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Miniaturized TEG with thermal generation of free carriers

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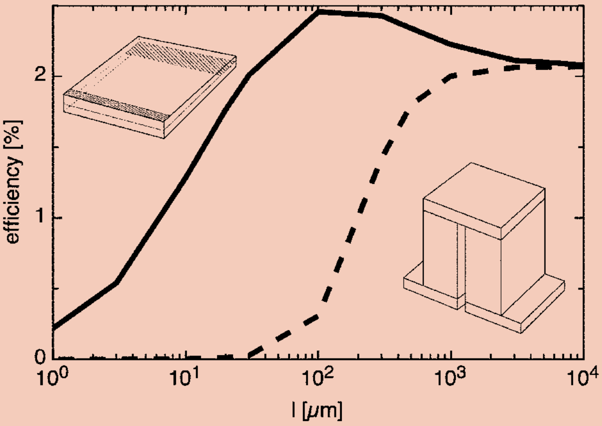
The rising interest in low temperature heat energy conversion encourages the application of thermoelectric devices. However, conventional thermoelectric devices used in the Seebeck mode as thermoelectric generators have several shortcomings and thus are inefficient when used as a generator. Additionally, the high cost–power ratio of these modules anticipates the commercial success on a broad basis. One way to achieve better suited products is provided by miniaturization of thermoelectric devices in order to enable the use of mass production methods. But in small devices the contact effects become dominant and reduce the efficiency and power density considerably. We show that using pn-junctions with thermal generation of free carriers offers the possibility to achieve better contact properties and thus higher efficiencies and power densities.



1 Introduction

Thermoelectric generator devices are a promising approach for direct energy conversion due to their outstanding reliability and low maintenance effort.

However, the poor efficiency of today's devices limits their application to niche markets and prevents an introduction in waste heat recovery applications on a large scale. Steadily increasing energy costs and upcoming environmental awareness in politics and economy are stimulations of increasing importance for further development and optimization.

Thermoelectric devices are usually built as devices with two legs made of semiconducting materials with opposing doping and connected by metallic contacts on the heated side. Electrically insulating ceramic layers provide thermal contacts with high thermal conductivity. The thermoelectric figure of merit, $Z_T = \alpha^2\sigma/\lambda$, is generally used to describe the material's suitability for thermoelectric energy conversion within a certain temperature range. The figure of merit is closely related to the conversion efficiency of the device, which describes the ratio between the generated electric power output and the ingoing heat flux $\eta = P_e/Q_{in}$.

2 Miniaturized devices

A key issue for economically profitable devices is a good exploitation of the material employed within the device. Thus, high power densities are favored and miniaturized devices become interesting candidates because of their promising low internal resistances due to their geometry.

However, as a consequence of the reduced internal resistances, the electrical and thermal contact properties become dominant and depict a limiting factor for the power

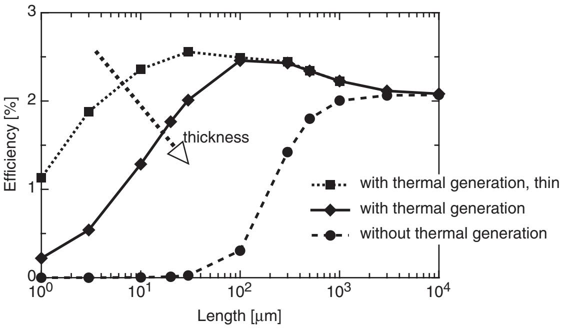


Figure 1 Influence of the device length on the efficiency with metallic contacts and contacts substituted by thermal generation.

density and efficiency. With small cross-sectional areas perpendicular to the temperature gradient, the contact resistances become more important and limit the overall resistance optimization induced by length reduction in the devices. Furthermore, with decreasing leg length the temperature drop shifts from the thermoelectrically active zone to the contact region resulting in a lower thermal yield [1, 2]. Within conventional thermoelectric generators, this behavior forces a tradeoff between reasonable efficiencies and high power densities in the competition region of the device. The efficiency drop with decreasing leg lengths is illustrated in Fig. 1, dashed line, for a simulated thermocouple.[1] The efficiency approaches very small values below a certain length because of the lower available temperature difference in the active region.

3 Hot side contacts by thermal generation

A promising approach to overcome these restrictions is the introduction of structures without hot side metallic contacts that need to be electrically insulated by a ceramic layer. The metallic contacts and the thermoelement are substituted by a large area pn-junction [4–8] perpendicular to the applied temperature gradient as sketched in Fig. 2. The electrical insulation can be provided using very thin oxide or enamel layers having appropriate thermal expansion coefficients. As a big advantage, the hot side temperature is not limited by any solder material. Such structures use the effect that in a reverse-biased pn-junction thermal generation of free carriers is responsible for an electric current in spite of the built-in potential step [9].

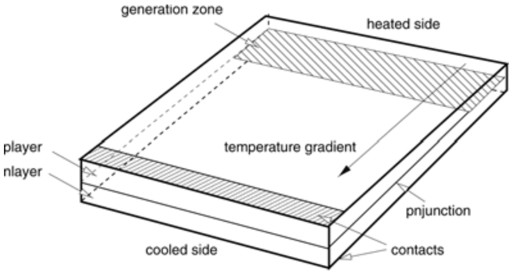


Figure 2 Large area pn-junction with applied temperature gradient. Thermal generation takes place on the heated side of the structure, both electric contacts are mounted on the cooled end.

