Type II heterojunction tunnel diodes based on GaAs for multi-junction solar cells: Fabrication, characterization and simulation

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Abstract— **In this work, Molecular Beam Epitaxy (MBE) grown tunnel junctions (TJs) based on GaAs(Sb)(In) materials are experimentally and numerically studied. From simple GaAs TJs grown with various n-doping levels, we develop a semi-classical interband tunneling model able to quantify the magnitude of the tunneling current density, which shows that direct interband tunneling is the predominant tunneling mechanism in GaAs tunnel junctions instead of trap-assisted-tunneling mechanisms. Numerical simulations based on non equilibrium perturbation theory through Non Equilibrium Green's Functions (NEGF) and a multi-band kp hamiltonian that includes both gamma and L valleys were performed by the IM2NP (Marseille) and confirmed this result. In order to further improve the performance of the TJs, we are fabricating a type II tunnel heterojunction based on GaAsSb and InGaAs materials.**

I. Introduction

Tunnel junctions are key devices for multi-junctions solar cells (MJSCs), in which they ensure the electrical serie connection between each subcells. In MJSCs, the subcells are designed and stacked to absorb a specific spectral domain of the solar spectrum, which enhanced the global absorption of the solar cell and reduce the thermalization losses making it possible to reach efficiency as high as 46% [1]. TJs consist in a P+/ N+ junction made of degenerately doped materials, thus enabling a "broken-gap" like band diagram in which carriers can tunnel from one band to the other one. In this work, we investigate the nature of the predominant tunneling mechanism based on experimental GaAs TJs in order to propose an improved GaAsSb / InGaAs TJ.

II. Experiments

A. Fabrication of GaAs and type II heterojunction

6 GaAs TJs with various n-doping levels were fabricated on n-doped GaAs:Si substrates using a Riber 412 MBE system. The P+ doping levels were fixed to $3x10^{19}$ cm^{-3} whereas the N+ doping levels were fixed in the range of [$4x10^{18}cm^{-3}$ - $9x10^{18}cm^{-3}$]. The structure were mesa-isolated in 800 µm diameters circles and TiAu contacts were deposited on the top and the back of the structure.

B. Characterization of the doping levels and the electron effective masses

All the doping levels were previously calibrated on especially designed Hall calibration samples. Because of the reported variation of the electron effective mass in Si doped GaAs due to the non-parabolicity of the conduction band [2], IR reflectometry and ellipsometry were performed by the CEA-LETI and the IES on these samples in order to track the frequency of the Brewster mode, which is doping levels and effective mass dependant.

III. Experimental and numerical models

A. Presentation of the semi-classical tunneling model

As pointed out in [3], the physical nature of the transport mechanisms in TJs has been a subject of debate in the literature. Recent literature suspect that trap related mechanisms could be the predominant tunneling effect in such devices [4]. However, we presented in previous work [5] a direct interband tunneling model model able to quantify the current-voltage characteristics of GaAs tunnel junction from reliable materials data when the coupling between the Conduction Band (CB) and the Light-Holes Valence Band (LH-VB) is carefully taken into account by the Flitener's formula for the tunneling probability evaluation. As presented in figure 1, the model succeed in quantifying the current density of a P + ($3x10^{19}$ cm^{-3}) / N+ ($4.5x10^{18}$ cm^{-3}) when uncertainties up to 4% are considered on the N+ doping level.

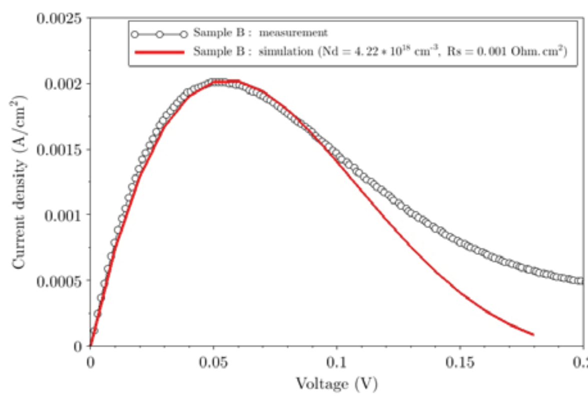

Figure 1: Experimental and simulated J-V characteristic of a GaAs TJ

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B. Influence of the N+ doping level

The validity of the previously mentioned model was tested for a wide range of N+ doping levels. The evolution of the electron effective mass with the doping level in GaAs:Si was experimentally studied following the procedure described in II- B and taken into account in the modeling. The experimental evolution with the previously reported curve of [2] is represented in figure 1.

