Optimizing Quantum Well Solar Cell Efficiency Through Genetic Algorithms

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ABSTRACT

This work presents a research about photovoltaic cells using quantum wells. The use of quantum wells has been seen as an alternative to increase the cells energy conversion efficiency. The main target is the development of a methodology based on genetic algorithms to design these devices and establish a project to synthesize an optimized cell. The results archived are in agreement with the physical experiments and demonstrate the potential of the quantum wells in the growth of photovoltaic cells efficiency.

Keyword: Photovoltaic Cells, Quantum Wells, Genetic Algorithm.

1 SEMICONDUCTOR SOLAR CELLS

Most of the photovoltaic cells are PN junction devices, also known as diodes. The current-voltage relationship of a diode on lighting is provided by equation 1 [1], [2], [3].

$$J(V) = J_0(e^{\frac{qV}{kT}} - 1) - J_{ph} \qquad (1)$$

J_{ph} is the density current generated by the incident light on the device. This term is also known as photocurrent. J_0 is the density of the reverse saturation current q is the electric charge key, k Boltzmann constant and T the temperature.

When a photovoltaic device is not under illumination, the term J_{ph} takes the value zero and the resulting characteristic curve is called dark current curve. This current flows in the opposite direction of the photocurrent when the device is under forward bias. A good photovoltaic device must have a low dark current to favor the photocurrent [2]. It is easy to see that a solar cell with a good income must have high values for V_{oc} and J_{sc}. However, this statement is not completely correct. In fact, this condition is necessary but not sufficient for high performance of a photovoltaic device.

To achieve a better energy conversion, the voltage-current relation of the device must be rectangular as possible and, in the ideal case, formed by the hatched rectangle defined by J_{sc} and V_{oc}. The term Fill Factor (FF) means the measure that indicates how close to an ideal rectangle the diode curve is. This parameter is defined as the ratio between the area of hatched rectangle (ideally) and the area of the rectangle defined by JM and VM

which defines the maximum power point. This relationship is shown in equation 2. With these three

parameters V_{oc} , J_{sc} and FF, in equation 3, it is defined the most important figure of merit for a photovoltaic cell, the efficiency.

$$FF = \frac{V_m J_m}{V_{oc} J_{sc}} \qquad (2)$$

$$\eta = \frac{P_m}{P_{in}} = \frac{FF V_{oc} J_{sc}}{P_{in}} \qquad (3)$$

In a photovoltaic cell operating, various electronic processes occur, inherent to the device, which cause loss in power conversion capacity. Figure 1 illustrates these losses. The incidence of photons with less wavelength than the gap of the material will not contribute to the generation of the photovoltaic effect; they will not be absorbed by the semiconductor. In the case of a solar cell, in which the radiation occurred is composed by photons with various wavelengths, this will result in a loss of conversion efficiency of the device. This process is indicated by 1 in the figure.

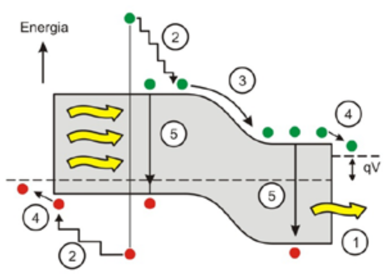

Figure 1: Losses in photovoltaic cell.

2 LIMITS OF EFFICIENCY

The efficiency of a photovoltaic cell is limited by the nature of energy conversion. The thermodynamic processes involved require the retention of physical quantities such as entropy, temperature and energy and, consequently, set a limit to the effectiveness of the device.

In 1961 Shockley and Queisser made a study about energy efficiency of solar cells using PN junction with a single material [4]. Shockley and Queisser's work was extended by Henry, performing the calculation for terrestrial solar cells [5]. In his work, Henry related the efficiency to the gap of the material that is used in homojunction.

Considering limits imposed for solar cells with PN homojunction by the theory of detailed balance, many types of photovoltaic devices that could overcome this limit have been proposed over the years. Such devices were known as high-efficiency photovoltaic cells.

In order that efficiency of a solar cell be not limited by Shockley-Queisser theory, the device must be designed in such a way that does not meet the assumptions imposed by it.

This study will address the solar cells using strained quantum wells. The expectation is that this type of technology helps to increase the efficiency of solar cells, as some experimental results.

The solar cells using quantum wells have been proposed by [6]. The aim of this formulation was to take advantage of absorption in different regions of the spectrum, increasing the short-circuit current without influencing the open-circuit voltage. Thus it would be possible to optimize separately these two figures of merit of a photovoltaic device.

Another advantage of the insertion of quantum wells is the reduction of losses by thermalization. The discretization of energy levels in one direction contributes to increased spectral selectivity, preventing a carrier is excited to higher levels. Systems using quantum wells have been studied a lot during the 90's for applications on LEDs, semiconductor lasers and photo detectors. Despite the maturity of research in natural systems, its application for photovoltaic devices is still under investigation [7], [8], [9], [10].

The structure of a photovoltaic cell using quantum wells is shown in Figure 2. Its organization is composed of a PIN diode with quantum wells embedded in an intrinsic layer, theoretically not doped.

