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## Enhanced efficiency by the effect of strain on the structure of a solar cell

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### Abstract

This paper is expected at the study of  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  based solar cell. The effects of indium concentration, lattice parameter mismatch and thickness of the  $\text{SiO}_2$  insulating layer on the characteristics and efficiency of the  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  structure were investigated. We noticed that for higher indium concentration, the band gap energy decreases considerably. We found that the efficiency reaches 18% in a lattice-matched  $\delta=50\text{\AA}$ . For a concentration  $x > 0.48$ , we have a compressive strain  $\Delta a/a > 0$  which leads to a higher efficiency. For  $x=90\%$ ,  $\delta=5\text{nm}$  and a strain equal  $\Delta a/a=3\%$ , we achieved an efficiency of 27%. The results show that light conversion efficiency has considerably boosted by varying insulating strain values.

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### 1. Introduction

Materials with a bandgap energy  $E_g < 1.4\text{ eV}$  grown on GaAs substrates are of major interest for optoelectronic devices like multi-junction solar cells [1],  $1.3\text{ }\mu\text{m}$  wavelength emitting lasers [2]. The ternary  $\text{Ga}_{1-x}\text{In}_x\text{As}$  is an attractive material with a bandgap ranging from 1.44 eV for GaAs decreasing to 0.35 eV for InAs. Unfortunately, the lattice constant of this material also changes significantly when we modify the composition. Besides, lattice-matched substrates are not available for most  $\text{Ga}_{1-x}\text{In}_x\text{As}$  compounds. This letter is the first report on the successful deposition of  $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}/\text{Ga}_{0.83}\text{In}_{0.17}\text{P}$  tandem solar cells grown lattice mismatched to the GaAs substrate material.

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GaInP/GaAs tandem cells currently represent the highest efficiency monolithic solar cells and are in commercial production for space applications [4]. Strained semiconductors can be successfully incorporated into photovoltaic devices, as long as the critical thickness is respected for each separate layer as for the whole structure [5]. Metal/semiconductors heterojunctions (SC) and SC A / SC B have a great impact on the realized PV solar cells. The electronic structure of the interface determines the electronic behavior of heterojunctions and Schottky barrier height [6]. In our work, we have used indium/gallium-based compounds to prepare our structures. With these materials we are able to prepare different alloys by adding III-V compounds. Ternary alloys like  $\text{Ga}_{(1-x)}\text{In}_x\text{P}$  and  $\text{In}_x\text{As}_{(1-x)}\text{P}$  or quaternary compound like  $\text{In}_x\text{Ga}_{(1-x)}\text{As}_y\text{P}_{(1-y)}$ . In this type of materials, the forbidden band width could be changed which means that optical properties could be altered and improved at a certain spectral wavelengths range..

## 2. Solar cell structure

We have realized a solar cell using N-type  $\text{Ga}_{(1-x)}\text{In}_x\text{P}$  epitaxially grown on P-type GaAs. We have followed by the deposition of a thin Tin oxide ( $\text{SnO}_2$ ) film that replaces the metal layer and acts as window layer and antireflective coating due to its interesting optoelectronic characteristics (gap = 3.6 eV, refractive index 1.9-2.0). the last step is the deposition of silicon ( $\text{Si}$ ) thin layer which have a large forbidden band of 9eV with a high resistivity. Under light illumination, the generated electrons-holes pairs are directly separated by the internal electrical fields which yield a photocurrent density  $j_{ph}$ . Two types of electrical fields are produced; one at the depletion region of the MIS contact and the other field is located at the contact depletion region of semiconductor 1 and semiconductor 2 ( Fig;1).

The insulating layer inserted between the metal and the semiconductor leads to the decrease of the thermoelectronic current as a result of the higher Schottky barrier. Concerning the  $\text{Ga}_{1-x}\text{In}_x\text{P}$  / GaAs interface, we have noticed that the two semiconductors have different conduction band energies and valence band energies. The electric potential difference  $V$  of the illuminated solar device is the sum of two components:  $V_i$ , generated at the insulating layer and  $V_s$ , produced at the depletion region of the semiconductor. The difference of potential is then  $V = V_s + V_i$ . The voltage  $V_i$  heightens the barrier between  $\text{SnO}_2$  and GaInP which will make difficult for electrons to pass through by thermal effect  $B^* = B_n + V_i$ . A higher barrier means that tunnel effect is the common mechanism for electron to get through the insulating layer. The current density in the  $\text{SnO}_2/\text{SiO}_2/\text{GaInP}$  structure is:  $J = J_{TH} - J_{TE}$ .

