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COMPARISON OF MEASURED PERFORMANCE AND THEORETICAL LIMITS OF GaAs LASER POWER CONVERTERS UNDER MONOCHROMATIC LIGHT

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Abstract. *Evaluation of GaAs laser power converters (LPC) is reported in light of theoretical maximum limits calculated with detailed balance method as proposed by Shockley and Queisser (SQ). Calculations were done for three different theoretical structures of LPCs homogeneously illuminated by monochromatic light. Effects of LPC thickness, central wavelength of a monochromatic light source and various irradiance levels are discussed. Reflection of incident light from the interface between air and GaAs is calculated and countermeasures in the form of single and double layer anti reflection coatings are theoretically studied. Measurements of single junction, single segment GaAs LPC illuminated by monochromatic light with central wavelength* λ_0 *= 808 nm are presented and compared with the theoretical maximum values.*
The conversion efficiency η_{meas} *= 54,4 % was measured for GaAs LPC illuminated with power density of monochromatic light* p_{illum} *= 14,3 W/cm*^{2} *at the temperature of the LPC casing T = 302 K. For the same parameters conversion efficiency* η_{SQ} *= 76,6 % was calculated resulting in utilization ratio* η_{meas}/η_{SQ}*=0,71. Measured* J_{sc} *and* V_{oc} *achieve 88,5 % and 89,2 % of theoretically calculated SQ limit values.*

Key words: *laser power converter, Shockley-Queisser limit, GaAs, monochromatic efficiency*

1. INTRODUCTION

Shockley-Queisser (SQ) limit [1]–[3] is fundamental, widely adopted figure of merit used for evaluating efficiency limits of photovoltaic devices. It is based on detailed balance method and assumes radiative recombination as the sole loss mechanism in a solar cell. Calculations of the SQ limits were already done under standard solar spectra (AM1.5, AM1.0 and AM0) or for black body radiation spectrum. For purposes of power beaming, where photovoltaic cell is illuminated by artificial light source in order to transfer energy with no electrically conductive path, SQ limit under monochromatic illumination [4] will be calculated, since those systems commonly employ laser diodes as a source of monochromatic illumination. Light energy irradiated from a laser diode is

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converted to electrical energy by GaAs laser power converters (LPC) optimized for monochromatic light sources at specific wavelength. In practice laser diodes with central wavelength between λ_0 = 800 – 850 nm are often utilized, due to their low price and good system efficiency when employing GaAs LPCs as optical energy to electrical energy converters.

Currently state-of-the-art GaAs LPCs achieve efficiencies greater than 56 % [5-6] while illuminated with monochromatic light with central wavelength λ_0 between 810 – 820 nm and p_{illum} between 50-124 W/cm^2.

In this paper we present theoretically calculated efficiency limits based on detailed balance principle compared with measured GaAs LPC. Conversion of optical energy to electrical energy will be presented with loss analysis for both theoretical and measured LPC.

2. Model

SQ current density limit is calculated as difference between photogenerated current density and loss of available current density due to radiative recombination as (1):

$$J = J_{ph} - q * RR. \tag{1}$$

J_{ph} – photogenerated current density
q – elementary charge of electron
RR – radiative recombination rate of electron-hole pairs (e – h)

2.1. Photogenerated current density

Photogenerated current density is calculated from the flux of e – h pairs generated by absorbed photons (2). In this paper we present calculation of SQ limit under monochromatic illumination applied for a GaAs photovoltaic cell.

$$J_{ph} = q * \Phi_{e-h} \tag{2}$$

Φ_{e-h} – flux of photogenerated e – h pairs

Φ_{e-h} presents number of generated e – h pairs in absorber per unit time per unit area and is calculated using absorption coefficient α_0 of GaAs as measured by [7] including Urbach tail with slopes E_0 below E_g and E' above E_g [8] and fitted to the following equation (3) [9]:

$$\alpha(E_{ph}) = \begin{cases} \alpha_0 * e^{\frac{E_{ph}-E_g}{E_0}} & E_{ph} \le E_g \\ \alpha_0 * \left(1 + \frac{E_{ph}-E_g}{E'}\right) & E_{ph} > E_g \end{cases} \tag{3}$$

E_{ph} – energy of photons incident on LPC surface
E_g = 1.42 eV – band gap of GaAs
α_0 = 8000 cm^{-1}
E_0 = 6,7 meV
E' = 140 meV