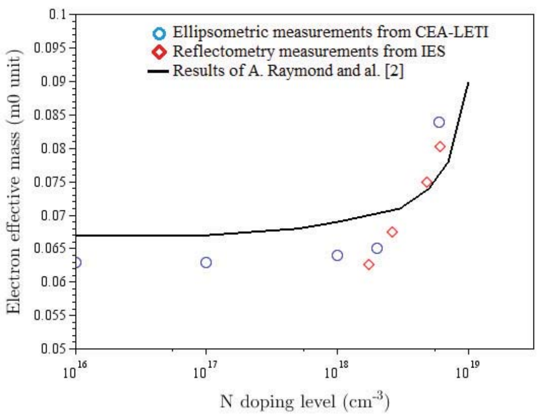

Figure 2: Electron effective mass dependence with N doping level in GaAs:Si

Such consideration of the electron effective mass evolution make it possible to accurately model TJs for N+ doping levels higher than $5x10^{18}$ cm^{-3}, as shown on the example of figure 3.

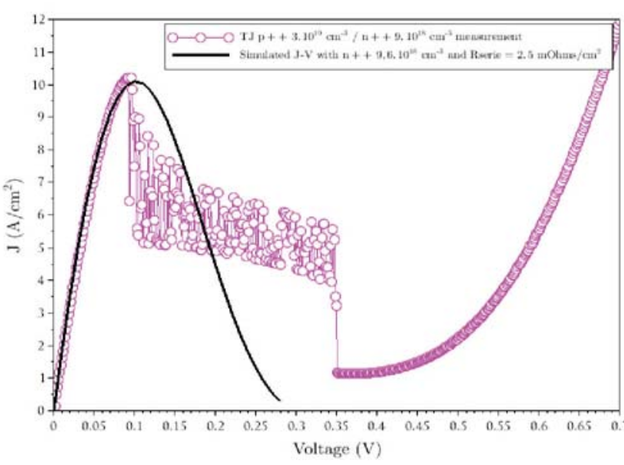

Figure 3:Experimental and simulated J-V characteristic of a P+ (3.10^{19} cm^{-3}) / N+ (9.10^{18} cm^{-3}) TJ

C. Comparison with an NGEF based model

The previously reported experimental and numerical results were then confronted to a full quantum model developed by the IM2NP and based on the equilibrium perturbation theory through Non Equilibrium Green's Functions (NEGF) and a multi-band kp hamiltonian that includes both gamma and L valleys [6], in which no traps into the barrier are considered. As presented in figure 4, a great agreement was found between the two simulated J-V characteristic and the experimental results for the TJ simulated in figure 1.

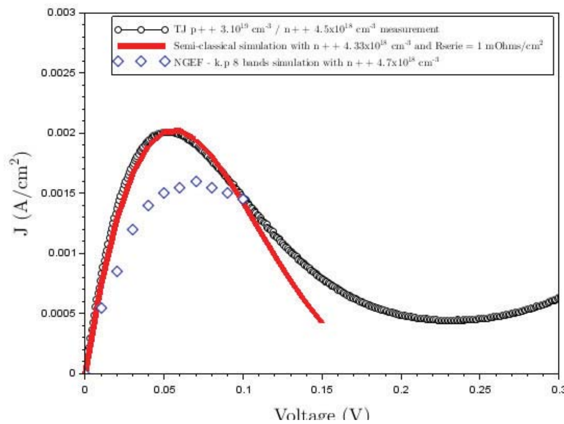

Figure 4: Comparison of the semi-classical model and the NGEF based model for the example of figure 1.

Such good matching between the two different models uphold the hypothesis that direct interband tunneling instead of trap assisted tunneling is the predominant tunneling mechanism in such GaAs TJs.

IV. CONCLUSION

Based on a wide range of experimental GaAs TJs devices, we had shown with the development of a simple semi-classical direct interband tunneling model and a full quantum approach that direct interband tunneling is probably responsible for the large current density in such devices. Based on this results, we are developing an improved TJ by the addition of In and Sb compounds in order to form a type II tunnel heterojunction.

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