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A Study on Solar Thermophotovoltaic System

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Abstract

STPV Technique is an abbreviation of Solar-Thermal Photo Voltaic system, in simple words; It is the technique in which Electricity is generated from heat waves. The different ways and steps involved in this techniques have been discussed also the recent studies on this topic has been overviewed in detail.

Keyword- STPV (Solar Thermal Photovoltaic), TPV (Thermo Photovoltaic) (Gasb) Gallium Antimonide, (PV) Photovoltaic, (IR) Infrared

I. INTRODUCTION

Thermophotovoltaic (TPV) energy conversion is a direct conversion process from heat to electricity via photons. A basic thermophotovoltaic system consists of a thermal emitterand a photovoltaic diode cell. The temperature of the thermal emitter varies between different systems from about 900 °C to about 1300 °C, although in principle TPV devices can extract energy from any emitter with temperature elevated above that of the photovoltaic device (forming an optical heat engine). The emitter can be a piece of solid material or a specially engineered structure. Thermal emission is the spontaneous emission of photons due to thermal motion of charges in the material. For these TPV temperatures, this radiation is mostly at near infrared and infrared frequencies. The photovoltaic diodes absorbs some of these radiated photons and converts them into electricity. Thermophotovoltaic systems have few to no moving parts and are therefore quiet and require little properties make thermophotovoltaic systems suitable for remote-site and portable maintenance. These electricity-generating applications. Their efficiency-cost properties, however, are often poor compared to other electricity-generating technologies. Current research in the area aims at increasing system efficiencies while keeping the system cost low. TPV systems usually attempt to match the optical properties of thermal emission (wavelength, polarization, direction) with the most efficient absorption characteristics of the photovoltaic cell, since unconverted thermal emission is a major source of inefficiency. Most groups focus on gallium antimonide (GaSb) cells. Germanium (Ge) is controlling the emitter's properties. TPV cells have been proposed as auxiliary power conversion devices for capture of otherwise lost heat in other power also suitable. Much research and development concerns methods for generation systems, such as steam turbine systems or solar cells. A prototype TPV hybrid car was built, the "Viking 29"[2] (TPV) powered automobile, designed and built by the Vehicle Research Institute (VRI) at Western Washington University. TPV research is an active area. Among others, the University of Houston TPV Radioisotope Power Conversion Technology development effort is attempting to combine a thermophotovoltaic cell with thermocouples to provide a 3 to 4-fold improvement in system efficiency over current radioisotope thermoelectric generators.

II. DIFFERENCE BETWEEN CONVENTIONAL PHOTOVOLTAICS AND THERMOPHOTOVOLTAICS

General photovoltaic cells are influenced by visible light of solar spectrum which has short wavelength, this happens because of the band gap in photovoltaic cells. Thermal radiation has longer wave length than visible light in solar spectrum, So different solar cells with different band gap can be used to convert these thermal radiations of the solar spectrum. Now multi junction cells have been developed to convert the maximum wave length of the solar spectrum In multi junction cells different materials are used to form different junctions so that it can provide different band gap for different wave length of the spectrum, Solar irradiation contains less than half of the solar spectrum. Conventional solar photo voltaic cells convert only visible light into electricity.

III. OPERATING PRICIPLES OF STPV

A new approach to harvesting solar energy, could improve efficiency by using sunlight to heat a high-temperature material whose infrared radiation would then be collected by a conventional photovoltaic cell. This technique could also make it easier to store the energy for later use, It is found that a new way is opened .In this case, adding the extra step improves performance, because it makes it possible to take advantage of wavelengths of light that ordinarily go to waste. A conventional silicon-based solar cell “doesn’t take advantage of all the photons,” That’s because converting the energy of a photon into electricity requires that the photon's energy level match that of a characteristic of the photovoltaic (PV) material called a band gap. Silicon's band gap responds to many wavelengths of light, but misses many others. To address that limitation, a two-layer absorber-emitter device is used and it is made of novel materials including carbon nanotubes and photonic crystals between the sunlight and the PV cell. This intermediate material collects energy from a broad spectrum of sunlight, heating up in the process. When it heats up, as with a piece of iron that glows red hot, it emits light of a particular wavelength, which in this case is tuned to match the bandgap of the PV cell mounted nearby. This basic concept has been explored for several years, since in theory such solar thermophotovoltaic (STPV) turns it to heat. This layer is bonded tightly to a layer of a photonic crystal, which is precisely engineered so that when it is heated by the attached layer of nanotubes, it "glows" with light whose peak intensity is mostly above the bandgap of the adjacent PV, ensuring that most of the energy collected by the absorber is then turned into electricity. It is found that this device produces peak efficiency when its intensity was equivalent to a focusing system that concentrates sunlight by a factor of 750. This light heated the absorber-emitter to a temperature of 962 degrees Celsius. Systems could provide a way to circumvent a theoretical limit on the energy-conversion efficiency of semiconductor-based photovoltaic devices. That limit, called the Shockley-Queisser limit, imposes a cap of 33.7 percent on such efficiency, but it is possible that with TPV systems, "the efficiency would be significantly higher — it could ideally be over 80 percent. "There have been many practical obstacles to realizing that potential; previous experiments have been unable to produce a STPV device with efficiency of greater than 1 percent. But Lenert, Wang, Associate professor of Physics and their team have already produced an initial test device with a measured efficiency of 3.2 percent, and they say with further work they expect to be able to reach 20 percent efficiency - enough, they say, for a commercially viable product. The design of the two-layer absorber-emitter material is key to this improvement. Its outer layer, facing the sunlight, is an array of multiwalled carbon nanotubes, which very efficiently absorbs the light's energy and. This level of concentration is already much lower than in previous attempts at STPV systems, which concentrated sunlight by a factor of several thousand. But the MIT researchers say that after further optimization, it should be possible to get the same kind of enhancement at even lower sunlight concentrations, making the systems easier to operate. Such a system, the team says, combines the advantages of solar photovoltaic systems, which turn sunlight directly into electricity, and solar thermal systems, which can have an advantage for delayed use because heat can be more easily stored than electricity. The new solar thermophotovoltaic systems, they say, could provide efficiency because of their broadband absorption of sunlight; scalability and compactness, because they are based on existing chip-manufacturing technology; and ease of energy storage, because of their reliance on heat. Some of the ways to further improve the system are quite straightforward. Since the intermediate stage of the system, the absorber-emitter, relies on high temperatures, its size is crucial: The larger an object, the less surface area it has in relation to its volume, so heat losses decline rapidly with increasing size. The initial tests were done on a 1-centimeter chip, but follow-up tests will be done with a 10-centimeter chip, they say.Zhuomin Zhang, a professor of mechanical engineering at the Georgia Institute of Technology who was not involved in this research, says, "This work is a breakthrough in solar thermophotovoltaics, which in principle may achieve higher efficiency than conventional solar cells because STPV can take advantage of the whole solar spectrum.