From known absorption rate α, absorptivity A for three different hypothetical structures of thickness L of GaAs LPCs as seen in Fig. 1 were considered as follows [3,4]:

A) Planar front surface with complete absorption on the back surface (4), representing a single pass of photons through absorber.

$$A(E_{ph}, L) = 1 - e^{-\alpha(E_{ph})\,L} \tag{4}$$

B) Planar front surface with perfect reflecting mirror on the back surface (5), representing a double pass of photons through absorber.

$$A(E_{ph}, L) = 1 - e^{-2\alpha(E_{ph})\,L} \tag{5}$$

C) Random texture on front surface with perfect reflecting mirror on the back surface (6), representing multiple passes of photons through absorber.

$$A(E_{ph}, L, n_{GaAs}) = \frac{4n_{GaAs}^2\alpha(E_{ph})\,L}{4n_{GaAs}^2\alpha(E_{ph})\,L + 1} \tag{6}$$

n_{GaAs} – refractive index of GaAs

All considered structures have thickness dependence, noted with L and are assumed to be exposed in the air. For randomly textured dependence of absorptivity of GaAs on refractive index n_{GaAs} of GaAs can be also noted.

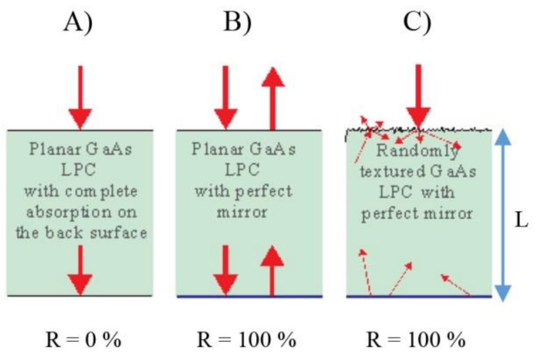

Fig. 1 Different theoretical structures of GaAs LPCs considered in calculations. Arrows shows the light path through GaAs absorber.

R – reflection of light from bottom surface

With known A, J_{photo} can be calculated from a flux of photons incident on an LPC front surface. Reflection of incident light from the front surface is not taken into account here, but is added and discussed later.

Laser spectrum around central wavelength λ_0 was interpolated with Gaussian distribution as shown in the following equation (7).

$$LaserSpectrum(\lambda) = \frac{1}{\sqrt{2\pi}\left(\frac{FWHM}{2\sqrt{2ln2}}\right)} e^{-\frac{(\lambda-\lambda_0)^2}{2\left(\frac{FWHM}{2\sqrt{2ln2}}\right)^2}} \tag{7}$$

Laser spectrum was weighted with power density of incident light entering the front surface of LPC resulting in spectral irradiance (8), (10).

$$Spectral\ Irradiance(\lambda) = p_{illum} * LaserSpectrum(\lambda) \tag{8}$$

$$p_{illum} = \frac{LaserPower}{LPC_{area}} \tag{9}$$

$$Spectral\ Irradiance(E_{ph}) = Spectral\ Irradiance(\lambda)|_{\lambda=\frac{hc}{E_{ph}}} \tag{10}$$

FWHM – full width at half maximum
λ_0 – central wavelength
h – Planck's constant
c – speed of light

Equation for a flux of photons (11) entering front surface per unit energy $\Phi_{ph}\,(E_{ph})$ can be derived from known spectral irradiance.

$$\Phi_{ph}\,(E_{ph}) = Spectral\ Irradiance(E_{ph})\frac{1}{E_{ph}}\frac{hc}{E^2{}_{ph}} \tag{11}$$

Integration of A multiplied by $\Phi_{ph}\,(E_{ph})$ over energy content of photons presented in spectral irradiance results in a flux of $e-h$ pairs (12) generated by a flux of photons for defined laser parameters λ_0, *FWHM* and laser power density and LPC thickness L.

$$\Phi_{e-h}(E_{ph}, L) = \int A(E_{ph}, L)\Phi_{ph}\,(E_{ph})dE_{ph} \tag{12}$$

Photo generated current density can be calculated from a known flux of $e-h$ pair (13) as a function of incident photon energy and thickness of LPC.

