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GaAs Vertical-Tunnel-Junction Converter for Ultra-High Laser Power Transfer

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***Abstract*— High power laser transmission is being intensively researched as a potential solution to transfer power to remote systems, being the power converter (PC) one of the main limiting factor to improve the system efficiency (η). Current PCs are mostly horizontal structures in which the η heavily decreases at large input power. In this work, we propose a novel GaAs-based vertical-tunnel-junction (VTJ) PC suitable for ultra-high (UH) input power density (P_{in}). This structure does not suffer from η degradation at high P_{in} because it is designed to have low current density, high output voltage and reduced series resistance (~ 2 orders of magnitude lower than the state-of-the-art PCs). We have demonstrated increasing η with P_{in}, reaching values higher than 76% at 3000 W·cm^{-2}. This vertical-based architecture enables a new set of potential applications for wireless PC to power remote systems with η exceeding today´s state-of-the-art PC designs.**

***Index Terms*— Laser power transfer, power converter, vertical-structure, tunnel-junction, GaAs, series resistance**

I. Introduction

WIRELESS power transfer (WPT) technology has attracted increasing interest, becoming a billion market within the last years [1]. One of the most promising WPT technologies is high-power laser transmission (HPLT) since it offers electrical isolation, reduced electrical noise and electromagnetic interference and the ability to transfer energy without wires. HPLT uses a monochromatic light source, usually a laser, to transfer power to a remote system via a power converter (PC). There is an intensive research underway to increase the efficiency (η) and power transmission of PCs [2]–[5]. However, current devices have their peak η at input powers (P_{in}) lower than 100 W·cm^{-2} [6]. For a paradigm shift, the development of new generation ultra-efficient PC suitable for converting power in the order of kilowatts with high η is crucial [7]. This would allow to reduce PC surface, to increase the distance range and the number of applications of this technology [8], [9].

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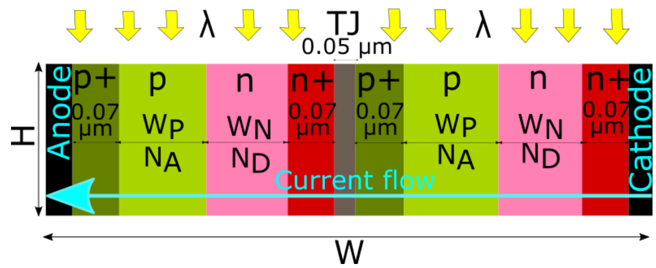

Fig. 1. 2D scheme of the VTJ GaAs power converter structure. W_P/N_A and W_N/N_D are the width/doping of the p and n-layers respectively, which will be subject of the optimisation.

State-of-the-art PCs are mainly GaAs-based horizontal structures [10], [11], [12] in which the efficiency (η) heavily decreases at large P_{in} values. The limitation of these materials to achieve high η at extreme P_{in} under real operating conditions are imposed by the unavoidable series resistance (Rs) losses and the high current density of these designs under ultra-high (UH) input powers. To solve these issues, York et al. [13] proposed to vertically stack several NP junctions connected in series, which reduces the current density and increases the operating voltage, achieving a record η of 66% at a P_{in} of 64.4 W·cm^{-2}. However, this design, as the conventional PCs, still has the electrical contacts on the top and bottom of the device, which implies a trade-off between the shadowing of the front metal-grid and the R_S, limiting the η at high and UH P_{in} [14].

In this work, we introduce a novel GaAs-based vertical-tunnel-junction (VTJ) PC that aims to decrease the R_S losses, reducing the current density while increasing the output voltage, placing the contacts perpendicularly to the incident light. The proposed design is based on the UH concentrator solar cell structures recently proposed by the authors [15], [16]. In this case, this early design is investigated for the first time for its potential application as PC suitable for UH laser power. The VTJ PC exhibits, increasing η with P_{in}, reaching values higher than 76% for a P_{in} of 3000 W·cm^{-2}.

II. Device Structure and Simulation

The PC presented in this work is based on a VTJ structure, introduced for Concentrator PhotoVoltaics in [17], composed of two identical GaAs-based PN junctions connected by a highly doped GaAs tunnel junction (TJ). This III-V material has been selected because is widely used in photovoltaic and power converter applications and presents the best known η results in PCs [10], [18].

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TABLE I
OPTIMUM VALUES OBTAINED FOR THE VTJ-BASED POWER CONVERTERS

	P_{in}	λ	W	H	W_P	W_N	N_A	N_D	η
PC1	10	0.847	20.1	7.5	2.6	7.3	$2\cdot10^{16}$	10^{14}	69.5
PC2	3000	0.849	10.3	10.5	2.5	2.5	$3\cdot10^{17}$	10^{14}	76.3

Input power density: P_{in} (W·cm^{-2}), wavelength: λ (µm), width: W (µm), height: H (µm), width of the P/N layers respectively: W_P/W_N (µm), acceptor/donor concentration: N_A/N_D (cm^{-3}) and efficiency: η (%).

