MicroPelt®: State Of The Art, Road Map and Applications

H. Böttner[1)], J. Nurnus[1)], M. Braun[1)], J. Wöllenstein[1)], F. Volkert[2)], A. Schubert[2)]
[1)] Fraunhofer-Institut für Physikalische Messtechnik (IPM), Heidenhofstraße 8, D-79110
[2)] Infineon Technologies AG, München, Germany

Abstract

Due to their unique properties, thermoelectric micro-devices-especially Peltier-coolers-are of high demand for different applications. Thus, worldwide efforts are undertaken to expand the technology for thermoelectric devices into the field of typical micro-system technologies including high volume production aspects. Key drivers for emerging markets are the applications around ambient temperatures. Up to now, the bismuth telluride (V-VI) related compounds are the favoured material systems. Recent results prove the capability to implement this material system into micro-system devices and demonstrate wafer-based microelectronic technologies for the fabrication of thermoelectric devices.

Here, we present the state-of-the-art and roadmap of MicroPelt® devices. The properties of MicroPelt® devices, in particular their fast response time, offers new possibilities e.g. for known laser tuning and humidity sensing. Results of applications utilizing MicroPelt® Peltier coolers will be presented.

Introduction

Looking at commercially available devices, the field of thermoelectrics is dominated by Peltier coolers based on $(Bi,Sb)_2(Te,Se)_3$ active bulk materials. The performance data of these devices such as ΔT, heat flux densities and COP are related to the thermoelectric performance of the materials characterized by the so called dimensionless figure of merit *ZT*. Although there is no theoretical limitation for *ZT*, realized thermoelectric bulk materials did not exceed *ZT*~1 for almost 50 years. Typical characteristics of macroscopic Peltier coolers are ΔT=70K and heat pump densities of ~10 W cm^{-2}.

The research efforts in the field of thermoelectric thin films increased substantially in the past years. This is partly due to costumers' interest in thermoelectric thin film coolers promising extremely high cooling power densities of more than 500 $W\ cm^{-2}$already for ZT=1 materials. Additionally, the *ZT* enhancements predicted for thermoelectric thin film nanostructures promise further improvements of the device performance.

Worldwide efforts for the realization of thin film cooling devices are undertaken using various technological approaches and material deposition techniques such as electroplating, co-deposition, MBE or MOCVD [1,2,3,4]. All this approaches are limited by the achieved material quality or the usability in the customer relevant cooling applications.

In this paper we shortly summarize the state-of-the-art of today's MicroPelt® Peltier coolers [5] as well as the roadmap for further performance improvements. Measurements using miniaturized thin film coolers in a hybrid setup will be presented for the first time.

MicroPelt® - State-of-The-Art and Roadmap

The MicroPelt® technological approach is based on a two - wafer technology. The several 10 µm thick polycrystalline Bi_2Te_3 and $(Bi,Sb)_2Te_3$ n- and p-type materials are deposited by sputtering on 4" wafers with prestuctured electrodes. The thermoelectric properties of the individual layers are optimized by a post-annealing process. For the final joining of p-and n-parts, a high temperature solder is deposited. In figure 1 (upper part) such a wafer is shown. The definition of the individual n- and p-type legs is done using dry etching techniques. Figure 1 (down, left) shows a SEM picture of an etched wafer. The electrode structures and the thermoelectric legs are easily visible. A cross section of one single thermoelectric leg is shown in figure 1 (down, right). After dry etching, the hot and cold sides are singularized and soldered together resulting in MicroPelt® Peltier coolers shown in figure 2 (upper part). Figure 2 (lower part) illustrates the grade of miniaturization by comparing a MicroPelt®- to a commercial bulk cooler.

Further details on the material properties and the production process can be found in [5].

