Advancing Solar Energy Conversion Efficiency to 47.6% and Exploring the Spectral Versatility of III-V Photonic Power Converters

Henning Helmers[1], Oliver Höhn, David Lackner, Patrick Schygulla, Malte Klitzke, Jonas Schön, Carmine Pellegrino, Eduard Oliva, Michael Schachtner, Paul Beutel, Stefan Heckelmann, Felix Predan, Jens Ohlmann, Gerald Siefer, Frank Dimroth

Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany

ABSTRACT

III-V compound semiconductors provide a high degree of flexibility in bandgap engineering and can be realized through epitaxial growth in high quality. This enables versatile spectral matching of photovoltaic absorber materials as well as the fabrication of complex layer structures of vertically stacked subcells and tunnel junctions. This work presents progress in two fields of applications of III-V photovoltaics: concentrator solar cells and photonic power converters. We present latest results in advancing solar energy conversion efficiencies to 47.6% based on a wafer-bonded four-junction concentrator solar cell. Furthermore, we provide an overview of the latest development results regarding photonic power converters, showcasing several record devices. We briefly introduce a new metallization technique using electro-plated silver for handling high currents and first 10-junction InGaAs devices for optical telecommunication wavelengths. Overall, this paper highlights the potential of III-V compound semiconductors in achieving high efficiencies and spectral matching, offering promising prospects for future applications.

Keywords: III-V, photovoltaics, multi-junction, solar cell, photonic power, CPV, optical power transmission, power beaming.

1. INTRODUCTION

The large design space of III-V compound semiconductors enables the realization of highly efficient photovoltaics. Adjusting the composition offers the possibility to tune the absorber materials bandgap over a broad range from 0.35 eV for InAs or even 0.17 eV for InSb to 2.45 eV for AlP, see Fig. 1. Such tuning allows to realize photovoltaic devices which are ideally matched to the incident spectral irradiance.

For solar energy conversion, the concept of multi-junction solar cells has been introduced in the mid of the 20th century and picked up significant development efforts in the 1990s. The concept is based on the idea to vertically stack several subcells made of different absorber materials with bandgap decreasing from top to bottom, so that the broad band solar spectrum is split into spectral bands which are converted by the individual subcells. This way thermalization losses (for photons with energies above the bandgap) as well as transmission losses (photons with energies below the bandgap) can be minimized.[1–6] First applications for high efficiency III-V solar cells were in space where the higher power density is specifically beneficial, later the technology was introduced on Earth in concentrating photovoltaics (CPV). Recently, pathways for significant cost reduction[7] promise further applications through integration in other technologies, ranging from high-altitude pseudo satellites (HAPS) and 'new space' satellite constellations in low-Earth orbit (LEO) to e.g. automotive integration (vehicle integrated photovoltaics, VIPV).

Beyond solar cells, the potential for fine tuning of the absorber material and spectral matching to the incident spectral irradiance is of great value in optical power transmission. Here, III-V photovoltaic cells are developed to be used as photonic power converters (PPC)[8–10] for narrow band artificial light sources. In such power-by-light systems, typically a laser or LED transmits light over optical fibers (power-over-fiber)[11] or through free space (laser power beaming). At the receiver is it converted back to electricity to power downstream applications without galvanic connection between power source and remote location. Power-by-light technology is a power solution that omits the copper cable and as such can be

[1] Corresponding author: henning.helmers@ise.fraunhofer.de; phone +49 761 4588-5094; www.ise.fraunhofer.de

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considered an enabling technology that is increasingly adopted in various technological fields. Given the optical nature of the power link, a combination with optical fiber based telecommunication or optical wireless communication (OWC) is possible and offers particular advantages for various applications.[12–15]

This work is divided into two parts and presents latest results of the III-V based photovoltaic cells developed at Fraunhofer ISE. First, a wafer-bonded four-junction concentrator solar cell is presented which achieved unprecedented solar energy conversion efficiency. Second, an overview of latest development results regarding PPCs is given.

