International Journal on Emerging Trends in Electronics & Communication Engineering
http://eurekajournals.com/IJETECE.html
ISSN: 2581-558X

A brief review on High Efficiency GaAs based Solar Cell

Mritunjay Kumar Pandit[1], Debangana Paul[1], Adarsh Kumar[1], Manika Bachhar[1], Prof. (Dr.) Koushik Sarkar[2]

[1]Final year Student, ECE, Future Institute of Engineering and Management, Kolkata-150.
[2]ECE, Future Institute of Engineering and Management, Kolkata-150.

Abstract

GaAs-based solar cells have been researched for many years, comparable to silicon solar cells that are readily available. Even though gallium arsenide-based cells now have the best efficiency of any type. They are appealing because of their unique features, particularly in some places. Owing to their resilience in harsh environments, they can be used in locations where other solar cells have already seen severe degradation. A brief idea about some significant research work done on GaAs based solar cell has been presented. A few research findings have highlighted the comparative discussion on the basis of performance. This paper outlines the applications of GaAs photovoltaic cells-past, present, and future. It looks at improvements.

Introduction

Recent years have seen a significant amount of study on the integration of silicon-based integrated circuits with III-V material-based (opto) electronic devices. III-V materials have better high-speed behaviour than silicon devices and are helpful for photonic devices due to their wide spectrum of direct bandgaps. On the other hand, III-V device technology is not as advanced as that of silicon devices, and the mismatch in lattice and thermal expansion coefficients makes it difficult to grow high-quality III-V materials on silicon substrates. A technique that shows promise for integrating III-V devices with foreign substrates is epitaxial lift-off (ELO), which permits the substrate to be reused without requiring significant additional processing. In order to improve the performance of photovoltaic systems, the study covers the necessity to increase solar cell efficiency and determine the ideal multi-junction solar cell concentration and thickness combination. Because fossil fuels have finite life spans and cause environmental problems, photovoltaic (PV) energy is becoming more and more popular as a renewable energy source. PV cell efficiency is a big concern, as are problems like high power electronics device usage, sophisticated power controllers, and reliance on solar irradiation. The increasing popularity of multi-junction solar cells, especially those based on III-V materials like AlGaAs, can be attributed to their superior conversion efficiency over single-junction cells. Because of their direct bandgap, better absorption coefficient, capacity to operate at higher temperatures, and higher carrier mobility, GaAs-based solar cells are preferred over Si-based ones. The greater recombination rate of GaAs cells is still a problem, though it has been demonstrated that using AlGaAs as a window layer and back surface field (BFS) greatly enhances solar cell performance. Photovoltaic equipment are required to transform solar energy, which is a dependable and convenient renewable energy source, into usable energy. The goal of the research is to simulate and model a high-efficiency GaAs PIN- solar cell compared to silicon solar cells. GaAs has a lower temperature coefficient, greater electron mobility, and a larger density of states, making it a desirable option for photovoltaic applications. The performance of solar cells is significantly impacted by surface recombination (SR), which results in efficiency loss. The purpose of the review article is to survey on carrier mobility, carrier lifetime, and surface recombination velocity (SRV) effect variations in quantum efficiency (QE) [2-4].

GaAs semiconductors' straight band gap and strong absorptive properties allow them to perform better in solar cells than silicon semiconductors. GaAs cells are attractive for use in space applications because of their excellent radiation damage resistance, heat insensitivity, and high efficiency. Wide design possibilities are made possible by GaAs, allowing for precise control over the creation and collection of electrons and holes. This effort aims to decrease front surface reflectance in order to increase the conversion efficiency of single junction GaAs solar cells. Anti-reflective coatings (ARC) on GaAs are used to curtail reflectance. To improve the efficiency more, texturing the front surface at a particular angle and depth is suggested [9] .GaAs solar cells have been widely employed because of its high efficiency and minimal degradation under space radiation, especially for space applications. The creation of GaAs solar cells has been significantly hampered by the rate of surface recombination. Surface recombination initially restricted the performance of GaAs cells to about 10%; however, this issue was largely resolved by developing a layer of Ga_{1-x} Al_x on the surface of GaAs. Performance has improved with the adoption of a heterojunction structure with Ga_{1-x} Al_x/GaAs layers; in the late 1970s, efficiencies were above 20%. GaAs solar cells today have efficiency levels between 20 and 25 percent. In order to maximize the efficiency of GaAs solar cells, the study analyzes many parameters, including those related to the window layer, base, emitter, and BSF layer. The impact of adding a Ga_{1-x} Al_x window layer to GaAs solar cell results in 26.7% increase in cell efficiency [15]. One of the main obstacles to the efficiency of solar cells is light reflection from their front surface. Due to production costs and the availability of rare elements, GaAs-based solar cells are costly for large-area applications despite having high conversion efficiencies. Because of their high refractive index, GaAs surfaces have reflectivity of above 32. In order to increase the reflectance spectrum and external quantum efficiency (EQE) of GaAs solar cells, the study focuses on modelling anti-reflection coatings (ARCs) and textural architectures on the solar cells [11].

Literature review

Hamadani et al. [1] explained the method of obtaining spectrally and spatially resolved photoluminescence pictures in GaAs solar cells using a wide-field hyper spectral imaging apparatus that has been calibrated in the research. According to the authors, the solar cells' active layer contains localized flaws that are responsible for the unusual double-peak light emission. The defects exhibit a double-peak emission, where the band-to-impurity optical transition below the band gap energy and the primary band-to-band transition both have maximum peak energies. The defects' peak energy and intensity, as revealed by temperature-dependent imaging, fit the profile of a deep impurity centre free-to-bound recombination model, most likely a GaAs defect. The band-to-band transition's temperature dependency and how well it agrees with an analytical model of photoluminescence are also covered in this work. The open circuit voltage of the solar cells throughout a wide temperature range is one example of an external device parameter that the authors examine in connection with the modelling results.

P.R. Hageman et al. [2] resolute on the application of epitaxial lift-off (ELO) for GaAs solar cells in the paper with an emphasis on lowering the cost of III-V solar cell modules and increasing energy conversion efficiency. The research outlines a modified ELO process that can produce III-V films up to 2 inches in diameter and 1-6 microns thick without any cracks, facilitating the launch of large area devices such as solar cells. The GaAs EL0 cells' energy conversion efficiency was 9.9% (AM1.5G), however series and shunt resistances continue to cause a low fill factor. It was looked into if reusing GaAs substrates following ELO could lower the price of III-V solar cell modules. It was discovered that GaAs substrates could be utilized at least four times without compromising the minority carrier lifespan or carrier mobility of the developed epilayers by following a straightforward cleaning technique. The epitaxial films freed from the GaAs substrate by ELO were found to have material quality that remained intact, suggesting that the GaAs substrate might be extensively reused. There appears to be a limit to the number of reuses for the basic cleaning procedure, as the roughness of the GaAs substrate gradually increased with repeated EL0 and cleaning. Reusing GaAs substrates in conjunction with ELO has a great deal of potential, as evidenced by the measured minority carrier lifetime and Hall mobility of the EL0 films on repurposed substrates that were found to be comparable to those of the reference samples generated on new substrates.

