Lifetime enhancement for multiphoton absorption in intermediate band solar cells

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Received 22 March 2017
Accepted for publication 14 June 2017
Published 5 July 2017

Abstract
A semiconductor structure consisting of two coupled quantum wells embedded into the intrinsic region of a p–i–n junction is proposed as an intermediate band solar cell with a photon ratchet state, which would lead to increasing the cell efficiency. The conduction subband of the right-hand side quantum well works as the intermedidated band, whereas the excited conduction subband of the left-hand side quantum well operates as the ratchet state. The photoelectrons in the intermediate band are scattered through the thin wells barrier and accumulated into the ratchet subband. A rate equation model for describing the charge transport properties is presented. The efficiency of the current generation is analyzed by studying the occupation of the wells subbands, taking into account the charge dynamic behavior provided by the electrical contacts connected to the cell. The current generation efficiency depends essentially from the relations between the generation, recombination rates and the scattering rate to the ratchet state. The inclusion of the ratchet states led to both an increase and a decrease in the cell current depending on the transition rates. This suggests that the coupling between the intermediate band and the ratchet state is a key point in developing an efficient solar cell.

Keywords: intermediate band solar cells, intersubband transitions, multiphoton processes, quantum well, cell current

(Some figures may appear in colour only in the online journal)
semiconductor band gap [3, 13]. However, the carrier extraction from localized states often involves inelastic processes, like multiphoton excitation [5, 14]. This becomes a new problem due to the low carrier lifetime within the QW subbands with respect to interband recombination processes [1].

To overcome this difficulty, designed structures with photon ratchet states were first proposed by Yoshida and coworkers [1] in order to enhance the efficiency of an IBSC by increasing the electron lifetime into the IB, allowing efficient sequential photon absorption [1, 6, 7]. The ratchet states are states optically—and electrically—coupled to the CB and decoupled from the VB, acting as scattering channels for electrons excited in the IB. The coupling between the IB and the ratchet states allows increasing the lifetimes of the excited electrons into the IB. This might increases the multiphoton transition probability and, consequently, the solar cell efficiency [7].

In order to check the viability of using QW-based IBSC, Pusch and coworkers [7] developed a thermodynamical model to describe ISBC efficiency in terms of its absorptivity. They showed that the inclusion of the intermediate band by itself is not a determining condition for overcome Shockley–Queisser limit [9]. They provide conditions in which the IBSC presents poorer efficiency than the single junction one and conclude that, only when adding ratchet states the IBSC will always be more efficient then a single junction one, independently of the absorptivity. These results give motivation to analyze in details the structures that consider ratchet states and, more importantly, the mechanisms underlying the ratchet transport dynamics.

Quantum cascade laser (QCL) design-like has been proposed both theoretically [6, 7] and experimentally [5, 15] as the ratchet transport dynamics in the IBSC. It was showed feasible and promising for increasing the cell efficiency. In such an approach, the energy difference between the states in the IB and the ratchet states are set to be nearly equal to the host-semiconductor LO-phonon energy [16]. This gives rise to a phonon-assisted scattering process between the IB and the ratchet states. Therefore, the optically generated electron–hole pair is spatially shifted, the recombination probability is decreased, and the electron lifetime is increased within the IB. As a concept proof of using QCL-like devices to enhance solar cell efficiency, an optimization algorithm to design a type-II antimonide-based superlattice was developed by Curtin et al [6]. They showed the possibility of using QW-based structures with QW subbands working as ratchet states in the IBSC. Sugiyama and coworkers [15] provided experimental evidence for multiphoton absorption processes when QW-based structures are employed as an IBSC. They claimed the importance of the cascade process to enhance the electron lifetime within the IB. Noda and coworkers [10], also experimentally showed that the multiphoton absorption increases the efficiency of the QW-based IBSC. They pointed out that the relations between recombination and escape rates mainly determine the increase in the photocurrent. However, more information about the transport dynamics along the excitation/scattering/excitation process, which can directly affects the efficiency of an IBSC with ratchet states, is still missed in the literature.

In what follows, we propose a $p-i-n$ layered structure with two coupled QWs embedded into the intrinsic semiconductor region, to be implemented as an IBSC with the photon ratchet state. The transport dynamics follows closely the QCL-like operation in the IB. We analyze the current response of the cell by means of a rate equation model, where the recombination and generation rates are obtained directly from the QWs eigenfunctions. Once we are dealing with quantum devices, studies of this kind of structures must rely on their quantum properties. In the present case, the QW subbands are the basis of the cell operation [8, 12, 17], and, therefore, a quantum mechanics treatment is required.

