A FLUX ANALYSIS OF THE SOLAR CELLS

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A flux method for the analysis of the excess carrier transport in multiple layer solar cells is described. This method avoids the assumptions of the usual macroscopic device theory that the physical dimension of the system should be large compared with the mean free path of the excess carrier. In this analysis the macroscopic current is described in terms of the microscopic parameters of the excess carrier like mean free path, mean life time, and mean thermal velocity. The general formalism, presented here, can be applied to almost any type of solar cell structure. In the appropriate limits, the results of this formalism are shown to reduce to those obtained by earlier restricted analysis.

1. INTRODUCTION

The usual macroscopic theory[1] used to solve the problem of excess charge carrier transport in semiconductors involves the solution of the continuity equation together with a first order Boltzmann transport equation. This theory is based on the assumption that the mean free path of the charge carrier is much smaller than the physical dimension of the transport region[2]. In some very small scale devices and also in the depletion layer of some solar cell[2,3], this condition is not satisfied. In such cases one can question the validity of using the conventional macroscopic transport theory. In addition to this, in a very narrow depletion layer, electric field intensity is very high, which invalidates the first order Boltzmann transport equation.

In order to avoid these difficulties McKelvey, Longini and Brody[2] developed an alternative approach called flux method. Inicially this method was developed for isotropic transport in systems with no internal or external electric fields. Later on, the method was extended for nonisotropic transport in the presence of electric field[3,4]. Recently this method has been applied to model surface barrier[5-7] and multiple junction solar cells[8].

The flux method has the following advantages over the conventional macroscopic theory:

i) It is applicable to systems where usual continuity equation analysis is expected to break down. This occurs in systems whose physical dimension is of the order of or smaller than the mean free path of the charge carriers.

ii) It is easy to include the effects of scattering and absorption processes in any part of the transport region and the effects of boundary conditions at the surfaces and internal boundaries.

iii) The form of the flux equations is identical in every part of the transport region. Therefore, by determining the flux contributions from any region of the device, one can immedialy write down the expressions for the flux contribution from any other region. This modular nature of the flux equations makes it particularly more attractive for the multiple layer semiconductor devices.

iv) It provides an enhanced conceptual simplicity and physical insight for the processes of scattering and absorption of charge carrier in the bulk as well as at the surfaces.

In this article we study the nonisotropic charge carrier transport in a multiple layer semiconductor device in the presence of a uniform electric field. The general formalism, developed here; is an extension of that of Hinckley, McCann and Haneman[8]. Our formalism can be applied to any multiple layer solar cell for example p-n homojunction, p-n heterojunction, Schotlky barriers, and cascade solar cells etc. We have applied this method to obtain charge carrier flux in a single layer and found the results of earlier workers in appropriate limits.

2. THE FLUX METHOD

2.1 - REFLECTION, TRANSMISSION, AND ABSORPTION COEFFICIENTS IN A SEMICONDUCTING LAYER

The flux method describes the transport of charge carriers by accounting the carrier flux as it proceeds through a layer of a semiconductor material of arbitrary thickness. When the carrier flux, F_0, is incident on the surface of a semiconducting layer as shown in Fig. 1, the carriers go through a number of scattering and absorption processes. A part of the flux, $T(x) F_0$, is transmitted through the opposite side of the incident surface and another part, $R(x) F_0$, is reflected towards the side of the incident surface. The carrier flux, $A(x) F_0$, which is neither transmitted nor reflected is absorbed inside the layer due to absorption processes. In a semiconductor, absorption may occur either through the processe of electron and hole recombination or by trapping of charge carrier by trapping centers.

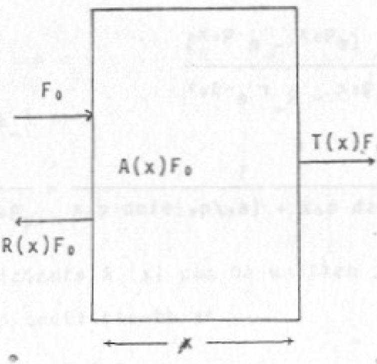


Fig. 1 - Transport of the charge carrier flux F_0 incident on a layer of thickness x.

