Thermoelectric Field Effects in Low Dimensional Structure Solar Cells

Stefan Kettemann, and Jean-Francois Guillemoles

aI. Institut f. Theoretische Physik
Jungiusstr. 9, 20355 Hamburg Germany
bENSCP Rue Pierre et Marie Curie, 75231 Paris France

Abstract
Taking into account the temperature gradients in solar cells, it is shown that their efficiency can be increased beyond the Shockley-Queisser limit [1]. The driving force for this gain is the temperature gradient between this region and its surroundings. A quantitative theory is given. Though the effect is found to be weak in conventional solar cells, it is argued that it can be substantially increased by proper choice of materials and design of the device. In particular, it is shown that the insertion of a quantum well can enhance the efficiency beyond the one of a single gap cell, due to the presence of temperature jumps at the heterojunctions.

Keywords: thermoelectric field, low dimensional structures, solar cell

1. Introduction
The suggestion of Barnham and Duggan, that the efficiency of solar cells can be increased when low dimensional structures like multi quantum wells are inserted between their p-n contact [2], sparked off a renewed interest in the derivation of the efficiency limits of ideal solar cells. It was soon realized, that detailed balance theory would result in the limiting efficiency of the lower band gap material. Thus, no enhancement beyond the SQ limit is found (as obtained for a single band gap material, taking into account radiative recombination [3]), if the assumption of full thermalization of excited electron-hole pairs in two bands is made [4]. Recently, it has been argued that a solar cell with multibands may exceed this efficiency limit, since the assumption of fast thermalization may only be valid within each subband, due to slow interband nonradiative recombination. Thus, under illumination the charge carriers can have separate quasi-Fermi levels in each subband [5,6], which results in efficiency limits corresponding to the one of multiple tandem cells [7]. Recent experiments on multi-quantum well solar cells seem not to be in accord with a model of two quasi-Fermi levels [8]. It has been suggested that low dimensional structures like superlattices of quantum dots could be preferable for a realization of multiband solar cells [9]. In these structures interband electron-phonon relaxation can be reduced substantially [10], although this effect can be overturned by many-body effects [11] and high temperature. Intersubband absorption of photons [12], interband transitions due to electron-electron scattering, or the inverse Auger effect [13] can be ways to have multiple quasi-Fermi levels under detailed balance conditions, and thus an increase of efficiency beyond the single gap limit.

Here, another mechanism is explored, which could lead to an enhancement of the efficiency of solar cells, even when the local distribution of charge carriers is well described by two quasi-Fermi levels: the heating of the optically active region of the semiconductor. As a result, the thermoelectric force due to temperature gradients in the cell may enhance the output voltage. There may also be an enhancement of current and output voltage due to thermionic emission from the optically active region, if a semiconductor with a lower band gap than the emitter and basis is inserted, there. The efficiency of semiconductor thermoelements which turn temperature gradi-
ments into electrical current is limited by the figure of merit $TZ = TS^2/\kappa q^2$, with the thermopower $S$, the conductivity $\sigma$, and thermal conductivity $\kappa$. It might be of interest to combine solar cells with thermoelements to reach a larger overall efficiency. Here, we will explore if temperature gradients inside a solar cell can increase their efficiency beyond the SQ limit. We will assume fast thermalization of the charge carriers with the lattice, neglecting hot electron effects, considered in Refs. [15, 16].

In the second chapter, the limiting efficiency as function of band gap and temperature is reviewed for a single band gap solar cell. In the third chapter, the effect of temperature gradients on the performance of a single band gap solar cell is explored. In the final chapter, it is studied, if the insertion of a lower band gap material in the presence of the temperature gradients, may enhance the efficiency further.

It is assumed that the surrounding of the solar cell is not heated and stays at the temperature $T = 300\,K$. Furthermore, in order to study the efficiency limit, we assume that radiative recombination between the conduction and valence band is predominant, and nonradiative recombination can be disregarded. The temperature gradient is assumed to be caused by the fast thermalisation of the carriers in the optically active region.

