

# Silicon, germanium and silicon/germanium photocells for thermophotovoltaics applications

**Bernd Bitnar**

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

E-mail: bernd.bitnar@psi.ch

Received 25 October 2002

Published 4 April 2003

Online at [stacks.iop.org/SST/18/S221](http://stacks.iop.org/SST/18/S221)

## Abstract

Silicon (Si) and germanium (Ge) are semiconducting materials, which are industrially used for the large-scale production of various electronic devices. Solar cells are commonly manufactured from Si. For thermophotovoltaics (TPV) Si has the disadvantage of a high bandgap of 1.1 eV, which requires the use of a spectrally matched selective emitter.  $\text{Yb}_2\text{O}_3$  is widely used as an emitter material to illuminate Si photocells. Si concentrator solar cells have been investigated for TPV applications, because they have a high performance at a typical illumination density of  $1 \text{ W cm}^{-2}$  in a TPV system. Non-concentrator solar cells achieve lower efficiencies under TPV conditions, but up to now they are more cost effective than concentrator cells. A new Si photocell optimized for TPV has a front side textured with rectangular grooves with vertically evaporated contact fingers and a rear surface mirror to reflect sub-bandgap radiation back to the emitter.

Ge photocells have a bandgap of 0.66 eV and can effectively be illuminated by a selective  $\text{Er}_2\text{O}_3$  emitter. Their efficiencies are lower than those of photocells from low bandgap III/V materials, such as GaSb. But, due to low free carrier absorption in Ge, an effective rear surface mirror can be formed. A reflectance of up to 82–87% for sub-bandgap radiation and a cell efficiency of 13% for solar air mass 0 (AM0) radiation with a cut-off for wavelengths smaller than 900 nm have been achieved with a Ge TPV cell.

SiGe photocells allow the variation of the bandgap as a function of the Ge content. In principle, a SiGe photocell can be matched to a given selective emitter spectrum. A first SiGe quantum dot solar cell has achieved 12% efficiency, but still suffers from a low open circuit voltage.

The first TPV systems working with Si photocells have been built. A system efficiency of 2.4% can be achieved. The most promising application of Si-based TPV is likely to be an electrically self-powered residential heating system. For a self-powered operation, a TPV system efficiency of 1–2% is sufficient and Si photocells have the advantage of being inexpensive.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Si and Ge are indirect semiconductors with bandgaps of 1.1 and 0.66 eV, respectively. The 1.1 eV bandgap of Si is well placed for the illumination of Si photocells with

sunlight. For a blackbody radiation source with  $T < 2000 \text{ K}$ , which is typical for thermophotovoltaics (TPV) emitters, the maximum of the emission spectrum appears at photon energies of  $< 0.9 \text{ eV}$  and the Si bandgap is too high for an efficient conversion. On the other hand, monocrystalline Si solar cells

are industrially manufactured on a large scale. They are relatively cheap, especially when compared to low bandgap III/V photocells. Because of the long-term optimized Si technology, the efficiency of the best cells is close to the theoretical limit. Therefore, several efforts have been made to use Si photocells for TPV and to develop technologies to achieve sufficiently high system efficiencies, despite the relatively large Si bandgap.

Ge has a bandgap of 0.66 eV, which is matched well to the spectra of emission sources with temperatures at 1500–2000 K. At the start of photovoltaics, Ge solar cells were produced, but because of their low open circuit voltage and efficiency they were replaced by Si shortly after. Now, Ge photocells are used for tandem and triple cell applications. Therefore, the cell technology is well developed. Ge is more expensive than Si by about a factor of 4 to 5, but it is much cheaper than III/V low bandgap materials.

SiGe is a promising material to match the bandgap to a given emitter spectrum by varying the Ge content of the alloy. SiGe photocells can either be produced from SiGe wafers or from thin, epitaxially grown structures on Si substrates. For thin epitaxial layers, the problem of weak absorption occurs. Nevertheless, some efforts have been made to use quantum well or quantum dot structures as optically active regions in SiGe photocells.

## 2. Radiation emitter

The main difficulty for TPV is the spectral match of the emitter radiation with the spectral sensitivity of the photocells. The temperature of the emitter is typically limited to below 1800 K to restrict the emission of  $\text{NO}_x$  for many applications. Therefore, the emission spectrum of a continuous radiator is shifted to lower photon energies compared to solar irradiation. A blackbody emitter with  $T = 1800$  K emits only 6% of its radiation power at photon energies above 1.1 eV. For the use of Si photocells with a bandgap of 1.1 eV, a selective emitter with strongly reduced infrared emission is very important for achieving high efficiencies.

