Thermionic Current Modeling and Equivalent Circuit of a III-V MQW P-I-N Photovoltaic Heterostructure

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Abstract: - We explore the relation between photogeneration and recombination currents in an illuminated III-V p-i -n multiple quantum well (mqw) solar cell, via an improved p-n junction equivalent circuit. P-i-n solar cells with their intrinsic region replaced by a multilayered heterostructure (e.g. GaAs-AlGaAs thin successive layers) are devices of exceptional performance, when illuminated, for two main reasons (a) they provide wider optical windows to incident solar photons, compared to their bulk counterparts, and therefore higher number of photo-excited carriers and (b) they reduce recombination in the intrinsic region, thus leading to more pronounced thermal currents out of the quantum wells. In the present communication, incident photons are modeled as two current sources representing photogenerated (I_{ph}) and recombining electrons (I_r) respectively, along with the shunt and series resistance of such devices. General relations are developed for open circuit voltage V_{oc}, short circuit current I_{sc}, incident power, all as functions of net (after recombination) thermionic currents $I_{th} = I_{ph} - I_r$. The basic device equivalent circuit is improved by including (a) a photogeneration current-source and (b) a recombination (due to losses) current-source, the net effect of which is a third thermionic current source I_{th}. The latter circuit element strongly depends on the incident photon flux and on the selected geometry of the p-i-n heterostructure device.

Key-Words: - Solar cells, equivalent circuit, photogeneration, recombination

1. Introduction

Photo-carriers in GaAs-AlGaAs quantum well systems are subject to recombination mechanisms that may lead to a reduction of overall collected currents. Single or multiple quantum wells are useful probes for the study of trapped carriers that may escape recombination and eventually contribute to thermionic currents of various types of devices. General theoretical expressions are developed here, for trapped excess carriers in such quantum wells, when illuminated through incident photon flux G(λ). The situation of intrinsic and/or lightly doped quantum wells based on III-V semiconductor layers (e.g. low-gap GaAs layers grown on wide-gap AlGaAs layers) has become a common p/i/n solar cell design aiming to better understanding [1,2] and overall device improvement. In general, two types of quantum well designs are of interest: (a) quantum wells are far from each other (AlGaAs layers are much thicker compared to narrow GaAs layer widths) ensuring *negligible* tunneling current contribution and (b) thin potential barriers that may sustain tunneling. In either case, when the device is illuminated, excited carriers (coming from generated electron-hole pairs (ehp's)) may find themselves in the quantum wells, where they face two options: either recombine or contribute to current. Now, depending on the geometry design mentioned above, these carriers might either escape thermionically to the continuum of the conduction band or tunnel through thin potential barriers to be collected at the end of the device. In the absence of any type of tunneling, it is desired to analytically calculate any non-negligible thermionic current density (*in mA/cm²/per quantum well*), by considering low background doping of the GaAs layers (thus, minimizing impurity scattering).

2. Theory

2.1 Carrier diffusion

The device structure in mind is a p/i/n GaAs-AlGaAs solar cell with the intrinsic region (length L_i) comprised of a sequence of quantum wells and potential barriers made out of low and wide gap GaAs and AlGaAs layers respectively. Miniband solutions are expected to exist in these finite quantum wells, so that they may serve as traps of photogenerated carriers arising from the valence band after optical excitation. It is expected that illumination of the intrinsic region will cause direct generation of electron-hole pairs (ehp's), thus contributing to increased carrier-concentration in each quantum well. Such population increase is then expected to escape from the wells into the conduction band continuum leading to prospective current density components. The task here is to propose a method of (a) determining photo-carrier concentration δN (in cm^{-2}) in each well, and (b) evaluating thermal currents out of each quantum well. In the process, two recombination mechanisms are taken into account, namely, Auger and radiation recombination, while Shockley-Read-Hall (SRH) recombination is not included, for not being dominant in direct-gap systems as the one adopted here [3,4,5].

