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Enhanced current transport in GaN/AlN based single and double barrier heterostructures

Shibin Krishna[a,e], Anurag G. Reddy[b], Neha Aggarwal[a,e], Mandeep Kaur[c], Sudhir Husale[c], Dinesh Singh[d], Manju Singh[c], Rajib Rakshit[c], K.K. Maurya[d], Govind Gupta[a,e,*]

[a] Advanced Materials and Devices Group, CSIR-National Physical Laboratory (CSIR-NPL), Dr. K.S. Krishnan Road, New Delhi 110012, India
[b] Department of Electronic Engineering, Graduate School of Engineering, Research Center for Advanced Science and Technology, University of Tokyo, Tokyo 153-8904, Japan
[c] Quantum Phenomena and Applications, CSIR-NPL, Dr. K.S. Krishnan Road, New Delhi 110012, India
[d] Sophisticated and Analytical Instrumentation, CSIR-NPL, Dr. K.S. Krishnan Road, New Delhi 110012, India
[e] Academy of Scientific & Innovative Research (AcSIR), CSIR-NPL Campus, Dr. K.S. Krishnan Road, New Delhi 110012, India

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ABSTRACT

Current transport through a unique structure design employing high quality GaN based heterostructure with sharp interfaces has been investigated. A novel approach of structure design has been adopted to enhance the current transport in GaN heterostructures with a specific number of barrier layers of AlN which includes Single Barrier Heterostructure (SBH) and Double Barrier Heterostructure (DBH) devices. The high band gap AlN can act as a barrier for current conduction between GaN layers and help in effectively enhancing the current transport in the device through tunneling phenomena. A highly enhanced current transport in comparison with No Barrier Heterostructure (NBH) has been observed in SBH and a further improvement is perceived in DBH. Moreover, the phenomenon of current conduction is explained through drift-diffusion model, in which current enhancement upon subsequent addition of high bandgap barrier layer has resulted in localized high electric field and thus charge carrier velocity overshoots. Further, this has also been explained via quantum model, by interference of transmitted and reflected electron wave at interfaces. UV photodetectors using such heterostructure designs with and without AlN barrier layers in metal-semiconductor-metal geometry have been fabricated. The UV photodetection device developed using DBH yields photoresponsivity 80 times higher as compared to NBH device under UV illumination (325 nm). Employment of such structures will enable scaling up the production of highly efficient optoelectronic devices.

1. Introduction

Enormous potential for optoelectronic device applications has sharpened the focus of research in the field of III-Nitride based semiconductors. Such devices include both light sources like light emitting diodes (LEDs), laser diodes (LDs) as well as detectors including solar/visible blind photo detectors (PDs) [1,2]. A range of applications varying from flame and radiation detection to astronomical studies, and optical communications in addition to chemical, environmental and biological analysis is presented by the use of UV radiation detectors [3]. Additional desirable features like high absorption coefficient and excellent thermal/radiation resistance [4,5] provides scope for highly stable and reliable devices even in harsh environment. In harsh environment applications such as missile plume, an additional requirement of thermally stable high performance detector is highly imperative. Group-III nitrides are considered to be a strategic material for the development of high-performance UV PDs. They have many advantages such as the ideal spectral selectivity with wide direct bandgap from the deep UV to the infrared region, high breakdown field and expected high responsivity [6].

Recent developments in high quality (Ga, Al) N material growth technology have led to the realization of high performance solar/visible-blind PDs operating in the UV spectral region [7]. The III-Nitride based UV PDs provide an added advantage over well-established UV-enhanced Si technology [8]. Since, III-Nitrides are direct and wide band gap materials such as GaN (E_g = 3.4 eV), AlN (E_g = 6.2 eV) compared to Si (E_g = 1.1 eV), the requirement of costly high pass optical filters and phosphors to block low energy photons is eliminated [9]. Further, the operation of Si based devices at elevated temperatures can increase the dark current thereby reducing efficiency [8]. These unwanted

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[*] Corresponding author at: Advanced Materials and Devices Group, CSIR-National Physical Laboratory (CSIR-NPL), Dr. K.S. Krishnan Road, New Delhi 110012, India.
E-mail address: govind@nplindia.org (G. Gupta).

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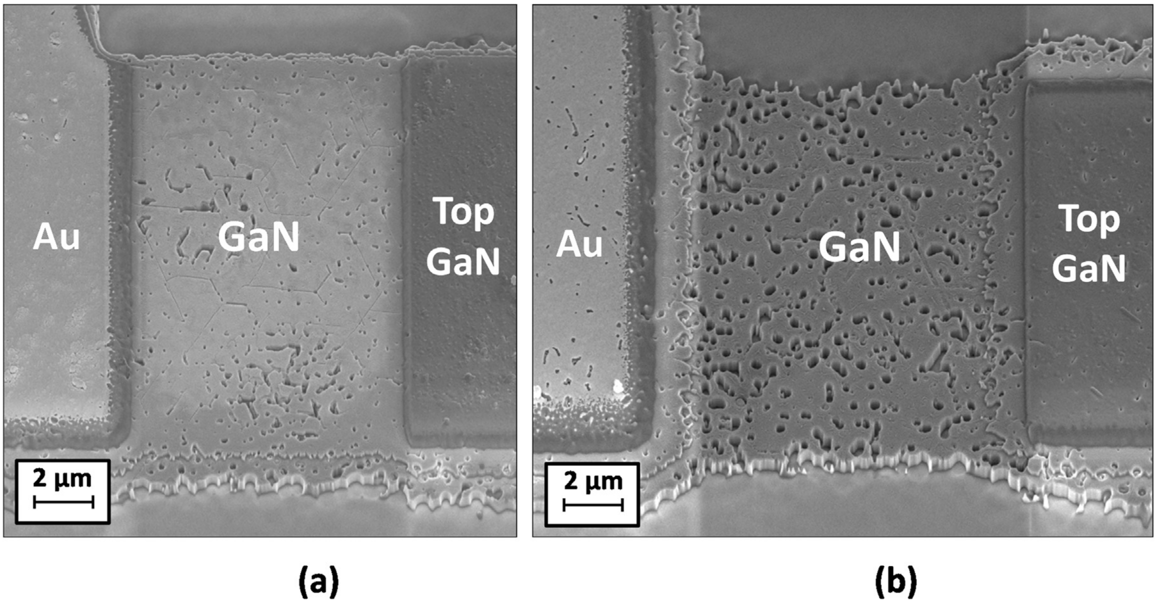