IV. ENERGY TRANSPORT IN STPV

In an STPV system solar energy spectrum is allowed to pass through an absorber, the absorber absorbs solar spectrum wavelengths of solar spectrum into low grade heat energy. This heat energy will be emitted from emitter which is internally coupled to the absorber in turn the photons those are emitted by the emitter the excite the ordinary PV cell which can convert the energy of photon into electricity. The intermediate and the most important part of the system is emitter that can emit the photons with definite wavelength which is suitable for PV cells. As soon as the infrared wavelengths along with visible spectrum has been made incident on the absorber. Heat energy will be produced by the action of emitters.Afer the complete conversion of solar spectrum into heat it becomes impossible to convert this heat into useful work in 100 %(second law of thermodynamics), that fades the efficiency of the system.

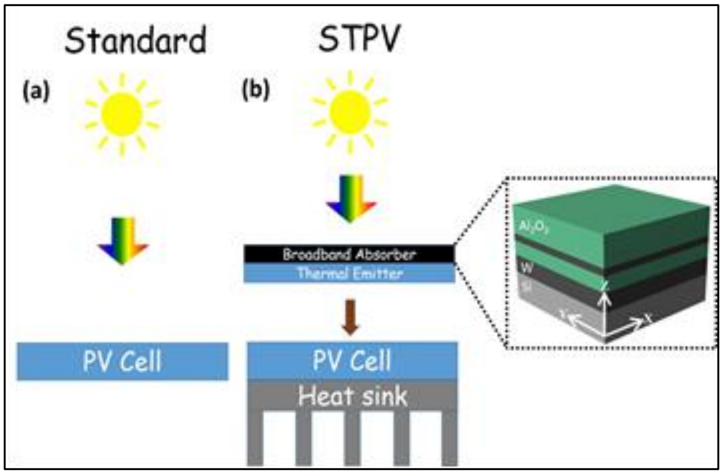

Fig. 1: STPV System solar energy

Photovoltaic thermal hybrid solar collectors, sometimes known as hybrid PV/T systems or PVT, are systems that convert solar radiation into thermal and electrical energy. These systems combine a solar cell, which converts sunlight into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module. And thus be more overall energy efficient than solar photovoltaic (PV) or solar thermal alone. A significant amount of research has gone into developing PVT technology since the 1970s. As thermal radiation, which is subsequently converted into electron-hole pairs via a low-band gap photovoltaic (PV) medium; these electron Photovoltaic cells suffer from a drop in efficiency with the rise in temperature due to increased resistance. Such systems can be engineered to carry heat away from the PV cells thereby cooling the cells and thus improving their efficiency by lowering resistance. Although this is an effective method, it causes the thermal component to under-perform compared to a solar thermal collector.

V. PRINCIPLE OF ABSORPTION

This system converts sunlight into electricity by absorbing solar photons as heat, which are then emitted -hole pairs are then conducted to the leads to produce a current [1– 4]. Originally proposed by Richard Swanson to incorporate a blackbody emitter with a silicon PV diode [5], the basic system operation is shown in Figure 2. However, there is potential for substantial loss at each step of the process, particularly in the conversion of heat to electricity. This is because according to Wien's law, blackbody emission peaks at wavelengths of 3000 μm•K T , for example, at 3 μm at 1000 K. Matched against a PV diode with a band edge wavelength λg < 2 μm, the majority of thermal photons have too little energy to be harvested, and thus act like parasitic losses. This phenomenon often reduces STPV system efficiencies well below those of their PV brethren. If efficiencies could be substantially improved, new applications such as solar power with integrated storage would open up.