A general method of dealing with the diffused photo-carriers has been provided elsewhere [6]. Photo-carriers are separated by the built-in field and then *diffuse* along the growth direction of the device. The latter event is described via the diffusion equation solution:

$$\delta n(x) = n_1 e^{x/L_n} + n_2 e^{-x/L_n} + n_3 e^{-\alpha x} + n_4 e^{-\alpha x/2} \qquad (1)$$

Thermionic currents are typically expressed in terms of excess carriers $\delta n(x)$ is the per-volume excess carrier concentration {v(E) is the carrier's thermal velocity as function of its kinetic energy, *g(E)* and *f(E)* are the density of states (DOS)} and Maxwellian distribution respectively

$$J_{th} = q\iint dx dE \delta n(x)[g(E)f(E)]v(E) \qquad (2)$$

Final excess carrier concentrations δN (cm^{-2}) depend strongly on a number of parameters, such as the geometry of the device, the absorption coefficient and the diffusion length of electrons. The term g(E)f(E) represents the "availability" factor including (a) the 2-d density of states (DOS) of the systems involved and (b) the occupation probability (Maxwell-Boltzmann distribution as long as E_c-E_F >3kT). The last term in the same line of current density represents the velocity of electrons escaping from the lowest energy level in the quantum wells E_1 (to infinity). The integrals involved sweep the extents of quantum wells and a continuum of energy values from lowest miniband to very high energies. Thermal current densities are found from (2):

$$J_{th} = A^{**} \times L_w \times \delta n \times T^{3/2} e^{-\delta E_1 / kT} e^{-(E_c - E_F)/kT} \qquad (3)$$

Where A** = 1.462mA/cm/$K^{3/2}$, δn is the net excess carrier (after recombination) per well, δE_1 is the energy miniband per quantum well, E_c-E_F energy distance of the Fermi level from the conduction band of each GaAs layer (bottom of the quantum well).

2.2 Equivalent Circuit

Equivalent circuit modeling of any solar cell includes the following "circuit" elements:

(a) independent current source I_{ph}, representing photocurrents directly connected to the incoming solar photon flux
(b) independent current source I_{rec} due to Auger and radiation recombination losses
(c) diode current I_d
(d) series resistance R_s
(e) shunt resistance R_{sh}

The net effect of I_{ph} and I_{rec} is *thermionic* current I_{th} (or thermal current density J_{th}). The latter is due to carriers (electrons) thermally escaping from quantum wells in the intrinsic region. The latter region's geometry includes a series of quantum wells (multiple quantum wells: mqw's) and generates electric current when illuminated: this current comes from escaping electrons (under no tunneling) and contributes to overall device conduction. Total load current density then reads as follows:

$$J = J_{th} - J_o \left(e^{q\beta_n (V + Jr_s)} - 1 \right) - \frac{V + Jr_s}{r_{sh}} \qquad (4)$$

Where J is the total load current density, J_o is the reverse saturation current of the diode (p-n junction), V is the output-load voltage, $\beta_n=(nkT)^{-1}$ is the temperature factor with the quality factor n included, r_s, r_{sh} (Ω cm^2) represent series and shunt resistance values, essentially resistivity times length. These ohmic elements are due to (i) bulk semiconductor resistance (ii) contact(s) resistance (iii) current leakage and (iv) imperfections in total device structure. Under open-circuit conditions (OC), the expression above becomes:

$$0 = J_{th} - J_o \left(e^{q\beta_n V_{oc}} - 1 \right) - \frac{V_{oc}}{r_{sh}} \qquad (5)$$

From which the T-dependence of open circuit voltage dV_{oc}/dT is found to be:

$$\frac{dV_{oc}}{dT} = \frac{r_{sh}J_oV_{oc}}{nkT^2}\frac{e^{q\beta_nV_{oc}}}{1+(r_{sh}J_oq\beta_n)e^{q\beta_nV_{oc}}} + \frac{r_{sh}(dJ_{th}/dT)}{1+(r_{sh}J_oq\beta_n)e^{q\beta_nV_{oc}}} \qquad (6)$$

