Thermophotovoltaic Cell

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Generally, waste heat is redundantly released into the surrounding by anthropogenic activities without strategized planning. Consequently, urban heat islands and global warming chronically increases over time. Thermophotovoltaic (TPV) systems can be potentially deployed to harvest waste heat and recuperate energy to tackle this global issue with supplementary generation of electrical energy.

Keywords: thermophotovoltaic ; InGaAs ; GaSb ; narrow bandgap ; performance

1. Introduction

A TPV system converts thermal radiations from various heat sources such as the combustion of fuels, industrial waste heat, concentrated solar or nuclear energy into electricity. For example, fossil fuels are the main energy source for world-wide energy consumption. However, they are non-renewable resources that will deplete over time due to impulsive mining. Panayiotou et al. [1] has estimated that 370.41 TWh/yr of waste heat is generated from European industries in 2017. This massive amount of waste heat generation has led to a worldwide concern on the global environmental impact and a quest for efficient use of waste heat in the industries. Therefore, there is an urgent need to explore alternatives to improve waste heat recycling and energy conversion efficiency to minimize the reliance on fossil fuels. In this regard, a thermophotovoltaic (TPV) system appears to be a potential candidate to meet these requirements. Moreover, the flexibility of converting various heat energy sources such as solar, nuclear, chemical combustion, and waste heat into high electrical power density broadens the TPV application ranging from micro-scale to large-scale TPV generators [2]. For instance, a worldwide potential of 3.1 GW electricity generation using TPV system in steel industry (>1373 K) was estimated by Fraas et al. [3].

In comparison to a solar photovoltaic system, a TPV system works for a longer operation time at a lower radiator heating temperature [4]. A TPV system consists of four main devices: a generator to provide heat energy from the fuel combustion process, a radiator to translate the heat energy into an emission spectrum, a filter to coordinate the emission spectrum to a TPV cell, and lastly a TPV cell to convert the photon radiation into electrical energy [5]. A comprehensive analysis has been conducted in each component of the TPV system to enhance the overall performance. Particularly, the TPV cell, which converts the photon radiation directly into electricity is the core component that contributes to the overall TPV system performance [6]. Therefore, this review comprehensively studied narrow bandgap TPV cells namely the gallium antimonide (GaSb), indium gallium arsenide (InGaAs) and a few other potential narrow bandgap materials such as germanium (Ge), indium arsenide (InAs), indium gallium arsenide antimonide (InGaAsSb), indium arsenide antimonide phosphide (InAsSbP), and indium gallium arsenide antimonide phosphide (InGaAsSbP) TPV cells. Their respective cell performances, improvements and challenges will be highlighted.

Over the last three decades, research on various parts of the TPV system has received tremendous attention. The advantages of noiselessness, high reliability, mechanical stability without moving parts, and a large power density, make TPV suitable for a vast range of terrestrial and space applications. Recently, numerous review papers have been published. In 2014, Ferraria et al. [7] presented and discussed a critical review of the TPV prototypes. In the next year, Daneshvar et al. [8] reviewed the development of all main components, discussed the fundamental and technical challenges facing commercial adoption of TPV and prospects of TPV. Mustafa et al. [9] summarized the progress of combustion-driven thermoelectric (TE) and TPV power generation systems for the years 2000–2016. Datas and Martí [10] reviewed the state of the art and historical development of TPV for space application along with the main competing technologies. Tain et al. [11] reported the recent progress of near-field and far-field radiative heat transfer, various design structures of metamaterials and their properties, and focused on the exploration of tunable radiative wavelength selectivity of nano-metamaterials. More recently, in 2019, Sakakibara et al. [12] reviewed the state of the art of radiator and presented a systematic approach for assessing radiators. A recent paper from Rashid et al. [13] has highlighted the recent development of TPV for waste heat harvesting application and investigated the potential implementation in coal-fired thermal power plant. Furthermore, Burger et al. [14] studied numerous decades of experimental TPV works and compared the energy-conversion of different systems with respect to experiment-specific thermodynamic limit. Based on the research gap, a review on the comparison of performance parameters of different TPV cell materials and their respective improvement and potential are yet to be conducted. Therefore, this paper focuses on the TPV cell, which is the main component in the TPV system. Furthermore, the comprehensive review on various TPV cells contributes to the understanding of the decades of advancement, future prospects, and applications of TPV cells.