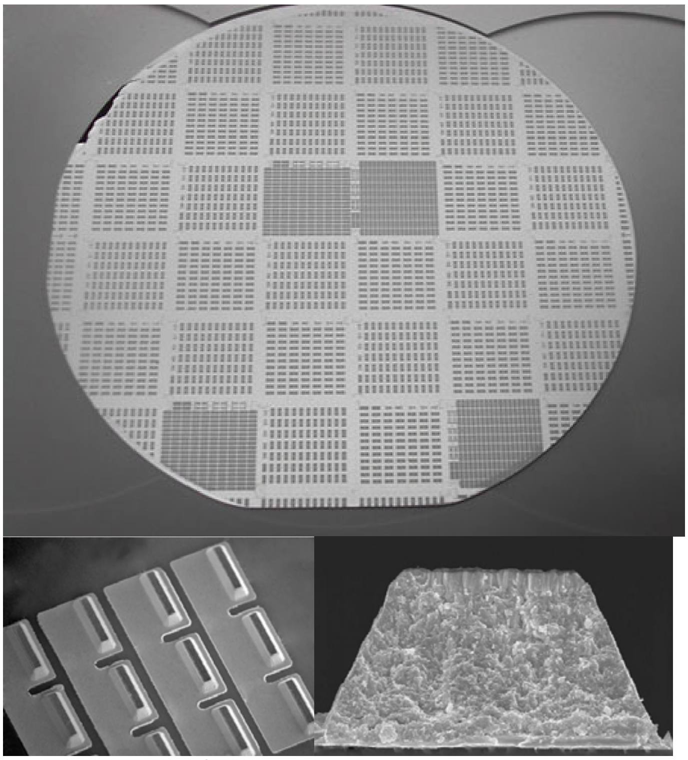

Fig. 1: MicroPelt®-Peltier coolers at different states of the production process

Up to now, maximum temperture differences of 32°C at a hot side temperature of 85°C are achieved under vacuum conditions for a current of 1.8 A (figure 3). Using the devices at lower tempertures results in somewhat reduced ΔT_{max}

values. This is due to the temperature dependence of the implented V-VI- thin films. Over the whole temperature range a good agreement between the measured and calculated values is obtained (see figure 4). Under atmosphere conditions, the achievable ΔTs are somewhat smaller due to convection losses (see figure 3).

From figure 4 it can be seen that using further optimized polycrystalline V-VI-materials (already realized in the lab but not implemented into devices up to now), maximum temperature differences of more than 50°C can be reached. For these devices maximum cooling power densities of 160 W cm^{-2} can be realized. Calculated COP and Q_{max} values for different temperture differences of this future devices are shown in figure 5.

Due to the miniaturization and thus the small thermal mass of the MicroPelt®-Peltier coolers (hot side: 1470 µmX720 µm, cold side: 720 µmX720 µm, total thickness: 426 µm) extremly fast response times τ in the region of some 10 ms are achieved for the already available devices. Compared to this value conventional coolers show more than 10 (20) times slower cool-down times for TE heights of 200 µm (~1 mm) [6]. Thus, MicroPelt® Peltier coolers offer several new applications in the fields of:

- MicroFluidics
- Medical, bio medical and pharmaceutical experiments (PCR, blood analysis, drug recovery)
- Sensing
- Temperature stabilization of emitters (lasers, LEDs)