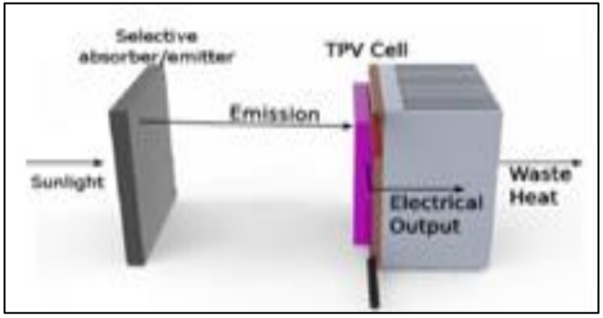

Fig. 2: Principle of Absorption

In modular design of a STPV system, such as the one shown in Figure 2 [6], the system efficiency of conversion could be splitted down as a product of three component efficiencies [7]:

$$\eta_{STPV} = \eta_o \eta_t \eta_{tpv}$$

Here η_o is the concentration efficiency, governed by the concentrating optics, η_t is the thermal transfer efficiency of light into usable heat [8] and η_{tpv} is the TPV efficiency of converting heat to electricity. Yet it is essential to denote that these independent terms still interact within the same system, and thus have many linkages, such as temperature, energy flux, and environmental conditions. The initial theoretical development and improvement of STPV proceeded over the course of several years. Using Richard Swanson's theory as a baseline [5], the first key condition for improving the system was to use a lower band gap PV cell than crystalline–silicon (c-Si). It is belived that up to 65% efficiency would be possible with the use of a semiconductor having a band gap of 0.8 eV [9], which is about twice the Shockley–Queisser limit for a single junction PV cell [10]. The primary reason is that many more thermal photons could be harvested with a lower band gap, which greatly reduces sub-band gap losses. The next key insight is to develop selective emitters that offer substantially different emission profiles than a blackbody [9, 11, 12]. It could be seen early on that creating a selective thermal emitter that only emits thermal photons at or above the energy of the PV diode could wholly eliminate sub-band gap losses, although it would be a difficult goal. Experimentally, selective emitter materials such as rareearth oxides (e.g., erbium oxide and ytterbium oxide [13]), as well as dielectric coatings on refractory metals (e.g., tungsten [W]) were shown to have potential for enhanced selectivity [14]. The third key insight was to introduce selective filters, in which a real selective emitter with less than-perfect selectivity could have sub-band gap photons returned to the emitter whence they came [4, 14, 15]. Subsequent calculations pointed toward experiments combining all three innovations [16]. On the strength of these results, it was subsequently re-estimated that in fact, STPV systems could in principle approach 85% conversion of sunlight to electricity under maximal concentration [17], a conclusion also reinforced by more recent work [18]. Developing integrated STPV systems to achieve even a fraction of the projected performance required significant advances in fabrication and characterization. A particularly key development was the adoption of a high-performance, low-band gap PV cell, made from Zndiffused gallium antimonide (GaSb) in the late 1980s and early 1990s [19, 20]. Another key development in 1994 allowed STPV systems to reach sustained temperatures up to 1350∘ C [21]. Reliable operation for hundreds of hours over 1200∘ C, with up to 29% conversion of selected thermal emission to electricity was achieved shortly thereafter [22]. Within a decade, it was shown that the key underlying process of heat-to-electricity conversion could exceed 23% efficiency in experiment [23]. In recent years, there has been a competition to fully integrate and quantify the effects of using sunlight as the exclusive source of heat, and to improve overall STPV conversion efficiencies toward theoretical limits. Early system level STPV results from Tohoku University in Japan [24] and Technical University of Madrid in Spain [25] reported experimental efficiencies below 1%. However, by 2013, an MIT group had achieved 3.2% efficient conversion [7]. Most recently, a collaboration out of Virginia and Argonne National Laboratories achieved 6.2% efficiency [26], although the test was performed with a 300 W laser diode source in lieu of direct solar simulation.

VI. PRINCIPLES OF SELECTION

The above work is not addressed how to gain higher efficiencies, particularly those above the Shockley–Queisser limit of 31% [10]; the key problem has been a requirement for unrealistic alignment of emitter and receiver. Careful modeling of such designs suggests that it may be possible to strongly concentrate thermal emission into a much narrower range of photon energies. In fact, an integrated strategy could eliminate a separate filter, while achieving higher performance. This approach gives rise to a new type of thermal conversion known as thermo photonics [27]. This term indicates that emitted photons will always have energy above a nontrivial band gap value. If typical sub-band gap and carrier thermalization losses due to above-band gap absorption can be strongly suppressed or even eliminated with this approach, extremely high heat-to-electricity power conversion efficiencies up to 50% could be achieved [28], well in excess of both the single junction and tandem-junction Shockley–Queisser limits for PV cells [10]. This would be possible at 1300∘C for band gaps ranging from 0.7 to 1.1 eV, encompassing a wide range of PV materials including GaSb and c-Si [29].

VII. SOLAR ABSORBER

The key to creating a material that would be ideal for converting solar energy to heat is tuning the material's spectrum of absorption just right: It should absorb virtually all wavelengths of light that reach Earth's surface from the sun — but not much of the rest of the spectrum, since that would increase the energy that is reradiated by the material, and thus lost to the conversion process.Now researchers at MIT say they have accomplished the development of a material that comes very close to the "ideal" for solar absorption. The material is a two-dimensional metallic dielectric photonic crystal, and has the additional benefits of absorbing sunlight from a wide range of angles and withstanding extremely high temperatures. Perhaps most importantly, the material can also be made cheaply at large scales.

The creation of this material is described in a paper published in the journal Advanced Materials, co-authored by MIT postdoc Jeffrey Chou, professors Marin Soljacic, Nicholas Fang, Evelyn Wang, and Sang-Gook Kim, and five others.

The material works as part of a solar-thermophotovoltaic (STPV) device: The sunlight's energy is first converted to heat, which then causes the material to glow, emitting light that can, in turn, be converted to an electric current.