$$J_{ph}(E_{ph}, L) = q\ \ \Phi_{e-h}(E_{ph}, L) \tag{13}$$

2.2. Radiative recombination rate

SQ limit assumes radiative recombinations in thermal equilibrium as sole loss mechanism present in the photovoltaic cell [1]. According to the detailed balance method used in calculation of SQ limit, all absorbed energy should be emitted for the system to be in equilibrium. Therefore the loss of energy due to thermal radiation is unavoidable. Derivation of *RR* can be found in literature [1] and recombination current density can be written as (14):

$$J_{rad}(E_{ph}, L, V) = q\ RR(E_{ph}, L, V) \tag{14}$$

Where:

$$RR(E_{ph}, L, V) = e^{\frac{qV}{kT}}\frac{2\pi}{c^2h^3}\int_0^\infty A(E_{ph}, L)\frac{{E_{ph}}^2}{e^{\frac{E_{ph}}{kT}} - 1}dE_{ph} \tag{15}$$

k – Boltzmann's constant
h – Planck's constant
V – voltage across device at open circuit condition
T – device temperature

It is remarked that RR in our case corresponds to an emission rate from the device surface (and not from the volume). Consequently its unit is m^{-2} s^{-1} (instead of more commonly used m^{-3} s^{-1}).

2.3. LPC model

Performance of the LPC is expressed with the same parameters as used in evaluation of solar cells. Efficiency η, fill factor FF, open-circuit voltage V_{oc}, short-circuit current density J_{sc} and available electrical power density at maximal power point $p_{\max}$ are derived from current density – voltage dependency, J – V (16).

$$J(E_{ph}, L, V) = J_{ph}(E_{ph}, L) - J_{rad}(E_{ph}, L, V) \tag{16}$$

Max power density is calculated numerically as (17):

$$p_{max}(E_{ph}, L, V) = max(J(E_{ph}, L, V) * V) \tag{17}$$

and V_{MPP} and J_{MPP} as (18):

$$V_{MPP}(E_{ph}, L) = V@p_{max}, J_{MPP}(E_{ph}, L, V) = J@p_{max}. \tag{18}$$

Conversion efficiency is calculated as (19):

$$\eta(E_{ph}, L, V) = \frac{p_{max}(E_{ph}, L, V)}{p_{illum}} * 100\% \tag{19}$$

and fill factor as (20):

$$FF(E_{ph}, L, V) = \frac{p_{max}(E_{ph}, L, V)}{J_{SC}(E_{ph}, L)\, V_{OC}(E_{ph}, L)}. \tag{20}$$

J_{SC} is obtained as (21):

$$J_{SC\_SQ}(E_{ph}, L) = J(E_{ph}, L, V)|_{V=0} \tag{21}$$

and V_{OC} is calculated as (22):

$$V_{OC}(E_{ph}, L) = \frac{kT}{q} ln \frac{\Phi_{e-h}(E_{ph}, L)}{RR(E_{ph}, L)/e^{\frac{qV}{kT}}}. \tag{22}$$

3. Simulation Results

All simulations of SQ performance limit were done for three different theoretical LPC structures discussed above with LPC thickness L = 1 μm at LPC temperature T = 300 K.

Source of monochromatic illumination was assumed to be homogenous across the LPC front surface with illumination power density $p_{illum} = 100\ \text{mW/cm}^2$, spectral distribution around a central wavelength $\lambda_0 = 808$ nm is Gaussian with $FWHM = 5$ nm. Simulation parameters different from those specified in previous statement are noted where necessary.

3.1. Effect of LPC absorber thickness on efficiency

As seen in Fig. 2 absorber layer thickness plays a significant role on SQ efficiency limit for structures with thickness less than 3 µm. For thicker cells, there is less than 1 % difference between the best and worst performing structure and efficiency saturates at η = 68,4 % for all structures and for given simulation parameters.