A direct correlation between the scattering rate to the ratchet state and the recombination rates is established which, under some circumstances, leads to the increase of the cell current. However, we met conditions that even with the electron scattering to the ratchet states a decrease of the net current is observed implying in a decrease of the IBSC efficiency.

2. Double quantum well as a intermediate band material

As discussed earlier, the major barrier of using QW subbands as IBs is the very short electron lifetime in the IB as compared with its recombination time back to the VB. Allowing for such an electron relaxing to the ratchet state might increase its lifetime and, consequently, the efficiency of the two-photon absorption process [6, 7].

In order to enhance the current generation, the chosen device was thought to have two QWs, and the operation based on the dynamics of photon absorption and emission processes across their states. As we can observe in figure 1, the left-hand side quantum well (QW$_{\text{left}}$) is wider, with two confined subbands in the conduction band, than the right-hand side one (QW$_{\text{right}}$), in which there is only one. The QW$_{\text{right}}$ subband is intended to work as the IB and the QW$_{\text{left}}$ excited subband as the ratchet state. Being the latter an excited state, it is decoupled from VB ground state for interband transitions according to the selection rules [18, 19]. The presence of the ratchet states enables new pathways to intersubband absorption processes hopefully increasing even more the current generation.

The material and parameters used to simulate the IBSC was taken from the literature [10]. The 1 μm wider intrinsic layer and the doped contacts have been chosen to be Ga$_x$Al$_{1-x}$As, with $x = 0.3$. GaAs layers form QW$_{\text{right}}$ and QW$_{\text{left}}$ with widths of 110 Å and 40 Å, respectively, coupled each other by a 80 Å GaAs heterobarrier, as shown in figure 1. The QW widths are chosen such that the energy shift between the QW$_{\text{right}}$ ground state and the QW$_{\text{left}}$ excited state is about 32 meV, the GaAs LO-phonon energy [19]. The source–drain contacts, $p$ and $n$ layers, respectively, are doped with concentrations of $N = 10^{17}$ cm$^{-3}$. With no bias applied to the device, the Fermi level, at thermal equilibrium, is the same throughout the structure (see the bold black-dashed line in figure 1(a)). This gives rise to a built-in potential, $\epsilon V_{bi} = 4.2$ eV, due to the depletion of the potential profile in the intrinsic region. Therefore a drift field is established, responsible for extracting
photogenerated carriers towards the drain (n) contact [8]. In order to restore the thermal equilibrium, the same amount of drained charge is re-injected by the source (p) contact into the cell, producing, as a net effect, the generation of a short-circuit current on the external circuit.

The energy diagram changes in the presence of a bias due to the thermodynamic equilibration of the contact electrochemical potential of the carriers, as shown in figure 1(b) for the reverse bias condition, and in figure 1(c) for the forward bias condition. The levels occupation is determined by the quasi-Fermi level equilibration and the charge transfer established by the contacts. For forward bias condition, the optical generation of current is not expected, because the CB states at thermal equilibrium are completely occupied, unless inelastic scattering processes (common in a p–i–n diode) [8], are taken into account. However, this is not considered in the present model.

3. Rate equation model

In order to describe the carrier excitation and recombination dynamics, a semiclassical rate equation model is developed considering the electronic subbands as simple levels. In figure 2 the optical processes are depicted schematically. The spaced-hatch orange boxes represent the valence levels at the QW_{left} and QW_{right}, with carrier concentrations N_{ir} and N_{ir}, respectively. The closed-hatch green boxes represent the intermediate levels, within carriers concentrations of N_{ir}, N_{il}^{\text{end}}, and N_{il}^{\text{ex}}, considering the QW_{left} with a ground and an excited levels. N_{c} is the carrier concentration of the CB level. G(R)_{ij}, with s = l, r, is the generation (recombination) rate for the photon absorption from band i to j at the s-hand side quantum well (s = l, r). T_{iv} is the scattering rate between QW_{left} and QW_{right} at I(V) band.

(c) Structure under forward bias

Figure 2. Levels schematics showing the possible transitions and their respective rates. The spaced-hatch orange boxes represent the valence levels at the QW_{left} and QW_{right}, with carrier concentrations of N_{ir} and N_{ir}, respectively. The closed-hatch green boxes represents the intermediate levels, within carriers concentrations of N_{ir}, N_{il}^{\text{end}}, and N_{il}^{\text{ex}}, considering the QW_{left} with a ground and an excited levels. N_{c} is the carrier concentration of the CB level. G(R)_{ij}, with s = l, r, is the generation (recombination) rate for the photon absorption from band i to j at the s-hand side quantum well (s = l, r). T_{iv} is the scattering rate between QW_{left} and QW_{right} at I(V) band.