Expression (5) is certainly more complicated and in more detail, than what is usually taken for granted in the wider literature [7].
Under short-circuit (SC)-conditions, (4) leads to (V=0, $J=J_{sc}$):

$$J_{th} = J_{sc}(1+\frac{r_s}{rr_{sh}}) + J_o(e^{q\beta_nJ_{sc}r_s} - 1) \qquad (7)$$

Temperature variation of J_{sc} is found from *(7)* above:

$$\frac{dJ_{sc}}{dT} = \frac{dJ_{th}/dT}{(1+\frac{r_s}{r_{sh}}) + q\beta_nJ_or_se^{q\beta_nJ_{sc}r_s}}$$

$$+\frac{qJ_oJ_{sc}r_s}{nkT^2}\times\frac{e^{q\beta_nJ_{sc}r_s}}{1+(q\beta_nJ_or_s)e^{q\beta_nJ_{sc}r_s}} \qquad (8)$$

Where again, (8) provides a more detailed expression of temperature dependence of J_{sc} than the one usually taken for granted for single p-n junction solar cells. Both (6) and (8) express, in detail, the temperature dependence of the two characteristic parameters of any photovoltaic structure: V_{oc} and J_{sc} (or I_{sc}). In both (6) and (8), resistive elements are explicitly involved via r_s and r_{sh}, which in turn may be related in the following way: on one hand r_{sh} can be found from (5), given V_{oc} and J_{th}, and on the other, r_s may be computed from a connection between expressions (5) and (7). It is found that, for mqw-based p-i-n photovoltaic heterostructures, values of r_{sh}/r_s ratios are well in excess of 100, in other words r_s can always be determined.

2.3 Power Considerations

Revisiting (4), one may re-write the J-V characteristic as follows:

$$J + (V/r_{sh}) = \frac{J_{th}+J_o}{1+(r_s/r_{sh})} - \frac{J_o}{1+(r_s/r_{sh})}e^{q\beta_n(V+Jr_s)} \qquad (9)$$

The voltage V of a typical mqw-pin solar cell does not exceed 0.85V [Aperathitis, Varonides et al], and the shunt resistance of such devices is well in excess of 3.4kΩ, so that the ratio (V/r_{sh}) represents current density values varying from $0.033mA/cm^2$ to $0.3mA/cm^2$, which makes the term negligible compared to total device current in the region of maximum current production from the device. In other words, under optimum or maximum power conditions, the second term in (9) may be neglected, so that (9) leads to expressing voltage as an (easier to deal with, in most practical applications) function of total J:

$$V = \frac{nkT}{q} ln\left\{ (1+\frac{J_n}{J_o}) - (1+\frac{r_s}{r_{sh}})\frac{J}{J_o} \right\} - Jr_s \qquad (10)$$

Incident power density P_{in} is calculated as follows:

$$P_{in} = \int_0^{J_{sc}} V(J)dJ = \frac{nkT}{q}(J_{sc} - \frac{J_o + J_{th}}{1+(r_s/r_{sh})})\left\{ ln\left[\frac{J_{th} - (1+(r_s/r_{sh})J_{sc}}{J_o} + 1 \right] - 1 \right\}$$

$$+ (\frac{J_{th} + J_o}{1+(r_s/r_{sh})}(nkT/q)\left\{ ln(\frac{J_o + J_{th}}{J_o}) + 1 \right\} - \frac{1}{2} r_s J^2{}_{sc} \qquad (11)$$

Expression (11) is used for computation of r_s [schroeder et al], under $r_{sh} >> r_s$ conditions, but in the present context, (11) could be used for incident power density evaluations within, specific limits of J_{sc}, namely from $J_{sc}/2$ to J_{sc} (within which the maximum power point may fall into).