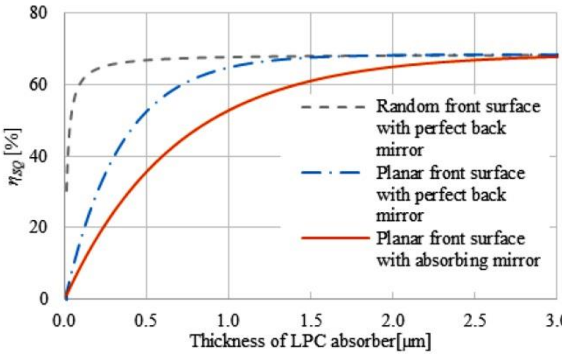

Fig. 2 Absorber thickness effect on efficiency of LPC

Similar strong rise with increasing thickness of absorber can be seen for J_{MPP} while values of V_{MPP} slightly fall (Fig. 3). Thickness is important to guarantee complete absorption of all photons which results in increased J_{MPP}. This is most notable in structure with no reflection from the back surface where only single pass of light through absorber occurs. Recombination

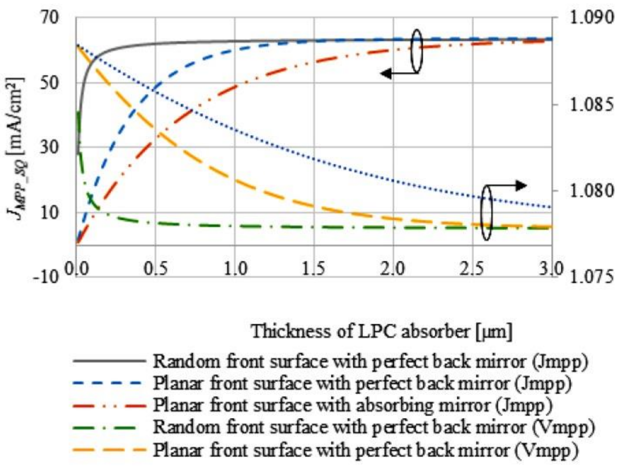

Fig. 3 Absorber thickness effect on J_{MPP} and V_{MPP} of LPC

rate of $e - h$ pairs increases with increasing thickness, resulting in increased J_{rad} and decreased V_{MPP}. Product of J_{MPP} and V_{MPP} is rising with a thickness of absorber resulting in increasing p_{MPP} and efficiency, since the gain from increased absorption is much larger than loss of voltage due to increased recombination rate of $e - h$ pairs.

3.1. Effect of central wavelength of monochromatic light on efficiency of LPC

SQ efficiency for three different 1 µm thick GaAs theoretical structures of LPCs as a function of monochromatic light with central wavelength λ_0 are shown in Fig. 4.

Maximal efficiency of η_{SQ} = 72,3 % is achieved for the randomly textured LPC with perfect back mirror at λ_0 = 872 nm which correlates to Eg=1,42 eV of GaAs. LPC with planar front surface and perfect back mirror achieves η_{SQ} = 65,0 % at λ_0 = 808 nm and planar LPC with an absorbing mirror on the back has η_{SQ} = 56,7 % at λ_0 = 728 nm. It is clear that a LPC structure does not only influence absolute maximum of efficiency, but also shifts peak of efficiency, marked with x in Fig. 4.

Commercially available lasers diodes with optimal performance between price and output optical power suitable for illumination of GaAs LPCs emit light with a spectral peak at approximately λ_0 = 808 nm marked with a vertical line in Fig. 4

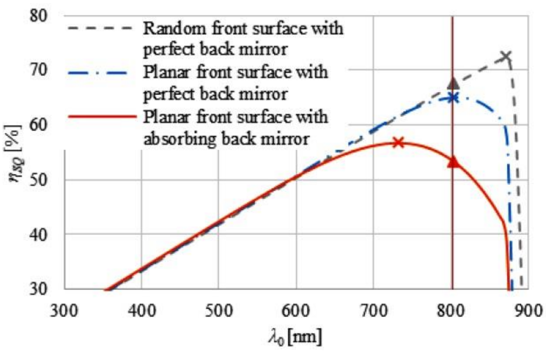

Fig. 4 Effect of central wavelength λ_0 of monochromatic source on SQ efficiency limit

3.2. Performance of LPC under high irradiance

LPCs are normally illuminated with high irradiance of monochromatic light, since efficiency increases with increasing illumination power density p_{illum}, calculated as $p_{illum} = LaserPower/LPC_{area}$. All three structures have logarithmic dependence of efficiency on p_{illum} as shown in semi-log plot in Fig. 5.

