SIMULATION- AND DEMONSTRATION MODEL OF A HIGH EFFICIENCY THERMOPHOTOVOLTAIC SYSTEM

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Thermophotovoltaics (TPV) is a technique to convert heat into electricity by the use of a radiation emitter and photocells. The main difficulty in the development of a TPV system is matching the radiation spectrum of the emitter to the quantum efficiency of the photocells. We focus on the combination of selective rare earth oxide emitters with Si or SiGe photocells.

A small TPV prototype system was built, working with an Yb_2O_3 selective emitter and high efficiency Si solar cells from University of New South Wales (UNSW), which is shown in Fig.1. A detailed study of selective Yb_2O_3 and Er_2O_3 emitters is presented in [1]. Technical details about the prototype system are given in [2]. This system produced 48 W electrical power P_{el} with 2 kW thermal input power P_{th}. The ratio of electricity output to heat input η was 2.4 %, a record value for Si TPV systems.

Fig. 1: *TPV prototype system. A selective Yb_2O_3 emitter, heated by a butane burner, illuminates high efficiency Si solar cells. The upper reflector is removed.*

To study this system in detail, a simulation model was developed [3]. Fig. 2 shows the cylindrically symmetric model schematically. It includes the relevant components: emitter, filter, photocells and axial reflectors, whose measured optical spectra are used as input parameters for the simulation. The balance of the energy fluxes Q_i is calculated numerically. Together with a combustion model, P_{el} can be calculated as a function of P_{th}.

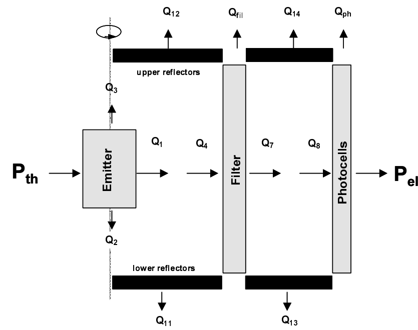

Fig. 2: *System model, for details see text.*

Table 1 gives the result of the simulation of the prototype system. The good agreement with the experimental data better 3 % demonstrates the high quality of the model.

	P_{th} [kW]	T_{em} [K]	P_{el} [W]	η [%]
sim	1.96	1777	47	2.4
exp	1.96	-	48	2.4

Table 1: *Results of simulation (sim) and experiment (exp). T_{em} is the calculated emitter temperature.*

Table 2 gives the result of a simulation series to study the influences of several system components on P_{el} and η. P_{th} = 1.85 kW was used for all calculations. Removing the upper axial reflector reduces P_{el} by 20%. The exchange of the UNSW photocell generator for an ASE photocell generator, which consists of cheaper monocrystalline solar cells with an efficiency $\eta_{AM1.5}$ of 16 %, achieves 29 W electrical power, which was experimentally proven, as well. The replacement of the quartz filter by an infrared (IR) reflective ZnO or SnO_2 filter, which is still under development, should increase P_{el} by around 10 %, because a higher T_{em} could be achieved due to the back-reflected IR radiation. A perfect filter (transmittance 100 % for convertible and reflectance 100 % for the remaining radiation) gives η = 7 % as an upper limit for the prototype system.

Another possibility to increase η is preheating the combustion air with heat from the exhaust gas by using a recuperator. Fig. 3 shows η and P_{el} as a function of the gas/air mixture temperature T_{in}, calculated with our model. With this technique, η could exceed 5 %, as well.

G	R	Filter	T_{em} [K]	P_{el} [W]	η [%]
UNSW	yes	quartz	1759	43	2.3
UNSW	no	quartz	1746	35	1.9
ASE	yes	quartz	1756	29	1.6
UNSW	yes	ZnO	1791	45	2.4
UNSW	yes	SnO_2	1787	47	2.5
UNSW	yes	perfect	1934	130	7.0

Table 2: *Simulation series of the prototype system demonstrating the influences of the upper reflector (R), the photocell generator (G) and infrared reflecting filters on* P_{el}. P_{th} *= 1.85 kW was used for all calculations.*

