# Thermoelectric Power Generation using Large Area Si/SiGe pn-Junctions with varying Ge-content

M. Wagner*, G. Span†, and T. Grasser*

*Institute for Microelectronics, TU Wien, Gußhausstraße 27–29/E360, 1040 Wien, Austria
†SAM - Span and Mayrhofer KEG, 6112 Wattens, Austria
e-mail: mwagner@iue.tuwien.ac.at

## 1. Introduction

The conversion of heat to electricity by thermoelectric devices is an interesting alternative for energy production and utilization for the near future. However, in order to meet that role, more efficient thermoelectric devices and materials are needed that are suitable for a wide range of temperatures.

Several ideas and approaches like heterostructures, nanowires, and superlattices using novel complex materials are currently under investigation [1–6]. So far, none of these approaches results in efficiencies high enough to allow economical use. To increase the efficiency of the conversion process, we present a new approach to thermoelectric power generation using large area pn-junctions [7].

## 2. New Approach

Our approach is based on the idea to separate thermally generated electron-hole pairs by the built-in potential gradient of the pn-junction. A temperature gradient applied along this pn-junction causes a flux of both carrier types from the hot to the cold region. This principle allows us to use layer structures similar to solar cells as thermoelectric elements. In addition, it could be used to rise the efficiency of solar cells by using non-uniform temperature distributions [8]. The use of SiGe with varying Ge content makes it possible to introduce a non-linear temperature distribution which enhances the amount of generated carriers while reducing the thermal conductivity of the overall structure. Effective development and optimization of thermoelectric elements and modules depend on a strong simulation environment based on accurate models. We use the device and circuit simulator MINIMOS-NT [9] for predictive simulation of our thermoelements. The validity of the physical parameter models was ensured for the unusually large temperature ranges required for this application.

## 3. Thermal Generation and Seebeck effect

Electron-hole pairs are thermally generated within a pn-junction and separated by the built-in potential gradient. In thermal equilibrium, the generation is exactly compensated by recombination and no net current occurs. The built-in potential becomes smaller with increasing temperature, which leads to a behavior known as the Seebeck effect. By having a temperature gradient along a large-area pn-junction, the free carriers experience a driving force from the hot to the cold part of the structure. This carrier movement alters the local carrier balance between generation and recombination and leads to enhanced generation of electron-hole pairs at the hot part and to increased recombination at the cold part of the structure. By installing contacts to the cold side the generated current can be used and the whole structure works as a source of electricity, a thermoelectric power generator. Thermoelectric modules can be manufactured by stacking these elements, similarly to [10].

## 4. Advantages of this technique

This assembly of elements and modules has several advantages over conventional thermocouples. Among them are: The strong correlation of thermal and electrical properties can be overcome. The generation of electron-hole pairs and the transport of the carriers are spatially separated and therefore can be optimized for each carrier type separately to achieve high electrical conductivity. The shape of the temperature gradient within the thermoelectric element influences the amount of generated carriers and thus the power density can be optimized by geometrical engineering and by using distributed material compositions. Thermoelectric elements can be fabricated using only one main material so fatigue due to thermal cycling can be avoided. The elements can be manufactured in a similar way to well established processes in the semiconductor and solar cell industry.

## 5. Influence of the temperature distribution

The generation of electron-hole pairs is a thermally activated process determined by the trap level and the band gap. Large areas of high temperature are needed to generate as much carriers as possible but at the same time a temperature gradient is necessary to remove the carriers effectively. The generation will be a maximum for a temperature distribution with a

1-4244-0461-4/06/$20.00 ©2006 IEEE

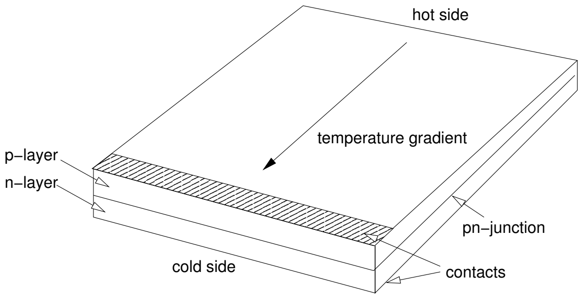

Fig. 1. Large area pn-junction with temperature gradient.

shallow slope for high temperatures and a steep slope approaching the cold part of the structure (Fig. 2). The temperature distribution is controlled by the device geometry and the local thermal conductivity distribution, which is a function of the Ge content. Using pure Si on the hot side in combination with SiGe on the cold side, the temperature distribution along the element can be taylored accordingly as shown in Fig. 2a. The thermoelectric element consists of a SiGe part with a Ge content of 0–50% on the cold end and pure Si on the hot end of the structure (Fig. 2b). The according amounts of generated carriers are shown in Fig. 2c. In Fig. 3, the corresponding generated powers with respect to an external load resistance are displayed. As expected, the power rises significantly with increasing Ge content.