The probability of reflection, transmission, and absorption of an incident carrier flux are given by the specific coefficients which can be easily derived[2]. Reflection and transmission coefficients depend upon the thickness of the layer and on back scattering and absorption probabilities. For carrier obeying the Maxwell Boltzmann statistics, the back scattering probability k_0 is[2]

$$k_0 = \frac{3}{4\lambda} \tag{1}$$

where λ is the carrier mean free path. The absorption probability ω_0 is[2]

$$\omega_0 = \frac{2}{\bar{c}\tau} \tag{2}$$

where $\bar{c}$ is the carrier mean thermal velocity and τ is the mean carrier lifetime. For isotropic transport processes, the reflection and transmission coefficients of a semiconducting layer of thickness x are given, respectively, by equations[2]

$$R(a_0, q_0, x) = \frac{k_0}{q_0} \frac{\sinh q_0 x}{\cosh q_0 x + (a_0/q_0)\sinh q_0 x}$$

$$= \frac{R_\infty (e^{q_0 x} - e^{-q_0 x})}{e^{q_0 x} - R_\infty^2 e^{-q_0 x}} \tag{3}$$

and

$$T(a_0, q_0, x) = \frac{1}{\cosh q_0 x + (a_0/q_0)\sinh q_0 x} = \frac{1 - R_\infty^2}{e^{q_0 x} - R_\infty^2 e^{-q_0 x}} , \tag{4}$$

where

$$a_0 = k_0 + \omega_0 \quad , \tag{5}$$

$$q_0^2 = a_0^2 - k_0^2 \quad , \tag{6}$$

and

$$R_\infty = \lim_{x\to\infty} R(a_0, q_0, x) = \frac{k_0}{a_0 + q_0} \sqrt{\frac{a_0 - q_0}{a_0 + q_0}} \tag{7}$$

In the presence of an electric field, the transport processes are nonisotropic. In this case back scattering and absorption probabilities are direction dependent. To treat this case, we can express the back scattering probability as k_+ or k_- depending upon whether it describes the carrier transport parellel or antiparallel, respectively, to the electric field direction. Similarly, the absorption probability is written as ω_+ or ω_-. In general,, the parameters $k_\pm$ and $\omega_\pm$ are position dependent quantities for a nonuniform electric field. Since, here, we consider a uniform electric field, we assume them to be position independent quantities. In a uniform electric field, the reflection and transmission coefficients are given as[3,4]:

$$R_\pm(x) = \sqrt{\frac{k_\pm}{k_\pm}}\; R(\overline{a}, q, x) \tag{8}$$

and

$$T_\pm(x) = e^{\pm\Delta x}\, T(\overline{a}, q, x) \quad , \tag{9}$$

whose

$$\overline{a} = \frac{1}{2}(a_+ + a_-) \quad , \tag{10}$$

$$\Delta = \frac{1}{2}\,(a_+ - a_-) \quad , \tag{11}$$

$$q_0 = \frac{1}{2}\,(\overline{a}^2 - k_+k_-) \quad , \tag{12}$$

and

$$a_\pm = k_\pm + \omega_+ \quad . \tag{13}$$

The absorption coefficients A (x) can be written in terms of reflection and transmission coefficients as

$$A_\pm(x) = 1 - R_\pm(x) - T_\pm(x) \quad . \tag{14}$$

2.2 - FLUX RELATIONS IN MULTIPLE LAYER SOLAR CELL

In a solar cell, the flux of excess charge carriers is generated by solar radiations and thermal energy. To study the transport of carrier flux in a multiple layer solar cell, we consider a solar cell structure of N homogeneous layers and N+1 boundaries as shown in Fig. 2. The layers and the parameters relating to the individual layer are denoted by the index i = 1...N. The layer i is bounded by the boundaries i-1 and i and each boundary i is located at a distance z_i from the front surface of the cell. The thickness of the layer i is denoted by $Y_1 = z_i - z_{i-1}$. The ith boundary is characterized by two reflection coefficients $R_i^\pm$ and two absorption coefficients $A_i^\pm$. The superscripts plus and minus refer to the flux travelling parallel and antiparallel to the electric field, respectively. The internal boundaries in a solar cell may correspond to the junctions between two semiconductors, junctions between different doping levels in the same semiconductors, or the boundaries between depletion and bulk layers etc.

