DOI: 10.63527/1607-8829-2024-4-26-33

K. H. Gresslehner[1, 4],
M. Krenn[1],
P. Kerepesi[2],
L. Gupfinger[1],
M. Höglinger[3],
P. Zellinger[1, 4],
B. Plank[3],
Ch. Beisteiner[5]

[1]Johannes Kepler University, Linz (Austria)
e–mail: karl-heinz.gresslehner@k1-met.com
[2]EVG Group. St. Florian / Inn (Austria)
[3]University of Applied Sciences Upper Austria, Wels (Austria)
[4]K1-MET GmbH, Linz (Austria)
[5]Beisteiner Printronics, Roitham (Austria)

NON-DESTRUCTIVE INSPECTION OF THERMOELECTRIC MODULES BY SCANNING ACOUSTIC MICROSCOPY

In this work we present the potential of Scanning Acoustic Microscopy (SAM) as an important non-destructive evaluation (NDE) method for process control as well as failure analysis of thermoelectric modules (TE-modules). SAM is one part of the so called 'Dream Team Concept' which is described in detail in section 2.

Keywords: thermoelectric modules, non-destructive inspection, scanning acoustic microscopy

1. Introduction

Thermoelectric generators (TEG) had been demonstrated to be a promising technique to convert any form of waste heat directly into the higher-value electrical energy. They are solid-state devices with the advantages of having no moving parts, no working fluids, no external energy required, low maintenance costs, easy scalability, noiseless operation and a long life-span. Fig. 1.1 shows the schematic of a TE-module. A typical TEG consists of more than a hundred of thermoelectric elements (legs) of n- and and p-type materials which are electrically connected in series and thermally parallel, while being positioned between two ceramic layers. Details are shown in Fig. 1.2.

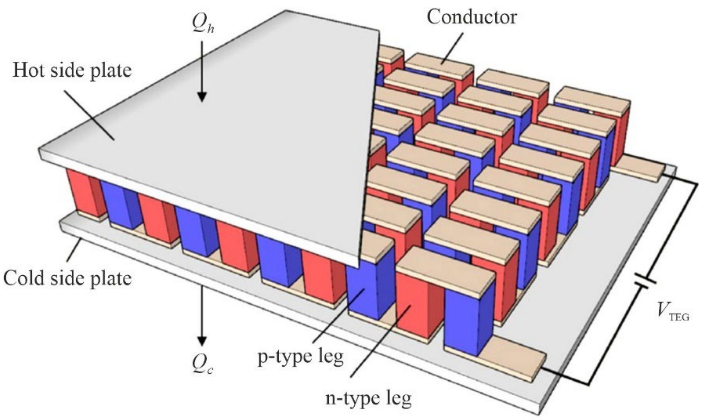

Fig. 1.1. Schematic overview of a TEG [1]

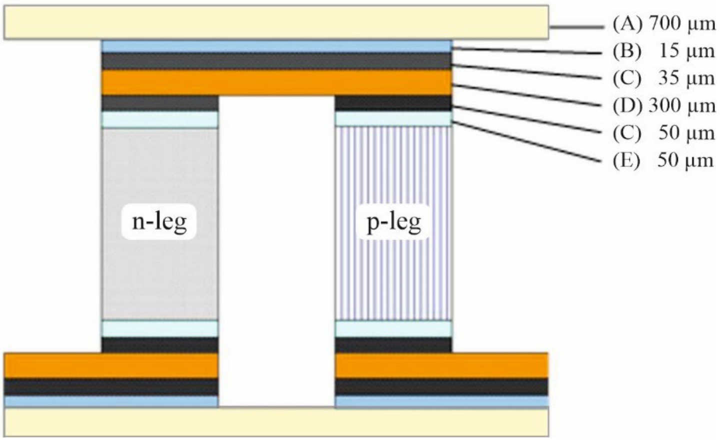

Fig. 1.2. Sketch of the layer structure of a thermoelectric couple in a TE-module. Typical layer thicknesses are given in parentheses: A – ceramic (700 μm); B – metallization (15 μm); C – soldering (35 μm); D – Cu-electrode (300 μm); E – diffusion barrier (50 μm)