Anik et al. [3] investigated with the modelling and simulation of an AlGaAs/GaAs solar cell with four layers-a window layer, emitter layer, base layer, and back surface field (BFS) layer—is the main topic of this article .The authors examine how changing the base layer's thickness and doping level affects the solar cell's efficiency. A base layer thickness of 2.2 μm and a doping concentration of 10^16 cm^-3 yield the maximum conversion efficiency of 31.1% .The suggested solar cell has an efficiency of 28.64% and a fill factor of 85.15, according to the simulation results. Future research outlined in the publication will examine how variations in thickness and doping concentration affect the solar cell's other layers . Future research outlined in the report will examine how variations in thickness and doping concentration affect the solar cell's other layers. The usage of PC1D simulation software for modelling and simulating the solar cell is also mentioned in the publication. For photovoltaic applications, the authors stress the significance of increasing efficiency and determining the ideal ratio of concentration to thickness in multi-junction solar cells.

Ali Imrana et al. [4] inquired into the modelling and simulation of a high-efficiency GaAs PIN-Solar Cell is the main emphasis of this paper. Compared to silicon solar cells, GaAs has a lower temperature coefficient, greater electron mobility, and a larger density of states, making it a desirable option for photovoltaic applications. Achieving optimum efficiency requires optimizing solar cell properties like carrier mobility, carrier lifetime, and surface recombination velocity. In order to optimize photovoltaic device structures, this research effort uses numerical simulation with COMSOL Multi-physics software. The Poisson's equation, which depends on carrier densities, is also applied in the study to calculate the generation of the electric field.

C F Kamdem et al. [5] scrutinized the design and optimization of a GaAs-based homojunction solar cell with $Ga_{0.5}In_{0.5}P$ serving as the back surface field (BSF) layer are the main topics of this work. Using SCAPS-1D software, the scientists ran simulations to assess the GaAs-based solar cell's performance for various ratios of $Al_xGa_{1-x}As$ and $Ga_yIn_{1-y}P$. It was discovered that 0.8 for x and 0.5 for y were the ideal values for great performance. Although the recombination phenomena were more noticeable with a thicker base, the efficiency of the solar cell was shown to rise with emitter thickness. The best performance was shown by the platinum (Pt) electrode in the study of the influence of variation in the work function of the back contact. A temperature coefficient of -0.036%/°C and a power conversion efficiency of 35.44% were attained by the GaAs-based solar cell that was optimized. These modelling results shed light on potential strategies for raising GaAs-based solar cells' efficiency. The selection of materials, such as GayIn1-yP for the BSF layer and AlxGa1-xAs for the window layer, is crucial to the solar cell's photogeneration efficiency.

K. C. Devendra et al. [6] explored the idea of the direct bandgap and greater absorption coefficient of GaAs-based solar cells that makes them superior to silicon-based solar cells. Promising materials for creating effective GaAs solar cells are InGaP and InAlGaP. A number of variables, including substrate type, doping level, window layer thickness, and thickness of the antireflection material, affect solar cell efficiency. A standard tool for analyzing the characteristics and functionality of GaAs solar cells with various window layers is PC1D simulation software. It is discussed how temperature affects solar cell performance, with greater temperatures resulting in lower efficiency .This research investigates the use of the InGaP window layer to enhance the efficiency of GaAs solar cells. Current-voltage (I-V) characteristics have been used to analyze the solar cell's performance. The InGaP/GaAs solar cell's short circuit current, open-circuit voltage, and power conversion efficiency have been reported at particular window layer thicknesses and doping levels .

Devendra KC et al. [7] surveyed the optimization of zinc selenide (ZnSe) as a window layer for GaAs solar cells is the main topic of this research, which also analyzes the material's thickness, carrier concentration, and bandgap. The investigation of the I-V characteristics and efficiency of GaAs solar cells with varying ZnSe window layer thicknesses and doping concentrations is conducted through the use of the PC1D simulation program .Zinc-selenium has been found to have potential as a window layer because of its low resistivity, strong photosensitivity, and large direct bandgap in earlier studies .According to the modelling results, a ZnSe window layer thickness of 50 nm yields the maximum power conversion efficiency of 24.55% .It has been determined that the ideal carrier concentration for attaining a high conversion efficiency in the GaAs solar cell is 1×10^{16} cm^{-3} . The suggested GaAs solar cell with a ZnSe window layer exhibits promise for low-cost, commercial production.

Deb Kumar et al. [8] explored the computational analysis of GaAs solar cells based on the Al_2O_3 antireflection coating (ARC) layer. For CdS-GaAs solar cells to operate efficiently, carrier lifetime and doping concentration adjustment are essential. Single-junction GaAs solar cells with optimal thickness and doping concentration have been studied in the past; these cells achieved efficiencies of 27.16% and 31.10%, respectively. The performance of solar cells is improved and reflection loss is reduced by the application of an ARC layer, such as Al_2O_3. One method that is frequently used to lower reflection loss in solar cells is quarter-wavelength AR coating. The wavelength and refractive index of the materials are utilized to compute the thickness of the ARC layer. This research presents a modelling analysis that optimizes the carrier lifetime, doping concentration, and window layer thickness for high-performance GaAs solar cells based on Al_2O_3 ARC.

In Mostafa Fedawy et al. [9], the goal of the work is to decrease front surface reflectivity of single junction GaAs solar cells by employing Si_3N_4 as an anti-reflective coating (ARC) to increase conversion efficiency. Si_3N_4 has been investigated for use as an ARC on GaAs, and its thickness has been tuned for the lowest possible reflection .This work has also examined the impact of doping and thickness of the GaAs base and emitter. It has been suggested that texturing the solar cell's front surface at a particular angle and depth will increase efficiency even more .In this work, the GaAs solar cell with and without the Si_3N_4 ARC layer has been designed and simulated using the simulation tool PC1D. Based on the results obtained, the efficiency and fill factor of the GaAs solar cell without ARC have been computed. The performance of the solar cell has been assessed.

In Athil S. et al. [10], the study offers a thorough analysis of photovoltaic (PV) cells, addressing a number of topics including their operation, the physical characteristics of the materials used in PV cells and the role that gallium arsenide (GaAs) thin films play in solar technology. Various photovoltaic methods are covered, such as crystalline silicon (c-Si) and thin-film semiconductors like GaAs, cadmium telluride (CdTe), amorphous silicon (a-Si), and copper indium gallium selenide (CIGS).The study emphasizes the use of numerical and mathematical modelling, particularly using MATLAB/Simulink and COMSOL Multiphysics, in assessing PV cell power conversion efficiency (PCE) and identifying the primary factors influencing power production. The function of GaAs thin films in solar technology is also examined, with a focus on their high efficiency and applicability for spacecraft-based solar energy and power generation in space. The research offers insights into how modelling and mathematical analysis can be used to improve PV cell performance and cost-effectiveness.