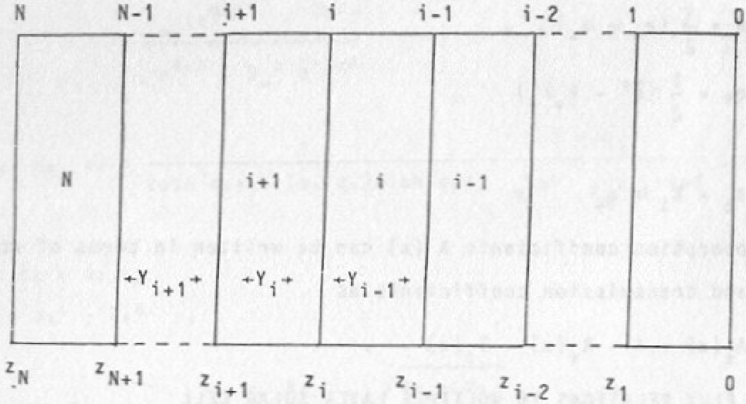


Fig. 2 - A multiple layer solar cell structure consisting of N layers and N+1 boundaries.

We wish to derive an expression for the flux incident on the k^{th} boundary $0 \leq k < i-1$ due to the generation of excess carriers in the i^{th} layer. For doing this, first we shall calculate the flux incident on the $(i-1)^{th}$ boundary. Let us assume that at any arbitrary point x in the i^{th} layer, there exists a point generation source which in a thin region of width dx generates carrier fluxes $g_i^+(x)$ and $g_i^-(x)$ moving in the directions parallel and antiparallel to the direction of electric field respectively. The exchange of carrier fluxes at the points z_i, x and z_{i-1} due to generation of fluxes $g_i^{\pm}(x)dx$ at the point x are shown in Fig. 3. The various fluxes shown in this figure are related by the following set of equations:

$$dF_i = c_{i+1}^- \, dF_i' \quad , \tag{15}$$

$$dF_i' = (1 - A_i^- - R_i^-) \, df_i' + R_i^+ \, dF_i \quad , \tag{16}$$

$$df_i = (1 - A_i^+ - R_i^+) \, dF_i + R_i^- \, df_i' \quad , \tag{17}$$

$$df_i' = R_+(z_i - x)df_i + T_-(z_i - x)dF' \quad , \tag{18}$$

$$dF = T_+(z_i - x)df_i + R_-(z_i - x)dF' + g_i^+ (x)dx \quad , \tag{19}$$

$$dF' = R_+(x-z_{i-1})dF + T_-(x-z_{i-1})dF'_{i-1} + g_i^-(x)dx \qquad (20)$$

$$dF_{i-1} = T_+(x-z_{i-1})dF + R_-(x-z_{i-1})dF'_{i-1} \qquad (21)$$

where c_{i+1}^- is defined as the effective reflection coefficient of the $(i+1)^{th}$ layer as seen by the flux travelling towards left of the i^{th} layer. This reflection coefficient includes the effect of reflection from the layers and boundaries extending from z_i to the back surface of the cell at z_N. On solving Eqs. (15) and (16), we get

$$dF' = T_{iE}^- \, df_i' \quad , \qquad (22)$$

where

$$T_{iE}^- = \frac{1 - A_i^- - R_i^-}{1 - c_{i+1}^- R_i^+} \qquad (23)$$

represents the effective transmission coefficient of the i^{th} boundary for transport in the direction opposite to the electric field. The effective reflection coefficient R_{iE}^- of the i^{th} boundary is obtained by solving Eqs. (15), (17) and (22). The simultaneous solution of these equations gives

$$df_i = R_{iE}^- \, df_i' \quad , \qquad (24)$$

where

$$R_{iE}^- = c_{i+1}^- (1 - A_i^+ - R_i^+) T_{iE}^- + R_i^- \quad . \qquad (25)$$