2. Temperature sensitivity of Single Gap Cell

While a uniform heating of the solar cell is commonly known to be detrimental to its efficiency, there are known exceptions, like GaAs heterojunction solar cells, in which an increase in efficiency by 1 per cent was measured, when raising the temperature to 350 K. Let us first review therefore the temperature sensitivity of a uniform single gap solar cell. From the decrease of Carnot efficiency, $\Delta\eta = -\Delta T/T_s$ with increasing temperature $T$, one expects the trend to decreasing efficiency. However, the energy gap is known to decrease with increasing $T$ in most semiconductors. Thus, one could also expect an increase of efficiency when the energy gap at room temperature is above the one giving optimal efficiency according to SQ. That is, for energy gaps above $E_G = 1.4\,eV$. In order to find out, which factor is dominant, the increase of photocurrent due to decreased band gap, or, the increase of radiative recombination, let us reconsider the ideal efficiency as function of temperature $T$.

The current is ideally given by the charge times the rate of absorbed photons with energy $E = h\nu$, exceeding the energy gap $E_G$, subtracted by the photons emitted by radiative recombination:

$$I(V) = I_{Solar}(E_G) + I_T(E_G) - I_T(E_G, V),$$

where $qV = \epsilon_C - \epsilon_V$, with the absolute value of the electron charge, $q$. It is assumed that the electron distribution in the conduction and valence band under illumination, is well described by a Fermi distribution with a Fermi level $\epsilon_C$ in the conduction band and $\epsilon_V$ in the valence band, respectively. The current terms are given by $I_{Solar}(E_G) = -A_s q k_b N_{Solar}(E_G)$, with the cell area $A_s$, the solar concentration factor $1 < k_c < 46050$. The rate of solar photons is modeled by a Planck distribution with temperature $T_S = 5800\,K$: $N_{Solar}(E_G) = (f_s/4\pi)(c/4)\int_{E_G/h}^{\infty} d\nu 2D_\nu/((\exp(h\nu/(k_b T_s)) - 1)$, where $D_\nu = 4\pi \nu^2/c^3$, $c$ being the velocity of light, and the solar solid angle $f_S = .000272$. Thus, $I_{Solar}(E_G)/A_s = -425 k_c (E_G/k_bT_s) dx^2/((e^x - 1)A/m^2$, where $k_B T_s = .5 eV$. The current due to absorption of thermal photons is $I_T(E_G) = -A_s q N_T(E_G)$ with a photon rate arising from the Planck distribution with surrounding temperature $T$, $N_T(E_G) = (c/2)\int_{E_G/h}^{\infty} d\nu 2D_\nu/((\exp(h\nu/(k_b T)) - 1)$. It is exponentially small for $E_G > k_B T$. The current, lost due to radiative recombination is, $I_T(E_G, V) = -A_s q N_T(E_G, V)$, where $N_T(E, V)$ is the photon rate emitted by a semiconductor with quasi Fermi-level separation $qV$ and temperature $T$ as given by the modified Planck distribution, $N_T(E, V) = c/2\int_{E_G/h}^{\infty} d\nu 2D_\nu/((\exp(h\nu - qV)/(k_b T)) - 1)$. Thus, the dark current is $I_T(E_G, V)/A_s = -435.2(T/300K)^3\int_{E_G/k_b T}^{\infty} dx/((\exp(x - qV/(k_b T)) - 1)A/m^2$. The efficiency of a one band solar cell is obtained by optimizing $I(V)V/\Delta P_s$ with respect to the voltage $V$, giv-
ing for $E_G - qV > k_B T$,

$$\eta = \eta_0 \frac{f^2}{1 + f}, \quad (2)$$

where $\eta_0 = \frac{4\pi^2 k_B T}{e B} \int_{E_G/eV}^{\infty} dx x^2 / (e^x - 1)$. 