For comparison efficiency of high efficiency GaAs LPCs are plotted in Fig. 5. Highest LPC efficiency known to the authors was achieved by Helmers et al. with η = 57,4 % at λ_0 = 805 nm and p_{illum} = 124 W/cm^2 [6]. GaAs LPC with similar efficiency η = 56,0 % at λ_0 = 820 nm and p_{illum} = 56 W/cm^2 was reported by Andreev et al.[5]. Efficiency η = 52,8 % at λ_0 = 810 nm and p_{illum} = 14 W/cm^2 was reported by Beaumont et al.[10]. Peña et al. developed LPC with efficiency η = 45,4 % at λ_0 = 808 nm and p_{illum} = 5 W/cm^2 [11]. For same illumination parameters Shan et al. report efficiency η = 53,2 % [12]. Reported high efficiency LPCs are marked with circles in Fig. 5.

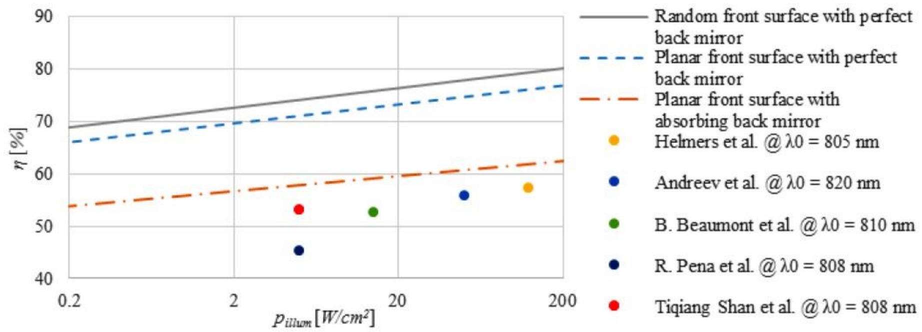

Fig. 5 Influence of high irradiance on efficiency of LPCs. Efficiencies of state-of-the-art GaAs LPCs obtained from the literature are marked with circles.

3.3. Single and double layer *AR* coating for reduced front surface reflection

So far in the paper no reflection of incident light from front surface was assumed in calculations, resulting in all light reaching absorption layer. In the real world reflection from interface between two media results in decrease of light coupled in photovoltaic structure.

Reflection of light perpendicular to the surface is defined with refractive indices of media on the interface (23). In our case interface consists of air and GaAs. Since refractive index of GaAs n_{GaAs} is dependent on photon energy [13], reflection R exhibits same dependence. For photon energy $E_{ph} = 1{,}6$ eV, representing monochromatic light with $\lambda_0 = 808$ nm, $n_{GaAs}=3{,}7$ [13]. Refractive index of air is $n_{air} = 1{,}0$ and is constant through broad range of light spectrum [14].

$$R(E_{ph}) = \left(\frac{n_{air} - n_{GaAs}(E_{ph})}{n_{air} + n_{GaAs}(E_{ph})}\right)^2 \tag{23}$$

Large difference of refractive indices between GaAs and air leads to high reflection of light from the interface and only 67,2 % of perpendicularly incident monochromatic light at λ_0=808 nm is coupled in the absorption region of GaAs.

Numerous schemes are deployed in order to reduce reflection depending on the spectrum of incident light. For broadband white light random texturing of front surface reduce reflectivity of broad wavelength range to few percent [15]. Another approach employed when using monochromatic light is to use thin film single layer antireflection *AR* coating with refractive index n_{AR} (24) and with quarter wavelength thickness d_{AR} (25) of incident light.

$$n_{AR}(E_{ph}) = \sqrt{n_{air} n_{GaAs}(E_{ph})} \tag{24}$$

$$d_{AR} = \frac{\lambda_0}{4 n_{AR}(E_{ph})|_{E_{ph}=\frac{hc}{\lambda_0}}} \tag{25}$$

When using monochromatic light single layer thin film *AR* coating may totally reduce reflection as seen in Fig. 6 while for broad white light spectrum single layer of *AR* coating reduce reflectance to around 10 % [16].