(considering the QW_{left} with a ground and an excited level). N_{c} is the carrier concentration of the CB level. G(R)_{ij}, with s = l, r, is the generation (recombination) rate for the photon absorption from band i to j at the s-hand side quantum well (s = l, r). T_{iv} is the scattering rate between QW_{left} and QW_{right} at I(V) band, which is related to the phonon-assisted scattering process between the IB and the ratchet state, and here is taken as a simulation control parameter. All these processes lead to time variation of the carrier concentrations.

Explicitly, the rate equations for the electron concentration in the specific bands can be written as

\[
\frac{dN_{il}}{dt} = G_{il}^{l}N_{il} + R_{il}^{l}N_{il} - (G_{il}^{l} + R_{il}^{l})N_{il} - T_{il}N_{il}.
\]  (1)

\[
\frac{dN_{il}^{\text{ex}}}{dt} = T_{il}N_{il} + R_{il}^{l}N_{il} + G_{il}^{l}N_{il}^{\text{end}} - (G_{il}^{l} + R_{il}^{l})N_{il}^{\text{ex}}.
\]  (2)

\[
\frac{dN_{il}^{\text{end}}}{dt} = G_{il}^{l}N_{il} + R_{il}^{l}N_{il}^{\text{ex}} - (G_{il}^{l} + R_{il}^{l})N_{il}^{\text{end}}.
\]  (3)

\[
\frac{dN_{il}}{dt} = G_{il}^{l}N_{il} + G_{il}^{l}N_{il}^{\text{ex}} - (G_{il}^{l} + R_{il}^{l})N_{il}.
\]  (4)

From equation (1) the steady state condition, dN_{il}/dt = 0, is such that

\[
N_{il} = \frac{G_{il}^{l}N_{il} + R_{il}^{l}N_{il}}{G_{il}^{l} + R_{il}^{l} + T_{il}}.
\]  (5)

Equation (2), also at steady state condition (dN_{il}^{\text{ex}}/dt = 0), yields
\[
N_{\text{gs}}^{\text{ex}} = \frac{G_i^1 G_i^1 N_i + (G_i^1 + R_i^1)(R_i^1 N_i + T_i N_i)}{G_i^1 + R_i^1}.
\]

Now, we can use equation (3) to determine the relation between the excited level in the QW left, considering once more the steady state condition, \(\text{d}N_{\text{gs}}^{\text{ex}}/\text{d}t = 0\). This gives
\[
N_{\text{gs}}^{\text{ex}} = \frac{G_i^1 G_i^1}{G_i^1 + R_i^1} + \frac{R_i^1 N_i}{G_i^1 + R_i^1}.
\]

Back to the equation (6), and after some simple algebra, we obtain
\[
N_{\text{gs}}^{\text{ex}} = \frac{G_i^1 G_i^1 N_i + (G_i^1 + R_i^1)(R_i^1 N_i + T_i N_i)}{G_i^1 + R_i^1}.
\]

Using equations (5) and (8), into equation (4), we arrive at
\[
\text{d}N_i = \kappa N_i + \frac{G_i^1 G_i^1 N_i}{\gamma} + \frac{G_i^1 + R_i^1}{\gamma} \left[ G_i^1 + \frac{G_i^1}{G_i^1 + R_i^1} \right] + \frac{1}{G_i^1 + R_i^1 + T_i},
\]

where
\[
\kappa = \frac{G_i^1 + R_i^1}{G_i^1 + R_i^1 + T_i} - 1
\]

and
\[
\kappa = \frac{G_i^1 + R_i^1}{G_i^1 + R_i^1 + T_i} - 1.
\]

4. Transition rates calculations

The photogeneration process is mainly a result of two interband transitions, one at the bulk region and the other one at the QW region. However, in the latter case, a second transition needs to take place in order to transit carriers from the confined subbands to the CB [1, 10]. Both the tunneling process and the intersubband transition to continuum states which are extended throughout the contacts region can be used as such additional process [6, 7, 15]. Therefore, the information about the transitions rates interplay is rather fundamental.

