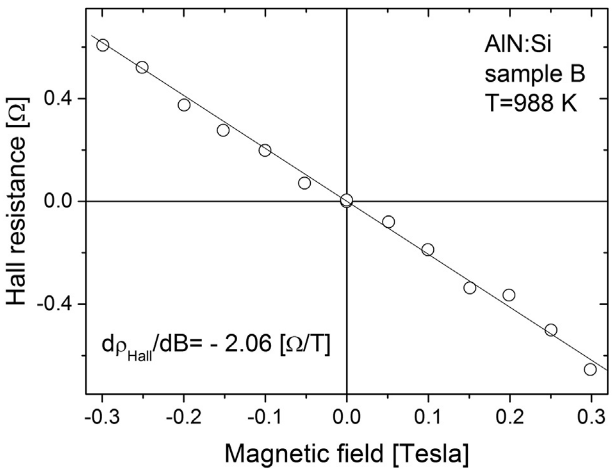

Fig. 1. Hall Effect measurements as a function of magnetic field at a temperature of 988 K for sample B: the slope $\beta = d\rho_{Hall}/dB = 2.06$ Ω/T correspond to the Hall concentration $n_H = 3.04 \times 10^{18}$ cm^{-3}.