Mrityunjoy Kumar Ray et al. [11] investigated on the reflectance spectrum and external quantum efficiency (EQE) of GaAs solar cells. The study focuses on modelling anti-reflection coatings (ARCs) and textural architectures on the solar cells. The simulations consider many characteristics, including surface recombination, texturing depth, and thin coatings of SiO_2 and ITO. The simulation tool of choice is PC1D software, and the structure of a simple p-n junction is used in the simulations. Due to production costs and the availability of rare elements, GaAs-based solar cells are costly for large-area applications despite having high conversion efficiencies. GaAs surfaces have a reflectivity of more than 32 because of their high refractive index. The goal of the research is to estimate the achievable short circuit current (Jsc) and EQE while optimizing the structure of GaAs solar cells with regard to total reflectance. The one-dimensional semiconductor equations based on Shockley-Read Hall recombination statistics are typically solved using PC1D software.

Nikola Papez et al. [12] investigated on GaAs-based solar cells with the goal of enhancing their performance and efficiency .It has been investigated whether using multi-junction or cascade structures in GaAs solar cells can increase efficiency by absorbing light at particular wavelengths. GaAs solar cells have been fabricated using epitaxial crystal growth methods such as metal-organic vapor phase epitaxy (MOVPE) and molecular beam epitaxy (MBE), where MOVPE offers quicker growth rates while MBE offers greater quality and pure materials. To enhance the performance of GaAs cells, the localization of faults in buffer layers with various lattice constants has been investigated. Because of their resilience in harsh environments, GaAs solar cells have found use in a variety of industries, including aerospace, aviation, the military, and concentrators.

Shin-ichiro Sato et al. [13] focused on modelling the degradation of triple-junction (3J) InGaP/GaAs/Ge solar cells exposed to proton irradiation. The investigation makes use of the PC1D one-dimensional optical device simulator to model the quantum efficiencies and assess the electrical characteristics of the cells. Each sub-cell's degradation behaviour is examined in relation to the damage coefficient and carrier removal rate. The research validates the efficacy of the degradation modelling technique created for 3J solar cell lifespan prediction. The thickness of each sub-cell and the cell size are two examples of the representative initial attributes of the 3J solar cells utilized in the investigation that are provided in the publication.

M. Abderrezek et al. [14] focused on the investigation on how the base and emitter layer thicknesses, as well as the doping amount, affect the cells' performance. According to the study, the ideal fill factor and conversion efficiency are 86.76% and 25.8%, respectively. For optimization reasons, the behaviour of the solar cell with regard to technological parameters including the doping level, base and emitter layer thickness, and front side recombination speed are examined.

In S. Khellaf et al. [15], the research examines many parameters, including those related to the window layer, base, emitter, and BSF layer. It is demonstrated how adding a $Ga_{1-x}Al_x$ window layer to GaAs solar cells can boost their energy efficiency from 24.9% to 26.7% .We go over the formulas for figuring out photocurrent densities at different wavelengths as well as how different layer thicknesses and doping affect photovoltaic characteristics. According to the document, the equation determining the density of the monochromatic photocurrent can be found in the paper, and the relationships that control the functioning of a silicon solar cell may also be applied to gallium arsenide.

Devendra KC et al. [16] examines the modelling and simulation of an AlGaAs/GaAs solar cell, with a particular focus on examining the impact of altering the base layer's thickness and doping concentration on the efficiency of the cell. Four layers make up the construction of the solar cell: P-GaAs for the base layer, n-AlGaAs for the emitter layer, n-AlGaAs for the window layer, and p-AlGaAs for the back surface field (BFS) layer. The solar cell was modelled and simulated by the authors using PC1D simulation software .A base layer thickness of 2.2 µm and a doping concentration of 10^16 cm^-3 were found to yield the best conversion efficiency of 31.1% .For the suggested solar cell, the modelling results revealed a fill factor of 85.15 and a conversion efficiency of 31.10 .

Devendra et al. [17] considered Zinc selenide (ZnSe) as a window layer for GaAs solar cells is investigated in the study, and its performance is analyzed using PC1D simulation software. ZnSe is optimized in terms of bandgap, thickness, and carrier concentration as a window layer. By altering various window layer parameters, the PC1D modelling tool is utilized to examine the current-power curve and efficiency of the GaAs solar cell. For the window layer, the maximum power conversion efficiency of 24.55% is seen at a thickness of 50 nm. At a distance of 0 µm to 5 µm from the front, the electron and hole densities are found to be 1.1 × 10^16 cm^−3 and 1 × 10^15 cm^−3, respectively.

Devendra1et al. [18] investigated on the application of an InGaP window layer in GaAs solar cells and employed PC1D simulation software to evaluate its usefulness. The study looks into how changing the InGaP window layer's thickness and doping concentrations affect the solar cell's performance. Using current-voltage (I-V) characteristics, the solar cell's performance is assessed. It is discovered that at a window layer thickness of 30 nm and a doping level of 1.00E+17 cm3, the short circuit current, open-circuit voltage, and power conversion efficiency are optimum. The impact of temperature on solar cell performance is also reviewed in this work. It has been found that a solar cell's efficiency increases with temperature and reaches its maximum at 25°C.

Raed. M et al. [19] explored the design and simulation of an AlGaAs/GaAs solar cell. The authors investigate the performance of the solar cell by varying the thickness and doping concentration of the window layer and the absorber layer. With an absorber layer doping concentration of 10^{15} cm^{-3} and a thickness of 3.67µm, the study's maximum efficiency of 31.4581% was attained. Isc, Voc, F.F., and η, the final solar cell parameters, were found to be 31.8mA, 1.109 V, 89.32%, and 31.4581%, respectively.

Structure and Composition of GaAs Solar Cells

As mentioned in the introduction, not only have single-junction solar cells been developed for a long time, but multi-junction structures are being created to achieve the highest possible performance. The composition of these structures depends on the specific use. Thus, it is clear that, for example, the light of a different spectral range than on Earth will fall on the surface of Mars due to its atmosphere. Therefore, the Earth's atmosphere filters not only harmful radiation for humans but also radiation that the solar cell can use. For multilayer structures, emphasis is placed on high crystal perfection in order to avoid recombination of generated minority carriers at cracks and other defects [28-29]. By default, production takes place by growing on a doped substrate. The specific substrate is chosen depending on the next layer that will grow on it to induce an ideal lattice within the epitaxy. The most typical materials are described in Table 1.

Table 1: Currently and commonly used materials for III-V compound solar cells, their bandgap E_g at 0 K and 300 K, type of the structure (d direct or i indirect) and the lattice constant at 300 K. Germanium and silicon are also given below for the comparison [30-31].