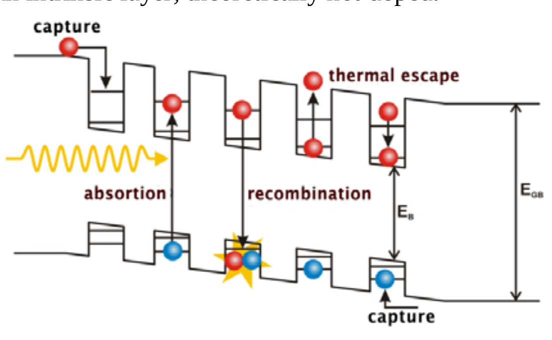

Figure 2: Band diagram of a quantum well solar cell.

The quantum well layers create discrete levels, in the growth direction, smaller than the gap of the material which constitutes the cell. This causes an increasing of the spectral range of absorption. When the electron-hole pairs are produced by absorption, they are trapped in the potential well. The wells are considered large enough so that carriers do not tunneling the potential barrier. Therefore, the only way to a carrier contribute to an electric current is to escape the potential well by thermal excitation. As in [10], it is assumed that this process occurs with probability near to unit for room temperature.

The intrinsic layer is formed using semiconductors with different band gap in the barrier and well. Generally the barrier material is the same as used in the N and P layers of the cell. The semiconductors must be selected such that the difference in lattice parameter not may cause a defect. In device with tensioned wells, the lattice parameter of the material of the barrier and well are very different, causing a voltage between the layers. This phenomenon can lead to defects in materials, increasing energy losses. However, the use of materials with different lattice parameters is necessary to achieve deeper wells and thus get more levels of absorption. This constraint leads to an optimization problem here discussed.

3 CELL OPTIMIZATION

A genetic algorithm is employed to evolve cell's parameters using a simulator that provides the efficiency of solar cell that it represents. The design of solar cells using quantum wells shares the same characteristics. Six design parameters are common to all models: width, depth and number of wells. In addition to the doping of phase separation, the width of layers P and N. Depending on the model used or the carrying out of minor changes the number of variables increases.

Another hinder action in this project is a committed relationship among the variables involved. For example, the increase of wells' number elevates the short-circuit current. However, it reduces the open-circuit voltage. As we have already seen, both are directly linked to efficiency, being necessary to look for a balance point. One of the challenging aspect found in this project is that the tension between the layers well / barrier cannot produce defects. This is a nonlinear constraint that is best described with their equations in [11], which is approached by using the GENOCOP technique [12].

4 RESULTS AND CONCLUSIONS

The device that will be presented is a solar cell illuminated by AM1.5 spectrum. The input variables of the optimization system, with the result obtained by the genetic algorithm, are shown in Table 1. One way to evaluate a solar cell using quantum wells is comparing its performance to a homojunction cell with the same configuration. The purpose of this comparison is to measure the real benefit of the inclusion of quantum wells in the intrinsic layer. In the cell obtained by the optimization system, the increase of efficiency over its equivalent homojunction is 4.5%. In Table 1, it can be observed that the insertion of wells in the intrinsic layer degrades the open-circuit voltage but the increase in short-circuit current is sufficient to compensate for the loss and increase efficiency. In the references there are results considering the same cell type but these results cannot be compared, because they use experimental techniques for increasing efficiency as anti-reflection covers and the performance provided by these devices are not in the simulator.

The low barrier height is justified by the adequacy of the solution to the restriction of not generating defects between the layers. The genetic algorithm identifies that there is a major benefit in increasing the amount of wells and decrease the absorption spectrum.

Parameter	Optimized Cell	Homojunction Cell	Limits
Doping (cm-3)	4.70 x 10^{15}	4.70 x 10^{15}	[10^{15}, 10^{19}]
N thickness (nm)	5700	5700	[20, 7000]
P thickness (nm)	100	100	[20, 500]
Ga barrier (%)	0.9	0.9	[0.0, 1.0]
Well thickness (nm)	46	-	[1, 50]
Number of wells	21	15	[5, 30]
J_{SC} (A/m^2)	184.48 (+5.87%)	174.25	-
V_{OC} (V)	0.92 (-2.13%)	0.94	-
Efficiency (%)	14.6 (+4.50%)	12.67	-

Table 1: Results of the evolution of a solar cell using quantum wells.

The low level of doping is an expected result. It induces the enlargement of the wide diffusion of minority carriers, increasing the absorption of layers N and P. The thickness of the neutral zones reflects two of the best features of the genetic algorithm. The area P has an intermediate thickness, but it is not thick enough to affect the absorption into the deeper layers and not so thin to decrease its contribution to the photocurrent.

Layer N has to be very thick in order to absorb all light that passed through the upper layers. In the output of optimization system, there are 50 solutions that correspond to the size of population. In some of them, efficiency values were identical and only the value of N thickness was different. This reflects an interesting characteristic discovered by the genetic algorithm. From a certain value of the thickness increase, area N is irrelevant to the performance of the device, since it does not mean an increase in the photocurrent.

The amount available in Table 1 for the N layer thickness does not correspond to the smallest possible value. It corresponds to the lower value of solutions provided by the optimization system, although it is possible to modify it to attend this constraint. The greatest benefit provided by the genetic algorithm was the ability to meet the strong restriction of non inclusion of defects in strained layers. The device does not generate faults obtained in accordance with the equation used strained quantum wells and provide a major mechanism for increased efficiency. The use of genetic algorithms in the design of this type of photovoltaic device is unprecedented. The technique proved attractive qualities such as flexibility of use and low need for specific knowledge of the problem.

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