GaInN/GaN solar cells made without p-type material using oxidized Ni/Au Schottky electrodes

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ABSTRACT

GaInN/GaN solar cells made without p-type material are demonstrated using an oxidized Ni/Au Schottky barrier design to collect photo-generated carriers. The best devices exhibit a short-circuit current density of 0.065 mA/cm^2 with an open-circuit voltage of 0.4 V under AM0 (1-Sun) illumination. Preliminary computer simulations are in reasonable agreement with experimental results, giving a pathway to improve device performance via iterative redesign and testing.

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1. Introduction

GaInN semiconductor alloys cover an unusually wide energy range ($0.7 \leq E_g \leq 3.4$ eV) and have optical absorption coefficients approaching 10^5 cm^{-1} at energies just above their bandgaps [1]; making this material system a good candidate for developing multi-junction, thin-film solar cells [2]. Most GaInN/GaN solar cell designs evaluated to date contain some form of *p-n* doping profile to enable collection of photo-generated carriers [3–6]. The difficulty of making *p-type* GaN and $Ga_{1-x}In_xN$ ($x \leq 0.2$) of good electronic quality has been well documented in the literature on GaInN/GaN LEDs and laser diodes [7–8]. Moreover, there have been only a few reports of *p-type* GaInN with higher indium content [9–10]; which is necessary to make *p-n* GaInN solar cells with band gaps in the range 1.9–1.0 eV.

It was demonstrated long ago that solar cells could be made from material of one doping type (n *or* p) by employing a metal/semiconductor Schottky barrier to collect photo-generated carriers [11–12]. Recently, this concept was applied to make GaInN/GaN solar cells *using only n-type material* [13–14]. An oxidized Ni/Au composite film was employed as the *transparent* Schottky electrode. This choice was motivated by the knowledge that oxidized Ni/Au films make ohmic contacts to *p-type* GaN [15], and thus should form rectifying junctions when in contact with *n-type* GaN.

In this paper, the potential of such GaInN/GaN Schottky solar cells is evaluated further by characterizing the optical and electrical properties of the Schottky electrode, as well as the electronic behavior of its rectifying interface with n-type GaN, and by fabricating devices and comparing their photovoltaic response to results obtained via numerical simulation.

2. Experimental methods

The GaInN/GaN solar cell material employed in this study was grown by OMVPE on a c-plane sapphire substrate. The structure consists of a 4 μm n$^+$ GaN layer, followed by a 15-pair MQW absorber region (2.5 nm $Ga_{0.9}In_{0.1}N$ wells/12 nm GaN barriers), and capped by a 40 nm GaN layer. The GaInN/GaN MQW absorber and GaN capping layer were not intentionally doped but have n-type conductivity owing to residual donors. A layer schematic is shown in Fig. 1 for a fully processed device. The *oxidized* Ni/Au composite material forms a "broad-area" Schottky barrier with respect to the GaN capping layer.

A different n$^-$/n$^+$ GaN layer structure was used for preparation of Schottky diodes. It was grown under similar conditions to the solar cell material, but the n$^-$layer is lightly doped with silicon

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GaInN/GaN – Ni/Au Transparent Conducting Oxide Schottky Barrier Solar Cells

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Abstract — Schottky barrier solar cells made from two different GaInN/GaN material structures combined with Ni/Au transparent conducting oxide films are demonstrated herein. The GaInN/GaN multiple quantum well structure has a short-circuit current density of 0.062 mA/cm^2, open-circuit voltage of 0.468 V, and fill-factor of 69.8%. The GaInN/GaN double-heterostructure exhibits a 51% reduction in short-circuit current density, 47% lower open-circuit voltage, and 27% smaller fill-factor. Preliminary computer simulations indicate that a 10-fold increase in short-circuit current density should be possible for the GaInN/GaN multiple quantum well structure. The Ni/Au layer is responsible for some of this shortfall as its optical transparency varies from a low of 46.4% at 300 nm to a high of 76.8% at 500 nm. There is also evidence that photo-generated carriers are not being collected from the entire illuminated device area. The Ni/Au bi-layer has an electrical resistivity of 2.9 x 10^{-5} Ωcm, but it is very thin and no effort has been made to trade-off its electrical behavior against its optical properties. Work is now underway to increase the open-circuit voltage of these devices by adopting "barrier height enhancement" schemes.

Index Terms — heterojunction, indium gallium nitride, photovoltaic cells, quantum wells, schottky diodes.

I. INTRODUCTION

Thin film solar cells made from GaInN semiconductor alloys are of considerable interest because this material system covers an unusually wide energy range (from 3.4 eV for GaN to 0.7 eV for InN), has optical absorption coefficients approaching 10^5 cm^{-1} at energies near the band edge, and exhibits better radiation hardness than conventional III-V semiconductors [1]-[3]. Several different material structures have been evaluated over the past ten years, including InGaN homojunctions [4]-[5], InGaN/GaN heterojunctions [6]-[7], and InGaN/GaN multiple quantum well structures [8]-[9]; all of which contain some form of *p-i-n* doping profile to enable collection of photo-generated carriers. The difficulty of making *p-type* GaN and In$_x$Ga$_{1-x}$N (x ≤ 0.2) of good electronic quality has been widely documented in the literature on GaN/InGaN LEDs and laser diodes [10]-[12]. Moreover, there have been very few reports on well-conducting *p-type* InGaN with higher indium content [13]-[15], such as would be necessary to make *p-i-n* InGaN solar cells with band gaps in the range 1.9 to 1.0 eV.