Reflectance R for perpendicularly incident light as a function of thickness d_{AR} and energy of photon E_{ph} for single layer *AR* coating can be written as [17] (27):

$$\delta(E_{ph}, d_{AR}) = \frac{2\pi}{\lambda_0} n_{AR}(E_{ph}) d_{AR} \tag{26}$$

$$R(E_{ph}, d_{AR}) == \frac{n_{AR}^2(E_{ph})\left(n_{air} - n_{GaAs}(E_{ph})\right)^2 X + \left(n_{air} n_{GaAs}(E_{ph}) - n_{AR}^2(E_{ph})\right)^2 Y}{n_{AR}^2(E_{ph})\left(n_{air} + n_{GaAs}(E_{ph})\right)^2 X + \left(n_{air} n_{GaAs}(E_{ph}) + n_{AR}^2(E_{ph})\right)^2 Y} \tag{27}$$

λ_0 – wavelength of monochromatic light in air
$X = \cos^2\delta(E_{ph}, d_{AR})$
$Y = \sin^2\delta(E_{ph}, d_{AR})$

For monochromatic light with central wavelength λ_0=808 nm, 105,5 nm thick single layer *AR* coating with refractive index n_{AR}=1,92 reduce reflectance to zero as seen in Fig. 6, resulting in all incident light coupled in absorption layer. Since material with exact same refractive index at specified wavelength doesn't exist, it is informative to calculate reflection from front surface when using already deployed materials of *AR* coatings.

Fig. 6 shows reflections for three different materials of *AR* coating deployed on GaAs as a function of their thickness. The best material regarding refractive index for *AR* coating on GaAs is silicon nitride (Si_3N_4) with refractive index 2,00 at 808 nm [18]. GaAs with 101 nm thick layer of Si_3N_4 reflect around 0,1 % of incident light. Another appropriate material for *AR* coating of GaAs is Al_2O_3 or alumina. Al_2O_3/GaAs interface is widely studied [19], [20] since it has many uses in semiconductor industry such as insulator layer in IGFET transistors [21], diode laser coatings [22] and *AR* coating for high efficiency solar cells [23]. 114,8 nm thick layer of alumina on GaAs with refractive index n_{Al2O3}=1,76 [24] at 808 nm resulting in front surface reflection under 1 %. Another commonly used material for *AR* coating on solar cells is SiO_2 or silica with refractive index n_{SiO2}=1,45 at 808 nm [25]. Since the refractive index of silica is far from optimal for *AR* coating on GaAs around 7,4 % of incident light is reflected in the best case scenario.

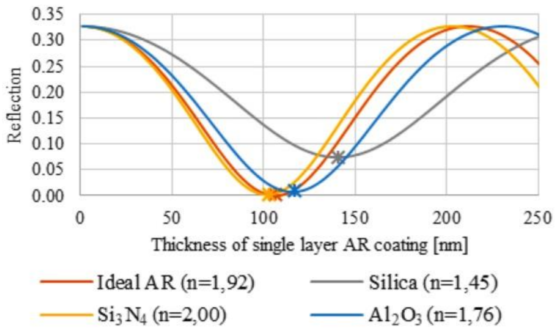

Fig. 6 Influence of single layer AR coating on reflection from interface GaAs/air

Single layer *AR* coating provides sufficient reduction of reflection for monochromatic light from the interface GaAs/air, but put strict requirements on *AR* coating material, since it requires exactly specified refractive index in order to achieve good results. It also performs well only for designed wavelength so performance of single layer *AR* coating is decreased in real world scenario where wavelength of diode laser varies due to manufacturing tolerances and temperature of operation. To overcome this limits, double layer *AR* coating can be deployed.

For quarter wavelength thicknesses of both *AR* coatings in double layer *AR* stack, for perpendicularly incident light *R* is defined as [17] (28):

$$R(E_{ph}) = \left(\frac{n_{AR2}^2(E_{ph})n_{air} - n_{AR1}^2(E_{ph})n_{GaAs}(E_{ph})}{n_{AR2}^2(E_{ph})n_{air} + n_{AR1}^2(E_{ph})n_{GaAs}(E_{ph})}\right)^2 \quad (28)$$

R will be minimized when (29):

$$\frac{n_{AR2}}{n_{AR1}} = \sqrt{\frac{n_{GaAs}}{n_{air}}} \quad (29)$$

n_{AR1}, n_{AR2} – refractive index of thin layer one and two of double layer *AR* coating

To minimize reflection from interface air/GaAs when using monochromatic light with $\lambda_0 = 808$ ratio of $n_{AR2}/n_{AR1} = 1,92$ should be utilized. Well suited materials for *AR* coatings that approach this ratio are MgF_2 and TiO_2. Refractive indices of those two materials at 808 nm are $n_{TiO2} = 2,52$ [24] and $n_{MgF2} = 1,37$ [26] resulting in ratio of $n_{AR2}/n_{AR1} = 1,84$. Fig. 7 shows reflection of double stack *AR* coating deployed on GaAs as function of thickness of MgF_2 and TiO_2. Reflection is reduced to zero with thickness of $d_{MgF2} = 72,2$ nm and thickness of $d_{TiO2} = 58,1$ nm.