Bitnar *et al* [1] have described the development of rare-earth selective emitters, which have emission spectra matched to the bandgap of Si and Ge photocells. The  $\text{Yb}_2\text{O}_3$  and  $\text{Er}_2\text{O}_3$  emitters radiate 20% and 33% of their total radiation power at photon energies above the Si and Ge bandgaps, respectively. An estimation using a modelled Si photocell and the  $\text{Yb}_2\text{O}_3$  emitter spectrum gives a system efficiency of about 2% for a TPV system without filter and recuperator [1].

## 3. Silicon photocells

Si is still the primarily used material for the production of solar cells. Monocrystalline Si photocells are used for the fabrication of highly efficient solar cell modules. Therefore, these cells are available in large quantities and are relatively cheap. Si is non-toxic and, therefore, Si cells can be placed close to a 1800 K hot emitter without the risk of the emission of toxic gases in the case of a system malfunction. The disadvantage of the high Si bandgap of 1.1 eV can effectively be circumvented by illuminating the cells with a selective emitter.  $\text{Yb}_2\text{O}_3$  is the primarily applied selective emitter material for the illumination of Si photocells.

There are several requirements for Si photocells for  $\text{Yb}_2\text{O}_3$  irradiation [2]:

- The selective emission peak has its maximum at 1.27 eV and a tail up to 1.05 eV (see [1]). For an efficient conversion, the external quantum efficiency of the cells between 1.5 and 1.1 eV should be as high as possible.
- This needs a minimized external reflectance in this photon energy range.
- The bulk as well as the back surface recombination should be minimized.
- Typically, the emitter radiation density is concentrated by at least a factor of 5 compared to solar irradiation. The series resistance of the cells has to be small enough to reach a sufficiently high fill factor under these concentrating conditions.

Several authors have investigated the use of Si photocells in a TPV system. In [3] monocrystalline solar cells from SunPower with 20.5% solar irradiation efficiency were used to build a module for a TPV cogenerating heating system. The cells were illuminated with an  $\text{Yb}_2\text{O}_3$  emitter coated on to the burner. The system produced about 190 W electricity with a system efficiency of 0.76%. Concentrator Si solar cells from SunPower were used in [4] for the development of a portable TPV power supply. In this system, a high temperature of 2000 K of the  $\text{Yb}_2\text{O}_3$  fibre emitter was achieved using a recuperator. A system efficiency of 1.6%, with 90 W generated electrical power at an illumination density of  $2.7 \text{ W cm}^{-2}$ , was achieved.

An approach using relatively inexpensive solar cells in a simply designed small TPV system with an  $\text{Yb}_2\text{O}_3$  emitter is reported in [2, 5]. The monocrystalline solar cells from ASE have an efficiency of 16% under solar irradiation. The external quantum efficiency is about 0.9 at the maximum of the  $\text{Yb}_2\text{O}_3$  emission peak. Eight cells with a total area of  $380 \text{ cm}^2$  were used. The radiation of an  $\text{Yb}_2\text{O}_3$  incandescent mantle emitter passes a water filter, which absorbs the unconvertible infrared radiation, so that there is no need for a water-cooling circuit for the cells. This system produced 21 W electrical power. An improved system is presented in [6], which achieved 48 W electrical power corresponding to a system efficiency of 2.4% using Si solar cells from the University of New South Wales with 21% solar irradiation efficiency. The technology of the prototype was scaled up to a demonstration system using the 16% efficient solar cells from ASE to study the feasibility of an electrically self-powered residential heating system. This demonstrator achieved 164 W electrical power with a system efficiency of 0.82%.

The development of a Si MIS photocell specified for TPV applications is described in [7]. This TPV cell has a rear contact reflector, which reflects sub-bandgap radiation, for which the cell is transparent, back to the emitter. This approach enhances the system efficiency without the need for a filter. The high reflectance of about 93% for sub-bandgap radiation was obtained by a  $\text{SiO}_2$  passivated rear side and an evaporated aluminium mirror with point contacts. The front side was textured with rectangular grooves, in which vertical grid fingers were evaporated. To reduce free carrier absorption in the emitter, the doping was limited to the region under the grid fingers and to a sheet resistivity of  $50 \Omega/\text{square}$ . A series

resistance of only  $0.15 \Omega \text{ cm}^2$  was measured. The cell achieved a current density of  $1 \text{ A cm}^{-2}$  under concentrated light and a fill factor of about 62%. Unfortunately, no experiments of this special Si photocell in a TPV system have been published.

A second Si TPV cell is mentioned in [8]. In this work, however, the authors focused on the investigation of a heat coupling substrate for this cell. As an optimum solution, a direct bonded copper on aluminium oxide substrate is suggested.