2. TPV Cell Fabrication

There are two methods of TPV cell fabrication, namely non-epitaxial and epitaxial methods. Non-epitaxial growth can be sub-categorized into two: diffusion method and ion implantation method. Diffusion method is commonly used to fabricate GaSb TPV cell [15][16][17] and InGaAs [18]. The conventional diffused GaSb-based TPV cell is manufactured in a pseudo-closed box (PCB) with the diffusion of Zn particle into Tellurium-doped single-crystal GaSb substrate [19]. Parameters studied on the diffusion profiles are temperature, diffusion time and precision of control for the depth of p-n junction. Tang et al. [15][16] presented a closed-quartz-tube for the diffusion process where Zn-Ga alloy is proven to be a suitable source that can suppress the formation of high concentration surface region in Zn profile with a lower fabrication cost.

Ion implantation method is the most suitable method to perform selective doping, as the spatial distribution of dopant atoms can be more precisely defined [20]. However, the use of ion implantation introduces undesirable damage to the lattice crystal structure due to the high annealing temperature [20][21][22]. The formation of junctions appears to be more difficult than diffused junctions [23][24]. This causes a non-uniform p-n junction formation due to different thicknesses of the active region. Rahimi et al. [25] demonstrated that the Be-implanted GaSb exhibits similar performance to the MBE-grown GaSb TPV cell. To achieve this, the implanted dopants on the semiconductor substrate must undergo a rapid thermal annealing (RTA) process where the cell is exposed to a high temperature to remove the implant-induced damage and therefore achieving a higher shunt resistance [21][26]. It is highlighted that inadequate isolation is produced from the ion bombardment process due to small intrinsic resistivity of InGaAs material [27]. The main limitation of the non-epitaxial growth method is the high front and back surface recombination which reduce the photocurrent collection. Several studies proposed an advance growth method that combined epitaxial and diffusion method [28][29]. The main advantage of the combined growth technique is to create a device with low surface recombination and low defect density.

Epitaxy is a process of depositing crystalline on a substrate that acts as a seed crystal, which is favorable for achieving a better cell performance with the advantages of better purity control, thickness control and doping level control. The epitaxy can be categorized into three different mediums: liquid, solid and vapor. Liquid phase epitaxy (LPE) is the deposition of liquid phase single-crystalline either in the solution or melt form on a substrate crystal below the melting temperature of deposited materials [30]. Most TPV cell structures are initially fabricated using LPE method due to the simplicity of the process. TPV cells grown by LPE method suffer from very high lattice mismatch [31] and poor thickness control, which affect the cell efficiency. Epitaxial lateral overgrowth (ELOG) is introduced to solve the mismatching issue in heteroepitaxy [32][33]. It is worth highlighting that ELOG blocks mismatching threats from substrate [34]. Cheetham et al. [35] described a well-established low bandgap structure using LPE growth method with $InAs_{0.62}Sb_{0.14}P_{0.24}/Ga_{0.03}In_{0.97}As_{0.83}Sb_{0.14}P_{0.03}$ on InAs substrate. In 2015, Krier et al. [31] developed a $InAs_{0.61}Sb_{0.31}P_{0.26}$/InAs p-n junction with 0.32 eV bandgap using the LPE method. Hence, LPE is a promising technique to produce a larger size single crystal with high-quality binary, ternary and quaternary TPV structures at relatively low growth temperature [36]. Despite the simplicity and low cost of LPE method, vapor phase epitaxy (VPE) is capable of producing cells with better crystal quality and higher performance.