Here, $f(g) = qV_m / k_B T$, is a function of $g = I_{Solar}/I_T(E_G, V = 0)$, only, as given by the non-linear equation $f = \ln g - \ln(1 + f)$. The decrease of the energy gap as function of temperature $T$ is close to room temperature, $T = 300K$, linear in $T$: $E_G(T) = E_G(0K) - z_G k_B T$, where $z_G$ ranges between 3 for Si and 5 for $Tio_2$.[21]. The efficiency is found to decrease linearly in temperature, for $E_G < 2.88 k_B T_S = 1.4eV$. For energy gaps exceeding the maximum of the solar radiation distribution, $E_G > 1.4eV$, the decrease of the energy gap with increasing temperature $T$ results in an exponential enhancement of the photocurrent, since the gap is in the exponentially decaying part of the Planck distribution. This can overcome the exponential increase of the dark current. Indeed, this results in a slight increase of efficiency $\Delta \eta \sim 0.1% \Delta T/K$ with temperature increase $\Delta T$, for $E_G > 1.4eV$. This increase can be enhanced by concentration $k_n$, as $ln k_n$. At higher temperatures it reaches a maximum at a temperature $T_M(E_G)$ for $1.4eV < E_G < 3.5eV$ and decreases than strongly. It reaches a maximum increase above the SQ limit by 1% at a temperature of 1000K, for a band gap of $E_G = 3.5eV$. At $E_G > 3.5eV$, the efficiency drops exponentially below 5%, and accordingly its increase with temperature becomes exponentially small, although the relative efficiency increase becomes larger. From Eq. [3], for $E_G > k_B T_S$ and $T \ll T_S$ the efficiency increase is for an ideal solar cell given by

$$\Delta \eta = 2.1 z_G 10^{-2} \left( \frac{E_G}{eV} \right)^2 \exp(-2E_G(0)/eV) \frac{\Delta T}{T}. \quad (3)$$

3. Thermoelectric field enhancement of Single Gap Cell efficiency

In this section we will address the question, if the inhomogenous heating of the solar cell under solar irradiation yields an enhancement of the output voltage and thereby an increase of the efficiency of an ideal gap solar cell beyond the SQ limit due to thermoelectric effects. The heating of the semiconductor due to the thermalization of the electron-hole pairs in the optically active region produces a temperature gradient, which acts as a driving force on the charge carriers away from the heat source. The efficiency of a thermoelectrical element alone, is $\eta_{TE} = W/Q$, where $W = IV$ is the extracted electrical work and $Q = K\Delta T + S I T_i/q$ the transfered heat from the source of temperature $T_i > T$ with thermal conductance $K$. $Q$ is smaller when a current $I$ is flowing, due to the Peltier cooling, as included, above. The efficiency limit of such a thermo element is known to be given by [21,3]

$$\eta_{TE} = \frac{T_i - T}{T_i} \frac{(1 + TZ)^{1/2}}{T / T_i + (1 + TZ)^{1/2}}, \quad (4)$$

with the figure of merit, $TZ = TS^2 \sigma / kq^2$, which is generally smaller than 1[3]. As a function of the temperature gradients in a solar cell under irradiation, one can find with Eq. (4) the efficiency to turn them into electrical work.

However, we are rather interested if the total efficiency of the solar cell, $\eta = IV/AF$, can exceed the limit derived in the previous section, when the temperature gradients are taken into account. To this end, the current voltage characteristics of the solar cell have to be rederived. The separation of the charge carriers is due to drift in the intrinsic electrical field of the p-n contact, a small ohmic driving field and due to diffusion. Due to the temperature gradient, there is the additional thermoelectrical current, driving electrons to the n-doped basis, and holes to the p-doped emitter. The electron current $I$ per area $A_s$ arriving at the back contact through the n-doped region is thus, in a classical drift diffusion model in the presence of a quasi-Fermi level gradient $\nabla \epsilon_c$, and the temperature gradient $\nabla T$, given by [21]