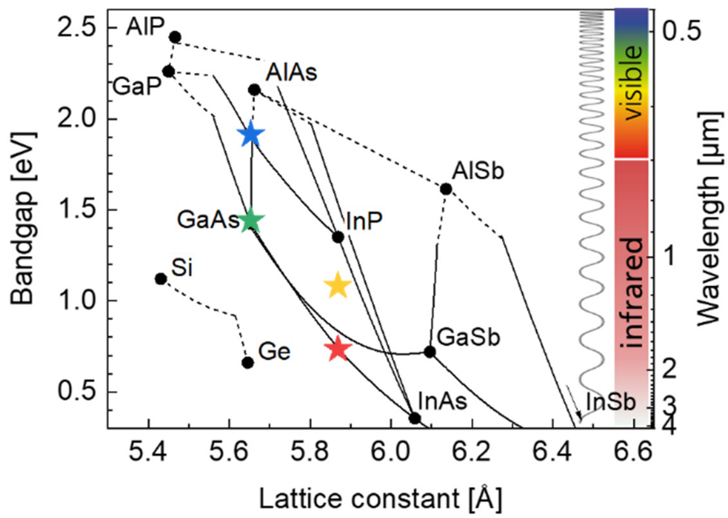

Figure 1. Bandgap versus lattice constant of III-V compound semiconductors. Circles represent binary materials, lines indicate ternary alloys, the area enclosed by lines represents the compositional space of quaternary alloys. Solid and dashed lines represent direct and indirect bandgaps. The corresponding wavelength is indicated on the right axis. Stars mark the absorber materials of our 4-junction wafer-bonded concentrator solar cell.

2. FOUR-JUNCTION WAFER-BONDED CONCENTRATOR SOLAR CELL

2.1 Design and fabrication

We have fabricated a four-junction solar cell following a wafer-bonding concept.[14, 4, 16] Two separate dual-junction cell stacks were grown by metal organic vapor phase epitaxy (MOVPE) using an AIXTRON 2800G4-TM reactor. An $In_{0.85}Ga_{0.15}As_{0.65}P_{0.35}/In_{0.53}Ga_{0.47}As$ bottom tandem cell structure was grown upright and lattice-matched on a 4" InP substrate. A $Ga_{0.51}In_{0.49}P/Al_{0.03}Ga_{0.97}As$ top tandem cell structure was grown invertedly lattice-matched on a 4" GaAs substrate. Target materials were defined by transfer matrix modeling of the absorptance aiming at current matching under standard testing conditions under the AM1.5d reference spectrum. Ternary and quaternary materials were modeled using an algorithm that morphs data between known compositions.[17] For the handover from modeling to epitaxial growth and then iterative feedback, the bandgap extracted from photoluminescence as well as from the external quantum efficiency *EQE* was used,[18] following the approach published by Schygulla *et al*.[19] Careful subcell absorber material characterization and optimization using X-ray diffraction analysis, spectrally and time-resolved photoluminescence, and atomic force microscopy along with precise MOVPE process control allowed to maximize the material qualities.

The two tandem structures were joined by direct wafer-bonding at Soitec in France. After wafer-bonding the GaAs substrate was removed by wet-chemical etching. During processing of the wafer, full area rear side and structured front side metallization were deposited, and a four-layer anti-reflection coating was applied. Finally, individual concentrator solar cells were separated by mesa etching. The nominal designated area of the fabricated GaInP/AlGaAs//InGaAsP/InGaAs concentrator solar cells is 0.054 cm².

2.2 Experimental results

Electrical characterization was carried out in the Fraunhofer ISE CalLab PV Cells using a grating monochromator setup for measuring the external quantum efficiency *EQE*,[20, 21] a multisource solar simulator for 1-sun *I-V* characteristics (X-Sim),[22] and a four-flash simulator (QuadFlash) with spectrum control for *I-V* curves under concentration.[23, 24]

The EQE data of the four subcells is shown in Fig. 2. The sum of the subcell EQEs reveals low parasitic absorptance in tunnel diodes, low reflectance and low finger shading. Under AM1.5d spectral conditions the current is limited by the top subcell with a current density of 13.47 mA/cm². Compared to the average current density of 13.56 mA/cm² the current mismatch is below 0.7%. Fig. 3 shows the *I-V* parameters measured under concentration, with the spectrum adjusted to the AM1.5d reference spectrum (ASTM G173-03, 1000 W/m²). Fill factor peaks at a concentration of *C*=295 with *FF*=84.2%. At 665-fold concentration an unprecedented peak efficiency of 47.6% is reached. The *I-V* characteristics of the champion device is shown in Fig. 4. The specific series resistance determined from the slope of the *I-V* curve around V_{OC} is around 20 mΩ cm², which allows for the operation of the device at high concentrations above 500 suns.