3 Results

A number of parameters of importance in these devices, namely, quantum well width L_w, photo-generated carriers δn (cm^{-2}), temperature as $T^{3/2}$, ground state dE_1 depending on the well width, and quasi-Fermi level position in reference with the conduction band of the GaAs layer (bottom of the quantum well). Computations of J_{th} from (2) via (1) show that 10nm GaAs layers interfaced with thick AlGaAs layers in the intrinsic region are expected to contribute thermal current density values between 0.1 to 0.9 mA/cm^2/per quantum layer under illumination levels of the order of 10^{17}incident photons/cm^2. Also, current of 9mA/cm^2/quantum well predicted at 30°C (10nm quantum well and 10^{12} cm^{-3} doping of the GaAs layer). Photo-generated carrier concentrations at levels of $\delta n=10^{12}$ cm^{-2}/L_w (= 10nm), may lead to current densities of values at 4.5mA/cm^2/well, at 30°C, and 4mA/cm^2/quantum well at -10°C. For low doping levels in the intrinsic region (so that impurity scattering is minimized) multiplicity of quantum wells in the illuminated intrinsic region of *p/n(mqw)/n* solar cells will improve overall collected current densities and hence efficiencies. Thermal current components J_{th} as computed via (3) become important current sources as circuit elements in the solar cell equivalent circuit. This component includes (1) temperature effects (2) loss mechanisms (via recombination) (3) device specific geometry (quantum well width, and therefore energy bands in the quantum wells) and (4) incident photon flux. Expression (6) provides an explicit temperature variation of the open circuit voltage V_{oc}, in terms of the resistive elements of the device and in terms of the temperature variation of the thermal current J_{th}. In a similar fashion expression (8) provides a detailed description of the temperature dependence of the short circuit current J_{sc} Finally, incident power P_{in} is calculated from (11), thus leading to a general relation for the series resistance of the device (area method of series resistance determination). It is found that a 40-quantum well (10nm) p-i-n solar cell (GaAs-AlGaAs) exhibits shunt resistance of the order of 3,400Ω, for series resistance values at usual cell operation at less than 5Ω.

4 Conclusions

The aim of this communication is two-fold: (a) to provide an explicit method of thermal current calculation out of the intrinsic region of a multi-quantum well pin-solar cell, when illuminated and (b) to deal with its circuit behavior under the above conditions. It is found that such a device may provide substantial current values, which may be appropriately interpreted as current sources. Such currents have been derived from general device physics considerations that have included losses (due to recombination mechanisms) and in the following sequence: first, given the incident power of solar photons, excited carrier concentrations in the quantum wells are being calculated, and the corresponding thermal current is provided as a function of the incident radiation wavelength and device geometry. Next, an equivalent circuit is proposed with net current sources involved and two resistive elements (shunt and series) computed. Finally, temperature variation of open-circuit voltage and short circuit current is provided by means of an improved generalized formula that includes temperature, both shunt and series resistive elements, and thermionic currents.

References

[1] E. Aperathitis, A.C. Varonides et al, Temperature Dependence of Photocurrent Components in Enhanced Performance GaAs/AlGaAs Multiple Quantum Well Solar Cells, *Solar Energy Materials & Solar Cells,* Vol. 70, 2001, pp. 49-69.

[2] K.K. Choi, *The Physics of Quantum Well Infrared Photodetectors,* World Scientific, 1997.

[3] D.K. Schroeder, The Concept of Generation and Recombination Lifetimes in Semiconductors, *IEEE Trans. Electron Devices, ED-29,* 1982, pp. 1336-1338.

[4] D.K. Schroeder, *Semiconductor Materials and Device Characterization,* Wiley Interscience, 1990.

[5] J. Pietzsch, T. Kamiya, Determination of Carrier Density Dependent Lifetime and Quantum Efficiency in Semiconductors with a Photoluminescence Method (Application to InGaAsP/InP Heterostructures, Appl. Physics A42, 1987, pp. 91-102.

[6] A.C. Varonides, Detailed Account of Net Photogenerated Carriers and Thermionic Currents at the Intrinsic Region of PIN/N^+ Single Quantum Well Solar Cells, *International Workshop on Nanostructures in Photovoltaics*, Max Planck Institute, Dresden Germany, 2001.

[7] Martin A. Green, *Solar Cells*, Prentice-Hall, 1982.