Semiconductor	Chemical Formula	Bandgap/eV (0 K)	Bandgap/eV(300 K)	Lattice constant
Gallium arsenide	GaAs	1.52	1.42	5.653
Indium phosphide	InP	1.42	1.35	5.869
Gallium antimonide	GaSb	0.81	0.72	6.096
Silicon	Si	1.17	1.12	5.431
Germanium	Ge	0.74	0.66	5.658

Well-established epitaxial crystal growth techniques include metal-organic vapor phase epitaxy (MOVPE) and molecular beam epitaxy (MBE). Both methods originated in 1960 and have some differences [34].

MOVPE is used to deliver faster growth rates for bulk layers and low breakdown at high temperatures and low vacuum. MOVPE does not require significant bake times and can recover more quickly from equipment failures than MBE. MBE is, unlike MOVPE, considered a method for superior quality and pure materials in ultra-high vacuum (UHV). It is easier to maintain and is able to grow thermody-namically forbidden materials [35].

There are also several grown concepts that can even be combined, as mentioned, for example, in the inverted metamorphic (IMM) solar cell. This structure is currently relatively frequently used. Lattice matched [36], Upright [37], Metamorphic [38]-use the localization of defects in a buffer layer located between layers with different lattice constants., Inverted [39]-this is an inverted growth of the structure, so materials with a higher bandgap grow here first.

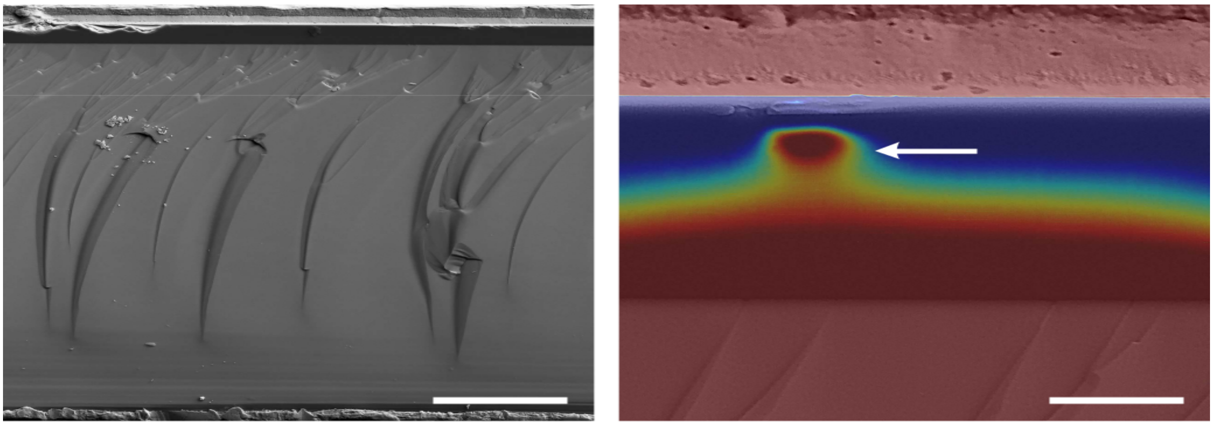

Figure 1: The images show cross-sectional view of the GaAs PV cell on a SEM microscope. The image (a) shows the complete structure of the PV cell. Contacts are visible from below and from top (contact is longitudinal along the edge). The largest part of the picture is occupied by germanium. However, the most important are the thin layers (the darkest part). The image (b) on the right represents the part marked with a yellow rectangle in image (a). The coloured EBIC method (b) is used to visualize the distribution of carriers in the pn junction area. There is also applied bias voltage of 1 mV. Impurity (pointed by arrow), which was probably contaminated during the fabrication, is electrically active and allows easier tunneling of electrons through the junction [41]

The structure is then rotated, and the substrate is removed. This leads to a better performance of the solar cell. After the growing process, the solar cell is finished by layer bonding, an anti-reflection coating (ARC), and contact metallization [40]. Very thin contacts in the range of micrometer units are often used. Figure 1 is presented to show cross-sectional view of the GaAs PV.

Applications of Solar Cells

Table 2: Results Comparison among different Research works

ARTCLE	Window Layer Width	Efficiency (η%)	Open Circuit Voltage(V_{OC})	Short Circuit Current (I_{SC})
Devendra et al.[3]	300nm	28.64%	1.046V	.3091A
Devendra et al.[6]	100nm	25.32%.	0.8788 V	.3195A
Devendra et al.[7]	100 nm	24.47%	0.871 V	.3204 A
Shah, D.K. et al.[8]	100 nm	21.12%	0.882 V	.264 A
Imran, Ali et al. [23]	100 nm	13.75	0.99 V	.165A
Abderrezek et al. [24]	500 NM	25.8	1.008V	.295A

As mentioned in the introduction, GaAs and multi-junction PV cells are used mainly in particular industries, where they are required to be highly efficient, durable, or lightweight. These are cutting-edge technologies for special purposes.

Aerospace and Military

Experimental high-altitude long-endurance UAVs are aircraft that are covered mainly with flexible solar cells because of stay in the air for up to months. They thus replace launch-ing satellites into orbits, which are usually covered by considerable expenses. UAVs can then serve for mapping, surveillance, border patrol, or search and rescue. For civilian use, they are used in flying cell phone towers and communications. Experiments with UAVs and solar cells have been around for over 20 years, and there is constant progress [42-44]. Recent advances have been made since 2017 by Alta Devices, where their flexible solar cells exceed efficiencies of 30%, aerial densities of 170 g/m^2, and are 30 µm thick. Their solar cells are widely used for aerospace purposes [45]. Microlink Devices Inc. also supplies solar cells to the UAV sector. For example, for Airbus Zephyr (Figure 2)- a solar high-altitude platform station operating in the stratosphere with >29% AM0 efficiency [46-47]. Last but not least is the Thales Stratobus airship capable of flying at an altitude of 20 km, which previously used a transparent envelope section that allows sunlight reflection in concentrator mirrors, which were directed to solar arrays inside the UAV. However, since 2018, this system has been abandoned and replaced by flexible multi-junction arrays installed on the top surface [48].

It is also worth mentioning other areas where flexible multilayer panels are, or have been, in use. These include Aquila by Facebook (discontinued) [50-51], Solara 50 by Google, formerly Titan Aerospace (discontinued) [52], HAWK30 by AeroVironment Inc. [53],

Figure 2: Airbus Zephyr during flight [49]

Figure 3: UAV PHASA-35 in hangar by Prismatic BAE [58]

Cai-hong (Rainbow) T-4 by the Chinese Academy of Aerospace Aerodynamics [54], PHASA-35 by BAE Systems (Figure 3) [55], Odysseus by Aurora Flight Sciences [56], etc. Even though GaAs flexible cells are constructed for most UAVs, these projects for the long-term sustainability of aircraft in the air are very demanding and have been evolving for a long time. Most of them are in experimental phases. In addition to Alta Devices, Sharp Corporation and SolAero Technologies Corp. are other significant manufacturers producing multilayer solar panels [57].