2. Reliability engineering

Bringing thermoelectricity from lab-scale into industrial applications, it is very important that their positive features, such as no moving parts, easy scalability, etc., can be fully exploited through a high long-term stability. The reliability and performance of a TE-module depends substantially on the quality of thermoelement junctions [1]. Therefore, reliability engineering plays an important role, whereby suitable stress tests must be carried out and defective TE-modules must be analyzed for their failure causes using non-destructive (NDE) and destructive evaluation (DE) methods. In this context, failure analysis (FA) is a key method in reliability engineering which aims to determine the root cause for the incorrect behaviour of a TE-module. FA is carried out in several steps where the focus must be on NDE techniques. As a general rule for performing failure analysis: NDE prior to DE.

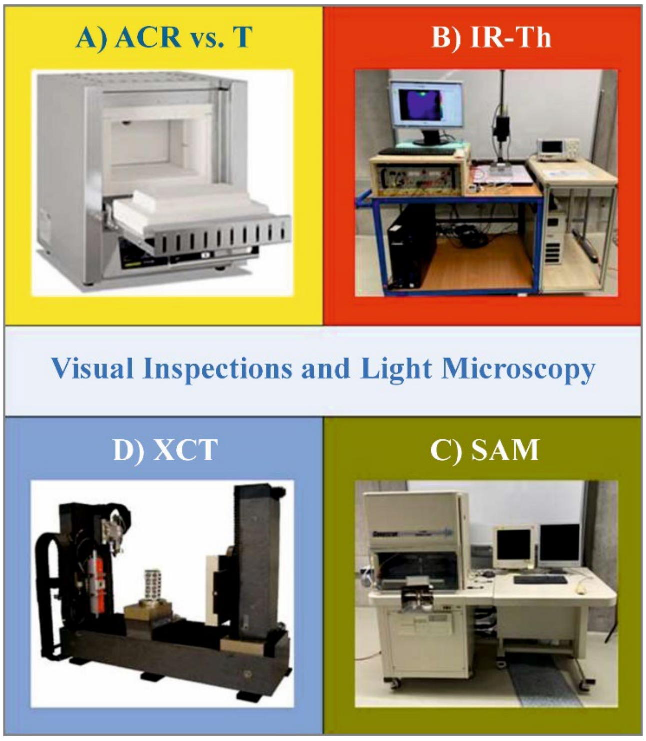

*Fig. 2.1. ‘Dream Team concept of NDE methods’ or ‘Magic Quartet of NDE methods’):
A – high temperature oven to measure the total AC-resistance (ACR) vs. T (The temperature dependence of the ACR is an indicator for the long-term stability of a TE-module [2]–[5]);
B – IR-Thermography test stand for the detection of subsurface defects (‚weak failures’);
C – Scanning Acoustic Microscope (SAM) for the detection of subsurface defects (‚weak failures’ as well as ‘hard failures’), SAM is described in detail in sections 3 and 4;
D – X-ray Tomography (XCT) is an important addition to SAM analysis, and enables a direct visualization of the internal structures of a TE-module.*

The Table 2 shows the applicability of the various NDE methods to detect weak and hard failures.

Table 1

Dream Team Concept

Type of failure	ACR vs. T	IR-Th	SAM	XCT
Weak failure (current can flow)	×	×	×	×
Hard failure (current can flow)			×	×

In the course of failure analysis of TE-modules it is practical to distinguish roughly between the two types of failures, namely **'weak failures'** and **'hard failures'** (see Table in Fig. 2.1). 'Weak failure' means that the TE-Module is working, but is out of specification, e.g. due to an increased internal electrical resistance (ACR). 'Hard failure' means that the TEG is completely inoperable, i.e. no current can flow due to e.g. a broken leg, internal cracks, etc. As an initial procedure for the inspection of TE-modules we have installed the so called **'Dream Team Concept of NDE-methods'** (also referred as **‚Magic Quartet of NDE-methods'**), which is illustrated in Fig. 2.1.