Some members of the team worked on an earlier STPV device that took the form of hollow cavities, explains Chou, of MIT's Department of Mechanical Engineering, who is the paper's lead author. "They were empty, there was air inside," he says. "No one had tried putting a dielectric material inside, so we tried that and saw some interesting properties."

When harnessing solar energy, "you want to trap it and keep it there," Chou says; getting just the right spectrum of both absorption and emission is essential to efficient STPV performance.

Most of the sun's energy reaches us within a specific band of wavelengths, Chou explains, ranging from the ultraviolet through visible light and into the near-infrared. "It's a very specific window that you want to absorb in," he says. "We built this structure, and found that it had a very good absorption spectrum, just what we wanted."

In addition, the absorption characteristics can be controlled with great precision: The material is made from a collection of nanocavities, and "you can tune the absorption just by changing the size of the nanocavities," Chou says.

Another key characteristic of the new material, Chou says, is that it is well matched to existing manufacturing technology. "This is the first-ever device of this kind that can be fabricated with a method based on current … techniques, which means it's able to be manufactured on silicon wafer scales," Chou says-up to 12 inches on a side. Earlier lab demonstrations of similar systems could only produce devices a few centimeters on a side with expensive metal substrates, so were not suitable for scaling up to commercial production, he says.

In order to take maximum advantage of systems that concentrate sunlight using mirrors, the material must be capable of surviving unscathed under very high temperatures, Chou says. The new material has already demonstrated that it can endure a temperature of 1,000 degrees Celsius (1,832 degrees Fahrenheit) for a period of 24 hours without severe degradation. And since the new material can absorb sunlight efficiently from a wide range of angles, Chou says, "we don't really need solar trackers" — which would add greatly to the complexity and expense of a solar power system. "This is the first device that is able to do all these things at the same time," Chou says. "It has all these ideal properties. "While the team has demonstrated working devices using a formulation that includes a relatively expensive metal, ruthenium, "we're very flexible about materials," Chou says. "In theory, you could use any metal that can survive these high temperatures. "This work shows the potential of both photonic engineering and materials science to advance solar energy harvesting," says Paul Braun, a professor of materials science and engineering at the University of Illinois at Urbana-Champaign, who was not involved in this research. "In this paper, the authors demonstrated, in a system designed to withstand high temperatures, the engineering of the optical properties of a potential solar thermophotovoltaic absorber to match the sun's spectrum. Of course much work remains to realize a practical solar cell, however, the work here is one of the most important steps in that process. “The group is now working to optimize the system with alternative metals. Chou expects the system could be developed into a commercially viable product within five years. He is working with Kim on applications from this project.The team also included MIT research scientist Ivan Celanovic and former graduate students Yi Yeng, Yoonkyung Lee, Andrej Lenert, and Veronika Rinnerbauer. The work was supported by the Solid-State Solar Thermal Energy Conversion Center and the U.S. Department of Energy.

Solar absorber converts solar radiation into thermal energy in its first stage of operation. A main challenge is making a solar absorber that can both absorb broadband solar radiation and suppress re-radiation at high temperature. Previous work used near-blackbody absorbers [30] like array of multi-walled carbon nanotubes [7] has very strong absorptance over a broad spectral range. However, their nonselective absorption also allows re-radiation over infrared (IR) wavelengths at high temperatures. Therefore, a selective solar absorber that has strong absorptance around the peak of AM 1.5 spectrum, yet weak absorptance at longer wavelengths, is preferred for high-performance STPV. There are several types of selective solar absorbers that are suitable for STPV applications, including metal dielectric composites, semiconductor–metal tandems, plasmonic absorbers, and one-dimensional (1D)/two dimensional (2D)/three-dimensional (3D) photonic crystals (PhCs). Among the listed selective absorbers, metal dielectric composites and semiconductor–metal tandems have similar thermal conversion efficiencies at temperatures higher than 700 K [8, 31]. One-dimensional aperiodic multilayer PhCs follow closely behind, but have more complex structures [32]. For plasmonic absorbers and 2D or 3D PhCs, the slightly higher thermal emittance decreases their thermal transfer efficiencies at high temperatures. It is also relatively more challenging to fabricate plasmonic absorbers and 2D or 3D PhCs that are durable for high temperature operations [33, 34]. Other types of selective solar absorbers that have been previously considered in the literature, but are not explored here in detail, include textured absorbers [35–38] and intrinsic absorber materials [36, 38–40]. 3.1 Metal-dielectric composite selective solar absorbers Metal-dielectric composite solar absorber typically consists of cermet layers deposited on metallic substrates. A cermet consists of nanoscale metal particles embedded within ceramic binders [30]. Typical ceramic binder materials include alumina (Al2O3) [41], silicon dioxide (SiO2), aluminum oxynitride (AlON) [8] and zirconium dioxide (ZrO2) [42]. The cermet layer by itself has strong solar absorption and high transmission in the mid-IR. Combined with a metallic substrate, which is highly reflective at midand far-IR, the cermet offers both strong solar absorption and low thermal emittance. The cutoff of strong absorption and scattering in cermet can be tuned by the sizes of the metal particles. For example, larger particle sizes correspond to longer cutoff wavelengths [43]. The thickness of the cermet layer also needs to be carefully engineered. Thicker cermets lead to stronger solar and IR absorption [43]. Previously, a graded concentration of metal particles was proposed to improve solar absorption within the cermet by gradually increasing the refractive index of each cermet layer [30]. A single layer of graded Ni/Al2O3 on stainless steel was reported to have an averaged solar absorptance of 94%, and an averaged thermal emittance of only 7% at 773 K [31]. It is also proposed that for Alsp-AlON (Al sputtered in AlON binder) cermet solar absorber, a tenlayer graded cermet can be simplified as a double-layer cermet, yielding 86% thermal transfer efficiency at 1 sun illumination and a temperature of 353 K [8]. Another type of cermet structure uses porous alumina as the ceramic binder. The pores are perpendicular to the metallic substrate and can be filled with nanoscale metal [nickel (Ni), vanadium (V), cobalt (Co), copper (Cu), chromium (Cr), molybdenum (Mo), silver (Ag), tungsten (W)] rods [44]. Finally, as shown in the simulated reflection spectra in Figure 3B, using W particles in an alumina binder multilayer structure (Figure 3A) is predicted to achieve up to ηt = 86% under 100 suns at 1000 K [45]