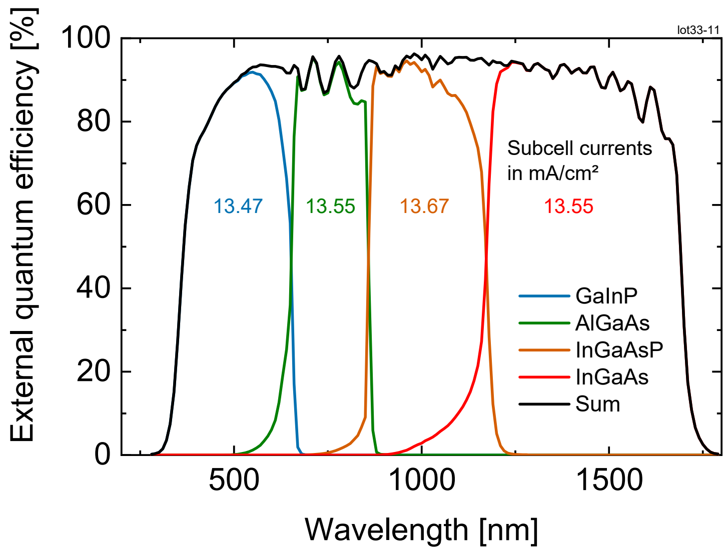

Figure 2. External quantum efficiency *EQE* of the four subcells (colored lines) plotted against wavelength. The black line represents the sum of the subcell EQEs. Resulting subcell current densities under the AM1.5d reference spectrum are stated in units of mA/cm² inside each subcell EQE curve.

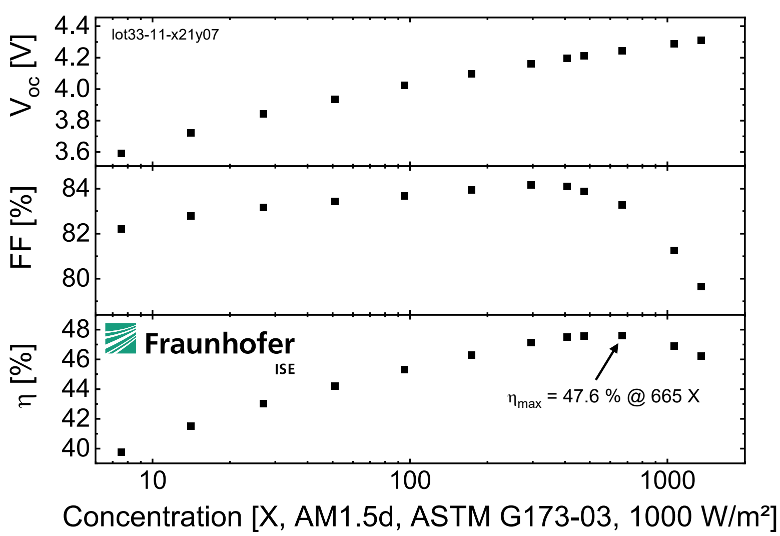

Figure 3. Performance metrics of the wafer-bonded 4-junction concentrator solar cell measured under a spectrally adjustable flash based solar simulator with four different light channels (QuadFlash) in the ISE calibration laboratory ISE CalLab PV Cells. Open-circuit voltage V_{OC}, fill factor *FF* and conversion efficiency *η* are plotted against concentration *C*. A record efficiency of 47.6% is reached at a concentration ratio of *C*=665 X.