3. Basic principles of SAM

The operational principle of the SAM is coupling of an acoustic wave to the surface of the sample by means of an ultrasonic transducer and analyzing the reflected echo (Fig. 3.1a) [6, 7]. This technique is known as reflection- or pulse-echo mode. To minimize the signal loss, the sample is immersed in a water bath. When the acoustic wave propagates through the sample it may be scattered, absorbed, reflected or transmitted at media interfaces. The reflected ultrasonic pulse can be analyzed by different scan modes (Fig. 3.1b, c) [6].

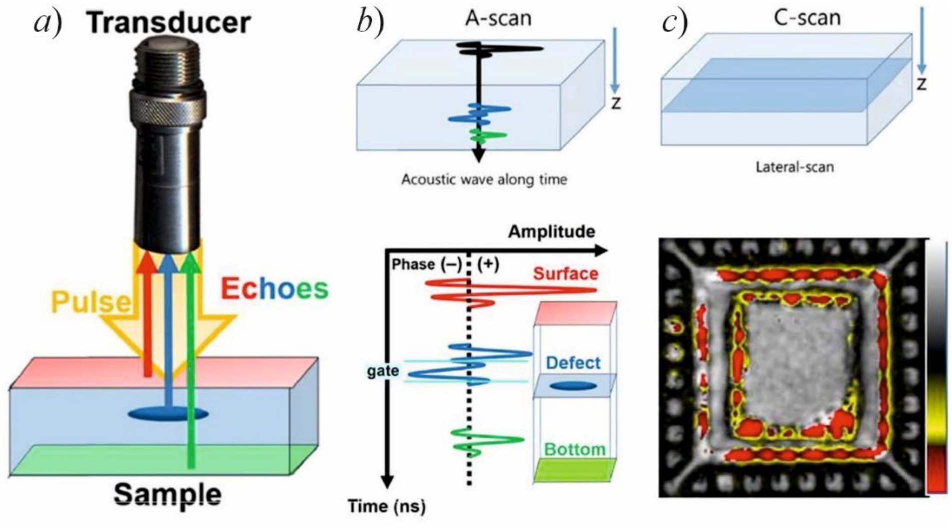

Fig. 3.1. Operational principle of a SAM: a) incident and reflected ultrasonic pulse; b) corresponding amplitudes of the reflected echos generated by the A-Scan. A-Scan provides an 'oscilloscope display' of vertical line information thru the depth of the sample at a predetermined point on the surface. It displays peaks at interfaces occurring at times proportional to their depth; c) C-Scan provides a video image display of a horizontal cross section of the sample at predetermined depth at which the transducer is focused and the gate is located [8]. The gate position determines the specific depth of an echo and the gate width (bright blue vertical lines in b)) the depth resolution. The colors yellow and red in the C-scan image indicates a negative polarity of the amplitude of the reflected signal ($R < 0$, or $Z_2 < Z_1$) while gray indicates positive echos ($R > 0$ or $Z_2 > Z_1$) (see color bar)

The polarity and amplitude $R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$ of the reflected wave is obtained from the acoustic impedances $Z_i = \rho_i$ (density) × C_i (speed of sound) of adjacent materials, where Z_i is the acoustic counterpart of the refractive index in optical microscopy. Fig. 3.1, c shows a C-Scan image of a plastic packaged IC with polarity analysis where the yellow and red regions indicate delaminations ($R < 0$) while the gray region indicates a good bonding ($R > 0$).

4. Analysis of a TE-module

The procedure of the incoming inspection of the commercial available 200°C BiTe-based TE-module #ALI_2305_01_06 is shown. To do this we have used: IR-Th (measurement as well as numerical simulation), SAM and cross sectioning. ACR and XCT measurements are not discussed here.