VIII. CONCLUSION

In this paper, STPV technique and application, efficiency obtained in solar energy converter has been explained and converters with slightly different efficiencies have been discussed from which it is simpler to compare them. The deep comparison of STPV in converter circuit gives immense knowledge about the design and performance of the circuits and new ways to analyze the different modes of energy converter. The data’s which obtained from internet and IEEE journals have been collected and presented here without the much loss from the fundamental concept.

REFERENCES

[1] Kolm HH. Solar-battery power source. Q Prog Rep, 1956, 13.
[2] Wedlock BD. Thermo-photo-voltaic 1conversion. Proc IEEE, 1963, 51, 694–698.
[3] Black RE, Martin L, Baldasaro PF. Thermophotovoltaicsdevelopment status and parametric considerations for power applications. Thermoelectrics, 1999. Eighteenth International Conference on, 1999, 18, 639 – 644.
[4] O’sullivan F, Celanovic I, Jovanovic N, Kassakian J, Akiyama S, Wada K. Optical characteristics of one-dimensional Si/SiO2 photonic crystals for thermophotovoltaic applications. J Appl Phys, 2005, 97, 33529.
[5] Swanson RM. A proposed thermophotovoltaic solar energy conversion system. Proc IEEE, 1979, 67, 446–447.
[6] Rinnerbauer V, Lenert A, Bierman DM, et al. Metallic photonic crystal absorber-emitter for eflcient spectral control in high temperature solar thermophotovoltaics. Adv Energy Mater, 2014,
[7] Lenert A, Bierman DM, Nam Y, et al. A nanophotonic solar thermophotovoltaic device. Nat Nanotechnol, 2014, 1, 1–5.
[8] Zhang Q-C. High eflciency Al-N cermet solar coatings with double cermet layer film structures. J Phys D Appl Phys, 1999, 32, 1938–1944.

