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Comparison of different energy harvesting solutions for printed circuit board production

用于印制电路板生产的不同能量收集解决方案之比较

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Abstract - **For energy harvesting of thermal energy two well-known physical effects are usable, the thermoelectric and the pyroelectric effect. These two effects have been compared in literature in terms of their energy output and the applicability. In this contribution the two effects will be compared in the particular environment of the printed circuit board production. For applications without a thermal energy source the approach to use ambient radio frequency energy harvesting will be tested.**

Furthermore, we present the pure energy output information of the harvesters in the regarded environment, so that these results can be compared with other sensor systems. Our system consists of a temperature sensor, a microcontroller and a radio transceiver. The wireless interface enables a real-time sensor-data transfer.

The soldering process is one important focus of research in a PCB production environment (e.g. reflow oven) for our generators, because of the available thermal energy in this process. Nevertheless, the testing of a PCB in a climate test chamber is also a suitable application, since there is a cyclic change of low and high temperature. A thermoelectric generator (TEG) seems to be the best choice for the reflow oven, whereas for the test chamber application a pyroelectric generator (PEG) is preferred, because of the high temperature change. But in other processes where no temperature is involved the radio frequency energy harvesting. In our contribution we will focus on the questions. What is the best generator solution for the given applications?

Keywords - **Thermoelectric Generator, Pyroelectric Generator, Printed Circuit Board, Energy Harvesting, PCB-manufacturing, RF energy harvesting**

I. INTRODUCTION

In the printed circuit board (PCB) production the trend leads toward more and more complex designs, particular in Europe with small quantities and high quality demands. To achieve these requirements the new production cycles need to have a higher yield and a faster adjustment speed. A solution is to increase the numbers of sensors inside the production equipment, as well as place sensors inside the product itself (the PCB).

In section II some required fundamentals are explained. We focus on the embedded sensor idea, the thermal energy harvesting, the RF harvesting and the test environment. After the basics we present in section III, preliminary consideration of the possible harvesting methods, the pyroelectric and the thermoelectric one, in a chosen printed circuit board environment. In the fourth chapter the setup for the whole system is given with the required elements. For some elements like a microcontroller a firmware is required, which will be also described here. The results are shown in chapter V for the energy consumption of the hardware components with the firmware compared to the harvested energy with the preferred generator. In the last chapter a comparison is given with some future remarks.

II. BASIC

In this section the fundamentals of the present paper will be shown. At first the embedded sensor principle, followed by the energy harvesting methods, which contain thermal energy harvesting and RF energy harvesting.

2.1. EMBEDDED SENSOR

The sensor inside the printed circuit board, as shown in Fig. 1, delivers information that can’t be measured from the outside or need to be manufactured manually at the PCB (increases time and cost), before the process. For example if the temperature at a solder pad should be tracked in a reflow oven. Today’s method is to attach a thermocouple near this solder pad and connect them with a wire to the data logger. The embedded sensor can be implemented near the pad and deliver information not only for the soldering process but also for the whole lifetime of the PCB.

Fig. 1, Embedded sensor in a PCB

2.2. TEST ENVIRONMENT

The tests are done in PCB-manufacturing equipment. A reflow oven and a temperature test chamber were chosen for this paper. The reflow oven temperature (see Fig. 2) can be adjusted individually in four different heating zones, set to a common solder profile (maximum temperature 230°C).

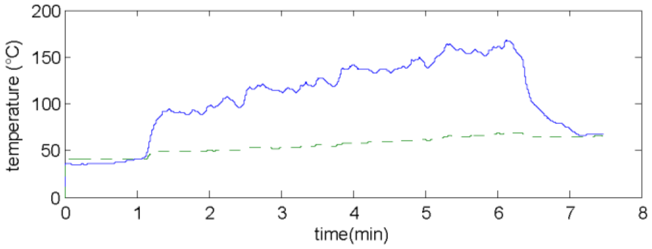

Fig. 2, Temperature of a device with heatsink in a reflow oven cold side (green) hot side (blue)

A temperature test chamber is used to test electronic components in terms of reliability by increased life cycle aging. This is done by changing the temperature inside the test chamber between 125°C to -40°C all 15 minutes. A temperature cycle is shown in Fig. 3.