$$I_n/A_s = \mu_n n_c (\nabla \epsilon_c - \nabla E_c - S_n \nabla T - S_D n \nabla T), \quad (5)$$

with the electron mobility $\mu_n = qT/m_c$, the scattering rate $\tau$, and effective mass $m_c$. The electron density is $n_c = N_C(T) \exp((q \phi - E_c + \epsilon_c)/k_B T)$, where, for parabolic energy dispersion, $N_C = 2.5(10^{19}/cm^3)(m_e/m)^{3/2}(T/300K)^{3/2}$. $S_n$ is the thermopower of the n-doped semiconductor un-
under nondegenerate doping conditions, given by

\[ S_n = k_B (\ln n_c/N_c - r - 5/2). \]  

(6)

The current, Eq. (3), is a sum of 1. the drift-diffusion current, governed by the conductivity, which is in the n-doped region given by \( \sigma_n = qn_c \mu_n \), and includes the additional term due to the gradient in conduction band edge \( \nabla E_c \). 2. the thermoelectric electron current, where \( r \) is the power of the scattering time as function of energy, \( \tau \sim E^r \), where \( r = -1/2 \) when electron scattering is dominated by acoustic phonon scattering, and 3. the last term, the electron current due to the phonon flux away from the higher temperature \( T_i \) region, dragging electrons with them. Accordingly, the phonon drag contribution to the thermopower, \( S_p \), is due to electron-phonon scattering. It can usually be disregarded at room temperature, since it is proportional to the phonon mean free path \( (S_p \ll k_B) \) [23]. The hole current arriving at the top contact through the p-doped region is accordingly given by \( I_p/A_s = \mu_p n_p (\nabla \epsilon_v + \nabla E_v - S_p \nabla T + S_D \nabla T) \). The hole conductivity is in the p-doped region given by \( \sigma_p = \mu_p q n_p \), with the hole mobility \( \mu_p \) and the hole density \( n_p = P_V(T) \exp((-q \phi - E_v + \epsilon_v)/k_B T) \), where \( P_V(T) = 2.5(10^{19}/\text{cm}^3)(n_c/m)^{3/2}(T/300 \text{K})^{3/2} \). The thermopower of the holes in the p-doped region is given by \( S_p = -k_B (\ln p_v/P_v - r - 5/2) \).

Now, one can obtain the current voltage characteristics of the solar cell, by the condition that all the current created in the n-region, \( I(V_i) \) arrives at the contacts, or \( I_p = I(V_i) = I_n \), where only the voltage drop across the optical region \( V_i \) enters, since radiative recombination mainly occurs there. The spatial dependence of the energy gap due to the temperature gradient results in a gradient in the conduction band edge \( \nabla E_c = -z_C k_B \nabla T \), and valence band edge, \( \nabla E_v = z_V k_B \nabla T \), where \( z_C + z_V = z_G \). Thus, one obtains for the gradient of the quasi-Fermi level in the n-doped basis:

\[ \nabla \epsilon_c = (-z_C k_B S_n) \nabla T + \frac{I(V_i)}{\mu_n N_D A_s}, \]  

(7)

and a corresponding expression for the gradient of the quasi-Fermi level in the emitter. Note that \( -\nabla \epsilon_c/k_B \nabla T > 1 \) is therefore possible. The temperature gradient is obtained from the heat flow balance,

\[ (1 - \eta) P_s = -\kappa \nabla T + T \frac{S}{q A_s} + P_O, \]  

(8)

where \( \eta \) is the solar cell efficiency and the second term is the Peltier heat which tends to cool the hot absorber for \( I < 0 \), thus reducing the temperature gradient. \( P_O = R T^2 \) is the ohmic heat due to the cell resistance \( R \). Thus, the cell efficiency is obtained from Eqs. (1), (7), (8), as

\[ \eta = I(V_i)/(V_i + d_n \nabla \epsilon_c(V_i)/q + d_p \nabla \epsilon_v(V_i)/q)/A P_s, \]

where \( d_n, d_p \) are the thickness of the basis and emitter, respectively, and \( \nabla \epsilon_v(V_i) \) is the gradient in the valence band of the p-doped emitter, as given by the equivalent of Eq. (7) for the holes. Rather than optimizing this efficiency with respect to the voltage \( V_i \), let us consider here first the magnitude of the thermoelectric gain.