VPE can be subcategorized into molecular beam epitaxy (MBE), metal-organic vapor phase epitaxy (MOVPE) and plasma-enhanced chemical vapor deposition (PECVD). MOVPE method was introduced for the growth of vapor phase III-V compound semiconductor materials, such as GaSb or InSb, on different types of substrate surfaces [37]. MOVPE is suitable for numerous commercialized low bandgap devices, with the advantages of a low reactor downtime, ease of maintenance, easy scalability for multi-wafer deposition, as well as more stable and controllable growth rates. In addition, MOVPE is more suitable for the growth of high-quality InP buffer and cladding layers due to lower arsenic contamination [38]. MOVPE is often use in high-quality materials and more complex structures with higher interface quality [39]. Material quality can be significantly improved by all parameters which reduce atomic surface diffusivity, such as decreasing growth temperature, increasing growth rate, and substrate miscut angle [40]. TPV cell technology is approaching 30% cell efficiency at 300 K cell temperature due to the gradual improvement in the MOVPE manufacturing process [41]. The experimental data of a simple Zn-diffused GaSb structure as compared to the complex MOVPE structure has proven that MOVPE structure had better performance with a maximum *FF* of 75% as compared to 70% with Zn diffusion structure [42]. One of the essential advantages of MOVPE method is the wide selection range of substrate materials. Most work in the MOVPE-fabricated TPV cells was conducted to improve the density of mismatching using cheaper substrate materials. For an InGaAsSb TPV cell, GaAs substrate is a better option compared to GaSb as the cost is cheaper with a higher potential to be commercialized [43]. Despite high lattice dislocation (7%) between GaSb p-n junction and GaAs substrate, the structure was improved by shifting the active junction away from the substrate material using selective epitaxy technique to create a buffer layer. The output power of GaSb/GaAs cell is only 30% lower than homojunction GaSb cell, under the same illumination condition. In another study, InGaAsSb on GaAs exhibited similar dark current-voltage characteristic with that on GaSb substrate. Furthermore, the J_{sc} and V_{oc} of the fabricated structure are comparable with GaSb-based structure under illumination from 1073 K silicon nitride radiator [44]. In another study, Lu et al. [45] reported the use of a novel metamorphic buffer layer to suppress the threading dislocations originating from the large lattice-mismatch of InGaAsSb on GaAs substrate, which included the interfacial misfit arrays at the GaSb/GaAs interface and strained InGaSb/GaSb multi-quantum wells acting as dislocation filtering layers.

MBE utilizes an ultra-high vacuum (UHV) with a low deposition pressure in the chamber (lower than 10 Torr). This technique provides a clean growth environment, higher purity, precise control of the beam fluxes and growth condition by changing the nature of the incoming beam. The MBE method has the advantage of generating complicated doping profiles due to the flexible control of the dopants. The MBE method provides promising fundamental device parameters such as low ideality factor (n = 1.0) and low dark current of 6 × 10^{-5} A. However, a GaSb structure grown over a large area is challenging due to the difficulty of finding an epi-ready substrate, non-uniform native oxide desorption, and shunt defect formation. A key advantage of using the MBE method to grow TPV cell is the generation of a higher V_{oc} when compared to the MOVPE and LPE methods [25][46]. **Table 1** provides a summary of characteristics, advantages and disadvantages for different types of TPV cell growth methods.

Table 1. Characteristics of Different Growth Methods for TPV Cells.

Growth Method		Growth Rate	Heterojunction	Temperature	Vacuum (Y/N)	Safety	Cost	Absorb Thickness	Thickness Control (Y/N)	Abs Dop
Epitaxial	MBE	0.082–0.278 nm/s [47][48][49]	Produces super lattice heterostructure structure [50][51]	723–808 K [46][52][53]	An ultra-high vacuum pressure lower than 5 × 10^{-11} Torr [50][54]	Toxic and required safety system for hydride gases [54]	Very expensive and complex [55]	2–10 μm [46][56][57] [58]	Precise control [26][59]	8x1 2x1 [28] [57] [6
	MOVPE	0.0006–0.63 μm/s [59][61][62] [63][64][65]	Suitable for heretojunction structure [59][62]	773–903 K [39][59][61][62] [63][64][65][66]	Pressure ranging between 40–600 Torr [63][64][65][67]	Highly toxic	Expensive equipment and complex than LPE [55]	1–6 μm [62][63][68] [69][70][71]	Precise control [59][66]	2.2 10^{1} × 1 [62] [68] [70]
	LPE	2–15 μm/s 10 to 100 times faster than MOVPE or MBE [61][72][73]	Not very suitable	623–883 K [31][33][35][72] [74][75]	Slightly above atmosphere pressure [31][35]	Produce non-toxic or less dangerous substances [74][75]	Simple and inexpensive method [74]	2–200 μm [35][73][75]	Less precise [50][61] but it can be improve with lower growth rate [76]	1 10^{1} × 1 [36] [7
Non-Epitaxial	Diffusion	2–5 h to complete the diffusion [15][78]	Not suitable	693–753 K [28][79][80]	Diffusion closed box at vacuum level [15]	n/a	Simple and inexpensive	100–400 μm	n/a	3 10 2.3 10 [18] [7
	Ion implantation	n/a	Not suitable	80–373 K [81]	300–1000 Torr [82]	Ionized radiation	Less expensive [26]	100–400 μm	n/a	n/

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