The transition rates are determined by means of the Fermi’s golden rule [19], using the eigenfunctions and eigenstates obtained by solving the time-dependent Schrödinger equation within the effective mass approximation and parabolic CB and VB decoupled from each other. The solution approach was the Split Operator method within the imaginary time evolution [20, 21].

The generation rate of electrons excited from VB to CB at bulk region, by photons with energy \(h\omega\), is given by [19]
\[
G_{\text{cc}}^{\text{bulk}}(h\omega) = \frac{2\pi n_{ph}^2}{3h\omega} \left( \frac{2\pi}{m^*} \right)^{3/2} D_{vc}(h\omega),
\]

where \(\omega = \pi e^2/hm^*c\), \(e\) and \(m^*\) are the electron charge and effective mass, respectively, \(c\) is the GaAs dielectric constant, \(n_{ph}\) is the photon density set to unity, and \(D_{vc}\) is the momentum matrix element, which is determined using the Kane approximation [18, 19]. \(D_{vc}\) is the 3D electronic density of states given by
\[
D_{vc}(h\omega) = \sqrt{\frac{(m^*)^{3/2}}{\pi^2\hbar^3}} \frac{\sqrt{\hbar\omega - E_g}}{E_g},
\]

with \(E_g\) being the semiconductor band gap.

In the QW region, the generation rates, \(G_{\text{cc}}^{\text{h1}}\), are obtained by changing the dimensional character of the density of states (from three to two) and taking into account the overlap of the envelope functions. So
\[
D_{vc}(h\omega) = \frac{m^{3/2}}{\pi\hbar^2 L_{\text{QW}}} \sum \left| \phi_{\text{e}}^n \phi_{\text{c}}^g \right|^2 \Theta(E_{mn} - h\omega),
\]

where the sum is over the valence \(\phi_{\text{c}}^g\) and the conduction band \(\phi_{\text{e}}^n\) eigenstates, separated in energy by \(E_{mn} = E_g - E_n - E_m\). \(L_{\text{QW}}\) is the well width, and \(\Theta\) is the Heaviside step function.

The interband generation rates, \(G_{\text{cc}}^{\text{h1}}\), are obtained by
\[
G_{\text{cc}}^{\text{h1}}(h\omega) = \frac{n_{ph} E_g}{\hbar\omega} \sum D_{vc}(F(E_m) f(E_m) - 1),
\]

where \(E_g = 23\) eV is the Kane energy for GaAs [19]. The sum is done over the VB \(m\) and CB states \(n\), weighted by their occupations given by the Fermi distributions \(f(E_{mn})\). The quasi-Fermi level is determined by the contacts electrochemical potentials [8].

The intersubband generation rates in the QW region, \(G_{\text{ic}}^{\text{h1}}\), are given by
\[
G_{\text{ic}}^{\text{h1}}(h\omega) = \omega h = \frac{n_{ph}}{\hbar\omega L_{\text{QW}}} \sum |p_{\text{ic}}|^2 f(E_i) - 1,
\]

where the sum is performed over the QW localized subbands \((i, j)\), also taking into account their occupations given by the Fermi distributions \(f(E_i)\). The intersubband momentum matrix element is
\[
p_{\text{ic}} = \sum_{\text{QW}} \frac{-\hbar \left| \psi_{\text{ic}}^{(h)} \right|^2}{\hbar L_{\text{QW}}} \psi_j^{(h)},
\]

where \(\psi_j^{(h)}\) is the left (right) QW ith subband eigenfunction, with energy \(E_j\). The intersubband recombination rate in the QW left, \(R_i^1\) is considered to be constant, with value equal to 10 GHz.
From the evaluation of generation and recombination rates we are able to feed the rate equation model of section 3 and determine the level dynamics. The results are presented in the next section.

5. Results and discussion

In the IBSC-like devices, the electrons, excited from both VB and IB towards CB, should be extracted from QWs regions by the drain contact, in order to restore the thermal equilibrium. Hence, in the model, we consider the infinite mobility limit \[ l = \infty \], in which every excited electron from IB to CB is extracted from the cell effective region, allowing efficient charge collection by the drain contact \[ l = 2 \]. The infinite mobility limit is modeled by preventing electrons to relax back from the continuum to the QW subbands, putting \[ N_{\text{ic}} = N_{\text{iv}} = 0 \] in the equation (10) such that \[ \kappa = 0 \].