As an example, the mobility of electrons in bulk GaAs, is at room temperature \( \mu_n = 5000 \text{cm}^2/\text{V} \text{s} \), at doping \( N_D \approx N_C = 5 \times 10^{17}/\text{cm}^3 \). With the heat conductivity, which is for GaAs about \( \kappa = 45 \text{W/Km} \) and the solar power \( P_S = k_b1400 \text{W/m}^2 \), one gets from \( (1 - \eta) P_s = \kappa \nabla T \), temperature gradients of \( \nabla T < 30 k_b \text{K/m} \) within the semiconductor solar cell, if all solar power is absorbed in the optically active region, only. Thus the temperature drop from the optically active region to its basis in a solar cell of basis thickness \( d_n = 100 \mu \text{m} \), is obtained to be \( \Delta T = (1 - \eta) 3 k_b \text{mK} \). With \( S_n \approx -z_D k_B \), where \( z_D \) is at strong doping \( z_D \approx 2 \) we obtain from the first term of Eq. (7) the positive thermoelectric voltage \( \delta V_{TE} = 1.3 k_b \mu \text{V} \). The negative ohmic voltage is, using the short circuit current given above, for GaAs, with \( E_G = 1.4 eV \), \( I_{SC}/A_s \sim 400 k_b A/m^2 \) obtained to be \( \delta V_{Ohm} = -1.0 k_b \mu \text{V} \). Thus, the change in output voltage obtained from \( \nabla \epsilon_e/q \), Eq. (7), is positive, the thermoelectric effect is dominating the ohmic one. But, the gain is even under strong concentration \( k_b = 1000 \) on the order of \( m \text{V} \), only. Can this be improved? Besides strong concentration there is another way to enhance the effect. When the solar irradiation is parallel to the p-contact, and the illumination is concentrated on the intrinsic region, only, the temperature gradients are enlarged by a
factor $d_i/d$, where $d$ is the thickness of the cell.

Recently, the reduction of perpendicular thermal conductivity of AlGaAs by insertion of GaAs quantum wells by a factor 1/10 has been reported \[17\], due to back scattering of phonons at the heterojunction. The figure of merit has been reported to be enhanced in GaAs/AlAs superlattices by a factor of 50 at strong doping \[22\]. This is another motivation to study the effect of insertion of quantum wells on the performance of solar cells in the next chapter.

4. Quantum well solar cells

In this section, we study if the insertion of a lower band gap material in the optical region, as proposed in Ref. \[2\], can enhance the efficiency of the solar cell beyond the SQ limit, when temperature gradients are taken into account. The transport of charge carriers out of the lower band gap region is due to drift in the internal electrical field, diffusion, and thermionic emission into the larger gap basis and emitter. Therefore, instead of Eq. (5), valid for a homogenous cell, only, the current across the hetero junction is given by,

$$I = -qn_L v_L \exp((E_{CL} - E_{CR})/(k_B T_L))$$
$$+ q n_H v_R + q n_R \phi',$$

where $n_s, v_s, E_{Cs}, T_s, s = L, R$ are conduction electron density, thermal velocity, conduction band edge, and temperature, to the right and left of the heterostructure, respectively, see Fig. 1. The electrical field, $\phi' = (V_{np} - V_i)/d_i$ is assumed to be constant across the i-region, where $d_i$ is the thickness of the intrinsic region which is taken here to coincide with the thickness of the quantum well, for simplicity. Thus, all photons are assumed to be absorbed in the quantum well region, giving $I = I(V_i)$ as given by Eq. (1). The average thermal velocity is $v_s = (k_B T_s/m_s)^{1/2}, s = L, R$, and the densities $n_s, s = L, R$ are functions of the local temperature and quasi-Fermi levels as given in the previous section. By expansion in the temperature drop $\Delta T = T_L - T_R$ across the heterojunction, a jump in the quasi-Fermi level is obtained, $\Delta \epsilon_c = \epsilon_R - \epsilon_L$ given by