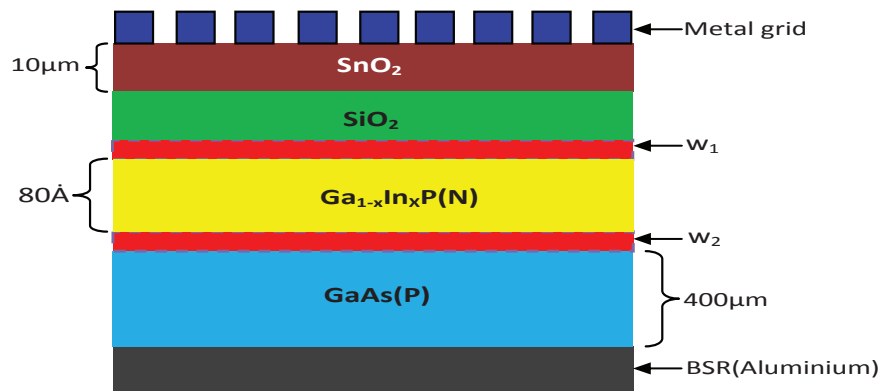


Fig .1: structure of the studied solar cell

## 3. Electrical characteristics of the $\text{SnO}_2/\text{SiO}_2/\text{GaInP}/\text{GaAs}$ solar cell

In the electrical characterization of solar cells, we have to extract Current-Voltage  $J(V)$ , curves under illumination condition and calculate the maximum power delivered by the device and its light conversion efficiency. The current density of the structure is given by the equation:

$$j = j_{ph} - j_0 \left[ e^{\left(\frac{q\Delta}{kT}\right)} e^{\left(\frac{qV_s}{kT}\right)} - 1 \right] - j_s \left[ e^{\frac{eV}{kT}} - 1 \right] \quad (1)$$

The short-circuit current ( $j_{sc}$ ) of the solar cell is expressed:

$$j_{sc} = j_{ph} - j_s \left[ e^{\left(\frac{q\alpha\Delta}{kT}\right)} - 1 \right] - j_0 \left[ e^{\frac{q(\Delta+\alpha\Delta)}{kT}} - 1 \right] \quad (2)$$

$\alpha$ : absorption coefficient of the semiconductor.

Open-circuit voltage  $V_{oc}$  of the solar cell is the sum of two voltages :  $V_{oc} = V_{oc1} + V_{oc2}$ .

$V_{oc1}$  of  $\text{SnO}_2/\text{SiO}_2/\text{GaInP}$  structure is given by:

$$V_{oc1} = \frac{kT}{q} \ln \frac{j_{ph} + j_0 + j_s}{j_0 \exp[q(\Delta + \alpha\Delta)/kT] + j_s \exp(q\alpha\Delta/kT)} \quad (3)$$

$V_{oc2}$  of the  $\text{Ga}_{(1-x)}\text{In}_x\text{P}/\text{GaAs}$  heterojunction structure is given by

$$V_{oc2} = \frac{E_{g-st}}{q} - \frac{kT}{q} \ln \left( \frac{j_0}{j_{cc}} \right) \quad (4)$$

The photocurrent density crossing the MIS device is expressed by the equation below [7]:

$$j_{ph} = q \int_{\lambda_1}^{\lambda_2} F(\lambda) QE.(\lambda) d\lambda \quad (5)$$

$F(\lambda)$ : is the solar spectrum AMG1.5,  $\lambda_1$  and  $\lambda_2$  are wavelengths limits of absorbed solar spectrum. Taking into account the multiple reflections of light in the front and rear surfaces of the solar cell, optical electron-hole pair's generation rate is expressed in the following:

$$QE(\lambda) = [1 - R(\lambda)] \times e^{\{-\sum_{i=1}^2 \alpha_i z_i\}} \times [1 - e^{(-\alpha_{\text{GaAs}} L_{\text{GaAs}} - h c_{\text{GaInP}} \alpha_{\text{GaInP}})}] \quad (6)$$

Where  $R(\lambda)$  is the surface spectrum reflectivity, the first exponential factor results from the attenuation of light in the previous layers of the cell,  $\alpha_i$  and  $z_i$  are respectively the absorption coefficient and the width of the precedent layers. It is noted that in our case, the upper layers are  $\text{SnO}_2$  and  $\text{SiO}_2$  which possess an absorption coefficient ( $\alpha_i = 0$ ),  $\alpha_{\text{GaAs}}$  and  $L_{\text{GaAs}}$  are the absorption coefficient and the width of the bulk material GaAs,  $\alpha_{\text{GaInP}}$  and  $h c_{\text{GaInP}}$  are respectively the absorption coefficient and the width of the top lattice layer.