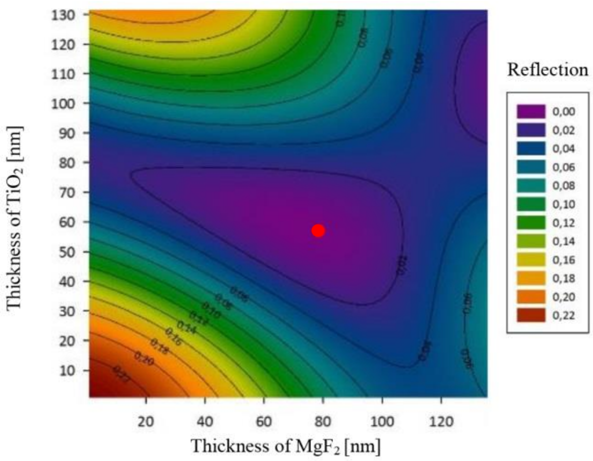

Fig. 7 Influence of double layer AR MgF2/TiO2 coating on reflection from interface GaAs/air

4. COMPARISON OF SQ EFFICIENCY LIMIT WITH MEASURED LPC EFFICIENCY

Following theoretical calculations, measurements were done on GaAs LPC pictured in Fig. 8. A single segment single junction circular GaAs LPC with radius 0,15 cm was fully illuminated with monochromatic light from semiconductor laser with $\lambda_0 = 808$ nm and total output power 1,06 W. Light from a laser diode is coupled into MM 105/125 µm, NA 0,22 fiber with output positioned perpendicular to the surface of the LPC so that whole area is illuminated and spillage of light is minimized. Impinging profile of incident light is near Gaussian resulting in uniform irradiance of front surface. Area of illumination was 0,074 cm^2 resulting in $p_{illum} = 14{,}3$ W/cm^2. LPC was mounted on TO-39 casing that was socketed and mounted on heatsink for efficient heat dissipation. I - V curve of illuminated LPC was measured with Keithley 2602A. Scan through whole I - V curve was done in under one second in order to minimize heating of the LPC. Measured temperature of the TO-39 casing was 302 K. Measurement results compared with theoretical SQ limits for the same parameters can be seen in Table 1.

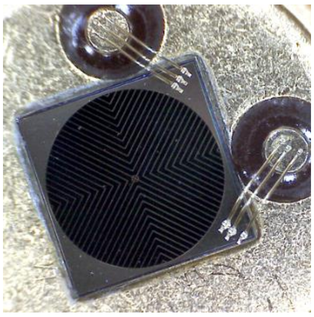

Fig. 8 Picture of measured GaAs LPC mounted on TO-39 casing.

Table 1 Measurement and simulated results for LPC under monochromatic illumination for $p_{illum} = 14{,}3$ W/cm^2

	GaAs LPC measured	GaAs LPC SQ	ratio [%]
η [%]	54,4	76,6	71,0
FF [%]	82,3	90,3	91,1
V_{oc} [V]	1,16	1,30	89,2
J_{sc} [A/cm^2]	8,24	9,31	88,5
V_{MPP} [V]	1,00	1,20	83,3
J_{MPP} [A/cm^2]	7,78	9,12	85,3
p_{max} [W/cm^2]	7,78	10,96	71,0

Measured I - V curve normalized to calculated SQ limit values of J_{SC_SQ} and V_{OC_SQ} [27] for the same parameters can be seen in Fig. 9. While J_{SC} and V_{OC} of fabricated LPC achieve around 90 % of the theoretical value, P_{max} at 71 % of theoretical limit still needs to be optimized. Reason for low measured P_{max} in power lost on series resistance R_s, which is beside grid shading dominant loss mechanism in manufactured single junction, single segment LPCs as discussed in [28].

