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Defects in nitride semiconductors: From nanoscale imaging to macroscopic device behavior

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Abstract

Scanning capacitance microscopy (SCM), atomic force microscopy (AFM), and conductive AFM are used to image the spatial distribution and electronic properties of threading dislocations in $Al_xGa_{1-x}N/GaN$ epitaxial layers grown by molecular-beam epitaxy. SCM imaging reveals that GaN growth directly on SiC substrates leads to clustering of negatively charged dislocations at nucleation island boundaries, while incorporation of an AlN buffer leads to a random spatial distribution of negatively charged dislocations. Numerical simulations demonstrate that clustered dislocations are less effective in depleting mobile carriers. AFM and conductive AFM imaging reveal the presence of highly conductive threading dislocations which lead to excessive reverse-bias leakage current flow in Schottky diodes. Temperature-dependent current–voltage spectroscopy is used to develop a model for current flow via these dislocations based on a Frenkel–Poole emission process. On the basis of this model, heterostructures are designed to suppress this emission mechanism. Conductive AFM imaging and electrical measurements then confirm the expected suppression of leakage current and specifically of the Frenkel–Poole emission process, demonstrating the validity of both the proposed mechanism of current flow and the approach for leakage current suppression.

Keywords: GaN; Atomic force microscopy; Scanning capacitance microscopy; Leakage current; Field-effect transistor

1. Introduction

Group III-nitride semiconductors have been a subject of intense interest and research activity for both electronic [1–3] and optoelectronic [4,5] device applications. However, the lack of a suitable substrate for homoepitaxial growth typically leads to high concentrations of defects, particularly dislocations, in epitaxial nitride films. Because threading dislocations in nitride semiconductors often exhibit prominent electrical behavior, including large negative charge densities in the dislocation core [6,7] and, in material grown by molecular-beam epitaxy (MBE), high conductivity, [8–10] characterization and understanding of the electrical properties of defects and material inhomogeneities plays an essential role in the science and engineering of nitride semiconductor materials and devices.

Here we characterize the presence, spatial distribution, and electrical behavior of dislocations in $Al_xGa_{1-x}N/GaN$ heterostructure field-effect transistor (HFET) epitaxial layer structures using

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scanning probe microscopy. The ability to image both surface structural morphology and either surface or near-surface electrical characteristics at the nanoscale enables the correlation of various electrical behaviors, such as charge modulation or conductivity, with the presence of individual defects identified via their manifestation in surface morphology. These studies are then combined with macroscopic electrical device characterization and numerical simulations to correlate the presence and properties of individual defects with the electrical behavior of macroscopic devices, and on the basis of the resulting understanding to design nitride semiconductor heterostructures in which key undesirable aspects of defect electrical behavior are mitigated.

2. Experimental methods

$Al_xGa_{1-x}N$/GaN HFET structures were grown by MBE on semi-insulating on-axis 4H-SiC substrates. The epitaxial layer structures consisted of a 25 nm $Al_xGa_{1-x}N$ layer with $x = 0.25$–0.26 grown on a 1.3–3 μm GaN film at 720–750 °C under slightly metal-rich conditions. All layers were nominally undoped. To determine the effects of a high-temperature (800 °C) AlN buffer layer on the properties of subsequently grown material, a pair of samples were grown under nominally identical conditions with and without a ~60 nm AlN buffer layer deposited on the SiC substrate. For electrical studies of Schottky diode leakage current characteristics, Ti/Al metallization annealed at 800 °C for 3 min was used to form Ohmic contact rings, within which 125 μm-diameter Ni dots were used to form Schottky contacts. Current–voltage characteristics were measured at temperatures ranging from 110 to 400 K.

Scanning capacitance microscopy (SCM) was carried out in a Digital Instruments Dimension 3100 microscope with W_2C-coated probe tips. Local conductivity measurements were carried out by conductive atomic force microscopy [11] (AFM) in a modified Digital Instruments Nanoscope® IIIa MultiMode™ microscope under ambient atmospheric conditions (~20 °C with 50% relative humidity) using highly doped diamond-coated probe tips. Two- and three-dimensional numerical simulation of material and device characteristics was carried out using Silvaco simulation software.

3. Analysis of spatial distribution of negatively charged dislocations

3.1. Experimental results

The presence and spatial distribution of negatively charged dislocations are revealed through local depletion, and accompanying capacitance shifts, that are imaged with SCM [12–14]. Representative SCM images of $Al_xGa_{1-x}N$/GaN HFET epitaxial layer structures grown with and without AlN buffer layers are shown in Fig. 1, in which regions depleted by charged dislocations appear bright [15]. Images of the sample grown with no buffer layer, shown in Figs. 1(a) and (b), exhibit a domain-like microstructure with negatively charged dislocations grouped at boundaries between 2 and 4-μm diameter domains. This columnar microstructure is commonly observed in GaN-based materials [16–18] and is a result of discrete island nucleation followed by island expansion and coalescence with dislocations forming at island boundaries to accommodate island orientation mismatch. SCM images of the sample grown with the AlN buffer, shown in Figs. 1(c) and (d), reveal an apparently random dislocation distribution, most likely arising from the relatively small lattice mismatch (~1%) between AlN and SiC, which results in two-dimensional pseudomorphic, rather than island, nucleation. By comparing the smaller scan areas

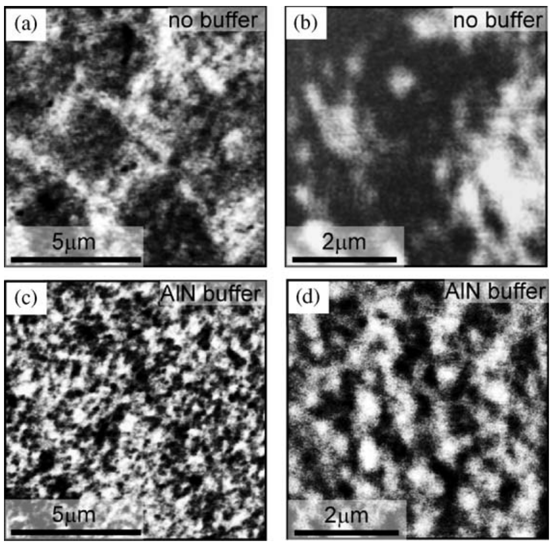

Fig. 1. (a) SCM images of (a) and (b) HFET structure with no AlN buffer layer, exhibiting dislocations at nucleation island domain boundaries, and (c) and (d) HFET structure with a ~60 nm AlN buffer, exhibiting randomly distributed dislocations.