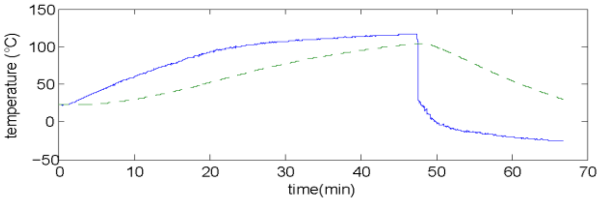

Fig. 3, Temperature of a device with heatsink in a temperature test chamber cold side (green) hot side (blue)

2.3. THERMAL ENERGY HARVESTING

The energy harvesters that are usable for the PCB manufacturing process are based on thermal energy and electromagnetic waves, because this energy can easily be archived at the manufacturing process.

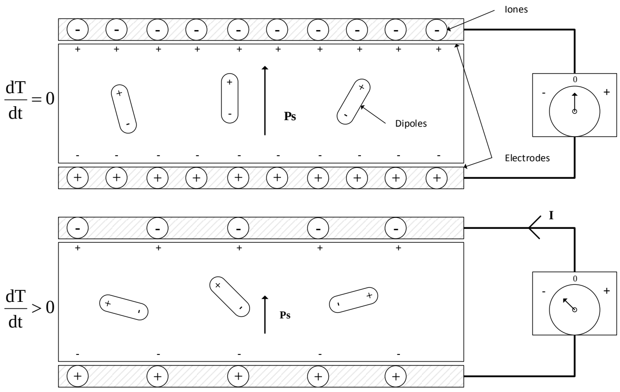

Fig. 4, Schematic principle of the pyroelectric effect

The thermal energy can be harvested by a thermoelectric generator (TEG) or a pyroelectric generator (PEG) [1], [2]. The TEG is based on the Seebeck-effect whereas the PEG utilizes the pyroelectric effect. A viable calculation for the energy generation of the PEG is shown in the following Eq. (1) from [3]:

$$I_{PEG} = \frac{pA\Delta T}{dt} \tag{1}$$

The Eq. (1) is used to calculate the current with the pyroelectric coefficient (p), the area (A) of the PEG, with the orthogonal temperature flow vector and the temperature difference (ΔT) between hot and cold side of the PEG devide by the derivation of the time. The differential component implicits the energy harvesting as a gradient of the temperature difference (see Fig. 4), whereas a TEG requires a steady temperature difference. In Eq. (2) the voltage (V) of a TEG is calculated with the temperature difference and the Seebeck coefficient (α) [4]

$$V_{TEG} = \alpha_{AB}\, \Delta T \tag{2}$$

2.4 EM-WAVE ENERGY HARVESTING

The electromagnetic energy harvesting or energy transfer can be done over a far distance to a transmitting device with an antenna setup or near distance with inductive coupling methods.

The available power in the far field can be described by Eq. (3), the power (dP) depends on the distance (r), the power of the transmitting device (P) and a defined Area (dA) of the antenna. The power level of a transmitter is regulated by country regulations, and can be set up to 25 mW equivalent isotropically radiated power (EIRP).

$$dP = \frac{P}{4\pi r^2} dA \tag{3}$$

The available power decreases with the distance to the transmitting device. The decreasing factor depends on the distance definition: the power in a near field is proportional to 1/3r, whereas for a far field the ratio is 1/r. Therefore, the highest energy transfer is possible in the near field region, discussed in chapter 3.2. For the near field energy with an integrated circuit the NFC defined coupling mechanics can be used. In [5]–[7] inductive coupling is used to transfer energy over the air. A calculation for the energy transfer with known Q factors (Q_1, Q_2 of each coil) and the coupling factor (k) can be done with:

$$\frac{P_{rec}}{P_{tran}} = k^2 Q_1 Q_2 \tag{4}$$

In Eq. (4) (P_{rec}) is the power of the receiver area, whereas (P_{tran}) is the power from the transmitter. This inductive coupling method can also be used to transfer the sensor information wireless, by adjusting the secondary coil load [5].

III. ENERGY HARVESTING

There are wide varieties of methods and technologies under the term of energy harvesting. As before, we focus on available thermal energy harvesting in the PCB manufacturing process and easy to archive energy supply with RF energy harvesting methods. In this chapter simulations and preliminary considerations for the energy harvesting methods will be discussed.

