Journal of ELECTRONIC MATERIALS, Vol. 42, No. 1, 2013
DOI: 10.1007/s11664-012-2278-0


# Implantation Studies on Silicon-Doped GaN

RONNIE SIMON,[1,3] REINER VIANDEN,[1,4] and KLAUS KÖHLER[2]

1.—Helmholtz-Institut für Strahlen- und Kernphysik, 53115 Bonn, Germany. 2.—Fraunhofer Institut für angewandte Festkörperphysik (IAF), 79108 Freiburg, Germany. 3.—JCNS-2, PGI-4, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany. 4.—e-mail: vianden@hiskp.uni-bonn.de

Silicon-doped GaN layers grown by low-pressure metalorganic vapor-phase epitaxy with Si concentrations ranging from $2 \times 10^{17}$ Si/cm$^3$ to $9.2 \times 10^{18}$ Si/cm$^3$ were investigated by means of the perturbed angular correlation (PAC) technique applied to implanted $^{111}$In(Cd). An undoped GaN film is used as a reference. The Si atoms replace Ga atoms in the lattice, and silicon, being a group IV element, acts as a donor on the Ga site and contributes one extra electron to the conduction band. Hall-effect measurements confirmed that the free charge carrier density is essentially increased and of the order of the silicon concentration. PAC investigations of the annealing behavior after implantation of the $^{111}$In probes show that best recovery is achieved after annealing at 1200 K and that high silicon concentrations make GaN films more stable at high temperatures. Further, it was found that the temperature dependence of the electric field gradient is reduced by increasing Si concentrations.

**Key words:** Nitride semiconductor, implantation, annealing, perturbed angular correlation

## INTRODUCTION

Group III nitride semiconductors, especially gallium nitride (GaN), have drawn much attention in recent years. One remarkable feature of these materials is the formation of continuous alloy systems, e.g., $In_xGa_{1-x}N$, in which the optical bandgap can be tailored by varying the concentrations of the constituents. This makes group III nitrides ideal for optoelectronic devices. In order to improve the possibilities of structuring GaN devices it is desirable to dope the material by ion implantation. Then, however, lattice damage is created and has to be annealed by an appropriate temperature program. Thus, in this work the effect of doping on the annealing behavior after ion implantation and stability of GaN films at high temperatures is investigated. Further, the influence of changes in the charge carrier density on the hyperfine fields in GaN and their temperature dependence is studied. A nuclear technique, namely the perturbed angular correlation technique, is employed in this work.

(Received June 26, 2012; accepted September 18, 2012; published online October 20, 2012)

## EXPERIMENTAL PROCEDURES

The perturbed angular correlation (PAC) method is an experimental technique of nuclear solid-state physics. It is based on the hyperfine interaction between a radioactive probe atom and fields present at the position of the probe atom. In more detail, the nuclear electric quadrupole and magnetic dipole moment interact with electric field gradients (EFG) and magnetic fields, respectively. In solids, an EFG can originate from the charge distribution in a noncubic crystal lattice such as the wurtzite structure found in many group III nitride semiconductors. Crystal defects such as substitutional and interstitial impurities or vacancies also lead to an EFG. Thus, lattice damage, which unavoidably occurs during the doping of semiconductors by ion implantation, can be investigated in detail by PAC.

Experimentally, the hyperfine interaction is observed in the time-dependent change of the angular correlation between two successive $\gamma$-rays in a $\gamma$–$\gamma$ cascade due to an external perturbation by an EFG. A comprehensive description of the theory of perturbed angular correlation can be found in the literature.[1]