$$\Delta \epsilon_c = k_B \ln(1 + m_R I m_L q v_R n_R) - S_L \Delta T,$$

where the thermopower is found to be given by $S_L = k_B (q \phi_L + \epsilon_L - E_{CR})/T$. As an example let us consider a GaAs quantum well between an Al$_{1/3}$Ga$_{2/3}$As emitter and basis with direct band gap $E_G = 1.8$ eV\[23\], effective mass $m_e = 0.095m_0$, and conduction band offset, $\Delta E_G = 0.8 \Delta E_G = 1.3$ eV \[24\]. From the heat conductivity of an AlAs/GaAs quantum well at room temperature of $k = 10 W/mK$, and the result of simulations which show that the drop in heat conductivity is mainly due to scattering of phonons at the heterostructure boundary \[17\], one can estimate a temperature drop by $\Delta T = k_e 10^{-4} K$ at the quantum well boundary under solar illumination with concentration $k_c$. Thus, Eq. (10), yields at forward voltage a jump of the quasi-Fermi level of $\Delta \epsilon_c = -3k_e 10^{-7}(eV - q 5V)$, which even under strong concentration does not exceed $meV$, but adds to the voltage across the basis and emitter, as derived in the previous section.

Thus, the efficiency of an AlGaAs/GaAs, quantum well cell is with a two band quasi-Fermi level distribution, slightly enhanced beyond the SQ limit, when the temperature gradients due to the absorption of the solar radiation in the optically active i- region is taken into account, and can exceed the respective efficiency of the single gap cell. The thermoelectric gain is found to be small however, so that it seems not to be possible to approach the tandem efficiency limit which is for a GaAs/Al$_x$Ga$_{1-x}$As tandem system, without concentration, $k_e = 1$, for $x = 1/3 \eta = 38\%$.

attachment:Figure 1. The energy conduction band edge $E_c - q \phi(x)$ with heterojunction is sketched by the full line, Quasi- Fermi levels, $\epsilon_L, \epsilon_R$ to the right (R) and left (L) of the junction, by broken lines.
5. Discussion

In summary, it has been shown that the thermoelectrical effect due to temperature gradients in solar cells enhances their limiting efficiency beyond the SQ limit. The insertion of a quantum well into the optically active region is found to enhance the thermoelectrical effect further, due to temperature drops at the hetero junctions and resulting positive jumps in the quasi-Fermi levels. This may explain recent experiments on quantum well solar cells showing positive jumps in the quasi-Fermi levels[8]. It seems worthwhile to extend the analysis to other heterostructure cells, like quantum dot solar cells, considering their reduced thermal conductivity and favourable thermoelectrical field effects[13]. Other semiconductor heterostructures than AlGaAs, like Si/Ge have been shown to be favourable thermoelectric materials[13]. Very low thermal conductivities of $\kappa \approx 1\text{W/mK}$, have been reported in nanocrystalline TiO$_2$[24], so that the thermoelectric voltage can be a relevant mechanism to enhance the output voltage in dye sensitized TiO$_2$ solar cells.

REFERENCES

[1] W. Shockley, H.J. Queisser, J. Appl. Phys., 32, 510(1961).

[2] K. W. J. Barnham, G. Duggan, J. Appl. Phys. 67, 3490(1990), Jenny Nelson, Thin Films, 21, 311(1995).

[3] G.L. Araujo, A. Martí, Sol. En. Mat. & Sol. Cells, 33, 213(1994); P. Baruch, A. DeVos, P. T. Landsberg, J. E. Parrot, Solar Energy Materials and Solar Cells, 36 201 (1995).