In the VTJ architecture the illumination is perpendicular to the PN junctions, and the contacts are placed laterally to extract the generated current (see the current flow in Fig. 1). Therefore, the limitation imposed by the trade-off between the shadowing of the front metallic contact and the R_S of the conventional structures is avoided. In this way, the R_S losses diminish and there is not any type of grid resistance or shadow effect. Using this structure, it is possible to increase the area of the device exposed to the light connecting more VTJs via TJ, increasing the output power and the voltage, while keeping the current constant due to the connection in series. The GaAs PC has two subcells, each one composed by two p-layers (p and p^+) and two n-layers (n and n^+). The p^+ and n^+ layers have a width (W) of 0.07 µm and are doped to $5\cdot10^{19}$ cm^{-3}. Both layers remain fixed during this study. On the other hand, the TJ is composed by a n^+/p^+ GaAs junction to avoid any mismatching problems in the structure. The TJ layers are doped to $7\cdot10^{19}$ cm^{-3} and have a 25 nm width. Note that in this vertical architecture the current density is very low and therefore the TJ will not be a limiting factor [19].

The PCs have been modelled using Silvaco TCAD [20], a software widely used by the photovoltaic community for designing and optimising solar cells [21], [22] and power converters [13], [23], because it provides realistic results. The Poisson and continuity equations, that relate the electrostatic potential and the carrier densities, are solved self consistently. Different recombination mechanisms (Auger, radiative and Shockley-Read-Hall (SRH)) have been taken in account in our simulations. The contacts are considered ideal and, we do not account for reflections since the incoming light is parallel to them. This approximation is feasible because of the low resistance of the contacts, typically ranging from 10^{-4} to 10^{-5} Ω·cm^2, compared with the standard technology [24]. All the simulations are 2D (assuming negligible changes in the third dimension), consider uniform, continuous and monochromatic illumination with a wavelength close to the bandgap and a temperature of 298 K. Further details of the simulation methodology and assumptions above can be also found in [25].

III. RESULTS AND DISCUSSION

In the present work, we propose two VTJ-based PCs, optimised for a low P_{in} value of 10 W·cm^{-2} (PC1) and an UH P_{in} value of 3000 W·cm^{-2} (PC2), with the aim of maximising the η and to evaluate the proposed structure for a wide range of operating conditions. The following parameters were optimised: input wavelength (λ), width (W) and doping of the p (N_A) and n (N_D) layers, and height (H) of the structure, see optimum values in Table I. Record η values of 69.5% at a P_{in} of 10 W·cm^{-2} for PC1, and 76.3% at 3000 W·cm^{-2} for PC2

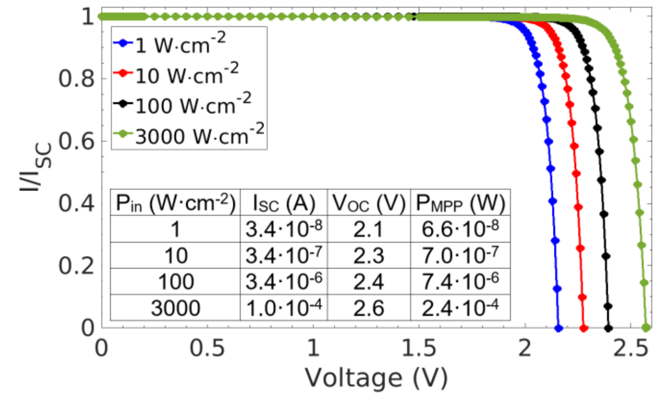

Fig. 2. Normalised IV curves at different input power densities (P_{in}) values for PC2. The short-circuit current (I_{SC}), open-circuit voltage (V_{OC}) and maximum power (P_{MPP}) are also included.