## 4. Results

Figure.1 shows the variation of the bandgap energy vs indium content. We have noticed that the gap decreases with increasing indium concentration whereas the strain decreases. For In concentration  $x=0.48$  (lattice matching), the gap equals 1.7eV but for  $x > 0.48$  the uniaxial compression gap is less than 1.7eV with the strain  $\Delta a/a > 0$ . A given example is for  $x=0.90$ , the strain is  $\Delta a/a = 3\%$  with the strain gap being  $E_{\text{ghh-st}}=1.46\text{eV}$ . We have maximum structure absorption in the case of a compressive strain as found elsewhere [8]. Figure.2 shows the variation of the absorption with incident light energy  $E$ . The absorption increases with higher indium concentration. In the case we have a compressive strain; the absorption is more significant than the case of a lattice match in grand extensive strain. For example, if  $\Delta a/a = 3\%$  the maximum absorption is  $\alpha_{\text{max}}=2.35.10^5\text{cm}^{-1}$ . After the results of the structure GaInP absorbs better than InAsN. Figure.3 shows the  $J(V)$  characteristics for different indium concentrations. For higher indium concentration, we notice that current density  $J_{cc}$  decreases while the open circuit voltage  $V_{oc}$  increase. The opposite happens in an extensive strain case  $\Delta a/a < 0$ ,  $J_{cc}$  is at a maximum and  $V_{oc}$  is minimal. The opposite effect is obtained

for a compressive strain  $\Delta a/a > 0$  and where we can see that the fill factor FF increases. Figure.4 shows the variation of the structure power with the voltage. The maximum power delivered by the solar cell augments with higher compressive strain and lowers with an extensive one. For example, in the case of lattice matching  $\Delta a/a = 0$ , the maximal power amounts to 43mW but if we increase the strain to  $\Delta a/a = 3\%$  the power reaches 49mW that is an increase of  $\Delta P_{\max} = 6\text{mW}$ .

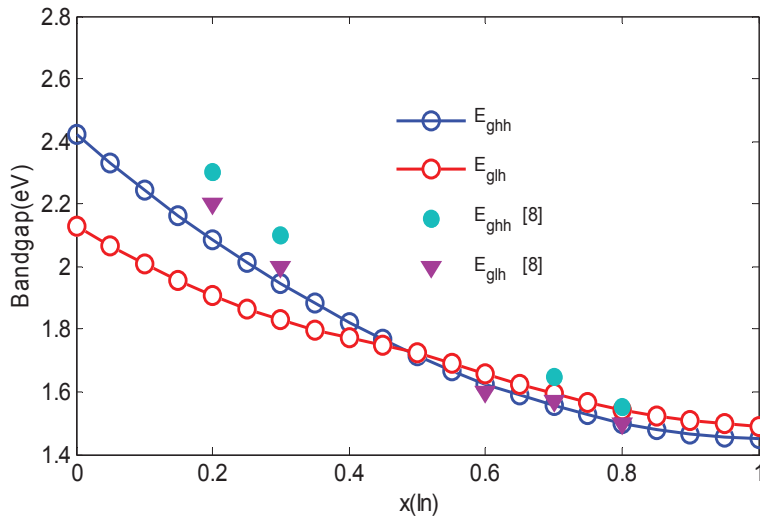


Fig.1: variation of the bandgap energy as a function of the indium concentration.

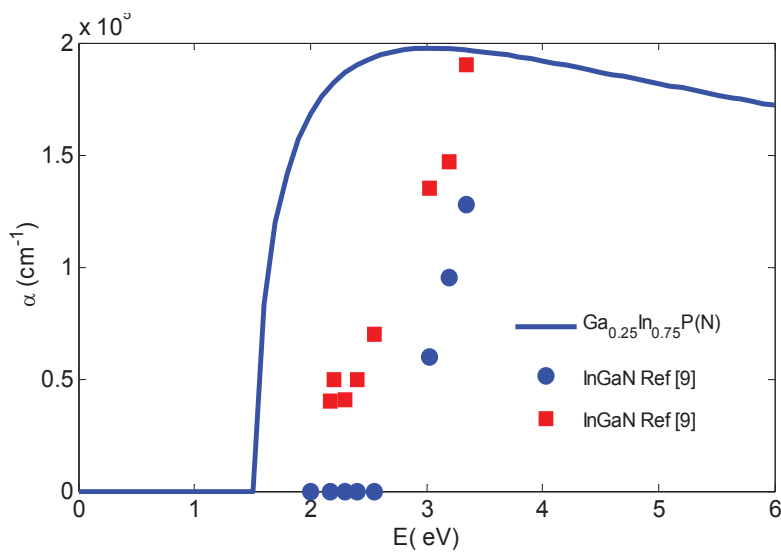


Fig.2: absorption variation of GaInP structure as a function of the incident energy for different indium concentrations