Because Si solar cells are commercially available, their use for TPV offers a possible market launch of TPV in the short term. Nelson [9] has presented a propane-fired torchlight, which uses an  $\text{Yb}_2\text{O}_3$  emitter as a visible light source. A TPV top piece for the torch using Si solar cells produced a few watts of electricity to be used for various low-power applications. Recently published steps towards an electrically self-powered residential heating system are given in [10]. A flexible photocell module was developed by laminating small stripes of crystalline Si solar cells between aluminium and ethylvinylacetate (EVA) foil. This module allows a good heat coupling to the substrate and can easily be bent into a cylindrical shape for mounting it into a residential furnace housing. The electricity cost from a projected system using this new module and an  $\text{Yb}_2\text{O}_3$  mantle emitter were calculated in [11] to be  $0.19 \text{ Euro kWh}^{-1}$ . The cost perspective of an improved system is only  $0.06 \text{ Euro kWh}^{-1}$ .

In conclusion, Si photocells for TPV applications have only been studied marginally up to now. The highest reported system efficiency is 2.4%, but this system was kept quite simple without the use of a recuperator or a filter [6]. High efficiency solar cells, which were not specially adapted for TPV, were used. The development of special Si photocells for TPV has started, but up to now no systems have been presented using these cells. Probably the most interesting applications for Si-cell-based TPV are electrically autonomous gas heating systems. A system efficiency of about 1% is sufficient for this application and the Si solar cells promise a sufficient cost effectiveness.

#### 4. Germanium photocells

The bandgap of Ge of 0.66 eV is located close to the radiation maximum of a blackbody with a temperature of 1600 K. Therefore, Ge seems suitable to convert the radiation of a broadband TPV emitter with a temperature below 1800 K. Furthermore,  $\text{Er}_2\text{O}_3$  is a selective emitting material matched well with the bandgap of Ge [1]. The convertible radiation power is about a factor of 2 higher for the  $\text{Er}_2\text{O}_3$  emitter/Ge photocell combination compared to  $\text{Yb}_2\text{O}_3$  emitter/Si photocell (see [1]).

Ge photocells have been intensively investigated for their use as infrared sensitive bottom cells in tandem or triple junction solar cells [12]. Venkatasubramanian *et al* [13] have reported an efficiency of 6.4% under solar AM0 irradiation of epitaxially grown Ge single junction solar cells. For the fabrication of tandem cells, Ge has the two advantages that GaAs can be grown epitaxially on Ge substrates without lattice mismatch and the bandgaps of Ge and GaAs allow a good current match to the AM0 spectrum for space applications [14].

Single junction Ge photocells were proposed for TPV applications at the beginning of the TPV development [15]. For a Ge photocell, Kittl *et al* [16] have reported an efficiency of 6.7% for  $\text{Er}_2\text{O}_3$  emission with an incident radiation density of  $22 \text{ W cm}^{-2}$ . Recent developments of Ge TPV photocells have been published in [12, 17–19]. The emitter was Zn-diffused to form the pn-junction in an n-doped Ge substrate [18]. These cells reached a high external quantum efficiency of 0.9–0.95 up to 1500 nm wavelength [17, 18]. The front side was passivated with a  $0.1 \mu\text{m}$  thin GaAs layer, which was grown by liquid phase epitaxy [17]. To obtain a spectral match between the emitter and photocell in a TPV system, a rear surface mirror was developed for the Ge cell. The mirror consists of an Au or Ag layer forming point contacts through an  $\text{MgF}_2$  film on the rear surface of the cells. A reflectance of 82–87% for sub-bandgap radiation was measured [12, 17]. The cells achieved an efficiency of 13% under AM0 irradiation with a cut-off for wavelengths shorter than 900 nm [19]. Andreev [12] calculated an efficiency of 16% for these cells by blackbody illumination with a cut-off for wavelength larger than 1820 nm. The efficiency is lower than that of GaSb photocells with a bandgap of 0.72 eV, but due to a lower free carrier absorption in the Ge, the reflectance for sub-bandgap radiation is higher for Ge cells than for GaSb cells [18]. Thus, the spectral match with a rear surface reflector in a TPV system is more effective when Ge photocells are used.