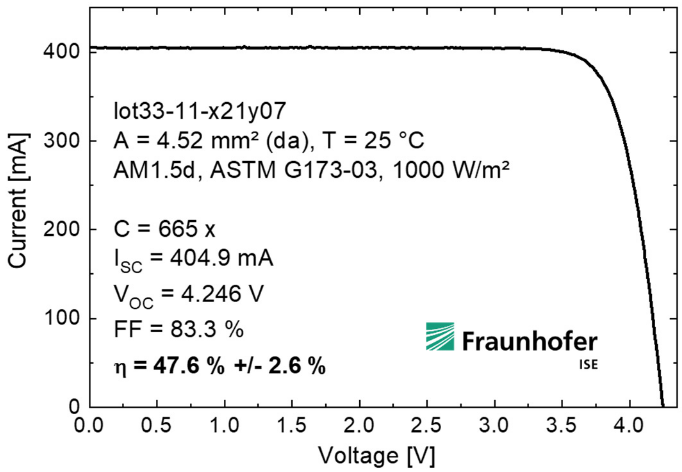

Figure 4. Current-voltage (*I-V*) curve of the champion device measured under a spectrally adjustable flash based solar simulator with four different light channels (QuadFlash) in the ISE calibration laboratory. The designated area was defined by a shadow mask which covered the edges of the chip.

3. PHOTONIC POWER CONVERTERS: SPECTRAL VERSATILITY

Spectral tuning of the absorber bandgap of III-V compound semiconductors enables minimization of transmission and thermalization losses, which represent the dominant loss channels in solar cells.[25] Highest monochromatic conversion efficiency was achieved with a GaAs absorber at a laser wavelength of 858 nm with a photon energy very close to the bandgap.[26] However, longer wavelengths, in particular around 980 nm and 1064 nm as well as in the optical telecommunication wavelength bands between 1260 nm and 1675 nm, are of interest for wireless and fiber based applications and receive increasing attention.[27–49] Given the typical attenuation of optical fiber reaching a minimum around 1550 nm, the classical telecom wavelength bands allow for long range transmission over hundreds or even thousands of meters and enable new applications such as optical powering of 5G fronthaul fiber links.[50] For wireless systems, these bands are also advantageous in terms of laser safety[51, 52] as well as due to atmospheric transmission windows around 1000-1100 nm, 1200-1300 nm and 1510-1750 nm.[53]

At Fraunhofer ISE we have demonstrated III-V based photonic power converters for a variety of wavelengths. An overview of example experimental spectral response *SR* curves as a function of wavelength is shown in Fig. 5. The plot illustrates how the absorption edge shifts with changing bandgap. Note that the conversion efficiency η is determined by[26]

$$\eta = SR \times V_{OC} \times FF \qquad (1)$$

where the open circuit voltage $V_{OC}=E_g/q-W_{OC}$ is determined by the bandgap E_g, the elementary charge q, and a bandgap-voltage offset W_{OC},[54] which is related to material quality. The fill factor FF is mainly determined by V_{OC} and series resistance R_s.[55] Consequently, peak efficiency η is reached at peak *SR*. While GaInP grown lattice-matched on GaAs (compare blue star in Fig. 1) is well suited for the red end of the visible spectrum, GaAs with a bandgap corresponding to 870 nm is well suited to the first fiber transmission window around 850 nm. Absorber materials for infrared wavelengths beyond 870 nm can be realized by either lattice-matched growth of InGaAsP on InP substrates or by metamorphic growth of lattice-mismatched GaInAs on GaAs substrates.[27] In both cases the composition can be finetuned to adjust the bandgap to the target value. $In_{0.53}Ga_{0.47}As$ (red star in Fig. 1) with a bandgap of 0.74 eV is the lower bandgap limit of the quaternary InGaAsP lattice-matched to InP. It can also be realized by metamorphic growth on engineered substrates on GaAs.[56] Further grading of the metamorphic buffer (so-called extended metamorphic growth) beyond the lattice-constant of InP even allows to realize lower bandgaps below 0.6 eV. Both approaches, lattice-matched InGaAsP on InP and metamorphic GaInAs on GaAs, have been used to realize PPCs for various infrared wavelengths, including 980 nm and 1064 nm, as well as O- and C- telecommunication bands around 1310 nm and 1550 nm.