To analyze the contribution of adding the QWleft to the structure, we first consider the QWs uncoupled from each other, i.e. taking \[ T_1 = 0 \] in equation (9). We obtain

\[
\frac{dN_{\text{ic}}^{T_1=0}}{dt} = \frac{G_{\text{ic}}^lG_{\text{ic}}^r}{\gamma}N_{\text{il}} + \frac{G_{\text{ic}}^lG_{\text{iv}}^r}{G_{\text{ic}}^l + R_{\text{iv}}^r}N_{\text{ir}}. \tag{16}
\]

We clearly see that both QWleft and QWright, when uncoupled, might contribute independently to carrier concentration change in the conduction band. The contribution is proportional to their valence band concentrations, \[ N_{\text{il}} \] and \[ N_{\text{ir}} \], weighted by the specific generation rate \[ G_{\text{ic}}^l \], with respect to the recombination rates \[ R_{\text{iv}}^r \]. As greater the recombination rate with respect to the generation one, as lesser effective the current generation process.

We now may define a net current, \( I_1 \), proportional to the difference of the carrier concentrations in the CB for coupled \( (T_1 = 0) \) and uncoupled \( (T_1 = 0) \) QWs, as

\[
I_1 = e \left[ \frac{dN_{\text{ic}}^{T_1=0}}{dt} - \frac{dN_{\text{ic}}^{T_1=0}}{dt} \right]. \tag{17}
\]

Substituting equations (9) and (16) into equation (17), we arrive at

\[
I_1 = eG_{\text{ic}}^lT_1 \left[ \frac{(G_{\text{ic}}^l + R_{\text{iv}}^r)G_{\text{ic}}^l}{\gamma} - \frac{G_{\text{ic}}^l}{G_{\text{ic}}^l + R_{\text{iv}}^r} \right]. \tag{18}
\]

Such a net current is interpreted as the contribution (to the current) of adding the additional scattering channel, charging the ratchet state. It would enhance the carrier lifetime at the IB, increasing the cell efficiency.

In figure 3, we present the net current, given by equation (18), as a function of the scattering rate \( T_1 \) and the potential of the cell. The potential is varied from reverse to forward bias relative to the built-in potential, uniformly spread through the intrinsic region of the cell (see figures 1(b) and (c)). For \( T_1 \) greater than 1 GHz, we observe an effective enhancement of the net current with a pronounced peak close to the value of the built-in potential for potential between 3 and 4 eV. The peak intensity increases with increasing the scattering rate until it saturates for \( T_1 \) greater than 500 GHz. Such a behavior is understood as follows. As given by Equations (13) and (14), the interband generation rate \( G_{\text{ic}}^l \), and the interband recombination rate \( R_{\text{iv}}^r \) are determined by a conjunction of three factors—the \( \Theta \) step function, the overlap between valence and intermediate subband eigenfunctions which appears in equation (13), and the Fermi distributions. Therefore, low energy photons (relative to the band separation) are unable to excite electrons from VB to IB as required by the step function. The photoelectron excitation at higher energies is conditioned by the external bias applied to the cell, which controls the quasi-Fermi levels, and by the overlap between the VB and IB eigenstates that decreases with increasing the energy separation from each other.

In the reverse bias condition, including the built-in potential condition, the hole subbands are kept occupied due to the electrochemical potential of the source contact, whereas the electron subbands are kept emptied by the drain contact as shown by the quasi-Fermi levels in the figure 1(b). The opposite turns out in the forward bias condition, as we can see in the quasi-Fermi levels shown in the figure 1(c). In this condition, the current flowing in the cell is zero except by the presence of inelastic scattering processes, in which electrons recombine back to the VB, for instance as in the LED, by emitting photons \[ 8, 18 \]. Therefore, the quasi-Fermi levels, determined by the bias potential, are an essential factor for determining both the generation and the recombination rates. The quasi-Fermi levels guide the behavior of the cell current, as will be discussed next.

As it was said before, the net current is non-null only for reverse bias, as determined by the levels occupations. Analyzing equation (18) in details, we observe that the first term of the square-bracketed factor, related to the transitions in the QWleft, exhibits a step-like shape approaching 1 for potentials smaller than \( -4 \) eV, and zero elsewhere. The second term, coming from the transitions in the QWright, has the same behavior, but the step value is close to 1 only for potentials smaller than \( -3 \) eV. Hence, the net current peak boundaries are given by the intensity relationship between the generation and recombination processes in the QWleft and QWright regions.

