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Cost-efficient thermophotovoltaic cells based on germanium substrates

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ABSTRACT

This paper describes the realisation of cost-efficient thermophotovoltaic (TPV) cells based on germanium substrates. Because the majority of the photons incident on the TPV cell in a typical TPV system will have a long wavelength it is important to apply optical confinement in the TPV cell. In this paper this has been done by using a highly reflective rear contact. Electrical contact at the rear has been created with a laser (laser fired contact, LFC) such that the metal is locally heated and contact is formed.

The optimal TPV cell is based on a low doped (1×10^{15} cm^{-3}) *p*-type germanium substrate having a 500 nm thick *n*-type emitter (1×10^{19} cm^{-3}), where front and rear are both passivated with hydrogen rich PECVD amorphous silicon. An AM1.5G record efficiency has been measured for a germanium TPV cell with an LFC rear contact. The application of optical confinement leads to a clear improvement of the spectral response in the wavelength region which is dominant in TPV systems and results in a potential 20% increase of current density compared to the use of a classical germanium photovoltaic cell.

1. Introduction

In photovoltaic energy conversion systems electric energy is directly generated out of photons that are absorbed by the photovoltaic cell. In classical photovoltaic systems these photons originate from the sun, but also other photon sources can be used. Another possibility is the use of photons emitted by a heat source as used in combustion systems in industry or in residential heating systems. Since these photons originate from a thermal source this type of photovoltaic energy conversion is called *thermophotovoltaic energy conversion* in which thermophotovoltaic is mostly abbreviated as TPV.

A thermophotovoltaic system basically consists of three different parts. A schematic TPV system is given in Fig. 1. From left to right the *heat source*, which can be a flame in an industrial system or a residential heating system heats up a *selective emitter*. This selective emitter radiates photons in a relatively narrow wavelength band. The emitted photons will directly be absorbed by the *thermophotovoltaic cells*, which have a bandgap well matched to the emitter's peak wavelength, from which electricity can be extracted. In order to prevent the receiver cells from heating up by sub-bandgap photons, a filter can be placed between the selective emitter and the cells.

An important aspect in TPV research is the reduction of cost. This paper describes the development of a low-cost low-bandgap TPV cell where the low-cost aspect will be achieved in two ways. First of all the TPV cell is fabricated on a germanium substrate, since germanium is a low-bandgap ($E_g = 0.66$ eV) semiconductor having a relatively low cost. Second, the germanium TPV cells are fabricated using low-cost processing techniques that can be implemented in industrial processes.

In order to compare TPV to PV systems, in Fig. 2 the spectrum emitted by the sun (the AM1.5G spectrum) is given together with the spectrum emitted by a typical selective emitter in TPV systems, Er_2O_3 [6]. When studying these two characteristics in more detail, it can be seen that there are two major differences which can directly be attributed to the differences in the system. First of all, the spectrum emitted by the Er_2O_3 selective emitter has a much higher intensity compared to the AM1.5G spectrum. This is due to the relative small distance between the heat source and the TPV cell in the TPV system compared to the distance to the sun in a PV system. The difference in temperature of the photon source in the TPV and PV systems, which are about 1680 and 6000 K, respectively, explains the second difference: the shift to long wavelength of the emitted photons in a TPV system.

These two main differences in system architecture have several consequences on cell level. Compared to the classical germanium cells for PV applications, the requirements for a rear contact in a TPV cell are somewhat different. Where the high generated current requires an excellent ohmic contact with a low contact resistance [3,4], the long wavelength together with the high absorption depth in germanium requires an excellent rear surface passivation together with a high reflectance.

In this paper the development of a TPV cell based on a germanium substrate will be discussed. First a theoretical derivation of the maximum achievable open circuit voltage of a

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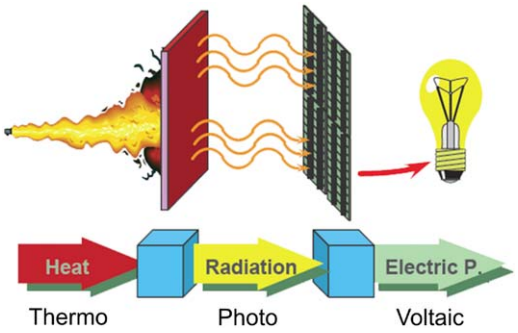

Fig. 1. Schematic representation of thermophotovoltaic energy conversion. Courtesy: Kassel University.