Solar Photovoltaic Concentrators

Together in the combination of GaAs PV cells, solar concentrators are widely used, i.e., devices consisting of various optical elements that concentrate light, most often sunlight, into one central point, which is a solar cell. Concentrator photovoltaics (CPVs) are used to express the intensity of concentration in the number of Suns or ratios. By default, if the light intensity on the solar cell exceeds 10 Suns, it is already necessary to use passive cooling of the PV cell. This system is considered a low-concentration photovoltaic system (LCPV), and silicon solar cells can still be used here. If the light intensity exceeds 100 Suns, the solar cell must already be actively cooled by cooling fluid, and in that case, it can be considered high-concentration photovoltaic (HCPV). This is a nearly relative number and varies in the literature. GaAs and multilayer structures are already used exclusively for such performance concentrators.

Many concentrator designs follow the concept of Fresnel lens, reflectors, parabolic mirrors, or luminescent concentrators. Notwithstanding, it always depends on their use. Kasaeian et al. summarized the parabolic and Fresnel-based photovoltaic thermal systems over several years, where GaAs cells have always given excellent performance compared to other conventional cells [58].

Solar cells, such as InGaP/GaAs/InGaAs inverted triple-junction, manufactured for the concentrator application, are also specially made for CPV, where Sasaki et al. achieved an efficiency of 45% [59]. In a similar way, concentrators can be created for a particular type of cell and used, for example, in space [60-61]. One such prototype was made by Warmann et al., which also served as ultralight multilayer optical coatings to increase the thermal emissivity of the concentrator and enhance radiative transfer. This unique parabolic concentrator was able to achieve a concentration of 15 Suns for the 1 mm wide cell [62].

One of the most applied and at the same time the oldest concentrators are Fresnel lenses, which are among the first concentrators to be used since 1979. Lenses are light and capable of achieving a short focal length and large aperture. They can be used in the construction in a shape of a circle focusing the light in a point like (which is considered the most widespread) or in a cylindrical shape focusing the light in a line, resulting in a lower ratio concentration than in the previously mentioned construction. Their disadvantage is that the optical efficiency is limited by low or high temperatures and consequently by a change in the refractive index or deformation of the Fresnel structure by virtue of thermal expansion [63].

Application example of Fresnel lens optic made with Silicon-on-Glass (SoG) technol-ogy and designed by Fraunhofer ISE are FLATCON® concentrator modules [65]. In 2003, the first module consisted of 16 cm^2 lenses and GaAs single-junction solar cells in 2 to 4 mm diameter. Later, Wiesenfarth et al. performed ten years of outdoor measurements, where triple-junction solar cells were used (Figure 5). Long-term stability was observed when the efficiency per year decreased by (0.25-0.18)% [66].

Steiner et al. measured the performance of 52 four-junction solar cells using FLATCON® modules (Figure 4) for one month under concentrator standard operating conditions (CSOC) and concentrator standard test conditions (CSTC). The rated efficiency was 35.0% at CSOC and 36.7% at CSTC, and was calculated as mean values [65].

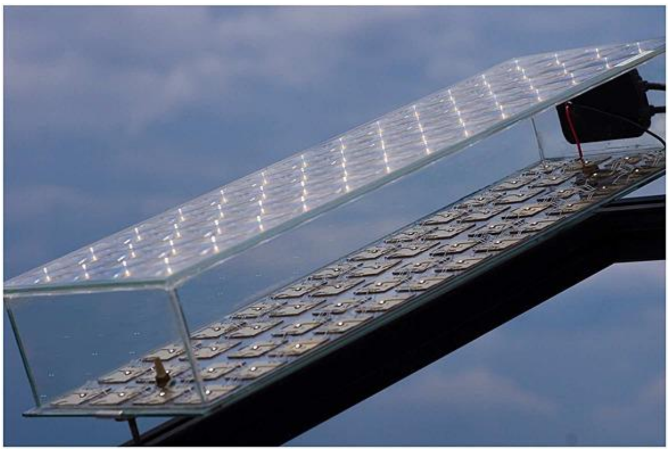

Figure 4: FLATCON® CPV module with 52 four-junction solar cells [65]

Figure 5: Image of the Ingenuity helicopter on Mars acquired on 7 April 2021 (Sol 46). IMM multi-junction solar cells are clearly visible from its top [72]

As another very popular concentrator type, and principally very powerful, where optical lenses are not used, is the parabolic concentrator [67]. It is usually utilized using two curved mirrors generally reminiscent of a parabolic antenna. The first larger mirror serves as a collector and the second as a focal point. However, various modifications exist where the focal point is already replaced by a solar cell. Like Fresnel lenses, they have a high ratio of around 500. These concentrators are often used in conjunction with thermal collectors (therefore, in the literature can be found for parabolic concentrators name collectors) and thus form a hybrid system. For example, in such a hybrid system, Widyolar et al. demonstrated the GaAs cell load of up to 365 °C with a thermal efficiency of around 37% [68]. More complex modern designs already count on a hybrid tubular thermoelectric generator, where the thermal model of the hybrid system with GaAs cells was studied [69].

Many other solar system probes and other spacecraft utilize this type of solar cell and are active in space. Examples are the Venusian probe Akatsuki (InGaP/GaAs/Ge) [70], the robotic lander InSight (InGaP/InGaAs/Ge) to study the deep interior of Mars or the asteroid study probes Hayabusa2 and OSIRIS-REx [71]. Another current example is mission Mars 2020, which started at the end of July 2020. The Ingenuity helicopter (Figure 5) equipped with inverted metamorphic multi-junction solar cells specially tuned to Mars conditions by SolAero, which, together with the Perseverance rover, was part of the cruise stage. Its entire primary part, which was dropped just before the touchdown, was also covered by multi-junction GaAs solar cells. SolAero, which was mentioned in aeronautics applications, is a company that is also very involved in manufacturing and space applications [72]. Concentrators in space can also be used. However, there are some limitations. For ex-ample, near-Earth applications should use lower concentrations (5 Suns) in virtue of the more difficult heat dissipation [73]. However, concentrators in space have become very useful for far-Sun missions to increase low light intensities [74]. It is, hence, essential to know which light intensities can affect the cell.

Advantages of GaAs over Silicon [21-27]

- Compared to Si cells, GaAs solar cells have a greater conversion efficiency; under one sun scenario, improved GaAs cells can reach efficiencies of up to 26.8%.

- Comparing GaAs cells to Si cells, the former show better conversion efficiency, a larger open-circuit voltage, and a smaller short-circuit current density.
- A1GaAs window layers are used by GaAs cells to lower surface recombination velocity, which improves performance.
- Molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) methods can be used to manufacture GaAs cells, providing more control over the device's performance and material quality.
- Under identical conditions, GaAs solar cells behave differently from Si solar cells, with GaAs modules generating greater power as the temperature rises.
- When compared to Si PV systems, GaAs PV systems produce more energy. However, employing fixed panels with Si solar cells results in a cheaper cost per produced kilowatt-hour (KWH).
- Compared to Si, GaAs exhibits greater optical absorption, particularly in direct-gap semiconductors.
- In general, electrons pass through crystalline structures composed of gallium arsenide (GaAs) more quickly than they do through structures made of silicon. Stated differently, GaAs structures facilitate superior solar energy conversion.
- GaAs is naturally resistant to heat, moisture, radiation, and ultraviolet light. Since this material can withstand harsh conditions, it's the ideal material for solar energy applications.
- Due to their greater efficiency, GaAs wafers in smaller solar cells absorb more sunlight than silicon wafers. This is ideal for things that have a limited surface area such as aircraft, cars or on small satellites.
- Gallium Arsenide is naturally resistant to damage from moisture, radiation and ultraviolet light. These properties make GaAs an excellent choice for aerospace applications where there is increased UV and radiation.
- GaAs is able to perform at high levels even when the amount of light available is low.