Figure. 5 depicts the efficiency evolution of the GaInP/GaAs structure vs the strain  $\Delta a/a$ . It is clearly seen that  $\eta$  increases when the strain increases. The solar cell efficiency is maximum when  $\Delta a/a > 0$  and is higher for thicker  $\text{SiO}_2$  insulating layers. For a deformation of  $\Delta a/a = 3\%$  and a thickness of  $\delta = 50\text{\AA}$  we will have an efficiency of 27%. For example, if we consider a GaInP/GaAs structure with a  $50\text{\AA}$  thick insulating layer and a deformation  $\Delta a/a = 1.2\%$ , having an efficiency  $\eta = 23\%$ , raising the deformation to  $\Delta a/a = 3\%$  will raise  $\eta$  to 27% : this is a relative improvement of  $\Delta\eta = 3.4\%$ . If we keep the deformation constant at  $\Delta a/a = 1.2\%$  and let the  $\text{SiO}_2$  insulating layer thickness vary between 10 and  $50\text{\AA}$ , the efficiency get boosted by  $\Delta\eta = 7\%$ .

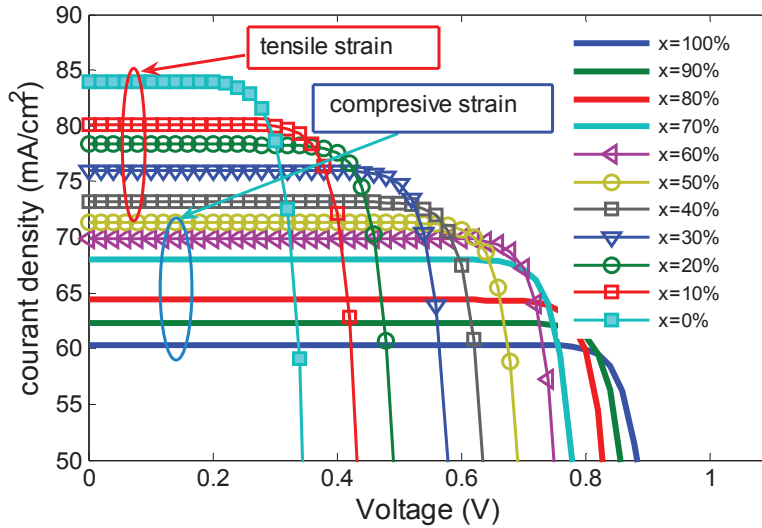


Fig.3: J(V) characteristic for various indium concentrations, voltage variation ( $V_{oc}$ ) and the current density ( $J_{cc}$ ) as a function of indium concentration

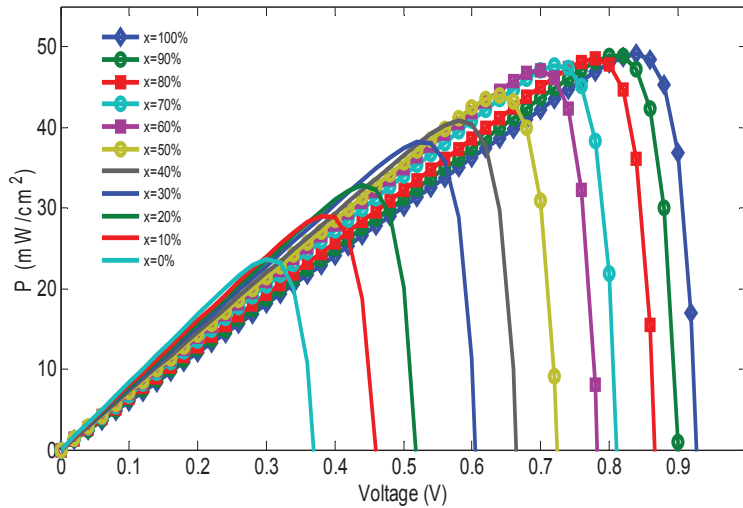


Fig.4: Variation of power according to the voltage for different indium concentrations

Figure.6 represents the variation of solar spectrum versus wavelength. The width of the absorption becomes larger when the strain varies. For an extensive strain of  $\Delta a/a = -0.025$ , we notice that the absorption width varies between 310 to 520 nm. In a lattice matched case, the width is larger and varies between 310 to 710 nm. In the opposite situation, where we have a compressive strain  $\Delta a/a = +0.03$ , the absorption width varies from 310 to 860 nm. Our structure prove the ability to turn more light into current and obtain higher efficiency by modifying the strain value and  $\text{SiO}_2$  insulating layer thickness.