3.1. THERMAL

To compare the thermal energy harvesting methods, both are simulated with known and reliable parameters. The pyroelectric generator is based on the research described in [8]. The parameters for the simulation are given in Table 1.

TABLE 1, PEG SIMULATION PARAMETERS

Unit	Value	Description
A	$1\ [cm^2]$	area
C_E	$1\ [\mu F]$	store capacitor
ε_0	$8.854e-12 [As/Vm]$	permittivity of vacuum
ε'	$14\ [As/Vm]$	real permittivity
d	$0.1\ [cm]$	thickness
p	$40\ [nAS/cm^2 * K]$	pyroelectric coefficient

As can be seen in Fig. 4, the energy harvesting of the PEG after 60 min is about 200 nWs. This harvested energy is simulated with a full bridge rectifier. The base equation for simulation of the voltage for each time step (n) with the parameters of Table 1 is

$$E_n = 0.5 C_E V_n^2\ ;\ V_n = \frac{pA\Delta T}{C_P + C_E} + \left(\frac{C_E \pm C_P}{C_E + C_P}\right) V_{n-1}. \tag{5}$$

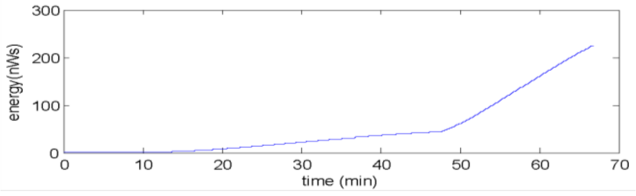

Fig. 4, Simulated energy output of the PEG in a test chamber

The TEG simulation on the other hand (Seebeck-coefficient of 0.03 [V/K]), with the same temperature curve as in Fig. 4, harvests an energy of about 40 Ws after 45 min. This could theoretical power the microcontroller about 50 times per second, based on the same energy consumption as mentioned for the PEG. This simulation proves the usability of a TEG to power the experimental setup, in theory.

3.2. RF-HARVESTING

For the far field energy harvesting a spectrum of the commonly used frequency range was measured with a Wi-Fi device, Bluetooth and a proprietary solution transmitting at the same time (Fig. 5). The measured power at a range of one meter was about 0.0177 Watt, under ideal conditions in an experimental setup (no fading, reflection or absorption). These measurements are done with a spectrum analyzer, which improves the result, and not an energy harvesting circuit with antennas made in PCB-technology.

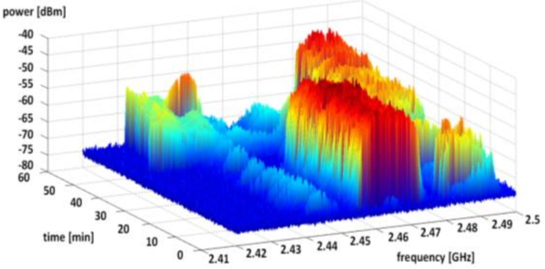

Fig. 5, Power density spectrum of the 2.4-2.5 GHz Band

As mentioned in [9] and [10] the efficiency of the radio frequency energy harvesting depends on the geometry of the antenna and requires a fixed frequency. The space for an antenna with high gain for 2.4 GHz is around 5-7 cm², with a maximum efficiency of 30% (2x2 Koch antenna array[10]). These requirements disqualify the far field energy harvesting for the given scenario of a PCB manufacturing environment, because the near field approach is usable with higher efficiency (80-90%). For another scenario to harvest over greater distances, this far field RF-harvesting may be the better choice.

The major advantage of the near field magnetic induction (NFMI) in the given scenario, is the possibility to power existing integrated circuits with the standardize method (NFC) at an efficiency of about 80-90% [5]. Therefore, the transmitting device don't need to be considered for the energy consumption calculation of the whole sensor system.

IV. TEST SETUP

4.1. HARDWARE

The hardware components are: a microcontroller (EFM32 Zero Gecko from Silicon Labs), a TEG (TEG 071-150-22 from thermalforce build of Bi_2Te_3) as energy harvester, a step up converter and power manager (LT3109 from Linear Technology) and for data transmission (TX) a low cost 433 MHz transmitter or a NFC device (RF430FRL152H from TI).