Conclusions

GaAs solar cells were covered extensively in this review. Both its construction and degeneration were studied in terms of use. As far as is known, these solar cells can be combined with many thin layers of other semiconductors, like AlGaAs, InP, GaInP, InGaAs, and InGaP, but with differing bandgaps. Using new or different growing manufacturing techniques and growing concepts that are more accurate and less demanding could be the answer. Utilizing concentrators, which were used to break the previously noted record, could be an additional method. A comparative discussion of the performance of GaAs solar cells with silicon solar cells is highlighted. Data are recorded on the performance of GaAs solar cells using different types of window layers. There is currently a development for high efficiency, miniaturization, or hybridization.

Acknowledgement

We would like to express our sincere gratitude to the research and innovation cell, ECE department, Future Institute of Engineering and Management.

References

Hamadani, B.H. et al. (2022) 'Visualizing localized, radiative defects in gaas solar cells', Scientific Reports, 12(1). doi:10.1038/s41598-022-19187-4.

van Geelen, A. et al. (1997) 'Epitaxial lift-off Gaas Solar Cell from a reusable GaAs substrate', Materials Science and Engineering: B, 45(1-3), pp. 162-171. doi:10.1016/s0921-5107(96)02029-6.

Kc, Devendra & Wagle, Raju &Gaib, Raid. (2020). Modelling and simulation of AlGaAs/GaAs solar cell. 9. 218-223.Nkjd

Imran, A. et al. (2020) 'Modeling and simulation of high-efficiency gaas pin solar cells', Journal of Computational Electronics, 20(1), pp. 310-316. doi:10.1007/s10825-020-01583-6.

Kamdem, Cedrik&Ngoupo, A. &Abega, Francois Xavier &Abena, A.M. &Ndjaka, Jean-Marie. (2023). Design and Performance Enhancement of a GaAs-Based Homojunction Solar Cell Using Ga0.5In0.5P as a Back Surface Field (BSF): A Simulation Approach. International Journal of Photoenergy. 2023. 1-17. 10.1155/2023/6204891.

K.C, D. (2020) 'InGaP window layer for gallium arsenide (GaAs) based Solar Cell using PC1D simulation', Journal of Advanced Research in Dynamical and Control Systems, 12(SP7), pp. 2878-2885. doi:10.5373/jardcs/v12sp7/20202430.

Devendra, K., Shah, D.K. and Shrivastava, A. (2022) 'Computational study on the performance of zinc selenide as window layer for efficient GaAs Solar Cell', Materials Today: Proceedings, 49, pp. 2580-2583. doi:10.1016/j.matpr.2021.06.077.

Shah, D.K. et al. (2022) 'A computational study of carrier lifetime, doping concentration, and thickness of window layer for gaas solar cell based on al2o3 antireflection layer', Solar Energy, 234, pp. 330-337. doi:10.1016/j.solener.2022.02.006.

Fedawy, Mostafa & Mostafa, Shereen &Abdolkader, Tarek. (2018). Efficiency Enhancement of GaAs Solar Cell using Si3N4 Anti-reflection Coating. Journal of Advanced Research in Material Science. 42. 1-7.

Al-Ezzi, A.S. and Ansari, M.N.M. (2022) Photovoltaic Solar Cells: A Review, MDPI. Available at: https://www.mdpi.com/2571-5577/5/4/67

Sasmal, Sajal. (2015). Improvement of Quantum Efficiency and Reflectance of GaAs Solar Cell. International Journal Of Engineering Research and General Science. 3. 642-647.

Papež, N. et al. (2021) 'Overview of the current state of gallium arsenide-based solar cells', Materials, 14(11), p. 3075. doi:10.3390/ma14113075.

Sato, S. et al. (2009) 'Degradation modeling of InGaP/GaAs/Ge Triple-junction solar cells irradiated with various-energy protons', Solar Energy Materials and Solar Cells, 93(6-7), pp. 768-773. doi:10.1016/j.solmat.2008.09.044.

Abderrezek, M. et al. (2013) 'Numerical modeling of gaas solar cell performances', Electronics and Electrical Engineering, 19(8). doi:10.5755/j01.eee.19.8.5392.

Khellaf, S. and Ounissi, A. (2014) 'Optimizing the efficiency of solar cells based on GaAs', International Journal of Advanced Science and Technology, 69, pp. 57-64. doi:10.14257/ijast.2014.69.06.

Kc, Devendra & Wagle, Raju &Gaib, Raid. (2020). Modelling and simulation of AlGaAs/GaAs solar cell. 9. 218-223.

Devendra, K., Shah, D.K. and Shrivastava, A. (2022) 'Computational study on the performance of zinc selenide as window layer for efficient GaAs Solar Cell', Materials Today: Proceedings, 49, pp. 2580-2583. doi:10.1016/j.matpr.2021.06.077.

K.C, D. (2020) 'Ingap window layer for gallium arsenide (GaAs) based Solar Cell using PC1D simulation', Journal of Advanced Research in Dynamical and Control Systems, 12(SP7), pp. 2878-2885. doi:10.5373/jardcs/v12sp7/20202430.

Humaidan, Raed.M., Dahham, A.T. and Majeed, Z.N. (2022) 'Designed and simulation of AlGaAs: Gaas Thin film solar cell using PC1D program', NeuroQuantology, 20(3), pp. 265-270. doi:10.14704/nq.2022.20.3.nq22254.

Devendra, K., Shah, D.K. and Shrivastava, A. (2022a) 'Computational study on the performance of zinc selenide as window layer for efficient GaAs Solar Cell', Materials Today: Proceedings, 49, pp. 2580-2583. doi:10.1016/j.matpr.2021.06.077.

Comparative Study Between Silicon & Gallium Arsenide ON Grid PV System Mahmoud M Ismail, .Wagdy R Anis, RashaGhoneim ISSN 2320-5407 http://www.journalijar.com

Liou, J.J. and Wong, W.W. (1992) 'Comparison and optimization of the performance of SI and gaas solar cells', Solar Energy Materials and Solar Cells, 28(1), pp. 9-28. doi:10.1016/0927-0248(92)90104-w.

Imran, Ali & Eric, Deborah & Zahid, Muhammad Noaman & Yousaf, Muhammad. (2019). Modelling and Simulation of of high efficiency GaAs PIN-Solar Cell.