A temperature gradient applied along the pn-junction drives the free carriers from the hot to the cold part of the structure. The resulting current alters the local carrier balance between generation and recombination and leads to enhanced generation of electron–hole pairs in the hot part as well as increased recombination in the cold part of the structure. Contacts at the cool end suppress this internal recombination in favor of an external current when connected to an appropriate load resistor. Hence, this device acts as a thermoelectric power source. A similar effect was proposed for enhancing the efficiency in solar cells due to thermal gradients [10]. In order to substitute a metallic contact, the reverse biased pn-junction at the hot side has to be able to transport the same electric current as the metal. Normally, pn-junctions are designed to block reverse currents, but deriving the thermal generation of free carriers within the pn-junction using the Shockley–Reed–Hall (SRH) model [9] shows that also the opposite effect, a very high conductivity, can be achieved. Because two Schottky contacts and their contact resistances can be avoided, the conductivity can even be increased. The thermal generation of an electric current I_g in semiconductor materials can be described in a wide range as

$$I_g \approx G = \frac{n_i}{\tau_g}, \tag{1}$$

where the generation rate G is a function of the intrinsic concentration n_i and the generation lifetime τ_g. n_i can be calculated using Eq. (2) with N_C and N_V as the effective densities of states for the conduction and valence bands, respectively, and the band gap E_g:

$$n_i = \sqrt{N_C N_V} \cdot e^{-\frac{E_g}{2kT}}. \tag{2}$$

The generation lifetime τ_g is modeled using Eq. (3) with the trap level E_T, and the intrinsic Fermi level E_i, the thermal velocity v_{th}, the electron/hole capture cross sections σ_0, and the trap density N_T. :

$$\tau_g = \frac{2\cosh\left(\frac{E_T - E_i}{kT}\right)}{v_{th}\sigma_0 N_T}. \tag{3}$$

The most effective generation centers have energy levels close to E_i.

τ_g is a function of both the temperature and the trap density. Since a higher trap density has the same effect on carrier lifetime as a higher temperature, it is possible to increase the generated current at given thermal circumstances by increasing the trap density, which is an easily modifiable parameter. Traps can be introduced by doping or by crystal defects. Doping materials introduce distinct levels, whereas

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[1] An extended version of the device simulator Minimos-NT was used for the simulations [3]. Because of its well established accurate model description, silicon was used as the base material in the simulations. The same basic device geometry was used for the simulations with and without implication of a thermal generation zone. The comparison shows the relative enhancement introduced by the thermal generation.

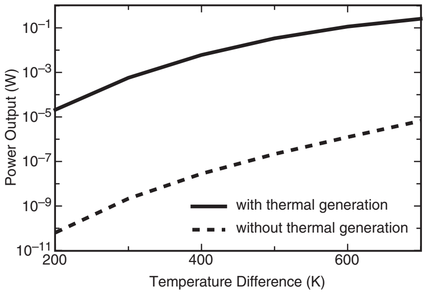

Figure 3 Comparison of power output of a simulated 20 µm long couple with and without thermal generation.

crystal defects cause a variety of levels all over the band gap and lower the generation lifetime considerably.

Since crystal defects are a good way to enhance the generation rate, it is of advantage to use manufacturing methods that produce only poor crystal quality, like sputtering. Measurements with sputtered samples made by Termo-Gen AB show a much higher current generation than in samples made by epitaxial methods.

4 Simulation results Figure 3 shows the effect of thermal generation and decreased thermal resistance of the contact region on the power output of a simulated thermocouple with a leg length of 20 µm as a function of the hot side temperature. The considered temperature range is adjusted to the band gap energy of silicon in order to activate the generation process. Several common materials for thermoelectric applications like lead chalcogenides or bismuth telluride have a smaller band gap and thus the generation process is already present at accordingly lower temperatures.

Especially at small temperature differences, several orders of magnitude more current is generated and the efficiency can be restored to values seen in long devices.

Figure 1 presents the different behavior with and without thermal generation of free carriers for similar geometries. With decreasing leg length, the efficiency of conventional devices can be held constant down to a certain length, where the contacts start to play a limiting role. Within that range, the power density increases. For shorter devices, the efficiency even increases in the simulated devices with thermal generation. The simulated devices consist of single crystal silicon and have a large minority carrier lifetime in the legs. Therefore an additional diffusion current can be seen in short simulated devices. Depending on the manufacturing method of devices the minority carrier lifetime will vary and the additional diffusion currents will be present at different leg lengths [11].

Additionally, the influence of the leg thickness on the efficiency is depicted by the dotted line. As expected, thinner structures have a lower temperature drop in the insulating layers and achieve higher efficiencies for very short devices.

Thermal generation also improves the specific power density as shown in Fig. 4 for short devices. While the specific power saturates or even shrinks for Peltier devices (dashed line in Fig. 4 and [2]), the improved properties allow to increase the specific power to noticable higher values.

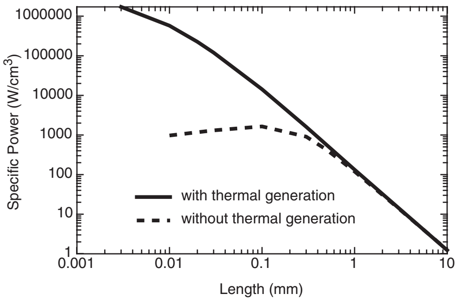

Figure 4 Estimated specific power for simulated devices with and without thermal generation at high temperature differences.

5 Conclusion Miniaturized thermoelectric generator devices based on thermoelements with metallic contacts and ceramic insulation layers experience a severe drop of the efficiency and power density when thermal and electrical contact properties can no longer be neglected. Because of this, there is only a limited potential for a reduction of the cost–power ratio.

Using thermal generation of free carriers is an easy possibility to improve miniaturized TEGs. Avoiding the metallic contacts and thick ceramic layers makes it possible to reduce the size of thermoelectric devices below the above limits. This size reduction simplifies the incorporation of advanced technologies like superlattices or expensive materials into cost sensitive products.

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