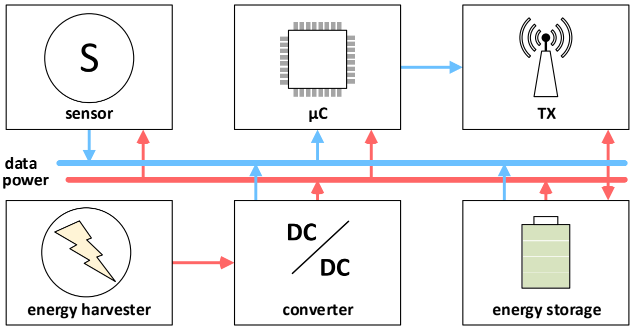

Fig. 6, Schematic hardware component setup

For the hardware components extra tests are done. For the microcontroller the energy consumption was measured with different firmware and used energy modes in combination with the 433 MHz transmitter. The TEG module was tested in a reflow oven with four heating zones and a test chamber for PCBs to compare the simulation results with real measurements.

The converter LTC3109 was tested with the TEG module together to compare the measurements taken with and without the integrated circuit converter. The big advantage of this converter in combination with a TEG, is the auto polarity feature what is useful when hot and cold side temperature changes, like in a test chamber. For storage a 470 µF capacitor was attached to the output of the converter.

For the experimental setup of the system some extra measurement devices are required. These are an oscilloscope (PicoScope 2205) and a data logger (globalPoint ICS). The oscilloscope measured the voltage at different point: the output of the TEG, the converter output, the current consumption of the microcontroller and the wireless transmitter. The data logger was used with thermocouple elements type K for temperature readings near the energy harvester and to verify the calculation software (described in the next chapter).

4.2 SOFTWARE

The required software can be divided into the firmware for the microcontroller and the software that runs on a personal computer to enhance the sensor information.

The demands for the firmware are to use the highest power saving modes of the chosen microcontroller as often as possible . The other energy saving aspect in the firmware is the duty cycle of the sensor data gathering process. Particularly, when the 433 MHz transmitter is used wireless data transfer cycles. These two cycles depend on the requirements of the production equipment. For example, if they need the sensor data every second, the cycles must ensure this.

The software for the control PC requires analyzing the sensor information from the embedded sensor. Therefore, the position of the sensor must be known. Because, the structure of the PCB on top and below the sensor influence the measurement. Consequently, an exemplary tool is written in [11] to calculate the thermal parameters (the thermal time constant in particular) based on the layout file of the PCB under test. Three different geometries over the sensor, were tested (see Fig. 7): a sensor inside FR4 with copper on top (a), a thermal via attached to the sensor (b) and an IC over the sensor (c). For further development the integration of the calculated thermal parameter into the firmware is proposed.

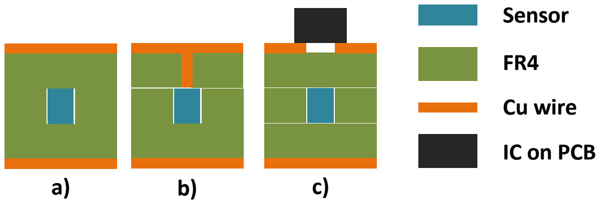

Fig. 7, Test-structure for the thermal time constant calculation

V. RESULTS

The results start with the energy harvesting of thermal energy by a TEG. Therefore, Fig. 8 shows the harvestable energy inside a temperature test chamber. Table 2 shows the simulated Energy of the PEG and the measured one of the TEG for the both test environments. The PEG energy output in nWs area and can't be used for powering the hardware components.

TABLE 2, THERMAL ENERGY HARVESTER BY ENVIRONMENT

Harvester	E_{PEG} $[mWs/min]$	E_{TEG} $[mWs/min]$
Reflow oven	$16e-6$	800
Test chamber	$200e-6$	330

The TEG on the other hand has an energy output of mWs, this can be used to power the required electronic components of the test setup. Therefore, the TEG was connected to the converter to test the combination of both.