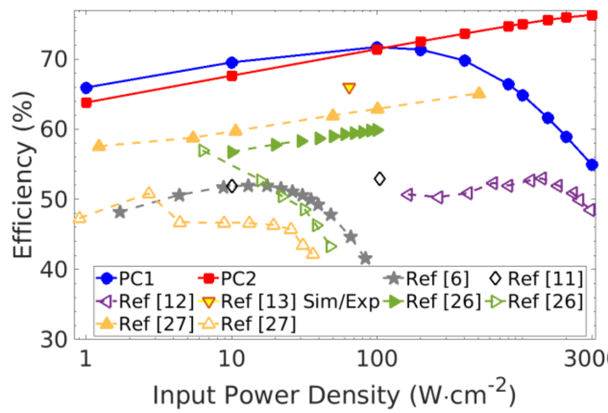

Fig. 3. Efficiency as a function of the input power density (P_{in}) in logarithmic scale for the two VTJ-based power converters optimised at P_{in} values of 10 W·cm^{-2} (PC1) and 3000 W·cm^{-2} (PC2), and for several experimental and simulated state-of-the-art PCs.

were obtained. The larger H value observed for PC2 compared to the PC1 value is due to the trade-off between increasing the absorption (via enlarging H) and increasing the current density (via reducing H). On the other hand, the larger the P_{in} the smaller the W of the n-layer to minimise the impact of recombination effects (see Table III for further details), due to the low mobility of minority carriers (holes) in this layer when compared with the p-layer. Fig. 2 shows the normalised IV curves for the PC2 at different P_{in} including the short-circuit current (I_{SC}), open-circuit voltage (V_{OC}) and the maximum power (P_{MPP}). Note the linear increase of I_{SC} with P_{in}.

Fig. 3 shows η versus of P_{in} for the two optimised VTJ-based PCs, and for experimental [11], [12], [13], [26], [27], (empty symbols) and simulated [6], [13], [26], [27] (filled symbols) state-of-the-art GaAs PCs available in the literature. Note that the simulated and experimental η values in [13] are virtually the same, validating the use of TCAD to evaluate the performance of new architectures and designs. For PC1 η increases with P_{in} until 100 W·cm^{-2} reaching a maximum of 71.7%, and then decreases rapidly with the increase of P_{in}. Note that this same behaviour has also been reported in previous work, see for instance [6], [12], [26], [27]. PC2 achieves slightly lower η values than PC1 at low P_{in} values (<100 W·cm^{-2}) since it was optimised for an UH P_{in} value but, maintains a linear increase in η with the logarithmic P_{in} for all

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TABLE II
INPUT POWER DENSITIES (P_{IN}), SERIES RESISTANCE (R_S) AND EFFICIENCY FOR STATE-OF-THE-ART SIMULATED AND EXPERIMENTAL PC_S AND THE VTJ-BASED PC_S

	P_{in} ($W\cdot cm^{-2}$)	Rs ($\Omega\cdot cm^2$)	η (%)	Ref.
Simulated	10	$3.4\cdot 10^{-2}$	56.8	[26]
	64.1	$1.6\cdot 10^{-1}$	66.0	[13]
Experimental	31.8	$1.1\cdot 10^{-1}$	48.6	[26]
	10 - 104	$4.7\cdot 10^{-2}$ -$5.6\cdot 10^{-3}$	51.9-52.9	[11]
	36.1	$1.9\cdot 10^{-1}$	42.2	[27]
	64.1	$1.1\cdot 10^{-1}$	66.0	[13]
	13.2-21.9	$8.3\cdot 10^{-2}$ -$6.9\cdot 10^{-2}$	52.0-51.6	[6]
PC1	3000	$4.1\cdot 10^{-5}$	55.0	This work
PC2	3000	$7.2\cdot 10^{-5}$	76.3	This work

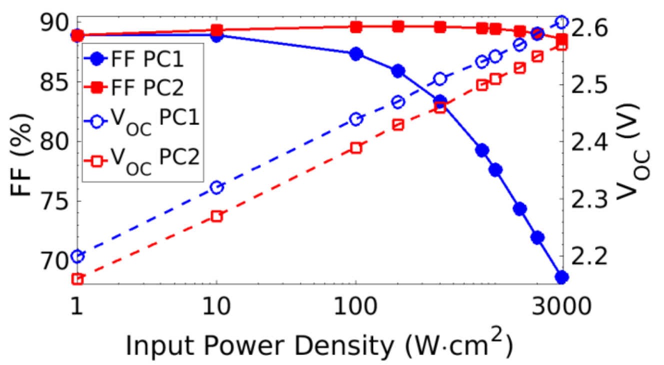

Fig. 4. Fill Factor and open-circuit voltage as a function of input power density in logarithmic scale for the VTJ-based power converters optimised for an input power density of 10 $W\cdot cm^{-2}$ (PC1) and 3000 $W\cdot cm^{-2}$ (PC2).