Abderrezek, M. & Djahli, F. & Fathi, M. & Ayad, M.. (2013). Numerical Modeling of GaAs Solar Cell Performances. Elektronika ir Elektrotechnika. 19. 41-44.

O'Connor, Joseph & Michael, Sherif. (2016). Thermodynamic Performance of Silicon and GaAs Solar Cells. Conference: 44th Electronic Materials Symposium At: San Jose, CA, USA Affiliation: IBM Almaden Research Center

Barnett, Allen & Mauk, M. & Zolper, J. & Hall, I. & Tiller, W. & Hall, R. & McNeely, J.. (1984). Thin-film silicon and GaAs solar cells. 747-754.

Papež, Nikola & Dallaev, Rashid & Ţălu, Ştefan & Kastyl, Jaroslav. (2021). Overview of the Current State of Gallium Arsenide-Based Solar Cells. Materials. 14. 3075. 10.3390/ma14113075.

T˘¸alu, S¸.; Papež, N.; Sobola, D.; Tofel, P. Fractal Analysis of the 3-D surface Topography of GaAs Solar Cells. In DEStech Transactions on Environment, Energy and Earth Sciences; DEStech Publications Inc.: Lancaster, PA, USA, 2018; [CrossRef]

Sobola, D.; T˘¸alu, S¸.; Tománek, P. Surface Condition of GaAs Solar Cells. Acta Tech. Corviniensis Bull. Eng. 2017, 27-32.

Kittel, C. Introduction to Solid State Physics; Wiley: Hoboken, NJ, USA, 2004.

NSM Archive-Physical Properties of Semiconductors. Available online: http://www.ioffe.ru/SVA/NSM/Semicond/ (accessed on 4 May 2021).

Varshni, Y.P. Temperature dependence of the energy gap in semiconductors. Physica 1967, 34, 149-154. [CrossRef]

Vurgaftman, I.; Meyer, J.R.; Ram-Mohan, L.R. Band parameters for III-V compound semiconductors and their alloys. J. Appl. Phys. 2001, 89, 5815-5875. [CrossRef]

Sharma, T.K. MOVPE and MBE growth of semiconductor thin films. AIP Conf. Proc. 2012, 1451, 18-23. [CrossRef]

Pelzel, R. A Comparison of MOVPE and MBE Growth Technologies for III-V Epitaxial Structures. In Proceedings of the CS MANTECH Conference, New Orleans, LA, USA, 13-16 May 2013.

Tu, C.W.; Beggy, J.C.; Baiocchi, F.A.; Abys, S.M.; Pearton, S.J.; Hsieh, S.J.; Kopf, R.F.; Caruso, R.; Jordan, A.S. Lattice-Matched Gaas/Ca 0.45 Sr 0.55 F 2/Ge(100) Heterostrucuures Grown By Molecular Beam Epitaxy. MRS Proc. 1987, 91, 359-364. [CrossRef]

Eaglesham, D.J.; Devenish, R.; Fan, R.T.; Humphreys, C.J.; Morkoc, H.; Bradley, R.R.; Augustus, P.D. Defects in MBE and MOCVD-grown GaAs on Si. In Microscopy of Semiconducting Materials, 1987; CRC Press: Boca Raton, FL, USA, 2020; pp. 105-110. [CrossRef]

Kim, Y.; Shin, H.B.; Lee, W.H.; Jung, S.H.; Kim, C.Z.; Kim, H.; Lee, Y.T.; Kang, H.K. 1080 nm InGaAs laser power converters grown by MOCVD using InAlGaAs metamorphic buffer layers. Sol. Energy Mater. Sol. Cells 2019, 200, 109984. [CrossRef]

Huang, X.; Long, J.; Wu, D.; Ye, S.; Li, X.; Sun, Q.; Xing, Z.; Yang, W.; Song, M.; Guo, Y.; et al. Flexible four-junction inverted metamorphic AlGaInP/AlGaAs/ In0.17Ga0.83As/In0.47 Ga0.53As solar cell. Sol. Energy Mater. Sol. Cells 2020, 208, 110398. [CrossRef]

Hagar, B.; Sayed, I.; Colter, P.C.; Bedair, S.M. Multi-junction solar cells by Intermetallic Bonding and interconnect of Dissimilar Materials: GaAs/Si. Sol. Energy Mater. Sol. Cells 2020, 215, 110653. [CrossRef]

Papež, N.; Dallaev, R.; Sobola, D.; Macku, R.; Škarvada, P. Microstructural investigation of defects in photovoltaic cells by the electron beam-induced current method. In Procedia Structural Integrity; Elsevier B.V.: Amsterdam, The Netherlands, 2019; Volume 23, pp. 595-600. [CrossRef]

Colozza, A.J.; Scheiman, D.A.; Brinker, D.J. GaAs/Ge Solar Powered Aircraft; SAE Technical Papers; SAE International: Warrendale, PA, USA, 1998. [CrossRef]

Scheiman, D.A.; Brinker, D.J.; Bents, D.J.; Colozza, A.J. Design of a GaAs/Ge solar array for unmanned aerial vehicles. In Proceedings of the Conference Record of the IEEE Photovoltaic Specialists Conference, Waikoloa, HI, USA, 5-9 December 1994; Volume 2, pp. 2006-2009. [CrossRef]

Wojtczuk, S.; Reinhardt, K. High-power density (1040 W/kg) GaAs cells for ultralight aircraft. In Proceedings of the Conference Record of the IEEE Photovoltaic Specialists Conference, Washington, DC, USA, 13-17 May 1996; pp. 49-52. [CrossRef]

Kayes, B.M.; Zhang, L.; Twist, R.; Ding, I.K.; Higashi, G.S. Flexible thin-film tandem solar cells with >30% efficiency. IEEE J. Photovolt. 2014, 4, 729-733. [CrossRef]

Stender, C.L.; Adams, J.; Elarde, V.; Major, T.; Miyamoto, H.; Osowski, M.; Pan, N.; Tatavarti, R.; Tuminello, F.; Wibowo, A.; et al. Flexible and lightweight epitaxial lift-off GaAs multi-junction solar cells for portable power and UAV applications. In Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference, PVSC 2015, New Orleans, LA, USA, 14-19 June 2015. [CrossRef]

Scheiman, D.; Hoheisel, R.; Edwards, D.J.; Paulsen, A.; Lorentzen, J.; Jenkins, P.; Caruthers, S.; Carter, S.; Walters, R. A path toward enhanced endurance of a UAV using IMM solar cells. In Proceedings of the Conference Record of the IEEE Photovoltaic Specialists Conference, Portland, OR, USA, 5-10 June 2016; pp. 1095-1100. [CrossRef]

D'Oliveira, F.A.; De Melo, F.C.L.; Devezas, T.C. High-altitude platforms—Present situation and technology trends. J. Aerosp. Technol. Manag. 2016, 8, 249-262. [CrossRef]

Zephyr-UAV-Airbus. Available online: https://www.airbus.com/defence/uav/zephyr.html (accessed on 1 May 2021).