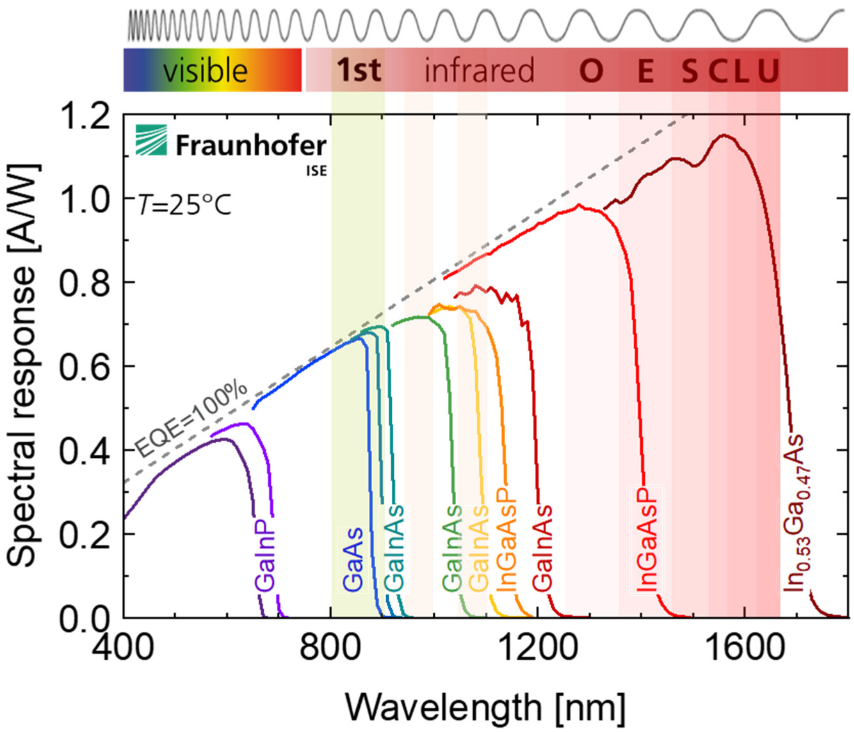

Figure 5. Experimental spectral response (*SR*) curves as a function of wavelength of various III-V absorber materials. The dashed line represents the maximum value for an external quantum efficiency (*EQE*) of unity. Laser bands of interest are highlighted (green: 1st transmission window around 850 nm, orange: 950-1000 nm, 1050-1100 nm, red: O/E/S/C/L/U telecommunication bands 1260-1675 nm).

An overview of experimental monochromatic conversion efficiencies plotted against wavelength is given in Fig. 6. Symbols in the graph represent PPC devices based on different absorber materials. The sizes of the circles scale with output power P_{mp}. We demonstrated a record conversion efficiency of 68.9% with a thin-film 1-junction GaAs based PPC with a back reflector.[26] This performance is enabled by leveraging optical resonance from the micro-cavity created by the mirror as well as enhancing the effective carrier lifetime by photon recycling. It reaches peak efficiency at 11.4 W/cm² 858-nm irradiance, resulting in a maximum power of 416 mW from the 5.3 mm² designated area. At higher irradiances, increasing current results in series resistance losses which scale with the current squared and limit performance. One way to mitigate this limitation is to introduce a transparent lateral conduction layer on the front side to support electrical transport to the metal grid.[57] Another option is to reduce current density by increasing the cell size while maintaining the absolute incident power constant. However, this prolongs the average grid line length, which in turn increases specific series resistance. To overcome this latter constraint, the front grid lines can be reinforced to reduce specific series resistance. Implementing this approach, we have realized a 1-cm² GaAs PPC with electroplated silver grid lines with a 15×15-µm² profile.[58] With below 8% grid shading the device demonstrated peak equivalent monochromatic efficiencies above 60% at 830 nm irradiance. At the highest measured irradiance of 62.6 W/cm², a maximum power output of 35.5 W was measured, which still corresponds to an efficiency of 56.7%.