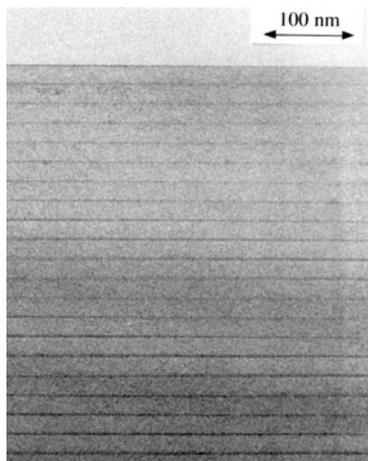
Another benefit of Ge cells compared to low bandgap III/V materials, such as GaSb, is their lower cost. Ge TPV cells are made on substrates, which are cheaper than GaSb by a factor of 6 to 7 [20]. In [20, 21] Ge cells were manufactured without the GaSb passivating front side, but their external quantum efficiency and open circuit voltage are lower than those of direct bandgap III/V cells with a comparable bandgap. Furthermore, the temperature coefficient of Ge cells is higher than that of GaSb or InGaAsSb [20, 21], which results in a stronger reduction of open circuit voltage and fill factor with increasing cell temperature.

Optical grade polycrystalline Ge, which is comparable in cost with monocrystalline Si, was used in [22, 23] as an epitaxy substrate for the growth of GaAs photocells. Cell efficiencies of 19% for a  $4 \text{ cm}^2$  cell and 21% for a  $0.25 \text{ cm}^2$  cell were achieved under AM1.5 spectrum [23]. The use of this material as an electrically active base has not yet been investigated.

#### 5. Si/Ge photocells

SiGe alloys allow a change of the bandgap by varying the Ge content. For a perfect spectral match of a photocell to a given TPV emitter, SiGe seems to be a promising material. Due to the higher mobility of electrons in SiGe compared to pure Si, SiGe structures are applied for high-frequency devices in large-scale production. So, various epitaxial techniques for the fabrication of SiGe devices are widely available. Only a few recently published works have investigated SiGe as a photocell material.

In [13], a  $\text{Si}_{0.07}\text{Ge}_{0.93}$  cell was epitaxially grown on to a Ge substrate. This cell was developed as a bottom cell for a tandem space solar cell, with a bandgap that is located at the optimum photon energy to convert the AM0 radiation



**Figure 1.** SiGe layers embedded between Si spacers. The  $\text{Si}_{0.75}\text{Ge}_{0.25}$  wells have a thickness of 3 nm.

spectrum. This cell achieved only a lower efficiency and open circuit voltage compared to a Ge reference, probably due to defects at the Ge/SiGe interface.

Raue *et al* [24] have described the fabrication of crystalline SiGe photocells. Polycrystalline SiGe ingots were grown. These were cut into wafers and the pn-junction was formed by P-diffusion. The short circuit current of the SiGe cells was slightly increased compared to a Si reference, but the open circuit voltage was reduced by about 150 mV. The carrier diffusion length in the SiGe substrates was drastically smaller than in Si wafers.

Said *et al* [25] have investigated the implementation of a 10  $\mu\text{m}$  thick  $\text{Si}_{0.9}\text{Ge}_{0.1}$  layer, grown by liquid phase epitaxy (LPE) and chemical vapour deposition (CVD), in the base of a Si photocell. Due to the lattice mismatch between Si and SiGe, the SiGe relaxes and forms misfit dislocations. An attempt was made to bind these misfit dislocations in a highly doped SiGe buffer layer. A maximum cell efficiency of 11.3% was achieved with an increase of 2  $\text{mA cm}^{-2}$  in short circuit current compared to Si. However, the open circuit voltage of the SiGe cell was below 560 mV.

Thick SiGe layers can be grown epitaxially on a virtual substrate on Si [26]. A virtual substrate consists of a SiGe layer with linearly grading Ge concentration forming a strain-relaxed substrate for the pseudomorphic growth of SiGe structures. Virtual SiGe substrates have been investigated for the development of fast field-effect transistors but, so far, there have been no reports of SiGe photocells grown on to virtual substrates.

Another way to avoid dislocations in SiGe layers grown on to Si is the growth of strained layers with thickness lower than the critical layer thickness [27]. In this way, stacks of thin SiGe layers embedded between Si spacers can be grown epitaxially. In [28] such stacks with a layer thickness of 3–5 nm and various Ge contents were grown using an ultra-high vacuum (UHV) CVD technique. Figure 1 shows a typical structure. It can be shown that, by increasing the layer thickness slightly above the critical thickness, the strain due to the different lattice constants in Si and SiGe results in a wave-like shape of the layers without forming dislocations.

The total thickness of such SiGe stacks is typically much below 1  $\mu\text{m}$  depending on the Ge content. The absorption

of light with photon energy close to the bandgap in such thin layers of indirect semiconductors is too weak to be used for electricity conversion in photocells. To investigate the influence of quantum confinement effects on the absorption coefficient in thin SiGe layers, Palfinger *et al* [29] measured the transmittance spectra of SiGe quantum well structures. They found a strong increased absorption coefficient in SiGe quantum wells compared to Si, but no evidence of an additional increase in absorption due to spatial confinement was observed. The absorption coefficient below the Si bandgap at 1.05 eV seems to be about one order of magnitude too low to extend the quantum efficiency of Si photocells to lower photon energies for TPV applications by using SiGe quantum well structures.