Maguire, Y. Building Communications Networks in the Stratosphere—Facebook Engineering. 2015. Available online: https://engineering.fb.com/2015/07/30/connectivity/building-communications-networks-in-the-stratosphere/ (accessed on 3 May 2021).

Maguire, Y. High Altitude Connectivity: The Next Chapter-Facebook Engineering. 2018. Available online: https://engineering. fb.com/2018/06/27/connectivity/high-altitude-connectivity-the-next-chapter/ (accessed on 3 May 2021).

Weintraub, S. Alphabet Cuts Former Titan Drone Program from X Division, Employees Dispersing to Other Units—9to5Google. 2017. Available online: https://9to5google. com/2017/01/11/alphabet-titan-cut/ (accessed on 3 May 2021).

Boyer, M. High-Altitude Pseudo-Satellite|Sunglider™ Platform Station|AeroVironment, Inc. 2019. Available online: https:// www.avinc.com/resources/press-releases/view/hawk30-takes-flight-aerovironment-achieves-successful-first-test-flight-of (accessed on 3 May 2021).

Boyuan, C. Rainbow Solar UAV to Make High-Altitude Flight Soon-China.org.cn. 2017. Available online: http://www.china. org.cn/china/2017-03/06/content_40418057.htm (accessed on 3 May 2021).

PHASA-35 First Flight|Newsroom|BAE Systems|International. 2020. Available online: https://www.baesystems.com/en/article/ground-breaking-solar-powered-unmanned-air craft-makes-first-flight (accessed on 3 May 2021).

High Altitude, Ultra-Long Endurance, Pseudo-Satellite-HAPS-Odysseus-Aurora Flight Sciences. Available online: https: //www.aurora.aero/odysseus-high-altitude-pseudo-satellite-haps/ (accessed on 3 May 2021).

Smith, J.M. Alta Devices moves out of the lab and into the valley. MRS Bull. 2012, 37, 794-795. [CrossRef]

Prismatic. Prismatic Completes First Two PHASA-35 HALE UAVs-Prismatic. 2019. Available online: https://www.prismaticltd. co.uk/news/prismatic-completes-first-two-phasa-35-hale-uavs/ (accessed on 1 May 2021).

Kasaeian, A.; Tabasi, S.; Ghaderian, J.; Yousefi, H. A review on parabolic trough/Fresnel based photovoltaic thermal systems. Renew. Sustain. Energy Rev. 2018, 91, 193-204. [CrossRef]

Sasaki, K.; Agui, T.; Nakaido, K.; Takahashi, N.; Onitsuka, R.; Takamoto, T. Development of InGaP/GaAs/InGaAs inverted triple junction concentrator solar cells. In AIP Conference Proceedings; American Institute of Physics Inc.: College Park, MD, USA, 2013; Volume 1556, pp. 22-25. [CrossRef]

Hudec, C.L. Construction of Gallium Arsenide Solar Concentrator for Space Use. Calhoun: Monterey, CA, USA, 1988.

O'neill, M.; Piszczor, M. Development of a dome Fresnel lens/gallium arsenide photovoltaic concentrator for space applications. In Proceedings of the 19th IEEE Photovoltaic Specialists Conference, New Orleans, LA, USA, 4-8 May 1987.

Warmann, E.C.; Espinet-Gonzalez, P.; Vaidya, N.; Loke, S.; Naqavi, A.; Vinogradova, T.; Kelzenberg, M.; Leclerc, C.; Gdoutos, E.; Pellegrino, S.; et al. An ultralight concentrator photovoltaic system for space solar power harvesting. Acta Astronaut. 2020, 170, 443-451. [CrossRef]

Hornung, T.; Hornung, T. Ein-und Mehrstufige Optische Konzentratoren für Photovoltaische Anwendungen. Ph.D. Thesis, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany, 2013.

Papež, N.; Gajdoš, A.; Dallaev, R.; Sobola, D.; Sedlák, P.; Motúz, R.; Nebojsa, A.; Grmela, L. Performance analysis of GaAs based solar cells under gamma irradiation. Appl. Surf. Sci. 2020, 510, 145329. [CrossRef]

Steiner, M.; Bösch, A.; Dilger, A.; Dimroth, F.; Dörsam, T.; Muller, M.; Hornung, T.; Siefer, G.; Wiesenfarth, M.; Bett, A.W. FLATCON® CPV module with 36.7% efficiency equipped with four-junction solar cells. Prog. Photovolt. Res. Appl. 2015, 23, 1323-1329. [CrossRef]

Wiesenfarth, M.; Steiner, M.; Dörsam, T.; Siefer, G.; Dimroth, F.; Nitz, P.; Bett, A.W. FLATCON® CPV module technology: A new design based on the evaluation of 10 years of outdoor measurement data. In AIP Conference Proceedings; American Institute of Physics Inc.: College Park, MD, USA, 2019; Volume 2149, p. 030007. [CrossRef]

Awan, A.B.; Zubair, M.; Praveen, R.P.; Bhatti, A.R. Design and comparative analysis of photovoltaic and parabolic trough based CSP plants. Sol. Energy 2019, 183, 551-565. [CrossRef]

Widyolar, B.K.; Abdelhamid, M.; Jiang, L.; Winston, R.; Yablonovitch, E.; Scranton, G.; Cygan, D.; Abbasi, H.; Kozlov, A. Design, simulation and experimental characterization of a novel parabolic trough hybrid solar photovoltaic/thermal (PV/T) collector. Renew. Energy 2017, 101, 1379-1389. [CrossRef]

Habchi, A.; Hartiti, B.; Labrim, H.; Fadili, S.; Benyoussef, A.; Belouaggadia, N.; Faddouli, A.; Benaissa, M.; Ntsoenzok, E.; EZ-Zahraouy, H. Performance study of a new hybrid parabolic trough collector system integrated with hybrid tubular thermoelectric generator. Appl. Therm. Eng. 2021, 192, 116656. [CrossRef]

Slooff, L.H.; Bende, E.E.; Burgers, A.R.; Budel, T.; Pravettoni, M.; Kenny, R.P.; Dunlop, E.D.; Büchtemann, A. A luminescent solar concentrator with 7.1% power conversion efficiency. Phys. Status Solidi RRL Rapid Res. Lett. 2008, 2, 257-259. [CrossRef]

Andreev, V.M. GaAs and High-Efficiency Space Cells. In Practical Handbook of Photovoltaics: Fundamentals and Applications; Elsevier Inc.: Amsterdam, The Netherlands, 2003; pp. 417-433. [CrossRef]

Leverington, D. New Cosmic Horizons: Space Astronomy from the V2 to the Hubble Space Telescope; Cambridge University Press: Cambridge, UK, 2000; p. 507.

Garner, R. Observatory-Electrical Power. 2017. Available online: https://www.nasa.gov/content/goddard/hubble-space-telescope-electrical-power-system/ (accessed on 3 May 2021).