## 6. Conclusions and outlook

By using the low thermal conductivity of SiGe to increase the average temperature along the pn-junction of the structure, the efficiency and power output of our thermoelectric elements can be increased dramatically. Further improvement can be achieved by using optimized graded Ge content to fully adapt the temperature distribution to our needs.

## 7. Acknowledgements

We acknowledge financial support through the FFG, the Austrian Research Promotion Agency (Österreichische Forschungsförderungsgesellschaft mbH) for SAM and project no. 810128–SCK/SA and the local government (Impulspaket Tirol).

## 8. References

[1] P. Hagelstein et al., APS Meeting Abstracts, pp. 26011 (2002)
[2] S. Yamaguchi et al., Appl.Phys.Lett., vol. 82, pp. 2065 (2003)
[3] D. Vashaee et al., J.Appl.Phys., vol. 95, pp. 1233 (2004)
[4] M. N. Tripathi et al., J.Phys.Cond.Matter, vol. 15, pp. 5359 (2003)
[5] B. Yang et al., Appl.Phys.Lett., vol. 80, pp. 1758 (2003)
[6] S.-M. Lee et al., Appl.Phys.Lett., vol. 70, pp. 2957 (2003)
[7] Span, G., Austrian patent AT 410 492 B; international patent application PCT/AT01/00123, granted in USA, Russia, Europe
[8] S. Kettemann et al., Proc. QUANTSOL 2004 (2004)
[9] IuE, MINIMOS-NT 2.1 User's Guide, TU Wien (2004)
[10] C.S. Tan et al., Proc. ATRCR 2004 (2004)

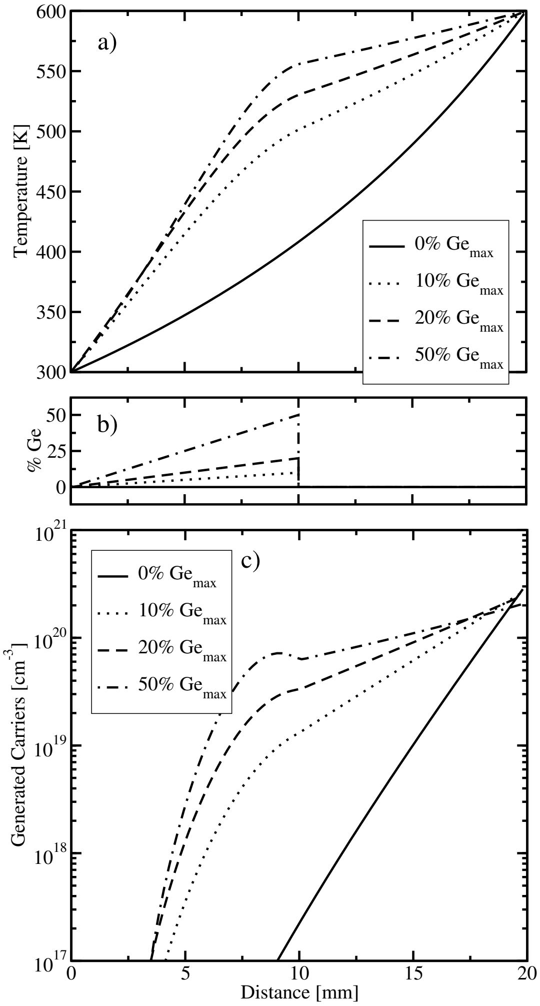

Fig. 2. a) Temperature distribution within the device. Higher Ge content means lower thermal conductivity and larger area of high temperature. b) Ge content along the pn-junction. c) Generated carriers for different Ge contents.

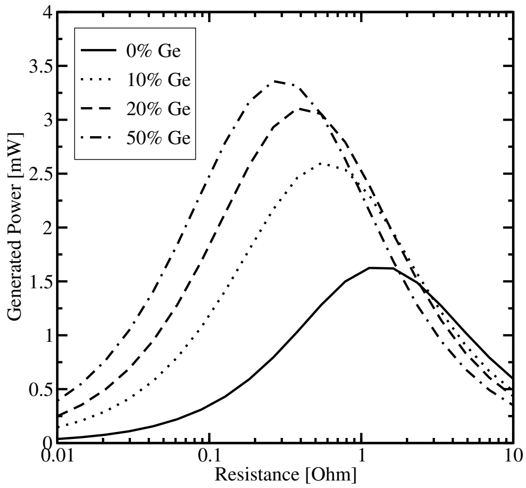

Fig. 3. Electrical power output for different Ge contents vs. electrical load resistance.