In the present work, the issue of p-type doping was circumvented by employing a Schottky diode configuration to collect photo-generated carriers [16]-[19]. More specifically, transparent conducting oxide (TCO) films made of thin Ni/Au bilayers were placed in intimate contact with *n-type* InGaN/GaN heterostructures to demonstrate the viability of InGaN Schottky barrier solar cells [20].

II. EXPERIMENTAL DETAILS

The two GaInN/GaN material structures employed in this study were grown by organometallic vapor phase epitaxy (OMVPE) on c-plane sapphire substrates. The precursor chemicals trimethylgallium, trimethylindium, ammonia, and disilane were employed in a mixed hydrogen/nitrogen ambient at 300 torr. The first structure consists of a 4.0 μm thick, Si-doped GaN ohmic contact layer (n = 2 ×10^{18} cm^{-3}), followed by a 0.2 μm thick, nominally un-doped GaInN absorber capped by a 40 nm thick, un-doped GaN surface layer. The second structure is nearly identical to the first except the absorber consists of a 15-pair MQW region with 2.5 nm thick GaInN quantum wells and 12 nm thick GaN barriers. The indium content in the InGaN alloy layers is about 10% in both samples. These two material configurations are referred to in the following discussion as *GaInN DH* and *GaInN MQW*, respectively.

Photoluminescence (PL) measurements were made at room-temperature to assess the relative "quality" of the two samples in their *as-grown* states. As evidenced in Fig. 1, the local PL maximum near 365 nm has a narrow spectral line-width (in both structures), which is indicative of good quality n-type GaN. The sample with the MQW absorber exhibits its maximum luminescence intensity at the wavelength (λ_p) of 438 nm with a corresponding spectral-line-width ($\Delta\lambda$) of 14 nm. In contrast, for the DH absorber, the luminescence peak occurs at shorter wavelength (λ_p = 420 nm) and the spectral line-width is considerably broader ($\Delta\lambda$ = 24 nm). Moreover, the DH absorber exhibits a very broad luminescence signal with maximum intensity around 560 nm, which is likely attributable

Heteroepitaxial Ge MOS Devices on Si Using Composite AlAs/GaAs Buffer

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ABSTRACT Structural and electrical characteristics of epitaxial germanium (Ge) heterogeneously integrated on silicon (Si) via a composite, large bandgap AlAs/GaAs buffer are investigated. Electrical characteristics of N-type metal-oxide-semiconductor (MOS) capacitors, fabricated from the aforementioned material stack are then presented. Simulated and experimental X-ray rocking curves show distinct Ge, AlAs, and GaAs epilayer peaks. Moreover, secondary ion mass spectrometry, energy dispersive X-ray spectroscopy (EDS) profile, and EDS line profile suggest limited interdiffusion of the underlying buffer into the Ge layer, which is further indicative of the successful growth of device-quality epitaxial Ge layer. The Ge MOS capacitor devices demonstrated low frequency dispersion of 1.80% per decade, low frequency-dependent flat-band voltage, V_{FB}, shift of 153 mV, efficient Fermi level movement, and limited C-V stretch out. Low interface state density (D_{it}) from 8.55×10^{11} to 1.09×10^{12} cm^{-2} eV^{-1} is indicative of a high-quality oxide/Ge heterointerface, an effective electrical passivation of the Ge surface, and a Ge epitaxy with minimal defects. These superior electrical and material characteristics suggest the feasibility of utilizing large bandgap III-V buffers in the heterointegration of high-mobility channel materials on Si for future high-speed complementary metal-oxide semiconductor logic applications.

INDEX TERMS Germanium (Ge), heteroepitaxy, metal-oxide semiconductor (MOS) devices, silicon (Si), III-V materials.

I. INTRODUCTION

Aggressive scaling of silicon (Si) complementary metal-oxide-semiconductor (CMOS) transistors has resulted in an exponential increase in device density, and thus computing power, over the past four decades. To mitigate the increased power consumption as a result of increasing transistor density, supply voltage scaling is essential to maintain low-power device operation, but at the cost of significantly degrading transistor drive current due to the low carrier mobility of Si [1]. Overcoming the limitations of device and voltage scaling without degrading transistor drive current requires the adoption of narrow bandgap channel materials with superior transport properties. However, the use of such materials as bulk substrates is cost-prohibitive. Thus, another key technical challenge is the heterogeneous integration of high-mobility alternative channel materials on affordable and established Si technology platform.

Germanium (Ge) is an attractive candidate for next-generation low-power devices operating at low-voltage (≤ 0.5 V) due to its high electron and high hole mobility ($2\times$ and $4\times$, respectively, as compared to those of Si) [2]. Although Ge has been successfully integrated on GaAs substrate [3]–[8], it remains an important issue to integrate Ge on to Si substrate. Thus, numerous methods for the epitaxial growth of Ge on Si have been reported in order to demonstrate the device-quality Ge as a future channel