For wavelengths around 980 nm and 1064 nm, we realized metamorphic GaInAs PPCs grown on GaAs substrates. With 5.4-mm² sized devices conversion efficiencies of 55.2% (42.9 W/cm²)[49] and 54.7% (14.2 W/cm²)[43] were achieved, respectively. With further increase of the wavelength and thus decreasing bandgap as well as increasing lattice-mismatch, at 1319 nm an efficiency of 48.7% (8.8 W/cm²) was demonstrated with a metamorphic device.[27] With a lattice-matched InGaAsP based PPC at a similar bandgap an efficiency of 52.8% (5.9 W/cm²) was achieved.[27] Targeting long-haul C-band applications, PPCs based on $In_{0.53}Ga_{0.47}As$ grown lattice-matched on InP were fabricated. Some of them were processed to thin-film devices by removing the InP substrate and depositing a back reflector. Similar as for the champion thin-film GaAs device, this back reflector enables optical resonance to be utilized, which explains the interference fringes in the *SR* of the $In_{0.53}Ga_{0.47}As$ device in Fig. 5. At 1550 nm a peak efficiency of 53.7% was determined.[34]

On the system side, a downside of the lower bandgap is the corresponding lower output voltage. To avoid dedicated power electronics for voltage up-conversion, the multi-junction approach known from high efficiency solar cells, namely the vertical stacking of subcells and their series connection by tunnel diodes, can also be applied to photovoltaic cells for monochromatic wavelength.[59] Instead of using different absorber materials in solar cells to better match the broad band spectrum, for PPCs subcells of the same absorber material are stacked. Due to the series connection, the device voltage is boosted to the sum of the subcell voltages, and thus can be adjusted by the number of junctions.[60] At the same time, the spectral response and, thus, current is divided among all subcells. To ensure current matching, i.e. all subcells generate the same current so that neither one limits the current of the series connection, careful design must take into account Beer-Lambert's law as well as the target operating temperature.[61] To boost the voltage of the InGaAs cells (E_g = 0.74 eV), we have grown and fabricated a 10-junction InGaAs PPC structure on InP substrate.[48] It demonstrates a V_{mp} of approximately 5 V and a measured peak efficiency under 1522 nm laser light of 45.6% (measured by collaborators at University of Ottawa's SUNLAB).

Finally, regarding combined reception of optical power and data, also known as simultaneous lightwave information and power transfer (SLIPT), III-V based photovoltaic cells are of interest. With a system based on free space optics and an eye-safe laser beam at 850 nm, a GaAs PPC with a circular area with 1 mm diameter, and an orthogonal frequency division multiplexing (OFDM) algorithm with adaptive bit and power loading (applied by collaborators at the LiFi Research and Development Centre at University of Strathclyde), maximal data rates above 1 Gb/s at short-circuit conditions were demonstrated and data rates of 0.78 Gb/s at maximum power point with simultaneous power harvesting of 1 mW.[13]