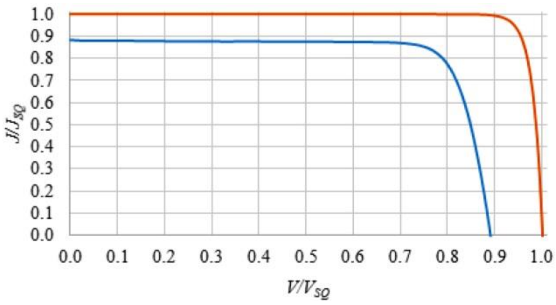

Fig. 9 Measured and simulated *I* - *V* curve of GaAs LPC normalized to values of V_{OC_SQ} and J_{SC_SQ}. Measurements and calculations were done under monochromatic illumination λ_0=808 nm for p_{illum} = 14,3 W/cm^2

5. Distribution of losses in LPC

Following the SQ limit we can divide energy conversion from light to electrical energy in LPC in groups. Loss analysis for randomly textured L = 1 µm thick LPC with perfect mirror on the back as best case theoretical structure at λ_0 = 808 nm, p_{illum} = 14,3 W/cm^2 and $FWHM$ = 5 nm at T = 302 K is shown in Fig. 8 in inner section of pie chart. 76,6 % of light energy is converted to useful electrical energy. 13,9 % of the light energy cannot be converted to electrical energy due to lower voltage at maximal power point V_{MPP} than voltage of bandgap, V_{g}. Radiative recombinations of e – h pairs contribute to 2,0 % of energy emitted from LPC and 7,5 % is transformed to heat due to the thermal relaxation of photons with energy higher than bandgap. Thermal losses could be minimized if monochromatic light source with central wavelength at peak efficiency as seen in Fig. 4 would be used.

Outer section of pie chart in Fig. 10 shows measured energy distribution in LPC. R_S contribute to significant drop of V_{MPP} resulting in increased loss of useful energy due to $V_{MPP} < V_g$. Another 13,3 % of energy is a sum of other electronic and optical losses.

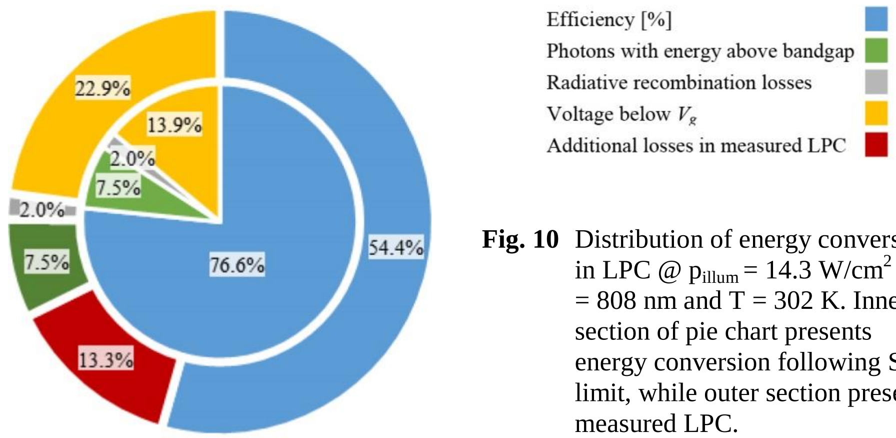

Fig. 10 Distribution of energy conversion in LPC @ p_{illum} = 14.3 W/cm^2 at λ_0 = 808 nm and T = 302 K. Inner section of pie chart presents energy conversion following SQ limit, while outer section presents measured LPC.

6. CONCLUSION

Calculation of SQ limits for LPC under monochromatic illumination is a method for evaluation of theoretically achievable limits of LPCs and comparing them to measured results of manufactured devices. We provided insights how LPC design can be further optimized together with appropriate light source in order to achieve high system efficiency. Irradiance should be high leading to small surfaces of LPCs and 80 % efficiency could be theoretically achieved for $p_{illum} = 100\ W/cm^2$. Comparison between calculated and measured values shows us that we can already achieve 90 % of theoretical values for J_{SC} and V_{OC} while measured p_{max} achieve 71 % of theoretical limit calculated with SQ method. Further work should be done to include effect of series resistance in the calculations, since it is a major loss mechanism in single junction single segment LPCs.

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