4.1. IR-Thermography

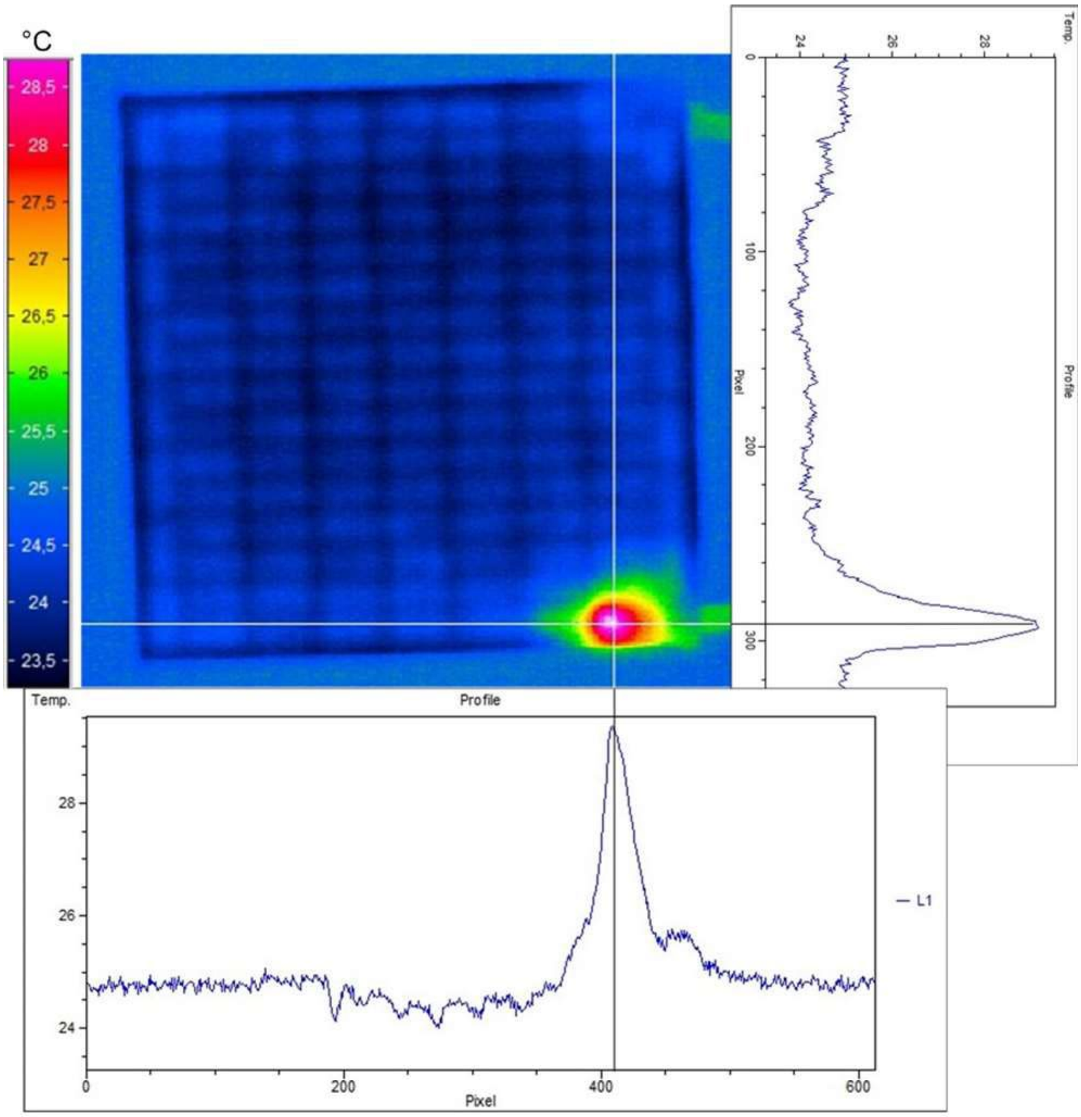

Fig. 4.1a. Hot-spot detection in the vicinity of the positive terminal of the TE-module. To better localize the failure position, line scans in x and y direction were carried out for the subsequent cross-sectioning