[9] Würfel P, Ruppel W. Upper limit of thermophotovoltaic solarenergy conversion. IEEE Transactions on Electron Devices, 1980, 27, 745–750.
[10] Shockley W, Queisser HJ. Detailed balance limit of eflciency of p-n junction solar cells. J Appl Phys, 1961, 32, 510–519.
[11] Demichelis F, Minetti-Mezzetti E. A solar thermophotovoltaic converter. Sol Cells, 1980, 1, 395–403.
[12] Edenburn MW. Analytical evaluation of a solar thermophotovoltaic (TPV) converter. Sol Energy, 1980, 24, 367–371.
[13] Guazzoni GE. High-temperature spectral emittance of oxides of erbium, samarium, neodymium and ytterbium. Appl Spectrosc, 1972, 26, 60–65.
[14] Höfler H, Paul HJ, Ruppel W, Würfel P. Interference filters for thermophotovoltaic solar energy conversion. Sol Cells, 1983, 10, 273–286.
[15] Ortabasi U. Rugate technology for thermophotovoltaic (TPV) applications: a new approach to near perfect filter performance. Fifth Conference on Thermophotovoltaic Generation of Electricity, 2003, 653, 249–258.
[16] Chubb DL. Reappraisal of solid selective emitters. IEEE Conf Photovolt Spec, 1990.
[17] Spirkl W, Ries H. Solar thermophotovoltaics: An assessment. J Appl Phys, 1985, 57, 4409–4414.
[18] Harder N-P, Würfel P. Theoretical limits of thermophotovoltaic solar energy conversion. Semicond Sci Technol, 2003, 18, S151–S157.
[19] Bett AW, Keser S, Stollwerck G, Sulima O V, Wettling W. GaSbbased (thermo) photovoltaic cells with Zn diffused emitters. Conf Rec Twenty Fifth IEEE Photovolt Spec Conf 1996, 1996.
[20] Fraas LM, Girard GR, Avery JE, et al. GaSb booster cells for over 30% eflcient solar-cell stacks. J Appl Phys, 1989, 66, 3866
[21] Stone KW, Leingang EF, Kusek SMM, Drubka REE, Fay TDD. On-Sun test results of McDonnell Douglas' prototype solar thermophotovoltaic power system. Proceedings of 1994 IEEE 1st World Conference on Photovoltaic Energy Conversion - WCPEC (A Joint Conference of PVSC, PVSEC and PSEC), 1994, 2, 2010–2013.
[22] Stone KW, Fatemi NS, Garverick LM. Operation and component testing of a solar thermophotovoltaic power system. Conf Rec Twenty Fifth IEEE Photovolt Spec Conf - 1996, 1996, 1421–1424.
[23] Wanlass MW. Recent advances in low-bandgap, InP-based GaInAs/InAsP materials and devices for thermophotovoltaic (TPV) energy conversion. AIP Conf Proc, 2004, 738, 427–435.
[24] Yugami H, Sai H, Nakamura K, Nakagawa N, Ohtsubo H. Solar thermophotovoltaic using Al2O3 / Er3/Al5/O12 eutectic Brought to you by | Purdue University Libraries Authenticated Download Date | 4/29/16 2:25 PM 18 | Zhiguang Zhou et al., Solar thermophotovoltaics: reshaping the solar spectrum composite selective emitter. Conf Rec Twenty-Eighth IEEE Photovolt Spec Conf 2000, 2000, 1, 1214–1217.
[25] Datas A, Algora C, Zamorano JC, et al. A solar TPV system based on germanium cells. AIP Conference Proceedings, 2007, 890, 280–290.
[26] Ungaro C, Gray SK, Gupta MC. Solar thermophotovoltaic system using nanostructures. Opt Express, 2015, 23, A1149.
[27] Harder N-P, Green MA. Thermophotonics. Semicond Sci Technol, 2003, 18, S270.
[28] Rephaeli E, Fan S. Absorber and emitter for solar thermophotovoltaic systems to achieve eflciency exceeding the Shockley-Queisser limit. Opt Express, 2009, 17, 15145–59.
[29] Zhou Z, Chen Q, Bermel P. Prospects for high-performance thermophotovoltaic conversion eflciencies exceeding the Shockley–Queisser limit. Energy Convers Manag, 2015, 97, 63–69.
[30] Kennedy C. Review of mid-to high-temperature solar selective absorber materials. NREL Tech Rep, 2002, 1617, 1–58.
[31] Sathiaraj TS, Thangarj R, Sharbaty AA, Bhatnagar M, Agnihotri OP. Ni-Al2O3 selective cermet coatings for photochemical conversion up to 500 C. Thin Solid Films, 1990, 190, 241.
[32] Sergeant NP, Pincon O, Agrawal M, Peumans P. Design of wide-angle solar-selective absorbers using aperiodic metaldielectric stacks. Opt Express, 2009, 17, 22800–22812.
[33] Rinnerbauer V, Yeng YX, Chan WR, et al. High-temperature stability and selective thermal emission of polycrystalline tantalum photonic crystals. Opt Express, 2013, 21, 11482–91.
[34] Sai H, Kanamori Y, Yugami H. High-temperature resistive surface grating for spectral control of thermal radiation. Appl Phys Lett, 2003, 82, 1685.
[35] Cuomo JJ, Ziegler JF, Woodall JM. A new concept for solar energy thermal conversion. Appl Phys Lett, 1975, 26, 557– 559.
[36] Pellegrini G. Experimental methods for the preparation of selectively absorbing textured surfaces for photothermal solar conversion. Sol energy Mater, 1980, 3, 391–404.
[37] Lehmann HW. Profile control by reactive sputter etching. J Vac Sci Technol, 1978, 15, 319.
[38] Seraphin BO. Optical properties of solids: new developments. North Holland Publishing Co., Amsterdam, 1976.
[39] Randich E, Allred DD. Chemically vapor-deposited ZrB2 as a selective solar absorber. Thin Solid Films, 1981, 83, 393– 398.
[40] Agnihotri OP, Gupta BK. Solar selective surfaces. New York: Wiley-Interscience Pub, 1981.
[41] Zhang Q, Mills DR. Very low-emittance solar selective surfaces using new film structures. J Appl Phys, 2006, 72, 3013–3021.
[42] Gao P, Meng LJ, Dos Santos MP, Teixeira V, Andritschky M. Study of ZrO2-Y2O3 films prepared by rf magnetron reactive sputtering. Thin Solid Films, 2000, 377–378, 32–36.
[43] Arancibia-Bulnes CA, Estrada CA, Ruiz-Suárez JC. Solar absorptance and thermal emittance of cermets with large particles. J Phys D Appl Phys, 2000, 33, 2489–2496.