Now solving Eqs. (18), (19) and (24), we get

$$dF = R_-^E(z_i - x)dF' + g_i^+(x)dx \quad , \qquad (26)$$

where

$$R_-^E(z_i - x) = R_-(z_i - x) + \frac{T_+(z_i - x)\, T_-(z_i - x)\, R_{iE}^-}{1 - R_+(z_i - x)\, R_{iE}^-} \qquad (27)$$

is the effective reflection coefficient corresponding to the region between the points z_i and x. Finally, the simultaneous solution of Eqs. (20), (21) and (26) give the differential flux dF_{i-1} arriving at the

$(i-1)^{th}$ boundary in terms of the differential flux dF'_{i-1} leaving out of the $(i-1)^{th}$ boundary towards left as

$$dF_{i-1} = c_i^- \, dF'_{i-1} + d\phi_i(x) \tag{28}$$

where

$$c_i^- = R_-(x - z_{i-1}) + \frac{T_+(x - z_{i-1})\, T_-(x - z_{i-1})\, R_-^E(z_i - x)}{1 - R_+(x - z_{i-1})\, R_-^E(z_i - x)} \tag{29}$$

and

$$d\phi_i(x) = \frac{\{R_-^E(z_i - x)g_i^-(x) + g_i^+(x)\}\, T_+(x - z_{i-1})dx}{1 - R_+(x - z_{i-1})\, R_-^E(z_i - x)} \tag{30}$$

In absence of any generating source, i.e, for the case $g_i^{\pm}(x) = 0$, if we replace i by i+1 in Eq. (28), we see that c_{i+1}^- is also given by (29). Hence Eq. (29) can be considered as the general expression for the effective reflection coefficient of the i^{th} layer for the charge carrier travelling opposite to the electric field. By substituting the expressions for reflection and transmission coefficients from Eqs. (8) and (9) respectively in Eqs. (27), (29) and (30), we get

$$R_-^E(z_i - x) = \frac{R_{i\infty-} - R_{iA}\, e^{-2q_i(z_i - x)}}{1 - R_{i\infty+}\, R_{iA}\, e^{-2q_i(z_i - x)}} \tag{31}$$

$$c_i^- = \frac{R_{i\infty-} - R_{iA}\, e^{-2q_i\gamma_i}}{1 - R_{i\infty+}\, R_{iA}\, e^{-2q_i\gamma_i}} \tag{32}$$

and

$$d\phi_i(x) = dx\left\{1 - R_{i\infty+}\, R_{iA}\, e^{-2q_i\gamma_i}\right\}^{-1}\Big\{(R_{i\infty-}g_i^-(x) + g_i^+(x)) \times e^{-(q_i+\Delta_i)(x - z_{i-1})} - R_{iA}(g_i^-(x) + R_{i\infty+}g_i^+(x)) \times e^{-2q_i\gamma_i}\, e^{(q_i-\Delta_i)(x - z_{i-1})}\Big\} \tag{33}$$

where

$$R_{iA} = \frac{R_{i\infty-} - R_{iE}^{-}}{1 - R_{i\infty+}R_{iE}^{-}} \tag{34}$$