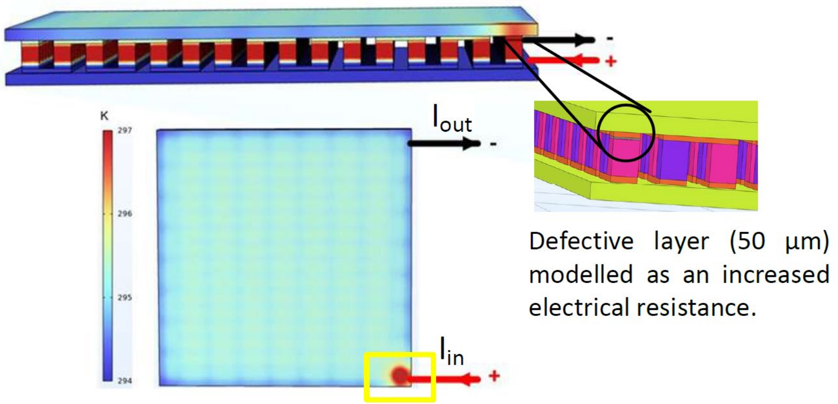

Fig. 4.1b. Numerical simulation of the temperature distribution with the following parameters: the TE-module is operated as a heat pump using the Peltier effect. The current I_{in} was set to 3 A, which is a typical value for IR thermography. For the cooled side a constant temperature of T = 293.15 K was assumed. The heat dissipation from the top side (IR-camera side) to the ambient (T = 293.15 K) was modeled as convective heat flux with a heat transfer coefficient of h = 6 W/(m²·K).

4.2. Scanning Acoustic Microscopy and Cross Sectioning

Fig. 4.2 shows the SAM equipment used in the ultrasonic analysis of TE-modules together with the relevant transducer data.

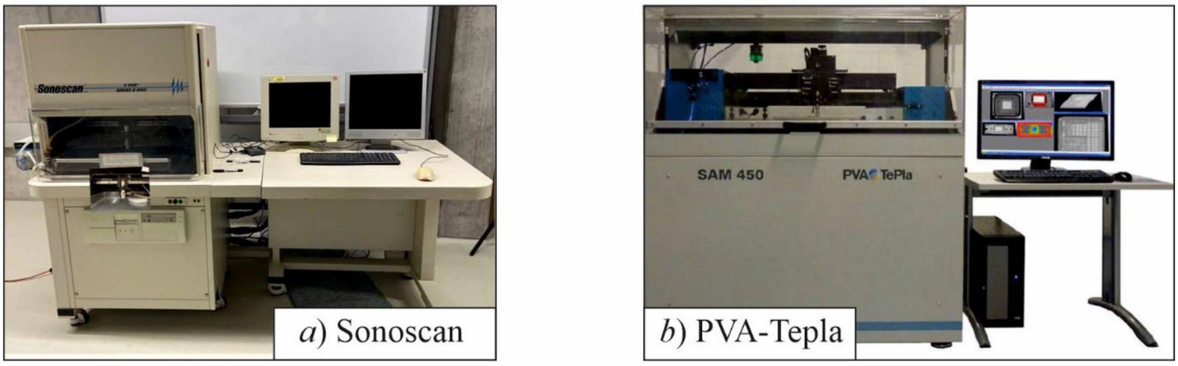

Fig. 4.2. SAM equipment used in the ultrasonic analysis of TE-modules

Table 2

The essential parameters of the transducers

SAM equipment \ transducer data	*f* [MHz]	*FL* [mm]	*D* [mm]	*F#* [mm]	Spot size [µm]	Δz [µm]	*DOF* [mm]
C-SAM Sonoscan D-9000	100	12.7	6.4	2	36.6	25.9	0.43
PVA Tepla SAM 450	87	8	2.0	4.0	3.0	13.7	0.07

f – center frecuency, FL – focal length; D – diameter; F# =FL / D – f-number which indicates the amount of sound coming through the lens; spot size = 2 × later resolution; Δz *– axial resolution; DOF – depth of focus = penetration depth.*