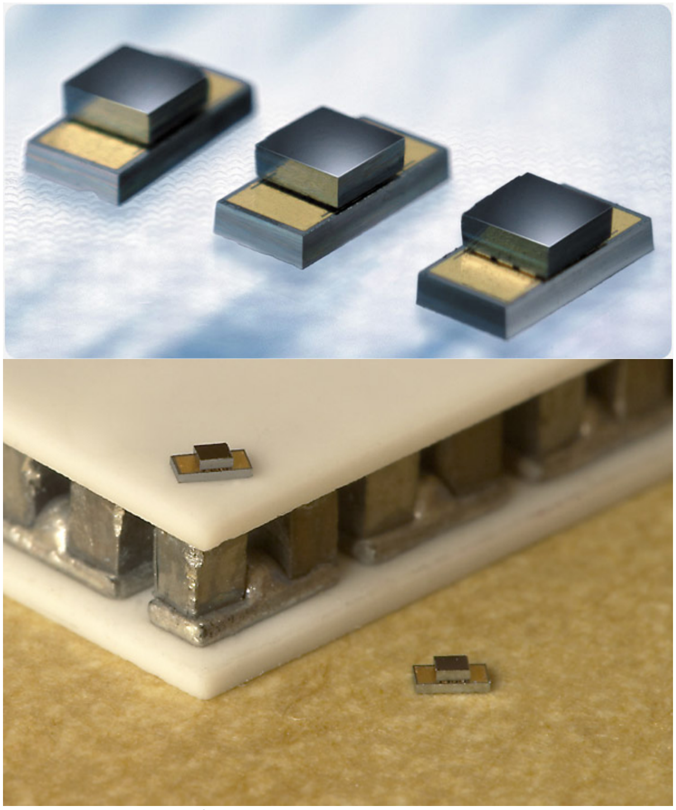

Fig. 2: MicroPelt® Peltier coolers (upper part) compared to commercial bulk Peltier Peltier cooler (lower part)

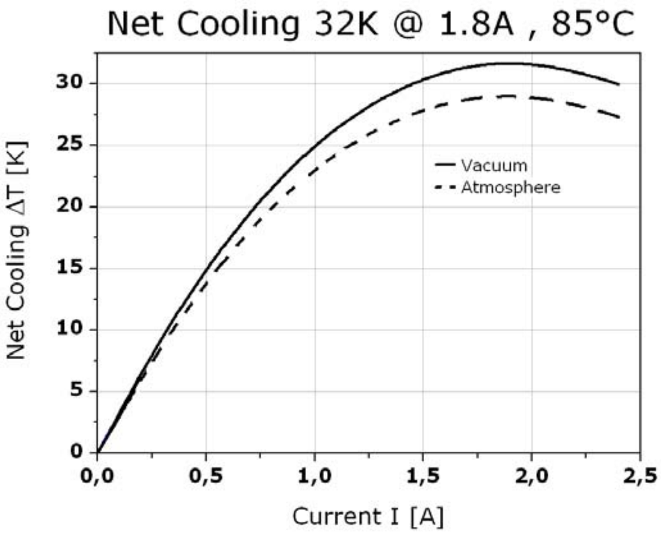

Fig. 3: Performance of a MicroPelt® Peltier cooler in atmosphere and under vacuum condition.

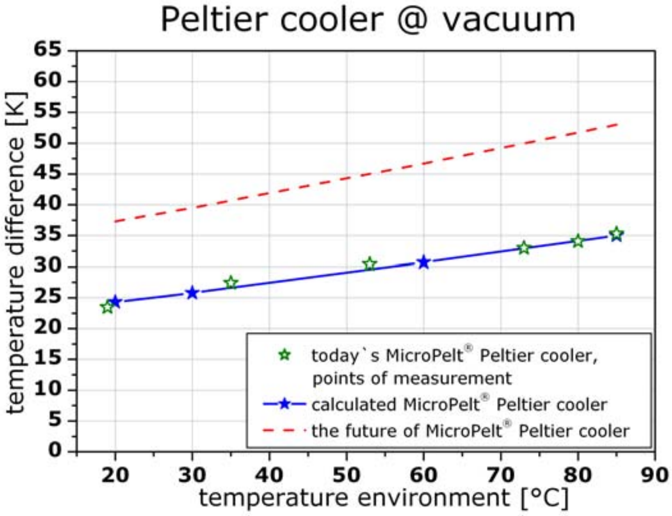

Fig 4: Measured performance of realized MicroPelt® Peltier coolers (blue line) and predicted (red line) performance of polycrystalline V-VI-thin film devices.

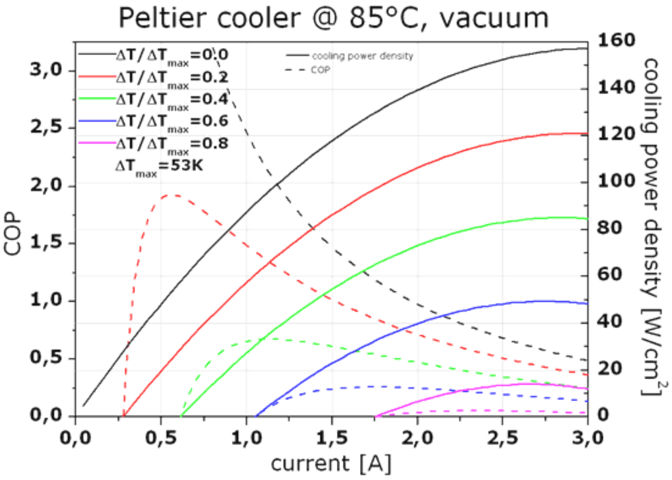

Fig. 5: Calculated COP and Q_{max} of polycrystalline V-VI future devices for different temperature differences.