[44] Niklasson GA, Granqvist CG. Selectively solar-absorbing surface coatings: optical properties and degradation. Materials science for solar energy conversion systems, Pergamon, Oxford, UK, 1991.
[45] Chester D, Bermel P, Joannopoulos JD, Soljacic M, Celanovic I. Design and global optimization of high-eflciency solar thermal systems with tungsten cermets. Opt Express, 2011, 19, A245–57.
[46] Messier R, Krishnaswamy S V., Gilbert LR, Swab P. Black a-Si solar selective absorber surfaces. J Appl Phys, 1980, 51, 1611.
[47] Seraphin BO. Chemical vapor deposition of thin semiconductor films for solar energy conversion. Thin Solid Films, 1976, 39, 87–94.
[48] Gilbert LR, Messier R, Roy R. Black germanium solar selective absorber surfaces. Thin Solid Films, 1978, 54, 149–157.
[49] Mattox DM. Deposition of semiconductor films with high solar absorptivity. J Vac Sci Technol, 1975, 12, 182.
[50] Bermel P, Ghebrebrhan M, Chan W, et al. Design and global optimization of high-eflciency thermophotovoltaic systems. Opt Express, 2010, 18, A314–A334.
[51] Wang X, Li H, Yu X, Shi X, Liu J. High-performance solutionprocessed plasmonic Ni nanochain-Al 2O3 selective solar thermal absorbers. Appl Phys Lett, 2012, 101, 1–6.
[52] Wu C, Neuner III B, John J, et al. Metamaterial-based integrated plasmonic absorber/emitter for solar thermophotovoltaic systems. J Opt, 2012, 14, 024005.
[53] Guler U, Boltasseva A, Shalaev VM. Refractory plasmonics. Science (80), 2014, 344, 263–264.
[54] Liu J, Guler U, Li W, Kildishev A, Boltasseva A, Shalaev VM. High-temperature plasmonic thermal emitter for thermophotovotaics. CLEO, 2014, 1, FM4C.5.
[55] Yeng YX, Ghebrebrhan M, Bermel P, et al. Enabling hightemperature nanophotonics for energy applications. Proc Natl Acad Sci U S A, 2012, 109, 2280–5.
[56] Ghebrebrhan M, Bermel P, Yeng YX, Celanovic I, Soljačić M, Joannopoulos JD. Tailoring thermal emission via Q matching of photonic crystal resonances. Phys Rev A, 2011, 83, 033810.
[57] Joannopoulos JD, Johnson SG, Winn JN, Meade RD. Photonic crystals molding the flow of light. Second. Princeton, NJ: Princeton University Press, 2008.
[58] Sergeant NP, Agrawal M, Peumans P. High performance solarselective absorbers using coated sub-wavelength gratings. Opt Express, 2010, 18, 5525–5540.
[59] Chou JB, Yeng YX, Lenert A, et al. Design of wide-angle selective absorbers/emitters with dielectric filled metallic photonic crystals for energy applications. Opt Express, 2014, 22, A144–54.
[60] Sai H, Yugami H, Kanamori Y, Hane K. Solar selective absorbers based on two-dimensional W surface gratings with submicron periods for high-temperature photothermal conversion. Sol Energy Mater Sol Cells, 2003, 79, 35–49.
[61] Fleming JG, Lin SY, El-Kady I, Biswas R, Ho KM. All-metallic three-dimensional photonic crystals with a large infrared bandgap. Nature, 2002, 417, 52–5.
[62] Rinnerbauer VR, Ausecker EL, Chäffler FS, Eininger PR, Trasser GS, Eil RDG. Nanoimprinted superlattice metallic photonic crystal as ultraselective solar absorber. 2015, 2, 18–21.
[63] Mousazadeh H, Keyhani A, Javadi A, Mobli H, Abrinia K, Sharifi A. A review of principle and sun-tracking methods for maximizing solar systems output. Renew Sustain Energy Rev, 2009, 13, 1800–1818.
[64] Chubb D, Pal A, Patton M, Jenkins P. Rare earth doped high temperature ceramic selective emitters. J Eur Ceram Soc, 1999, 19, 2551–2562. Brought to you by | Purdue University Libraries Authenticated Download Date | 4/29/16 2:25 PM Zhiguang Zhou et al., Solar thermophotovoltaics: reshaping the solar spectrum | 19
[65] Bitnar B, Durisch W, Mayor J-C, Sigg H, Tschudi HR. Characterisation of rare earth selective emitters for thermophotovoltaic applications. Sol Energy Mater Sol Cells, 2002, 73, 221–234.
[66] Torsello G, Lomascolo M, Licciulli A, Diso D, Tundo S, Mazzer M. The origin of highly eflcient selective emission in rareearth oxides for thermophotovoltaic applications. Nat Mater, 2004, 3, 632–7.
[67] Bitnar B, Durisch W, Holzner R. Thermophotovoltaics on the move to applications. Appl Energy, 2013, 105, 430–438.
[68] Nam Y, Yeng YX, Lenert A, et al. Solar thermophotovoltaic energy conversion systems with two-dimensional tantalum photonic crystal absorbers and emitters. Sol Energy Mater Sol Cells, 2014, 122, 287–296.
[69] Celanovic I, Jovanovic N, Kassakian J. Two-dimensional tungsten photonic crystals as selective thermal emitters. Appl Phys Lett, 2008, 92, 193101.
[70] Garín M, Hernández D, Trifonov T, Alcubilla R. Threedimensional metallo-dielectric selective thermal emitters with high-temperature stability for thermophotovoltaic applications. Sol Energy Mater Sol Cells, 2015, 134, 22–28.
[71] Liu X, Tyler T, Starr T, Starr AF, Jokerst NM, Padilla WJ. Taming the blackbody with infrared metamaterials as selective thermal emitters. Phys Rev Lett, 2011, 107, 045901.
[72] Tobler WJ, Durisch W. Plasma-spray coated rare-earth oxides on molybdenum disilicide – High temperature stable emitters for thermophotovoltaics. Appl Energy, 2008, 85, 371–383.
[73] Khan MR, Wang X, Sakr E, Alam MA, Bermel P. Enhanced selective thermal emission with a meta-mirror following Generalized Snell’s Law. MRS Proceedings, 2015, 1728.
[74] Sakr ES, Zhou Z, Bermel P. High eflciency rare-earth emitter for thermophotovoltaic applications. Appl Phys Lett, 2014, 105, 111107.

