Design of a lattice-matched III-V-N/Si photovoltaic tandem cell monolithically integrated on silicon substrate

A. Rolland, L. Pedesseau, J. Even, S. Almosni, C. Robert, C. Cornet, J.M. Jancu, J. Benhlal, O. Durand and A. Le Corre
Université Européenne de Bretagne, INSA, FOTON-OHM, UMR 6082, F-35708 Rennes, France

P. Rale, L. Lombez, J.-F. Guillemoles, E. Tea, S. Laribi
Institut de Recherche et Développement sur l'Energie Photovoltaïque (IRDEP), UMR 7174 - CNRS-EDF-ENSCP, EDF R&D, 6 quai Watier, 78401 Chatou Cedex, France

In this paper, we present a comprehensive study of high efficiencies tandem solar cells monolithically grown on a silicon substrate using GaAsPN absorber layer. GaAsPN quantum dots and quantum wells have been grown recently on GaP/Si susbstrate for applications related to light emission. For photovoltaic applications, we consider the GaAsPN diluted nitride alloy as the top junction material due to both its perfect lattice matching with Si and ideal bandgap energy for current generation in association with the Si bottom cell. Numerical simulation of the top cell is performed. The effect of layer thicknesses and doping on the cell efficiency are evidenced. In these structures a tunnel junction (TJ) is needed to interconnect both the top and bottom sub-cells. We compare the simulated performances of different TJ structures and show that the GaP(n+)/Si(p+) TJ lead to improved performances of the current-voltage characteristic.

Key words: **Tandem solar cells, tunnel junctions, numerical simulation, Photonics on silicon**

I. Introduction

Emphasizes on environmental protection increase and energy need make solar energy to become a major energy source in the future. In this context, there is a strong effort underway to lower the cost of the photovoltaic kilowatt-peak toward new material systems. However the concept of the single junction solar cell does not lead to the utilization of the whole solar spectra because its high energy part is lost by phonon recombination. To overcome this efficiency limitation, the concept of multi-junction solar cell has been proposed and efficiency up to 40% were reported for GaAs based cells [1-4].

Recent advanced processes in III-V alloys monolithic growth on silicon substrate [5, 6] make theses alloys become promising materials for multi-junction solar cells [7-9]. In this paper, we propose a GaAsPN diluted nitride alloy as the top junction material of a Si based tandem solar cell. Its perfect lattice matching with Si and ideal bandgap energy of 1.7 eV are appealing for optimal current generation with a 1.1 eV bandgap Si bottom cell. In this work we show numerical simulation results for the top PIN GaP/$GaAs_xP_{1-x}N$/GaP junction. Modeling is performed using the ATLAS device simulator [10]. Optimized conditions of layer thicknesses and doping for the top PIN GaP/$GaAs_xP_{1-x}N$ /GaP junction in terms of efficiency are evidenced. A key factor to achieve efficient tandem solar cells is the tunnel junction (TJ) between top and bottom sub-cells [3, 4]. We compare the theoretical performances of different TJ structures and show that the GaP(n+)/Si(p+) exhibits the best current-voltage characteristic.

II. Method

Modeling is performed using the ATLAS device simulator by Silvaco [10] which allows to numerically solve Poisson's equation coupled with continuity equations for both electrons and holes under steady state conditions. Identically, an important key feature of the tandem solar cell is the TJ interconnecting both top and bottom sub-cells. In this work we use the TJ model implemented in the ATLAS simulator to compare the performances of respectively GaP(n+)/Si(p+), GaP(p+)/Si(n+) hetero-junctions tunnel diodes as well as GaP(n+)/GaP(p+) and Si(n+)/Si(p+) homo junctions tunnel diodes.

III. Tunnel Junction

Four TJs have been studied *i.e.* Si(n)/Si(p), GaP(n)/GaP(p), GaP(n)/Si(p) and GaP(p)/Si(n). We used the defaults material parameters provided by the Atlas simulator for the Si (GaP) gap energy 1.08eV (2.26eV) and electron affinity 4.17eV (4.4eV). These key values will be carefully measured in the near future in our laboratory.

For a huge and uniform doping (10^{20}), the GaP(n)/Si(p) TJ is much more efficient than the Si(n)/Si(p) TJ (Fig.1).

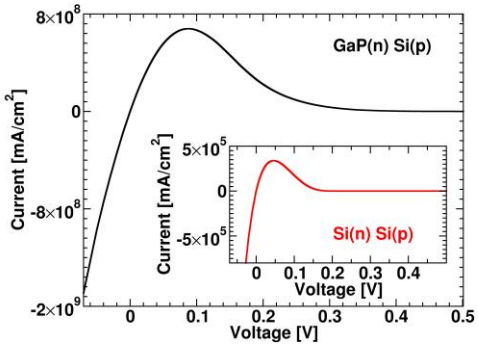

Fig. 1. Simulated current-voltage characteristic of a GaP-n+/Si-p+ and Si-n+/Si-p+ tunnel junctions at uniform doping of 10^{20}.

IV. Top Cell Structure and Material Parameters

Table I shows the basic structure of the GaAsPN top cell used for the simulation. To efficiently predict the device performances, it is necessary to introduce accurate material parameters so we measured refractive index (real and imaginary components) as a function of energy and the related absorption coefficient of the GaAsPN absorber.

TABLE I
Layer Thicknesses and Doping

GaP	P++	$5x10^{18}$ cm^{-3}	50nm
GaP	P+	$5x10^{18}$ cm^{-3}	200nm
$GaAs_{0.1}P_{0.9}N$	intrinsic		1000nm
GaP	n+	$1x10^{18}$ cm^{-3}	30nm

Table II reports the main material parameters used for the simulation.

TABLE II
Material Parameters of GaP and GaAsPN Used in the Simulation

Parameters	GaP	GaAsPN
E_g (eV)	2.2	1.7
μ_n ($cm^2V^{-1}s^{-1}$)	150	1000
μ_p ($cm^2V^{-1}s^{-1}$)	80	80
τ_n (s)	10^{-8}	10^{-10}
τ_p (s)	10^{-8}	10^{-10}
χ (eV)	3.8	4.3

V. Results

Another useful parameter to optimize current generation is the active layer thickness [8]. Fig. 2 shows the effect of the GaAsPN absorber layer thickness on the cell's current-voltage characteristic under AM1.5 solar flux. It can be seen that when increasing the GaAsPN layer thickness from 500 nm to 2000 nm, the open circuit voltage decreases because of the voltage drop due to the parasitic resistance effect, while the short circuit current increases because the density of generated carriers increases. Therefore, an optimum cell efficiency of 9.42% can be obtained for a GaAsPN layer thickness of about 1.5µm.

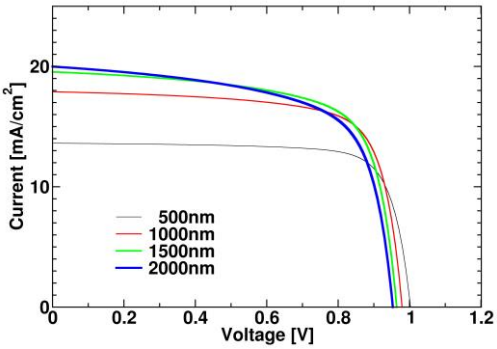

Fig. 2. Current voltage characteristic of the GaP/GaAsPN/GaP cell for different GaAsPN layer thicknesses

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