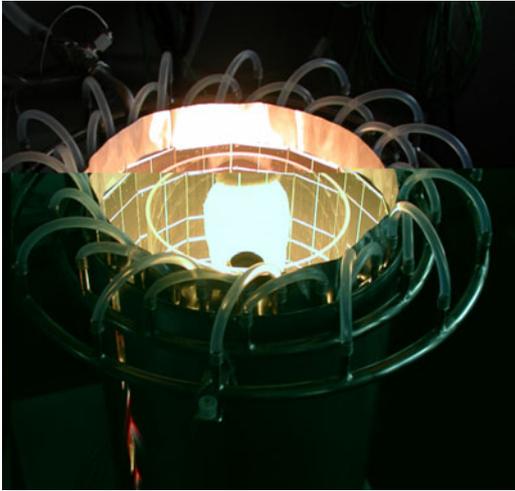
A higher degree of spatial confinement is expected in Ge quantum dots. When Ge is grown on to Si thicker than the critical thickness, Ge forms islands on the Si surface. These islands can be overgrown with Si to produce a stack with island layers embedded into Si. In [30] molecular beam epitaxy (MBE) was used to grow Ge quantum dot stacks for use in infrared sensitive photocells. To obtain dots with a high density of  $1.8 \times 10^{11} \text{ cm}^{-2}$ , their segregation and mobility during growth was suppressed due to an initial deposition of one monolayer of Sb. By incorporating this quantum dot structure into the space-charge region of a pn-photocell, the first Ge quantum dot solar cell was fabricated [30, 31]. This cell achieved a small increase in short circuit current of less than 1  $\text{mA cm}^{-2}$  compared to Si and the onset in photocurrent was shifted from 1.18 eV for Si to 1.10 eV due to the Ge dots. But the cell suffers from a decrease in the open circuit voltage of about 90 mV and a loss in fill factor. A comparison of photoluminescence (PL) with photocurrent (PC) measurements shows an energy difference between the PL and the PC peak of about 90 meV [31]. This indicates that the ground state in the quantum dots does not contribute to the current of the cell. The open circuit voltage, on the other hand, is determined by the ground state energy. Therefore, the efficiency of the SiGe cell is only 12% compared to that of Si (15.5%) [31].

The approach of using nanostructures in TPV photocells is more advanced for III/V materials than for SiGe. Abott *et al* [32] have presented a photocell structure containing strain-compensated InGaAs quantum wells with 62% and 47% In concentrations, which can be grown without the creation of dislocations on an InP substrate. With these cells, the quantum efficiency can be extended to 1800 nm compared to 1650 nm, which was achieved for lattice-matched bulk InGaAs. This matches the bandgap of the quantum well cell to the radiation spectrum of a selective thulium emitter.

## 6. TPV systems

Considering the large-scale availability of Si photocells, surprisingly, most of the TPV systems built to date are based on GaSb photocells.

A portable TPV electricity generator using an  $\text{Yb}_2\text{O}_3$  emitter and Si photocells has been described in [4]. The system efficiency is enhanced by a recuperator achieving a very high emitter temperature of more than 2000 K. No measurements of the  $\text{NO}_x$  emission have been published. Electrical output



**Figure 2.** TPV demonstration system. Light from the central  $\text{Yb}_2\text{O}_3$  emitter is reflected in a surrounding quartz tube. The Si photocells are glued on to water-cooled metal blocks.

power of 90 W corresponding to 1.6% system efficiency has been measured.

Probably the most promising application for TPV with Si photocells is their use in residential heating systems. When the TPV system is used for an electrically self-powered operation of the heater, a high system efficiency is not necessary. More important are the low costs of the TPV cells and the use of harmless materials to provide high security in case of a system malfunction; when the cells are strongly heated by the combustion flame, no toxic gases are emitted. Both requirements are fulfilled by Si photocells.

In [33] a gas-fired room heater with a TPV system working with Si photocells was proposed. Kushch *et al* [3] have described the practical realization of a Si TPV powered heater/hot-water boiler. The system includes the complete heater unit with burner/emitter, concentrator Si photocells, heat exchanger, cooling system, boiler, ignition system and electronics. The operation can be successfully demonstrated producing nearly 200 W electrical power with a system efficiency of about 0.8%. Another approach for a TPV residential heating system has been shown in [10]. This system was kept as simple as possible and was achieved by using solar cells with an AM1.5 efficiency of 16%, and 164 W electrical power corresponding to a system efficiency of 0.8%. The first steps towards the incorporation of this system into a residential gas-fired heating system are given in [6]. A photograph of this system during burning is shown in figure 2.