Fig. 4.3a shows the **A-Scan reflectrogram** (blue solid line) measured approx. in the center of the TE-module (white square) and its Hilbert transform (red dashed line). Hilbert transform is important to define the pulse peak in time domain for the time of flight (TOF) measurements [9]. The TOF was chosen as 9.9 µs which corresponds to a depth of focus (DOF) at the interface Cu-electrode/soldering (see layers D/C in the insert). Pulse peaks were detected at four interfaces where the TOF's correspond to the following layers: (1)–(2) ceramics (A), (2)–(3) Ni coating (B) and soldering (C), and (3)–(4) Cu-electrode (D). The yellow rectangle indicates the location of the hot-spot (Fig. 4.1a) and the green rectangle shows the area where a detailed C-Scan image is shown in Fig. 4.3b.

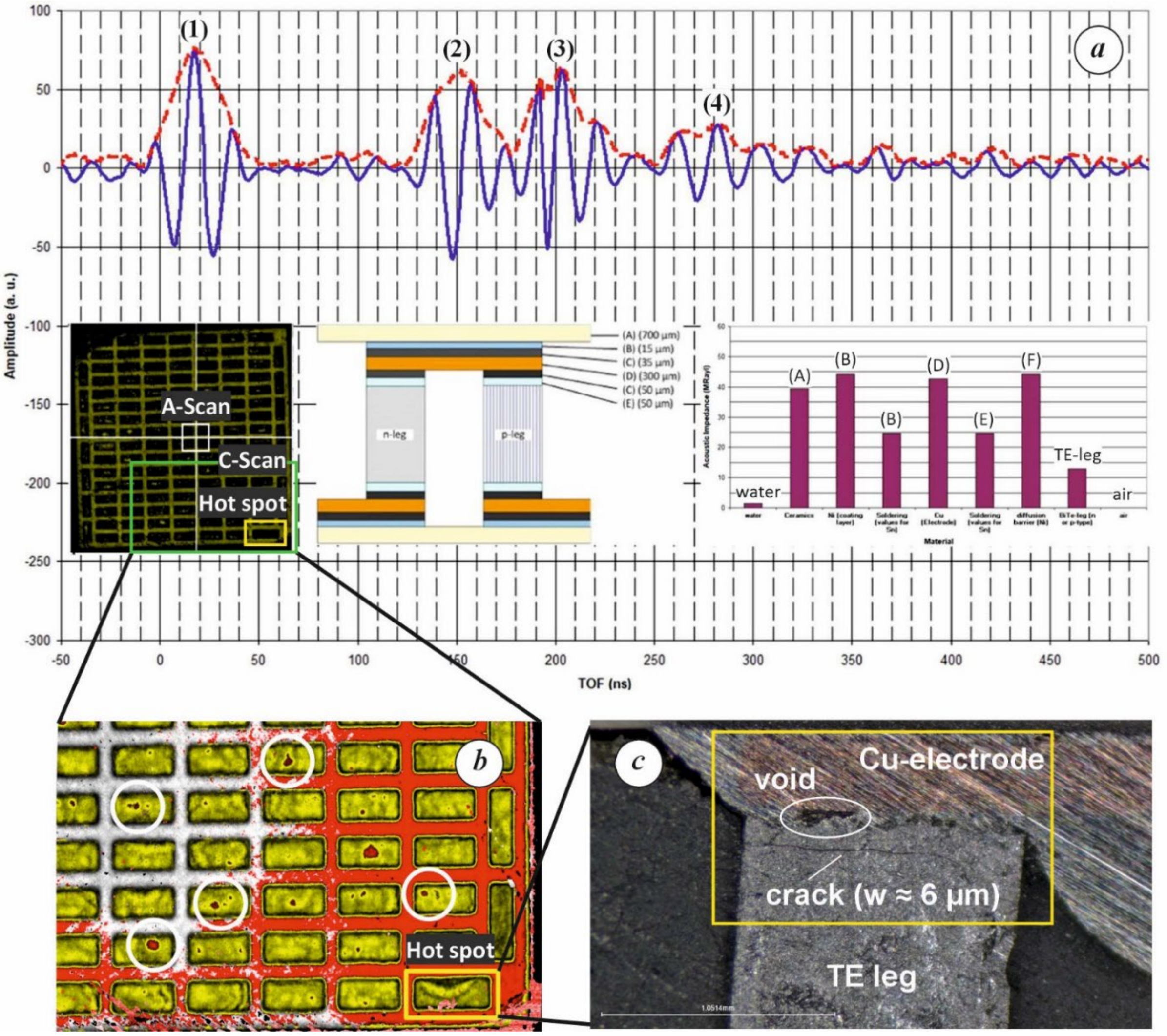

Fig. 4.3: TE-module #ALI_2305_01_06: a – A-scan reflectrogram using the C-SAM Sonoscan D-9000 (Fig. 4.2a); b – C-scan image using the C-SAM Sonoscan D-9000 (Fig. 4.2a); c – Light microscopy analysis after cross-sectioning and polishing.

Fig. 4.3b shows the **C-scan image** at the position of the hot spot (yellow rectangle in Fig. 4.3a). The analysis paramaters are given in Fig. 4.3a. At the position of the hot spot irregularities in the contact layer can be seen (yellow rectangle). The red spots within the white circles indicate voids (air gaps) at the interconnecting layers D/C, or C/E or E/TE-leg (see Fig. 1.2). These voids are, among other things, responsible for an increased electrical contact resistance which can significantly reduce the long term stability of a TE-module (especially when operating at higher temperatures).

Fig. 4.3c shows Light microscopy analysis after cross-sectioning and polishing. The polishing time was 1 h, with an average removal rate of approx. 13 µm/min. A crack (air gap) in the cross-sectional plane of the TE-leg with a width of approx. 6 µm can be seen. This is most likely the cause for the hot-spot, which probably occurred during the soldering process at the positive terminal.