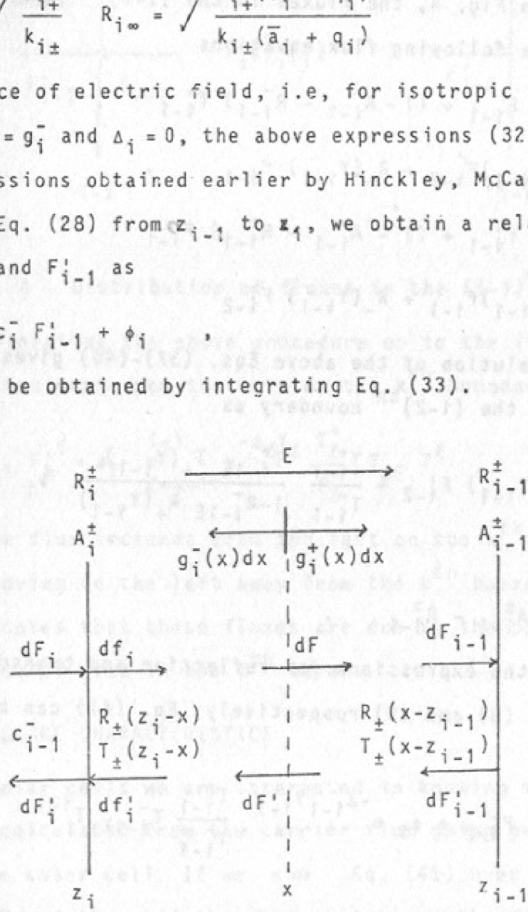
and

$$R_{i\infty\pm} = \sqrt{\frac{k_{i\mp}}{k_{i\pm}}} \quad R_{i\infty} = \sqrt{\frac{k_{i\mp}(\overline{a}_i - q_i)}{k_{i\pm}(\overline{a}_i + q_i)}} \tag{35}$$

In the absence of electric field, i.e, for isotropic transport when $k_{i+} = k_{i-}$, $g_i^+ = g_i^-$ and $\Delta_i = 0$, the above expressions (32) and (33) reduce to the expressions obtained earlier by Hinckley, McCann and Haneman[8]. Integrating Eq. (28) from z_{i-1} to z_i, we obtain a relation between the fluxes F_{i-1} and F'_{i-1} as

$$F_{i-1} = c_i^- F'_{i-1} + \phi_i \quad , \tag{36}$$

where ϕ_i can be obtained by integrating Eq. (33).



Fog. 3 - Distribution of fluxes in the i^{th} layer due to generation of fluxes $g_i^\pm(x)$ dx.

Now we calculate the flux at any arbitrary k^{th} boundary $(0 \leq k < i-1)$ due to the presence of a generating source of flux in the i^{th} layer. This can be done by calculating the flux incident at the $(i-2)^{th}$ boundary and then iterating the procedure up to the k^{th} boundary. As shown in Fig. 4, the fluxes in the $(i-1)^{th}$ layer can be obtained from the following flux equations

$$F'_{i-1} = R^{+}_{i-1} F_{i-1} + (1 - A^{-}_{i-1} - R^{-}_{i-1}) f'_{i-1} \quad , \tag{37}$$

$$f'_{i-1} = T_{-}(Y_{i-1}) F'_{i-2} + R_{+}(Y_{i-1}) f_{i-1} \quad , \tag{38}$$

$$f_{i-1} = R^{-}_{i-1} f'_{i-1} + (1 - A^{+}_{i-1} - R^{+}_{i-1}) F_{i-1} \tag{39}$$

$$F_{i-2} = T_{+}(Y_{i-1}) f_{i-1} + R_{-}(Y_{i-1}) F'_{i-2} \tag{40}$$

A simultaneous solution of the above Eqs. (37)-(40) gives the flux F_{i-2} incident on the $(i-2)^{th}$ boundary as

$$F_{i-2} = R_{-}^{E}(Y_{i-1}) F'_{i-2} + \frac{T^{+}_{i-1}}{T^{-}_{i-1}} \frac{T^{-}_{i-1E} T_{+}(Y_{i-1})}{1 - R^{-}_{i-1E} R_{+}(Y_{i-1})} \phi_i \quad , \tag{41}$$

where

$$T^{\pm}_{i-1} = 1 - A^{\pm}_{i-1} - R^{\pm}_{i-1} \quad . \tag{42}$$

By substituting the expressions for reflection and transmission coefficients from Eqs. (8) and (9) respectively, Eq. (41) can be simplified to

$$F_{i-2} = C^{-}_{i-1} F'_{i-2} + \phi_i \, e^{-\Delta_{i-1} Y_{i-1}} \frac{T^{+}_{i-1}}{T^{-}_{i-1}} T^{-}_{i-1E} \, T^{i-1} \quad , \tag{43}$$

where

$$T^{i-1} = \frac{1 - R^{2}_{i-1\infty}}{(1 - R^{-}_{i-1E} R_{i-1\infty+})(e^{q_{i-1} Y_{i-1}} - R_{i-1\infty+} R_{i-1A} e^{-q_{i-1} Y_{i-1}})} \quad . \tag{44}$$