Fig. 1. The FESEM images of (a) SBH and (b) DBH devices fabricated by FIB technique.

effects of expensive filters and low thermal stability are eliminated in III-Nitride materials yielding better device performance [10–12]. Further, the sensitivity of any optoelectronic device can be improved by implementing innovative device architecture which can augment the current transport, one of such structures can be developed by using multi quantum well structures (MQW) structures or multi barrier heterostructures [13,14]. The large and tunable band offset of III-Nitride heterostructures is a useful feature for devices relying on quantum confinement and tunneling transport. The diminution in current conduction instigated by interface roughness and alloy scattering can be effectually exemplified by tunneling phenomena. Alloy scattering effects can be minimized by employing such MQW designs. However, the successful implementation of suggested approaches depends on numerous parameters such as interface sharpness and roughness. Here, we demonstrate the enhanced current transport by using high band gap AlN semiconductor between GaN layers. The current conduction was investigated via current-voltage (I-V) measurements in undoped GaN layer as well as GaN based heterostructures with single and double barriers of AlN. An enhanced photoresponse has been observed from the UV photodetection device fabricated using GaN DBH compared to the device developed using NBH. A comprehensive analysis on significantly enhanced current transport in SBH (GaN/AlN/GaN) and DBH (GaN/AlN/GaN/AlN/GaN) devices is represented for the first time. The study opens up a new vista for the development of high efficiency nitride based devices where improvement in current transport is highly desired.

2. Methods

2.1. Growth and characterizations

GaN/AlN based DBH was grown on thermally cleaned c-plane sapphire substrate by Riber compact-21 Radio Frequency Molecular Beam Epitaxy (RF-MBE) system equipped with 6N pure Ga & Al materials filled in standard effusion cells and a RF - plasma source (ADDON) to supply active nitrogen (N*) species. The growth is initiated with nitridation of sapphire followed by GaN buffer layer over a thin Ga wetting layer (~1 nm) at 480 °C [15]. Then, AlN(30 nm)/GaN(70 nm)/AlN(30 nm)/GaN(70 nm) heterostructure was grown on 200 nm thick GaN epitaxial layer at a base pressure of 1.3E-5 Torr using RF plasma power of 500 W. For the multiple stack film deposition, Al and Ga have a beam equivalent pressure of 4E-8 Torr and 1E-6 Torr respectively. The growth rate of AlN is calculated to be 1 nm/min while for GaN is 2.3 nm/min. All the layers grown in the heterostructure are un-doped. In-situ Reflection High Energy Electron Diffraction (RHEED) analysis confirmed the high crystallinity of GaN and AlN grown layers while High Resolution X-Ray Diffraction (HR-XRD, Panalytical X′Pert PRO MRD System) and Time of Flight-Secondary Ion Mass Spectroscopy (ToF-SIMS, ION-TOF) have been employed to carry out structural characterizations. High Resolution Transmission Electron Microscopy (HRTEM) measurements have been performed for availing in-depth understanding about the structural properties of grown heterostructures. The prepared specimen was examined in TEM (FEI, Tecnai F30 G2 STWIN) operating at 300 kV with a point resolution of 0.205 nm and line resolution of 0.144 nm.

2.2. Device fabrication and electrical measurements

Standard cleaning procedure was followed prior to loading the samples in thermal evaporation chamber for metal contact formation. A sequence of three solvents i.e., acetone, methanol and iso-propanol were used to remove organic, inorganic and physical impurities such as dust or excessive moisture. The samples were then rinsed in de-ionized water and dried using pressurized nitrogen. The top contacts for all the samples were formed by depositing Au using physical vapor deposition. For fabricating SBH and DBH, required layers were etched out by Gallium ions using Focused Ion Beam (FIB, ZEISS AURIGA) (detailed description of optimization & etching process for SBH and DBH devices is shown in the supplementary information, Fig. S1). The final FESEM images of device structures for SBH and DBH are presented in Fig. 1. In SBH, a step was created by FIB etching till second GaN layer from the top whereas in case of DBH etching was carried out till the third GaN layer. Fig. 1a and b shows the developed device structure of SBH and DBH respectively. The metal contacts were deposited in-situ on the specific layer of GaN in SBH and DBH using the FIB setup. Noticeably, while etching down to the bottom of GaN layers, the pit density on GaN film increases. The increment in pit density at the preliminary stages of growth was due to the initial stress relaxation between the film and the substrate. Further, temperature dependent I-V measurements were performed by using Cryogenic micro manipulated Probe Station (EMP4 – HF, Lakeshore). The photoresponse measurements were carried out using probe station setup (Cascade Microtech EPS150TRIAX) which has shield enclosure (EPS-ACC-SE750) for low signal measurements. The spectrometer is equipped with a focused laser ($\lambda = 325$ nm, illumination