[75] Kohiyama A, Shimizu M, Kobayashi H, Iguchi F, Yugami H. Spectrally controlled thermal radiation based on surface microstructures for high-eflciency solar thermophotovoltaic system. Energy Procedia, 2014, 57, 517–523.–151.
[76] C W. Li, X. He, "Review of Non-Isolated High Step-Up DC/DC Converters in Photovoltaic Grid-Connected Applications", IEEE Transactions on Industrial Electronics, vol. 58, no. 4, April 2011.
[77] Q. Zhao and F. C. Lee, "High-efficiency, high step-up DC–DC converters," IEEE Transaction on Power Electronics, vol. 18, no. 1, pp. 65–73, Jan.2003.
[78] R.-J. Wai and R.-Y. Duan, "High step-up converter with coupled-inductor," IEEE Transaction on Power Electronics, vol. 20, no. 5, pp. 1025–1035, Sep. 2005.
[79] G. Henn, R. Silva, P. Praça, L. Barreto D. Oliveira, "Interleaved Boost Converter with High Voltage Gain", IEEE Transaction on Power Electronics, vol. 25, no. 11, pp. 2753–2761, Nov. 2010.
[80] R. J. Wai, R. Y. Duan, "High-efficiency Power Conversion for Low Power Fuel Cell Generation System", IEEE Transactions on Power Electronics, vol. 20, no.4, pp. 847-856, Jul 2005.
[81] N.A. Rahim, J. Selvaraj, and C. Krismadenata,"Five-level inverter with reference modulation technique for grid-connected PV system" Elsevier, Renewable Energy, vol. 35 no. 3, pp. 712-720, March 2010.
[82] D. Sera, R. Teodorescu, J. Hantschel, M. Knoll, "Optimized Maximum Power Point Tracker for Fast-Changing Environmental Conditions" IEEE Trans. Industrial Electronics, vol. 55, no. 7, pp. 2629-2637,Jul 2008.
[83] N. Femia, D. Granozio, G. Petrone, G. Spagnuolo, M. Vitelli, "Optimized One-Cycle Control in Photovoltaic Grid Connected Applications" IEEE Trans. Aerospace and Electronic Systems, vol. 42, no. 3, pp.954-972, Feb 2006.
[84] M. Fortunato, A. Giustiniani, G. Petrone, G. Spagnuolo, M. Vitelli, "Maximum Power Point Tracking in a One-Cycle-Controlled SingleStage Photovoltaic Inverter" IEEE Trans. Industrial Electronics, vol. 55, no. 7, pp. 2684-2693, Jul 2008.
[85] P. Sanchis, A. Ursua, E. Gubia and L. Marroyo, "Design and experimental operation of a control strategy for the buck-boost DC-AC inverter" IEE Proc.-Electr. Power Appl., vol. 152, no. 3, May 2005.
[86] L. Bowtell, A. Ahfock, "Direct current offset controller for transformerless single-phase photovoltaic grid-connected inverters" IET Renew. Power Generation, vol. 4, no. 5, pp. 428-437, 2010.
[87] M.F. Naguib, and L.A.C. Lopes, "Harmonics Reduction in Current Source Converters Using Fuzzy Logic" IEEE Trans. Power Electronics, vol. 25 no. 1, pp. 158-167, Jan 2010
[88] L. Hang, S. Liu, G. Yan, B. Qu, and Z. Lu, "An Improved Deadbeat Scheme With Fuzzy Controller for the Grid-side Three-Phase PWM Boost Rectifier" IEEE Trans. Power Electronics, vol. 26, no. 4, pp.1184-1191, April 2011.
[89] M. M. Rashid, N.A. Rahim, M.A. Hussain, and M.A. Rahman, "Analysis and Experimental Study of Magnetorheological-Based Damper for Semiactive Suspension System Using Fuzzy Hybrids" IEEE Trans. Industry Applications, vol. 47 no. 2, pp. 1051-1059, March/April 2011.
[90] M. Singh, and A. Chandra, "Application of Adaptive Network-Based Fuzzy Inference System for Sensorless Control of PMSG-Based Wind Turbine with Nonlinear-Load-Compensation Capabilities" IEEE Trans. Power Electronics, vol. 26 no. 1, pp. 165-175, Jan 2011.
[91] M.N. Uddin, and R.S. Rebeiro, "Online Efficiency Optimization of a Fuzzy-Logic-Controller-Based IPMSM Drive" IEEE Trans. Industry Applications, vol. 47 no. 2, pp. 1043-1050, March/April 2011.
[92] B.N. Alajmi, K.H. Ahmed, S.J. Finney, and B.W. Williams,"FuzzyLogic-Control Approach of a Modified Hill-Climbing Method for Maximum Power Point in Microgrid Standalone Photovoltaic System" IEEE Trans. Power Electronics, vol. 26 no. 4, pp. 1022-1030, April 2011.
[93] T. Wu, Ch. Chang, and Y. Chen, "A Fuzzy-Logic-Controlled SingleStage Converter for PV-Powered Lighting System Applications" IEEE Trans. Industrial Electronics, vol. 47, no. 2, pp. 287-296, April 2000.
[94] N. Femia, G. Granozio, G. Petrone, and G. Spagnuolo, "Predictive Adaptive MPPT Perturb and Observe Method" IEEE Trans. Aerospace And Electronic Systems, vol. 43, no. 3, pp. 934-950, Jul 2007.
[95] V. Agarwal, R. Aggarwal, P. Patidar, and Ch. Patki, "A Novel Scheme for Rapid Tracking of Maximum Power Point in Wind Energy Generation Systems" IEEE Trans. Energy Conversion, vol. 25, no. 1, pp.228-236, March 2010.
[96] M. Pucci, and M. Cirrincione, "Neural MPPT Control of Wind Generators with Induction Machines Without Speed Sensors" IEEE Trans.Industrial Electronics, vol. 58, no. 1, pp. 37-47, Jan 2011.
[97] A. Yazdani and P. Dash,"A Control Methodology and Characterization of Dynamics for a Photovoltaic (PV) System Interfaced with a Distribution Network" IEEE Trans. Power Delivery, vol. 24, no. 3, pp.1538-1551, Jul 2009.