the studied intervals, ranging from 63.8% at 1 $W\cdot cm^{-2}$ to 76.3% at 3000 $W\cdot cm^{-2}$. The two PCs proposed in this work have a significantly better η than the state-of-the-art converters for all studied P_{in}. The current record η for a PC (66.0%) was achieved at a relatively low P_{in} of 64.4 $W\cdot cm^{-2}$ [13], and for this same P_{in} value, PC1 and PC2 achieve 5.3% and 4.6% larger η values, respectively, even if they have not been optimised for this P_{in}. At a medium P_{in} (400 $W\cdot cm^{-2}$), the η of [27] is 8.5% lower than those of the VTJ-based PCs proposed. For UH P_{in} (3000 $W\cdot cm^{-2}$), the experimental maximum η obtained in [12] is 48.5%, a value significantly lower than the 76.3% achieved by PC2. The high η values of the VTJ-based PCs are due to the R_S of the vertical architecture (R_S losses are given by $J\cdot R_S^2$). To justify this statement, the Rs has been calculated using the slope of the IV curve close to the V_{OC} value (see Table II), following the strategy introduced in [28], for both the VTJ and state-of-the-art PCs. The R_S of the VTJ-based PCs is at least two or three orders of magnitude lower than those of the state-of-art PCs. These results highlight the importance of structures with low R_S values, such as the one proposed in this letter, to obtain high η at UH P_{in}.

Fig. 4 shows the dependence of the open-circuit voltage (V_{OC}) and Fill Factor (FF) vs. P_{in} for PC1 and PC2. V_{OC} linearly grows with the logarithmic increase of P_{in} for the two PCs, without any type of degradation. However, for PC1, the FF decreases with P_{in}, ranging from 88.9% at 1 $W\cdot cm^{-2}$ to 68.6% at 3000 $W\cdot cm^{-2}$. This reduction at UH P_{in} in PC1 is mainly attributed due to low value of the shunt resistance (R_{SH}), $2.5\cdot 10^{-2}$ $\Omega\cdot cm^{-2}$ at 3000 $W\cdot cm^{-2}$, as estimated following the methodology discussed in [29]. For PC1, the width of the n-layer is 7.3 µm, and at UH P_{in} the radiative recombination of carriers in this layer notably increases, deteriorating the device performance. Table III shows the η for the two VTJ-based PCs at 3000 $W\cdot cm^{-2}$ for different scenarios: all recombinations activated (AR), no recombination effects (NR) and the cases when only Auger, radiative or SRH are considered. Results show that radiative is the dominant effect, reducing the η for PC1 at UH P_{in} a 22.1% respect the NR case. This damaging effect of the total recombination is due to the large volume in which it can take place. This phenomenon is specific to the vertical architecture since the direction of the incident light is perpendicular to the location of the contacts. In any case, it can be minimised with a good optimisation of the layer dimensions. For instance, PC2 maintains high FF and η in all the P_{in} range because the recombinations are very low, reducing the η only by a 3.3%. Note that for PC2 the width of the n-layer is 2.5 µm, allowing two orders of magnitude larger R_{SH} (~3 $\Omega\cdot cm^{-2}$). This highlights the importance of optimising the device structure to improve the performance for a particular targeted P_{in}.

TABLE III
EFFICIENCY VALUES FOR DIFFERENT RECOMBINATION SCENARIOS

		Efficiency (%)				
	P_{in} ($W\cdot cm^{-2}$)	AR	NR	Auger	Radiative	SRH
PC1	3000	55.0	77.2	76.6	55.1	77.0
PC2	3000	76.4	79.7	79.6	76.8	78.6

Input power density: P_{in} ($W\cdot cm^{-2}$), AR: all recombinations, NR: no recombinations, Auger: only Auger recombination, Radiative: only radiative recombination, SRH: only Schockley-Read-Hall recombination.

Finally, although the manufacturing of the PC architectures is out of the scope of this letter, we would like to provide details about its feasibility. For this architecture, only GaAs material has been considered. This avoids lattice-mismatching problems and facilitates the fabrication process. In this sense, the structure could be monolithically grown as in standard III-V multi-junction concentrator solar cells. Also, the metallic contacts could be placed on the laterals using the same techniques as in the solar cell technology. After that, the solar cell can be rotated, so the input laser is perpendicular to the current flow.

IV. CONCLUSIONS

We have proposed a novel GaAs-based vertical-tunnel-junction (VTJ) power converter (PC) that shows increasing efficiency (η) values with the input power (P_{in}), reaching a η of 76.3% for a 3000 $W\cdot cm^{-2}$ P_{in}. This design achieves at least 4.6% larger η than that observed in the current record device, which is 66.0%, but only at a P_{in} of 64.4 $W\cdot cm^{-2}$. This architecture benefits from low series resistance values (~10^{-5} $\Omega\cdot cm^2$) and no shadowing effects of the front metal grid. In addition, if the structure is optimised for ultra-high (UH) P_{in} values, it does not suffer from performance degradation at these extremely high input power values. These results open a new route for the use of GaAs VTJ PCs in future high-efficiency and high-power remote applications.

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