A small-scale Si TPV system, which consists of a gas-fired torch with an  $\text{Yb}_2\text{O}_3$  emitter and a small Si photocell module that can be pinned on top of it, is described in [9]. This tiny TPV generator produced 3–5 W electrical power.

Small prototype systems with Si photocells are described in [34, 35]. These prototypes operate with a portable butane burner and achieve up to 2.4% system efficiency working without a filter or a recuperator. Simulations show that with a perfect filter the system efficiency can be enhanced up to 6.9% and with a recuperator up to 7.6% at 1300 K temperature of the gas/air mixture [6].

So far, the efficiency of Ge photocells has been too low, so that no investigations on Ge-cell-based TPV systems have been published. SiGe photocells are still in the early research stage.

## 7. Conclusion

Si solar cells are commercially available and it can be successfully demonstrated that they are suitable for TPV applications, when a system efficiency of 1–2% is sufficient [10, 11, 34, 35]. For this, the most promising application is an electrically self-powered residential heating system. The crucial requirements for the TPV generator are cost-effectiveness and compatibility with commercial heating boiler technology, whereas the design of the TPV system can be kept quite simple. Si photocells probably are optimally suited for these systems. Currently, the first TPV residential gas heating systems working with Si photocells are being built and tested. They have the potential to be the first widespread commercial TPV product.

The development of Si photocells optimized for TPV applications is in an early stage. These cells may help to increase the system efficiency of TPV heating systems in the future.

Whether Ge photocells will ever be applied in TPV systems remains doubtful. Their efficiency remains lower compared to low bandgap III/V materials such as GaSb. Today, Ge cells are cheaper than GaSb cells by a factor of 6 to 7, but this difference may change when GaSb cells are manufactured on a larger scale.

SiGe photocells, in particular cells with SiGe nanostructures such as quantum wells and quantum dots, are the object of intensive research. At present, we cannot predict whether these structures can be applied for TPV cells as well as for solar cells in the future.

Finally, it should be pointed out that the radiation power density of an  $\text{Yb}_2\text{O}_3$  emitter for illuminating Si TPV cells is limited, because of a maximum technically relevant temperature of about 1800 K. The main reason for this temperature limit is the emission of  $\text{NO}_x$  from a gas/air combustion, which increases with combustion temperature. Law regulates the maximum permissible  $\text{NO}_x$  emission. If either cheap  $\text{NO}_x$  reduction methods become available or solar  $\text{H}_2/\text{O}_2$  are used as combustion fuels, the emitter temperature will no longer be limited on that score. For an emitter temperature between 2500 and 3000 K, the radiation power density of an  $\text{Yb}_2\text{O}_3$  emitter reaches its maximum value increasing the benefit of using Si photocells for TPV. A limiting factor is certainly the thermal stability of critical components, but because of the high melting point of  $\text{Yb}_2\text{O}_3$  of 2708 K, in principle, this temperature range can be achieved. In an almost perfect system with a system efficiency close to the photocell efficiency, the  $\text{H}_2/\text{O}_2$ -Si-TPV may compete with fuel cells in the distant future.

## Acknowledgments

The author thanks his colleagues W Durisch, G Palfinger, D Grützmaier and J Gobrecht for many helpful discussions, E Müller for the TEM micrograph and V M Andreev (Ioffe

Institute, Russia) for providing information about Ge TPV photocells.