Application note: Fast temperature variation/

To our knowledge, only fundamental investigations on thin film coolers are reported in the literture [Venk, Harman, ..] up to now. However, none of this principle setups have been proven yet. Here, we present for the first time a hybrid application setup comprising a miniaturized thermoelectric thin film cooler.

For spectroscopic gas analysis the absorption of the gases in a matched range of wavelenths is investigated. In figure 6 the relative transmission of oxygen in this specific region around 762 nm is shown. Additionally, the emission spectrum of a vertical cavity surface emitting laser (VCSEL) has been recorded. Since the emission wavelength of the VCSEL can be altered by temperature variations ($d\lambda/dT \sim 0.05$ nm K^{-1}) aborption measurements in a wavelength range are possible. Usually, this variations are realized be simply increasing the VCSEL current, what results in an increase of the operating temperature in the active region, and thus an increased emission wavelength. However, the possible shift margin is narrow. Another possibility to change the operating temperature of the VCSEL is simply to change the VCSEL temperature by cooling the whole VCSEL. Using conventional macroscopic coolers, this is possible only with frequencies of about 0.5 Hz, owing to the slow cool-down times of the Peltier cooler. Here, the use of MicroPelt® Peltier coolers is investigated with respect to the significantly reduced time constants.

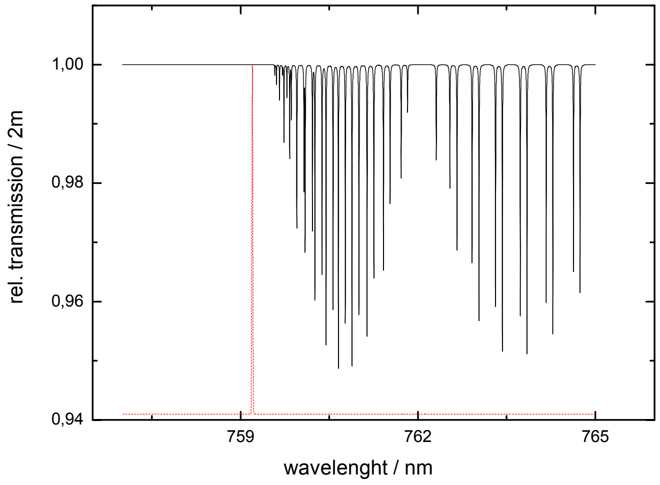

Fig. 6: Oxygen absorption bands (solid line) and exemplary emission spectrum of a VCSEL (dotted line).

A VCSEL with an emission wavelength of ~760 nm is mounted on top of the cold side of the MicroPelt® Peltier cooler, the hot side of the cooler is attached to a copper heat sink located in a TO8 housing with a window transparent in the emission range of the VCSEL. In order to avoid environmental influences the TO8 housing was sealed under nitrogen atmosphere. This hybrid device is shown in figure 6.

Using an optical bench, the VCSEL was located in front of a conventional photodiode. The measured photodiode voltage can be used as a measure for the oxygen absorption in the optical path between VCSEL and photodiode.

In our measurements a square current pulse with a pulse width of 75 ms was applied to the MicroPelt® Peltier cooler. This current pulse was monitored with an oszilloscope and is shown in figure 7 as a black line. The voltage response of the photodiode was measured simultaneously and is also shown in figure 7. As long as the cooler is turned off, a constant signal is found. As soon as the MicroPelt® Peltier cooler is turned on (here: operating current: 1 A, corresponding to a temperature change of 18 K) the emission wavelength shifts towards smaller wavelengths. By this the measured photodiode voltage shows several oxygen absorption lines according to the oxygen absorption pattern shown in figure 6. With increasing time, the absorption lines show increasing FWHM values. This is due to the fact that the temperature changes at the start are essentially larger than at the end of pulse, where the MicroPelt® Peltier cooler reaches its final operating temperature. During the “current-on” phase 8 absorption lines can be found. The measured wavelength at “current start” and “current stop” show that the wavelength of the VCSEL has changed by ~1 nm corresponding to a temperture change of ~20 K. When turning the current off, the MicroPelt® Peltier cooler again heats up towards its starting temperature, the wavelenght of the VCSEL increases and the 8 oxygen absorption lines can be detected in reverse order.