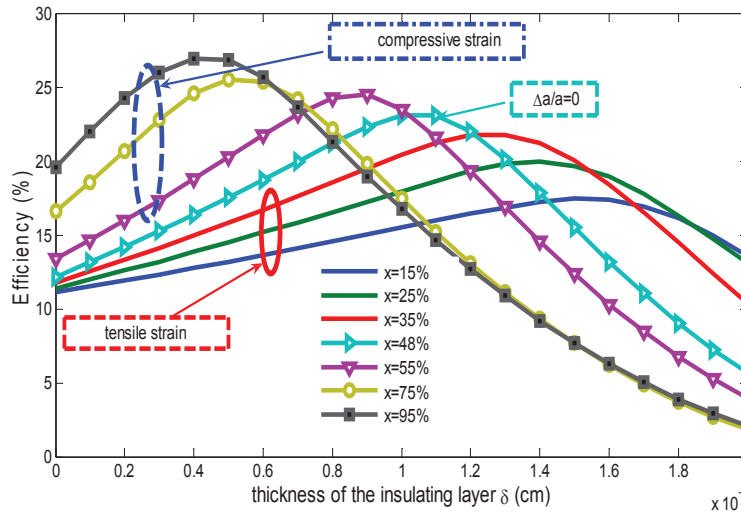


Fig.5: efficiency variation as a function of the thickness of the insulating layer  $\text{SiO}_2$  for different indium concentrations

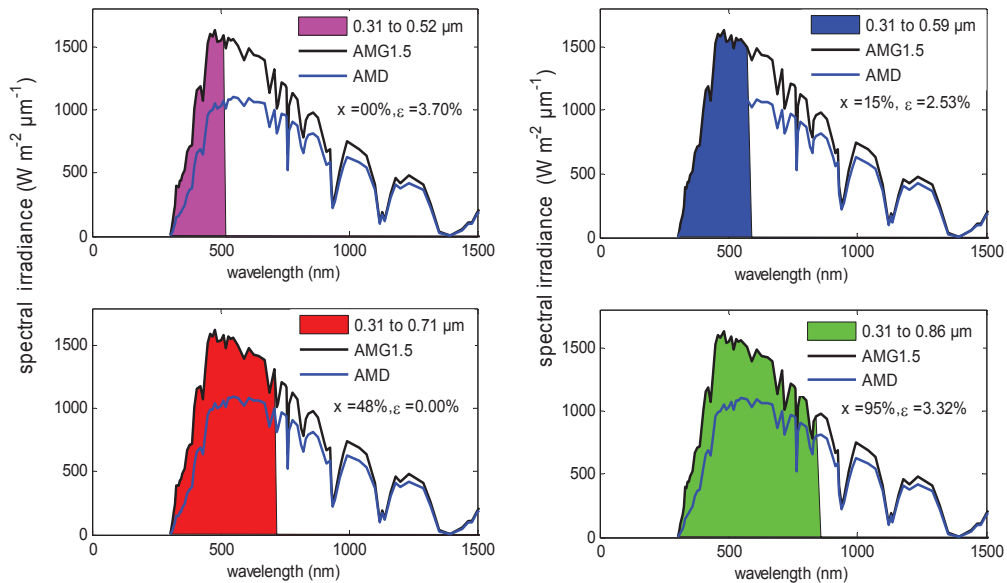


Fig. 6 The effect of the indium concentration on the absorption of solar spectrum

## 5. Conclusion

In our study, it has been shown the influence of the  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  structure strain and  $\text{SiO}_2$  insulating layer thickness  $\delta$  on the solar cell light conversion efficiency. We have demonstrated that the compressive strain influences considerably and enhances the absorption, the quantum efficiency and the efficiency. We noticed that a thicker  $\text{SiO}_2$  insulating layer ameliorates the efficiency ( $\eta$ ). Our findings show that for a compressive strain of  $\Delta a/a = 3\%$  and  $\text{SiO}_2$  thickness  $\delta = 5\text{nm}$ , the efficiency is  $\sim 27\%$  where as EQE reaches 92% in the spectral range 310–860 nm. These results show the effects of insulating layer thickness and strain parameters and their role in optimizing multi-junction and quantum multiwell structures.

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