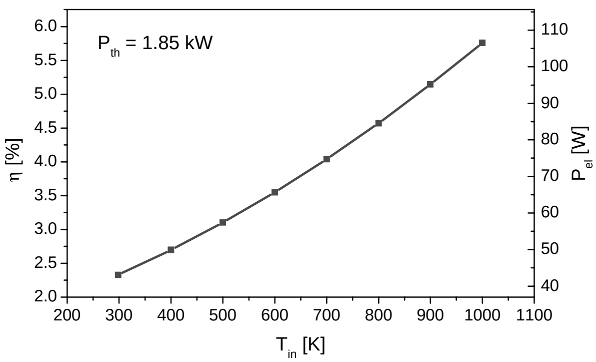

Fig. 3: *P_{el} and η of the modelled prototype system as a function of the temperature T_{in} of the gas/air mixture.*

The radiation power of a selective emitter increases, if the emission band is located closer to the radiation maximum of a blackbody with the corresponding temperature. For T_{em} < 2000 K Er_2O_3 is a suitable emitter material with an emission band at 1500 nm wavelength matched to the quantum efficiency of a photocell with a bandgap of < 0.8 eV. As an alternative to the often studied GaSb photocells [4], which are still very expensive and contain the toxic element Sb, we suggest the use of thin SiGe structures grown onto Si to extend the quantum efficiency of Si photocells far enough into the IR.

Using an UHV-CVD batch reactor we grew SiGe layer stacks on Si with various thickness and Ge content. Reaction gases were SiH_4, GeH_4 and B_2H_6 for growing p-doped layers. The samples were characterised using TEM and X-ray diffractometry to determine the quality of epitaxial growth, layer thickness and Ge content. The growth rates depend strongly on the Ge content. We found growth rates from 0.1 nm/min for Si to 1.4 nm/min for $Si_{0.7}Ge_{0.3}$ at a growth temperature of 550°C and a process pressure of $5*10^{-3}$ mbar.

Fig. 4 shows TEM photographs of two structures: a stack of 30 quantum wells (left) and a wavelike structure of thicker layers (right). The thin wells grew strained on the Si lattice, whereas the thicker layers form a wavelike structure to relieve its strain.

For the implementation of SiGe layers in TPV photocells, their absorption for IR radiation has to be determined. It is assumed, that in thin structures the absorption coefficient could be higher compared to bulk material due to quantum confinement effects. For the measurement of the absorption in thin SiGe structures, a design was developed, which uses multiple internal reflection of a light beam in the sample. As an early result, we found an absorption in the right structure in Fig. 4 starting at 1450 nm.

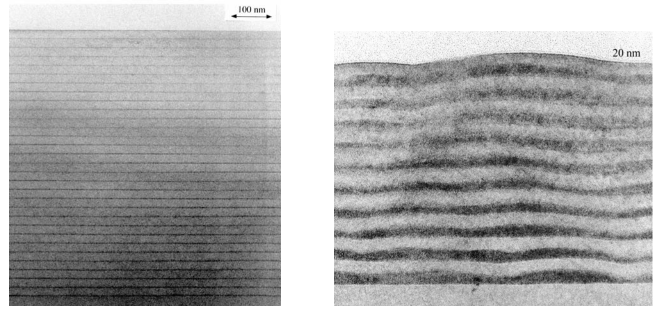

Fig.4: *TEM pictures of SiGe structures: 30 $Si_{0.75}Ge_{0.25}$ quantum wells with 3 nm thickness (left) and 10 $Si_{0.65}Ge_{0.35}$ layers with 5 nm thickness (right).*

An application for TPV is its integration into domestic boilers to generate the electrical power necessary for the operation of the boiler. In rural/mountainous regions TPV boilers might guarantee a very high heat supply security. Looking towards this application, a larger TPV demonstration system was built, based on a 20 kW methane burner. During laboratory tests, the demonstration system achieved 121 W electrical power at 12 kW thermal power, enough to run a boiler independently of the electricity grid. This system was mounted into a commercial domestic heating boiler from HOVAL AG, Vaduz (FL). For the near future, extensive tests of the complete system are planned. A detailed description of the system together with cost estimations for the electricity generated with this boiler, are given in [5].

REFERENCES

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