![Figure 3. Net current as a function of the potential applied to the cell and the scattering rate \( T_1 \) between the QWleft and QWright. The inset shows the profile of the liquid current for \( T_1 = 132.5 \) GHz.](image-url)
The step-like behavior of the net current discussed above follows closely the same behavior of the recombination rates \( R_{iv}^{lr} \). Even though the values of the recombination rates are three to four orders of magnitude smaller than those of the generation rates \( G_{ic}^{lr} \), the later are peaked functions with maxima at specific bias values and zero elsewhere. For such bias values, both the first and the second terms in the square-bracketed factor of equation (18) are close to 1, because the generation rates are the dominant terms. However, for bias greater than 3 eV (4 eV), \( R_{iv}^{lr} \) is the dominant rate and the term in the square brackets vanishes. Consequently, the net current is different from zero only in that specific potential range.

These results suggest that the inclusion of the additional QW subband promotes an effective enhancement of the cell current due to its coupling to the QW right. The width of the peak in the net current is, therefore, controlled by subband occupation of both QWs, which, in turn, determines the recombination rates cutoffs by the potential. So, the net current peak could in principle be enlarged by increasing the energy separation between the QW right state (IB) and the ground state of the QW left, responsible by uncoupling the ratchet state from the VB.

The saturation, which determines the net current peak intensity, is mainly driven by the first factor appearing in equation (18). It takes into account the balance between both recombination \( R_{iv}^{lr} \) and generation \( G_{ic}^{lr} \) rates of the QW right, with respect to the scattering rate between the QWs \( T_s \) themselves. Once more the step-like shape of the recombination rate \( R_{iv}^{lr} \) with a maximum value around 100 GHz, is responsible for controlling the net current. Increasing \( R_{iv}^{lr} \), the electron concentration decreases in the IB and, consequently, also the probability of such electrons to be scattered to the QW left with rate \( T_i \). Therefore, for \( T_i \) less than such a recombination rate, a decrease in the cell current is observed.

Our results clearly show an enhancement of the current generation in the IBSC, when the excited state of the QW left works as the photon ratchet state. This is in consonance with results of Pusch and coworkers [7], who pointed out that current enhancement of the IBSC is always achieved when the ratchet states are included.

However, we also observed that even introducing the photon ratchet state in our model there are conditions in which the enhancement of the IBSC current is not achieved. As discussed earlier, the net current behavior is a consequence of the contributions of several generation and recombination processes. Figure 4 depicts the net current dependence of the intersubband recombination rate \( R_i ^{iv} \) for the scattering rate of \( T_i = 10 \) GHz and a reverse bias of 3.8 eV. We observe the change in the net current signal, which becomes negative for high \( R_i ^{iv} \), indicating that increasing \( R_i ^{iv} \), which controls the electron concentration within the ratchet state, can give a unfavorable behavior of the net current for specific conditions.

Independently of how effective is the coupling between the IB and the ratchet state with respect to the scattering \( T_i \) rate, our model gives conditions in which the introduction of the ratchet states can not lead to the enhancement of the cell current. Allowing electrons to be scattered to the ratchet state should in principle increase their lifetime in the IB, but the balance between the recombination and the generation rates can either increase or decrease the solar cell current depending on the charge/discharge dynamics of the ratchet state.

6. Conclusion

In summary, we have demonstrated the possibility of considering QW subbands as the IB and the photon ratchet state of an IBSC, by employing a quantum cascade like approach. The cell was considered to be a double-coupled QW structure with GaAlAs and GaAs layers sandwiched by heavily doped GaAs contacts. The system eigenfunctions were numerically calculated by solving the time-dependent Schrödinger equation within the effective mass approximation and uncoupled parabolic VB and CB, by means of the split-operator method. The recombination and generation rates, used in a semiclassical rate equation model, were obtained by means of the Fermi’s golden rule. By allowing electrons to be scattered to the ratchet state, we have observed an effective increase in the cell current for specific values of bias close to the built-in potential of the cell. In accordance with other works, under some circumstances, the inclusion of the ratchet state increases the solar cell current, by increasing the electron lifetime in the IB. However, the addition of the ratchet state is not the only condition for determining the cell efficiency. The recombination and generation dynamics plays a fundamental role, and we can observe specific cases in which we do not achieve an enhancement of the cell current even with the inclusion of the ratchet state. Furthermore, to achieve an effective enhancement in the cell efficiency a better understanding of the generation, recombination and scattering processes should be considered.
Acknowledgments

This work is funded by the Brazilian agencies Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes). The authors thank Marcos H Degani for useful suggestions and Patricia L de Souza for a critical reading of the manuscript.

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