[4] S. Kettemann, J. F. Guillemeoles, Proc. of 13 th Photo Volt. Sol. Energy Conf., Nice (1995).

[5] A. Luque, A. Martí, Phys. Rev. Lett. 78, 5014(1997).

[6] C. H. Henry, J. Appl. Phys. 51, 4494(1980); H. Pauwels and A. DeVos, Solid State El. 24, 835(1981).

[7] M. J. Keevers, M. A. Green, 23rd IEEE Photovoltaics Spec. Conf. Proc., Louisville (1993), 140; R. Corkish, M. A. Green, ibid., 675.

[8] E. Tsui, J. Nelson, K. Barnham, J. Appl. Phys. 80, 4599 (1996), J. Nelson, J. Barnes, N. Ekins-Daukes, B. Kluftinger, E. Tsui, K. Barnham, J. Appl. Phys. 82, 6240 (1998).

[9] C. B. Honsberg, R. Corkish, and S. P. Brenner, Proc. of Glasgow, (2000).

[10] B. Bockelmann and G. Bastard, Phys. Rev. B 42, 8947 (1990); X.-Q. Li, H. Nakayama, and Y. Arakawa, Phys. Rev. B 59, 5069 (1999); T. Stauber, R. Zimmermann, and H. Castella, Phys. Rev. B 62, 7336 (2000); B. N. Murdin, et al., Phys. Rev. B 59, R7817 (1999); J. Urayama, T. B. Norris, J. Singh, and P. Bhattacharya Phys. Rev. Lett. 86, 4930 (2001).

[11] A. L. Efros, V. A. Kharchenko, and M. Rosen, Solid State Commun. 93, 281 (1995); V. I. Klimov, and D. W. McBranch, Phys. Rev. Lett. 80, 4028 (1998); S. W. Koch, T. Meier, W. Hoyer, and M. Kira, this issue (2002).

[12] A. F. Ioffe et al. Dokl. Akad. Nauk. SSSR, 106, 981 (1956).

[13] T. M. Tritt (ed.), Recent Trends in Thermoelectric Materials Research, Semiconductors and Semimetals, Academic Press, San Diego, 69-71 (2001).

[14] J. E. Parrott, IEEE Trans. Electron. Devices, 43, 809 (1996).

[15] R. T. Ross, A. J. Nozik, J. Appl. Phys. 53, 3813(1982).

[16] H. Z. Fardi, D. W. Winston, R. E. Hayes, and M. C. Hanna, IEEE Trans. Electron. Devices, 47, 915(2000).

[17] G. Chen, in volume 71 of Ref. 13 (2001).

[18] Zh. I. Alferov, V. M. Andreev, M. B. Kagan, I.I. Protasov, and V. G. Trofin, Soviet Phys. Semicond. 4, 2047(1971),[Fiz. Tekh. Poluprov., 4, 2378 (1970)].

[19] H. J. Hovel, Solar Cells, Semiconductors and Semimetals, Vol. 11, Academic Press, New York (1975).

[20] P. Wuerfel, Journal of Phys. C: Solid State Physics, 15, 3967(1982).

[21] K. Seeger, Semiconductor Physics 5th edition (Springer, Berlin) (1991).

[22] T. Koga, X. Sun, S. B. Cronin and M. S. Dresselhaus, Appl. Phys. Lett. 73, 2950 (1998).

[23] C. Herring, Phys. Rev. 96, 1163 (1954).

[24] S. M. Lee, D. G. Cahill, T. H. Allen, Phys.
Rev. B 52, 253 (1995).

[25] V. V. Mitin, V. A. Kochelap, M. A. Stroscio, *Quantum Heterostructures*, Cambridge University Press, Cambridge, 133(1999).

[26] T. Piotrowski, and S. Sikorski, Semicond. Sci. Technol. 16, 750 (2001).