Also voids can be seen at the interfaces between the Cu-electrode and the underlying materials (white ellipse), which could already be observed in the SAM analysis (Fig. 4.3b).

Conclusions

- In this work, we have discussed the performances of the NDE 'Dream Team concept' which is: measurement of ACR as a function of temperature, IR-Thermography, C-SAM and XCT.
- The advantages of these NDE methods are: they are easy to handle, there is no or little need of sample preparation and they can produce results very quickly.
- The results of the NDE methods are then an important basis for subsequent destructive analysis such as cutting, cross sectioning, polishing, etc. to determine the *root cause* of a faulty TE-modules.
- Only with these methods it will be possible to correctly interpret the results of reliability tests (stress tests) in order to ensure the longterm-stability of TE-modules.
- Therefore, to bring thermoelecricity from lab-scale to industrial applications these NDE and DE methods will make an important contribution to process and product control in manufacturing TE-modules.

Acknowledgements

The authors would like to thanks voestalpine Stahl GmbH and Energie AG Oberösterreich Umwelt Service GmbH for their financial support. The authors would like to thank Peltron GmbH Peltier-Technik for supplying thermoelectric modules free of charge and supporting to get TE-modules from other suppliers as well as many helpful discussions.

The authors would also like to thank Prof. Armando Rastelli and Prof. Stefan Müllegger from Institute of Semiconductor and Solid State Physics / JKU for the use of their equipments to perform failure analysis. Last but not least the authors would like to thank E. Nusko from Institute of Semiconductor and Solid State Physics / JKU and A. Nimmervoll from Institute of Applied Physics / JKU for their technical support.