Fig. 6: VCSEL mounted on MicroPelt® Peltier cooler in TO8 housing

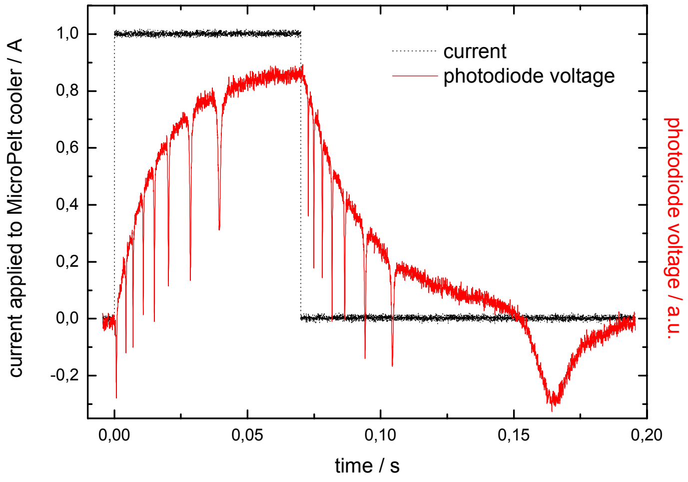

Fig. 7: First time oxygen measurements showing the unique fast response of MicroPelt® devices

Conclusions and Outlook

For the first time, a successful integration of thermoelectric thin film coolers into hybrid devices has been demonstrated. The presented absorption measurements show, that the already demonstrated fast response times of the MicroPelt® film coolers are also valid for hybrid setups: Temperture variations of ~20 K can be achieded with a frequency of up to 5 Hz. ("thermal duty cyle"=50%). In comparison: conventional macroscopic Peltier coolers only manage frequencies of 0.5 Hz, therefore, those classic Peltier coolers provide of about a factor 2 higher temperature differences. This difference will be almost compensated in the next generation of MicroPelt® Peltier coolers, which will manage temperature differences of up to 53°C due to optimized polycrystalline materials. Further performance improvements are expected for future devices thanks to the use of nanostructured active materials with strongly reduced thermal conductivities. Thus, MicroPelt® Peltier coolers have the potential to reach at least the ΔT known from macroscopic coolers. At the same time, the thermal response time of the MicroPelt® Peltier coolers will be of a factor 10 smaller and the cooling power density by more than a factor 20 higher than in today's commercial macroscopic Peltier coolers.

References

1. Harman, T.C. *et al.*, "Quantum dot superlattice thermoelectric materials and devices", *Science*, Vol. 297 (2002), pp. 2229 – 2232.
2. Venkatasubramanian, R. et al., "Thin-film thermoelectric devices with high room-temperature figures of merit", *Nature*, Vol. 413 (2001), pp. 597-602.
3. Da Silva, L.W. *et al.*, "Micro thermoelectric cooler fabrication: Growth and characterization of patterned Sb_2Te_3 and Bi_2Te_3 films", *Proc. 22nd Int. Conf. Thermoelectrics*, La Grande-Motte, France, 2003, pp. 665 – 668.
4. Lim, J.R. et al., "Thermoelectric Microdevice fabrication process and evaluation at the Jet Propulsion Labboratory (JPL)", *Proc. 21st Int. Conf. Thermoelectrics*, Long Beach, CA USA, 2002, pp. 535 – 539.
5. Böttner, H. *et al.*, "New Thermoelectric Components Using Microsystem Technologies", *IEEE Journal of Microelectromechanical Systems*, Vol. 13 (2004), pp. 414-420.
6. Semenyuk, V., "Thermoelectric micro modules for spot cooling of high density heat sources", *Proc. 20th Int. Conf. Thermoelectrics*, Beijing, China, 2001, pp. 391 - 396