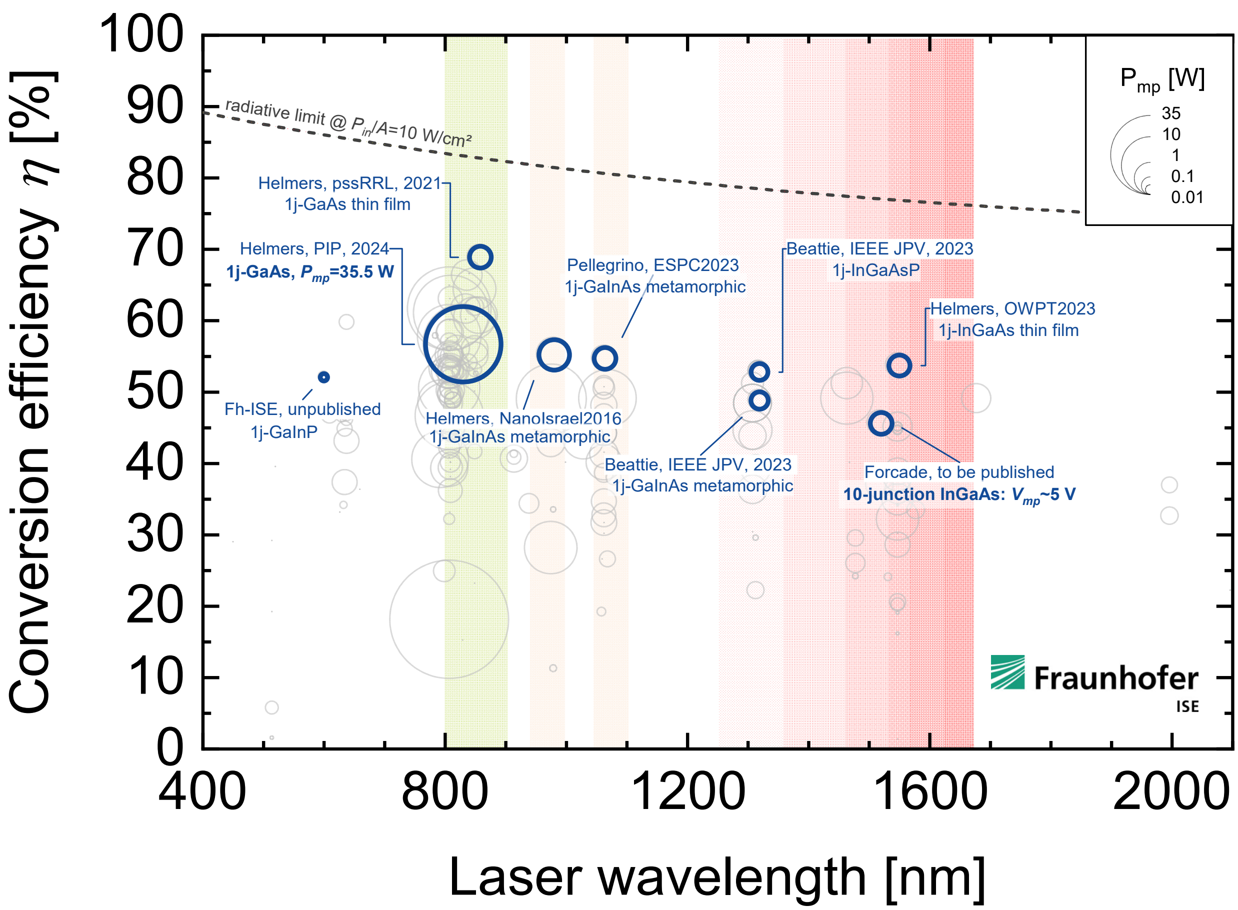

Figure 6. Measured conversion efficiencies of photonic power converters for various wavelengths. The size of the circle symbols scales with electrical output power P_{mp}. Blue symbols represent selected PPC devices fabricated at Fraunhofer ISE (Refs. 26, 27, 43, 34, 49, 58); the captions state absorber materials and device specific remarks. Gray symbols represent literature data of various research groups. Colored wavelength bands are the same as in Fig. 5.

4. CONCLUSION

This paper has explored the design and development of III-V compound semiconductors for highly efficient photovoltaics and photonic power converters. We fabricated a wafer-bonded multi-junction concentrator solar cell based on four subcells grown lattice-matched and of excellent material quality. Calibrated subcell *EQE* measurements revealed a current mismatch of below 0.7%. Using a spectrally adjustable four-source flash simulator, we performed detailed characterization under concentrated light. With a specific series resistance of around 20 mΩ cm², *FF* peaks at a concentration ratio of 295. At a concentration ratio of 665 (AM1.5d), we have demonstrated unprecedented solar energy conversion efficiency of 47.6%. This result highlights the potential of concentrating photovoltaics, in which such solar cell technology is applied. Furthermore, we have shown the versatility of III-V compound semiconductors in designing and fabricating photonic power converters. The ability to fine-tune the absorber material and spectral matching provides significant advantages in terms of minimizing transmission and thermalization losses. This approach has been used to realize several record devices. In addition, a new metallization technique using electro-plated silver for the handling of high currents was presented, along with a 10-junction InGaAs cell that divides current among N=10 subcells. Combining these two approaches would enable to multiply the deliverable power demonstrated by the high-power single-junction device by N. As cells with N=20 subcells have been demonstrated;[60] such combination offers a promising outlook on the possibility to deliver electrical powers approaching kW level (20×35 W=700 W) from a single 1-cm² chip.

5. ACKNOWLEDGMENTS

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