References

1. Chae, H., et al., Feasibility study on energy harvesting with thermoelectric generators in a photovoltaic-ground source heat pump system, *Energy Reports*, 11 (2024).
2. Chen, M., Note: Extraction of temperature-dependent interfacial resistance of thermoelectric modules, *American Institute of Physics* (2011).
3. Semenyuk, V., et al., Diffusion Protection of Thermoelectric Cooler Junctions as a Means of Increasing its Reliability, *Proc. of 5th European Conference on Thermoelectrics*, September 10–12, 2007, Odessa (2007).
4. Liu, W., et al., Understanding of the contact of nanostructured thermoelectric n-type $Bi_2Te_{2.7}Se_{0.3}$ legs for power generation applications, *J. Mater. Chem. A* (2013).
5. Liu, W., et al., Thermoelectric interface materials: A perspective to the challenge of thermoelectric power generation module, *Journal of Materiomics*, 5 (3) (2019).
6. Yu, H., Scanning acoustic microscopy for material evaluation, *Appl. Microsc.*, 50, 25 (2020).
7. Su, L., et al., Defect Inspection of Flip Chip Solder Bumps Using an Ultrasonic Transducer, *Sensors*, 13 (2013).
8. Sonolab, Introduction to Acoustic Micro Imaging, training materials (no date).
9. Mesquita, L. V., Failure Analysis of PV Modules using Scanning Acoustic Microscopy, *Albert-Ludwigs-Universität Freiburg*, Master Thesis (2019).

Submitted: 15.07.2024

Ґреccленер К. Г.[1, 4],
Крен М.[1],
Керепезі П.[2],
Ґупфінґер Л.[1],
Гьоґлінґер М.[3],
Целлінґер П.[1,4],
Планк Б.[3],
Байштайнер Х.[5]

[1]Університет Йоганна Кеплера, Лінц (Австрія)
електронна пошта: karl-heinz.gresslehner@k1-met.com
[2]Група EVG. St. Florian / Inn (Австрія)
[3]Університет прикладних наук Верхньої Австрії, Вельс (Австрія)
[4]K1-MET GmbH, Лінц (Австрія)
[5]Beisteiner Printronics, Ройтам (Австрія)

НЕРУЙНІВНИЙ КОНТРОЛЬ ТЕРМОЕЛЕКТРИЧНИХ МОДУЛІВ МЕТОДОМ СКАНУЮЧОЇ АКУСТИЧНОЇ МІКРОСКОПІЇ

У цій роботі ми представляємо потенціальну скануючу акустичну мікроскопію (SAM) як важливий метод неруйнівної оцінки (NDE) для контролю процесів, а також аналізу несправностей термоелектричних модулів (TE-M). SAM є частиною так званої "Концепції команди мрії", яка детально описана в розділі 2.

Ключові слова: термоелектричні модулі, неруйнівне дослідження, скануюча акустична мікроскопія

Література

1. Chae, H., et al., Feasibility study on energy harvesting with thermoelectric generators in a photovoltaic-ground source heat pump system, *Energy Reports*, 11 (2024).
2. Chen, M., Note: Extraction of temperature-dependent interfacial resistance of thermoelectric modules, *American Institute of Physics* (2011).
3. Semenyuk, V., et al., Diffusion Protection of Thermoelectric Cooler Junctions as a Means of Increasing its Reliability, *Proc. of 5th European Conference on Thermoelectrics*, September 10–12, 2007, Odessa (2007).
4. Liu, W., et al., Understanding of the contact of nanostructured thermoelectric n-type $Bi_2Te_{2.7}Se_{0.3}$ legs for power generation applications, *J. Mater. Chem. A* (2013).
5. Liu, W., et al., Thermoelectric interface materials: A perspective to the challenge of thermoelectric power generation module, *Journal of Materiomics*, 5 (3) (2019).
6. Yu, H., Scanning acoustic microscopy for material evaluation, *Appl. Microsc.*, 50, 25 (2020).
7. Su, L., et al., Defect Inspection of Flip Chip Solder Bumps Using an Ultrasonic Transducer, *Sensors*, 13 (2013).
8. Sonolab, Introduction to Acoustic Micro Imaging, training materials (no date).
9. Mesquita, L. V., Failure Analysis of PV Modules using Scanning Acoustic Microscopy, *Albert-Ludwigs-Universität Freiburg*, Master Thesis (2019).

Надійшла до редакції 15.07.2024