## References

- [1] Bitnar B, Durisch W, Mayor J-C, Sigg H and Tschudi H R 2002 Characterisation of rare earth selective emitters for thermophotovoltaic applications *Sol. Energy Mater. Sol. Cells* **73** 221–34
- [2] Bitnar B, Durisch W, Grützmaier D, Mayor J-C, von Roth F, Anna Selvan J A, Sigg H, Tschudi H R and Gobrecht J 2000 A TPV system with Si photocells and a selective emitter *Proc. 28th IEEE Photovoltaic Spec. Conf. 2000* (Piscataway, NJ: IEEE) pp 1218–21
- [3] Kushch A S, Skinner S M, Brennan R and Sarmiento P A 1997 Development of a cogenerating thermophotovoltaic powered combination hot water heater/hydronic boiler *Thermophotovoltaic Generation of Electricity: 3rd NREL Conf. (AIP Conf. Proc. 401)* ed T J Coutts, J P Allman and C S Benner (New York: AIP) pp 373–86
- [4] Becker F E, Doyle E F and Shukla K 1998 Operating experience of a portable thermophotovoltaic power supply *Thermophotovoltaic Generation of Electricity: 4th NREL Conf. (AIP Conf. Proc. 460)* ed T J Coutts, C S Benner and J P Allman (New York: AIP) pp 394–402
- [5] Durisch W, Grob B, Mayor J-C, Panitz J-C and Rosselet A 1998 Interfacing a small thermophotovoltaic generator to the grid *Thermophotovoltaic Generation of Electricity: 4th NREL Conf. (AIP Conf. Proc. 460)* ed T J Coutts, C S Benner and J P Allman (New York: AIP) pp 403–14
- [6] Bitnar B, Durisch W, Mayor J-C, Palfinger G, Sigg H, Grützmaier D and Gobrecht J 2002 Record electricity-to-gas-power efficiency of a Si solar cell based TPV system *Proc. 29th IEEE Photovoltaic Spec. Conf. 2002* (Piscataway, NJ: IEEE) pp 880–3
- [7] Hampe C, Metz A and Hetzel R 2002 Innovative Si-concentrator solar cell for thermophotovoltaic application *Proc. 17th Europ. Photov. Solar Energy Conf. and Exh. 2001* ed B McNelis, W Palz, H A Ossenbrink and P Helm (WIP Munich, ETA Florence) pp 18–23
- [8] Gordon R, Stone K and Garboushian V 2002 Design considerations for the development of a highly reliable densely packed photovoltaic array for TPV applications *Proc. 29th IEEE Photovoltaic Spec. Conf. 2002* (Piscataway, NJ: IEEE) pp 947–50
- [9] Nelson R E 2003 TPV systems and state-of-the-art development *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 3–7
- [10] Bitnar B, Durisch W, Meyer A and Palfinger G 2003 New flexible photocell module for thermophotovoltaic applications *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 465–72
- [11] Palfinger G, Bitnar B, Durisch W, Mayor J-C, Grützmaier D and Gobrecht J 2003 Cost estimates of electricity from a TPV residential heating system *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 29–37
- [12] Andreev V M 2003 An overview of TPV cell technologies *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 289–304
- [13] Venkatasubramanian R, Timmons M L, Pickett R T, Colpitts T S, Hills J S and Hutchby J A 1990 Development of low-bandgap Ge and SiGe solar cells for monolithic and mechanically-stacked cascade applications *Proc. 21st IEEE Photovoltaic Spec. Conf. 1990* (Piscataway, NJ: IEEE) pp 73–8
- [14] Tobin S P, Vernon S M, Bajgar C, Haven V E, Geoffroy L M, Sanfacon M M, Lillington D R, Hart R E, Emery K A and Matson R J 1988 High efficiency GaAs/Ge monolithic tandem solar cells *Proc. 20th IEEE Photovoltaic Spec. Conf. 1988* (Piscataway, NJ: IEEE) pp 405–10
- [15] Wedlock B D and Siegel R 1972 Investigation of p-i-n germanium diodes for TPV conversions *Proc. 25th Power Sources Symp. 1972* pp 182–6
- [16] Kittl E, Lammert M D and Schwartz R J 1975 Performance of germanium pin-photovoltaic cells at high incident radiation intensity *Proc. 11th IEEE Photovoltaic Spec. Conf. 1975* pp 424–30
- [17] Andreev V M, Khvostikov V P, Khvostikova O A, Oliva E V, Rumyantsev V D and Shvarts M Z 2002 Thermophotovoltaic cells with sub-bandgap photon recirculation *Proc. 17th Europ. Photov. Solar Energy Conf. and Exh. 2001* ed B McNelis, W Palz, H A Ossenbrink and P Helm (WIP Munich, ETA Florence) pp 219–22
- [18] Khvostikov V P, Khvostikova O A, Oliva E V, Rumyantsev V D, Shvarts M Z, Tabarov T S and Andreev V M 2002 Zinc-diffused InAsSbP/InAs and Ge TPV cells *Proc. 29th IEEE Photovoltaic Spec. Conf. 2002* (Piscataway, NJ: IEEE) pp 943–6
- [19] Andreev V M, Khvostikov V P, Khvostikova O A and Oliva E V 2003 Low band gap Ge and InAsSbP/InAs-based TPV cells *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 383–91
- [20] Sulima O V, Bett A W, Dutta P S, Mauk M G and Mueller R L 2002 GaSb-, InGaAsSb-, InGaSb-, InAsSbP- and Ge-TPV cells with diffused emitters *Proc. 29th IEEE Photovoltaic Spec. Conf. 2002* (Piscataway, NJ: IEEE) pp 892–5
- [21] Sulima O V, Bett A W, Mauk M G, Dimroth F, Dutta P S and Mueller R L 2003 GaSb-, InGaAsSb-, InGaSb, InAsSbP- and Ge-TPV cells for low-temperature TPV applications *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 434–41
- [22] Venkatasubramanian R, Malta D P, Timmons M L, Posthill J B, Hutchby J A, Ahrenkiel R, Keyes B and Wangenstein T 1994 Material and device characterization towards high-efficiency GaAs solar cells on optical-grade polycrystalline Ge substrates *Proc. 1st World Conf. on Photovoltaic Energy Conv. 1994* (Piscataway, NJ: IEEE) pp 1692–6
- [23] Venkatasubramanian R, Siivola E, O'Quinn B, Keyes B and Ahrenkiel R 1997 Pathways to high-efficiency GaAs solar cells on low-cost substrates *1st NREL Conf. on Future Generation of Photovoltaic Technologies (AIP Conf. Proc. 404)* ed R D McConnell (New York: AIP) pp 411–8
- [24] Raue P, Lawrenz A, Long L, Rinio M, Buhrig E and Möller H J 1997 Multicrystalline SiGe alloys for solar cell applications *Proc. 14th European Photovoltaic Solar Energy Conf. 1997* pp 1791–4
- [25] Said K, Poortmans J, Caymax M, Nijs J, Silier I, Gutjahr A, Konuma M, Debarge L, Christoffel E and Slaoui A 1998 Detailed analysis of the factors influencing the efficiency of thin-film crystalline SiGe solar cells *Proc. 2nd World Conf. on Photovoltaic Energy Conv. 1998* ed J Schmid, H A Ossenbrink, P Helm, H Ehmann and E D Dunlop (European Commission) pp 36–41
- [26] Seng H L, Osipowicz T, Sum T C, Tok E S, Breton G, Woods N J and Zhang J 2002 Probing the SiGe virtual substrate by high-resolution channeling contrast microscopy *Appl. Phys. Lett.* **80** 2940–2
- [27] People R and Bean J C Calculation of critical layer thickness versus lattice mismatch for  $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$  strained-layer