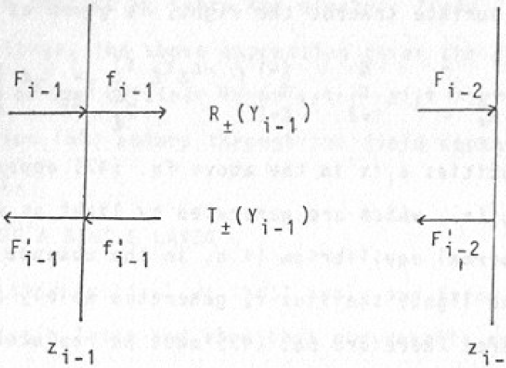


Fig. 4 - Distribution of fluxes in the $(i-1)^{th}$ layer.

By iterating the above procedure up to the $(k-1)^{th}$ layer, we get the flux incident from the left on the k^{th} boundary as

$$F_k^i = c_{k+1}^- F_k^{'i} + \phi_i \prod_{\ell=k+1}^{i-1} e^{-\Delta_\ell Y_\ell} \frac{T_\ell^+}{T_\ell^-} T_{\ell E}^- T^\ell \tag{45}$$

Here F_k^i is the flux incident from the left on the k^{th} boundary and $F_k^{i'}$ is the flux moving to the left away from the k^{th} boundary. The superscript i indicates that these fluxes are due to the presence of a generating source of flux in the i^{th} layer.

3. CURRENT-VOLTAGE CHARACTERISTICS

In solar cells we are interested in knowing the cell current which can be calculated from the carrier flux going out of the front surface of the solar cell. If we sum Eq. (45) over all values of i from i = 2 to N and then add the contribution of the first layer from Eq. (36), we get the total flux F_0 reaching at the front surface as

$$F_0 = c_1^- F_0' + \phi_1 + \sum_{i=2}^{N} \phi_i \prod_{\ell=1}^{i-1} \left\{ e^{-\Delta_\ell Y_\ell} \frac{T_\ell^+}{T_\ell^-} T_{\ell E}^- T^\ell \right\} \tag{46}$$

where $F_0 = \sum_i F_0^{i}$, and $F_0^{i} = \sum_i F_0^{i}$. Since $F_0^{i} = R_0^{+} F_0$, the flux f_0, going out of the front surface towards the right, is given as

$$f_0 = \frac{T_0^{+}}{1 - c_1^{-} R_0^{+}} \left[\phi_1 + \sum_{i=2}^{N} \phi_i \prod_{\ell=1}^{i-1} \left(e^{-\Delta_\ell \gamma_\ell} \frac{T_\ell^{+}}{T_\ell^{-}} T_{\ell E}^{-} \; T^{\ell} \right) \right] \quad . \tag{47}$$

The quantities ϕ_i's in the above Eq. (47) depend upon the generating fluxes $g_i^{\pm}(x)$, which are generated by light as well as by thermal energy. In thermal equilibrium (i.e, in the absence of external electric field and light) the flux f_0 generated solely by the thermal energy must be zero. Therefore Eq. (47) must be replaced by

$$f_0 = \frac{T_0^{+}}{1 - c_1^{-} R_0^{+}} \left[\phi_1 + \sum_{i=2}^{N} \phi_i \prod_{\ell=1}^{i-1} \left(e^{-\Delta_\ell \gamma_\ell} \frac{T_\ell^{+}}{T_\ell^{-}} T_{\ell E}^{-} \; T^{\ell} \right) - \left\{ \phi_1^{T} + \sum_{i=2}^{N} \phi_i^{T} \prod_{\ell=1}^{i-1} \left(e^{-\Delta_\ell \gamma_\ell} \frac{T_\ell^{+}}{T_\ell^{-}} T_{\ell E}^{-} \; T^{\ell} \right) \right\}_{E=E_0} \right] , \tag{48}$$

where E_0 is the internal electric field in the thermal equilibrium, E is the electric field in the presence of light and ϕ_i^{T}, contribution to ϕ_i due to thermal energy, is given by

$$\phi_i = \phi_i^{L} + \phi_i^{T} \quad . \tag{49}$$

Here ϕ_i^{L} is the contribution to ϕ_i due to light.

