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Photovoltaic properties and technological aspects of $In_{1-x}Ga_xN$/Si, Ge ($0<x<0.6$) heterojunction solar cells

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Abstract

Photovoltaic properties of n-$In_{1-x}Ga_xN$/p-Si, Ge (IGN) heterostructures, covering the compositional range $0<x<0.6$, have been evaluated by 1d device simulation, and are compared with the performance of c-Si homojunction thin film cells. Film morphology and physical properties were characterized by high-resolution transmission electron microscopy (TEM), secondary ion mass spectrometry (SIMS) and photoluminescence (PL). Best achievable cell performances under AM1.5 illumination conditions were 18% for p-Ge, and up to 27% for n-IGN/p-Si contacts, achievable under optimum cell design, materials and operation parameters. Pure InN bottom layers, exhibiting an intrinsic band gap of 0.7 eV, reveal a reduced efficiency of 2.5%. The cell efficiency is strongly affected by film quality, accounted for by variation of electron affinity, majority carrier mobility, minority carrier lifetime, film thickness and doping levels. The morphology of thin IGN and InN films deposited onto silicon and sapphire substrate material revealed granular growth, along with a high density of grain boundaries. TEM resolved the formation of a very thin homogeneous silicon nitride interlayer on silicon substrates. The electrically isolating layer almost completely suppresses the photovoltaic effect. Depth profiling of InN films deposited onto sapphire

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substrates by SIMS analysis indicated oxygen as the dominant material contamination. It accounts, among other effects, for a gradually increasing band gap throughout the film structure. Observed large photoluminescence broadening effects, and related short minority carrier lifetimes are most likely related to high levels of oxygen contamination and concentration of grain boundaries. Possible routes to overcome these problems are discussed.

Keywords: Solar cell; Thin film technology; III–V compounds; Nitrides; Performance analysis; Structural properties

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1. Introduction

The unusual physical properties of indium nitride have attracted considerable technological interest towards future photovoltaic applications of the material. Employing solid solutions of InN with GaN and/or AlN, the optical band gap can be adjusted over an exceptionally large range, ranging from the near infrared to ultraviolet region of the electromagnetic spectrum. Previous reports [1,2] on superior photovoltaic properties of a Si/InN heterostructure solar cell were based on an assumption of a direct optical band gap of InN, placed near a photon energy of 1.9 eV.This value would match favorably to spectral conditions, attained under AM0 irradiation conditions.

For tandem cells, where a top InN layer is deposited onto a bottom bulk silicon substrate, efficiencies of up to 30% have been proposed. The quality of deposited wurtzite phase InN films on (1 1 1) oriented Si-bottom substrates should be sufficient, despite 8% lattice mismatch to the (0 0 0 1) plane, which is substantially reduced to $<1\%$ for Ge substrates. Furthermore, reliable p-type doping of elemental group IV semiconductors is well established. It should be noted that present background doping levels of InN films are (degenerately) high n-type, with deliberate p-type doping being still difficult to achieve. Further advantage of the Si/InN heterojunction cell over other thin film cell configurations would be improved adjustments of film stoichiometry, since all precursor materials can be kept in gas-flow-controlled vapor phase. Another issue is safety conditions, which are crucial in large-scale production. No extremely toxic compounds, like arsine or phosphine, required for group III/V materials technology, need to be implemented into the film deposition processes.

Recently, using improved MOCVD/MOVPE thin film deposition methods, the fundamental optical properties of pure InN films [3] indicated a substantially red-shifted direct optical band gap E_G, placed now around 0.7 eV.As a consequence of the reduced E_G of InN, yet observable only for decent quality films, the photovoltaic properties and achievable cell efficiencies η of Si/InN hetero-structure thin film cells will be different and substantially lower than those proposed earlier in Refs. [1,2]. Thus a readjustment of E_G is required to increase η for the recently discovered reduced band gap InN material. It can be achieved by alloying indium with gallium