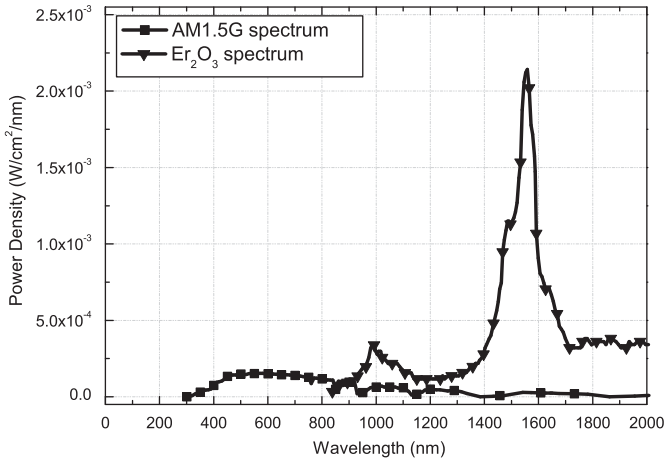

Fig. 2. Emitted power density as a function of the wavelength of a Er_2O_3 selective emitter, heated by a butane burner at 1680 K (triangles), compared with the standard solar spectrum (AM1.5G, squares).

germanium cell in TPV application is given. Furthermore the development of a highly reflective rear contact structure will be discussed followed by a detailed description of the cell processing. The paper will be finished by formulating some conclusions.

2. Theoretical derivation of the maximum open circuit voltage of germanium TPV cells

In this section the maximum open circuit voltage will be calculated for a germanium TPV cell realised in a *p*-type substrate. Since Auger recombination is more important than radiative recombination in indirect semiconductors like germanium [2] only Auger recombination is taken into account in the calculation for the open circuit voltage. For the calculation, a substrate having an ideally doped emitter on one side is considered. A second assumption is that the influence of Shockley–Read–Hall (SRH) recombination in the cell is disregarded. Since high illumination densities are present in TPV systems, both cases of low injection and high injection can be distinguished.

2.1. Low injection

In case of low injection, where the minority carrier concentration is a lot lower than that of the majority carriers throughout the cell, the open circuit voltage is given by [2,8]

$$V_{oc} = \frac{kT}{q}\ln\left[\frac{J_{sc}}{qn_i^2\sqrt{D_eC_p}}\right] + \frac{kT}{q}\ln\left[\coth\frac{W_B}{L_B}\right] \quad (1)$$

where n_i is the intrinsic carrier concentration, D_e is the minority carrier diffusion constant, C_p is the Auger coefficient for *p*-type material, L_B is the minority carrier diffusion length in the base and W is the base thickness. The first term of Eq. (1) corresponds to the long base cell where $W > L_B$ such that $\ln[\coth(W_B/L_B)] = 0$. Under illumination with an Er_2O_3 selective emitter, assuming unit absorption, the maximum current density generated by a germanium cell is 709 mA/cm^2 which is comparable to the current generated in a germanium cell illuminated by AM1.5G light with concentration ratio of about 11 suns. Using the maximum value for J_{sc} together with the values given in Table 1, the maximum achievable V_{oc} can be calculated for a germanium cell as being equal to 357.5 mV.

In case of a short base cell, where $L_B > W_B$ such that $\coth W_B/L_B \approx L_B/W_B$, Eq. (1) can be written as

$$V_{oc} = \frac{kT}{q}\ln\left[\frac{J_{sc}}{qn_i^2C_pW_BN_B}\right] \quad (2)$$

Inserting the parameters given in Table 1 into Eq. (2) results in a V_{oc} of 529 mV.

Table 1
Overview of the typical material parameters of germanium.

Parameter	Value
Boltzmann's constant (k)	1.38×10^{-23} J/K
Elementary charge (q)	1.602×10^{-19} C
Temperature (T)	25 °C
Intrinsic carrier concentration (n_i)	2.33×10^{13} cm^{-3}
Auger coefficient, *n*-type, e-e-h (C_n)	2.2×10^{-30} cm^6/s
Auger coefficient, *p*-type, e-h-h (C_p)	5.4×10^{-31} cm^6/s
Maximum electron mobility (μ_e)	3895 cm^2/V s
Maximum hole mobility (μ_h)	2295 cm^2/V s
Optimal base doping level (N_B)	1×10^{15} cm^{-3}
Maximum bulk lifetime (τ_{bulk}, measured)	500 μs
Base thickness (W)	170 μs
Minority carrier lifetime, Auger limit low injection $\left[\tau_B = \frac{1}{C_pN_b^2}\right]$	1.85 s
Minority carrier diffusion constant(electrons) $\left[D_e = \mu_e\left(\frac{kT}{q}\right)\right]$	100.03 cm^2/s
Minority carrier diffusion length in base $[L_B = \sqrt{D\tau}]$	13.6 cm

2.2. High injection

In case of high injection, where $n = p$, J_{sc} and V_{oc} are given by

$$J_{sc} = qW(C_n + C_p)(n_i^2)^{3/2}\exp\left[\frac{3qV_{oc}}{2kT}\right] \quad (3)$$

$$V_{oc} = \frac{2}{3}\frac{kT}{q}\ln\left[\frac{J_{sc}}{qn_i^3(C_n + C_p)W}\right] \quad (4)$$

As there are now expressions for V_{oc} in the low and high injection regime, for the long and short base, it is possible to calculate the maximal value for the V_{oc} limited by Auger recombination as a function of the base doping for a germanium TPV cell illuminated by a Er_2O_3 selective emitter heated by a butane burner at 1680 K. In Fig. 3 the results of these calculations