- heterostructures *Appl. Phys. Lett.* **47** 322–4  
People R and Bean J C *Appl. Phys. Lett.* **49** 229
- [28] Bitnar B, Palfinger G, Durisch W, Mayor J-C, Grützmacher D, Sigg H and Gobrecht J 2002 Simulation- and demonstration model of a high efficiency thermophotovoltaic system *Proc. 14th Quantsol Workshop 2002* ed L DeCola, C Königstein and D Vanmaekelbergh (*Europ. Soc. for Quantum Solar Energy Conv.*) pp 69–70
- [29] Palfinger G, Bitnar B, Sigg H, Müller E, Stutz S and Grützmacher D 2003 Absorption measurement of strained SiGe nanostructures deposited by UHV-CVD *Physica E* at press
- [30] Konle J, Presting H, Kibbel H and Banhart F 2002 Growth studies of Ge-islands for enhanced performance of thin film solar cells *Mater. Sci. Eng. B* **89** 160–5
- [31] Konle J, Presting H and Kibbel H 2003 Self-assembled Ge-islands for photovoltaic applications *Physica E* at press
- [32] Abbott P, Rohr C, Connolly J P, Ballard J, Barnham K W J, Ginige R, Corbett B, Clarke G, Bland S W and Mazzer M 2002 A comparative study of bulk InGaAs and InGaAs/InGaAs strain-compensated quantum well cells for thermophotovoltaic applications *Proc. 29th IEEE Photovoltaic Spec. Conf. 2002* (Piscataway, NJ: IEEE) pp 1058–61
- [33] Nelson R E 1995 Grid-independent residential power systems *Thermophotovoltaic Generation of Electricity: 2nd NREL Conf. (AIP Conf. Proc. 358)* ed J P Benner, T J Coutts and T J Ginley (New York: AIP) pp 221–37
- [34] Bitnar B, Mayor J-C, Durisch W, Meyer A, Palfinger G, von Roth F and Sigg H 2003 Record electricity-to-gas power efficiency of a Si solar cell based TPV system *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 18–28
- [35] Durisch W, Bitnar B, von Roth F and Palfinger G 2003 Small thermophotovoltaic prototype systems *Thermophotovoltaic Generation of Electricity: 5th Conf. on Thermophotovoltaic Generation of Electricity (AIP Conf. Proc. 653)* ed T J Coutts, G Guazzoni and J Luther (New York: AIP) pp 71–8