The electric current in a solar cell is carried by electrons as well as by holes. The individual electron and hole currents are given by the product of the electron charge and corresponding flux. The total current J is equal to the sum of the electron and hole currents J^e and J^h respectively,

$$J = J^e + J^h = -e f_0^{e} + e f_0^{h} \tag{50}$$

Here, superscript e and h indicate the contribution from the electrons and holes respectively, Since the electric field E can be related to the photovoltage, the above expression gives the current-voltage characteristic of any multiple layer solar cell. The electric field in the expression (50) enters through the field dependent quantities $k_i^{\pm}$, $a_i^{\pm}$ and $g_i^{\pm}(x)$.

4. EXAMPLE OF A SINGLE LAYER

In this section, we shall apply our formalism to the simplest case of a single layer and show that our results reduce to that of Thomchik and Buoncristiani[5] and McKelvey and Baloch[4] in appropriate limits. From Eq. (48), the outgoing flux f_0 in a single layer is given as

$$f_0 = \frac{T_0^+}{1 - c_1^- R_0^+} \quad (\phi_1{}^L + \phi_1{}^T - (\phi_1\,)\, E = E_0) \tag{51}$$

In both papers of Thomchik snf Buoncristiani[5] and McKelvey and Baloch[4] the transmission coefficient $T_0{}^+$ is assumed to be 1. Therefore, in this case $T_0{}^+/(1 - c_1^- R_0{}^+)$ reduces to 1.

Expressions of $\phi_1{}^L$ and $\phi_1{}^T$ can be obtained by integrating Eq. (33). In general, these expressions of $\phi_1{}^L$ and $\phi_1{}^T$ are quite complicated and in some cases one requires to evaluate the integrals in Eq. (33) numerically. However, under the following assumptions

1) Generating fluxes $g_{1L}^{\pm}(x)$ due to light are given as

$$g_{1L}^+(x) = g_{1L}^-(x) = \frac{\Phi\alpha_1}{2} \; e^{-\alpha_1 x} \tag{52}$$

where Φ is the light flux striking the front surface of the layer and α_1 is its absorption coefficients.

2) the effective reflection coefficient R_{1E}^- due to the I^{st} boundary is equal to 1, we get the result of Thomchik and Buon-

Buoncristiani as

$$\phi_1{}^L = \frac{\phi\alpha_1}{2[1 - R_{1\infty+} R_{1A} e^{-2q_1\gamma_1}]} \left[\frac{1 + R_{1\infty-}}{q_1 + \Delta_1 + \alpha_1} \times \right.$$

$$\times \left\{1 - e^{-(q_1 + \Delta_1 + \alpha_1)\gamma_1}\right\} + \frac{R_{1A}(1 + R_{1\infty+})}{q_1 - \alpha_1 - \Delta_1} e^{-2q_1\gamma_1} \times$$

$$\left. \times \left\{1 - e^{(q_1 - \Delta_1 - \alpha_1)\gamma_1}\right\}\right] \tag{53}$$

On the other hand, within the assumptions

1) the generating fluxes $g_{1T}^{\pm}(x)$ due to thermal energy are isotropic and uniform, i.e. $g_{1T}^{+}(x) = g_{1T}^{-}(x) = g_{1T}/2$, where g_{1T} is the constant generating flux due to thermal energy,

2) $R_{1E}^{-} = R_{\infty-}$, i.e., on the left of the Ist boundary there is a semiconducting layer of infinite width,

we get the integrated result of McKelvey and Balogh[4]

$$\phi_1{}^T = \frac{g_T(1 + R_{1\infty-})}{2(q_1 + \Delta_1)} \left\{1 - e^{-(q_1 + \Delta_1)\gamma_1}\right\} \tag{54}$$

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