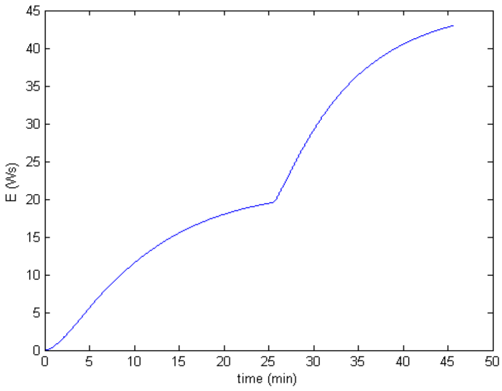

Fig. 8, Energy of a TEG in a temperature test chamber

In Fig. 9, the Voltage of the TEG with the connected converter in a reflow oven is shown. The blue curve displays the voltage at the output of the converter and the green one the voltage of the output of the TEG. The converter has a minimum voltage of 50-100 mV (depending on the used transformer ratio). The figure shows that the voltage of the TEG in a reflow oven is sufficient for the converter to power itself and load a 470 µF capacitor at the output.

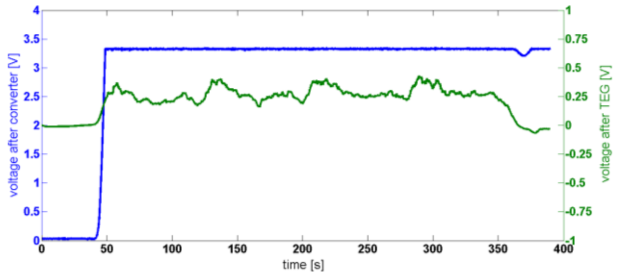

Fig. 9, Voltage of the TEG with the connected converter in a reflow oven

To check if the energy harvesting of the TEG in the tested environment is enough to power the sensor and the microcontroller some measurements are done, with the power consumption. In Fig. 10 the current consumption is shown for three different firmware cases:

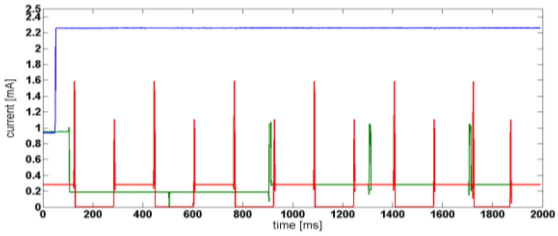

Fig. 10, Current consumption of the microcontroller with a 433 MHz transmitter - blue: always online – green: cycle 400ms & low power mode –red: cycle 200ms & ultra-low power mode

The blue curve shows the power consumption of an always on-line mode then in green an optimized low power mode with 400 ms cycle time is given, at least the red curve describe the ultra-low power mode with 200ms cycle time. The 200 ms are chosen to show that the mode consumes less power even if it has a higher duty cycle (DC). Table 3 shows the average energy consumption calculated with 3.3 V supply voltage.

TABLE 3, POWER CONSUMPTION OF THE MICROCONTROLLER WITH DIFFERENT FIRMWARE

mode	P_{avg} **[mW]**	P_{peak} $[mW]$
always one-line	7.3	7.5
low-power 400 ms DC	0.9	3.3
ultra-low-power 200 ms DC	0.6	5.2

The results of the software, to calculate the thermal parameter for an embedded temperature sensor, are shown in the following table 4. The values are considerably different from each other, which leads to different sensor information in terms of temperature depending on the structure. The heat flow is 100 times faster with a via attached to the sensor in comparison to bare FR4 in the way. The results demonstrate the gap between the structures, but require calculation for each layout independently.

TABLE 4, CALCULATED TIME CONSTANT FOR DIFFERENT STRUCTURES ABOVE THE SENSOR

structure	τ_{calc}**[s]**
FR4+Cu	4
with IC	32
with Via	0.005

VI. COMPARISON

We showed in this paper that a TEG as an energy harvester for an embedded sensor in a PCB within the PCB-manufacturing environment can be used. The PEG was not sufficient. For applications without thermal energy an energy harvester based on the RF harvesting can be used. In particular a near field inductive coupling method is preferred, because this energy concept is able to send the sensor data and the energy consumption of the transmitting device omitted.

In conclusion, the use of a TEG as a primary harvester to power the sensor and the microcontroller in a thermal environment is a suitable approach for this scenario. When it comes to data transmission a NFMI method has the advantage over a normal radio transmitter, because the power will be delivered from the receiving device and can lead to a NFMI powered solution of the whole sensor system.

The used microcontroller requires a firmware to ensure minimum power consumption. The results show that the best configuration for a cycle of about 1 s requires 300 µW (with peaks of 5.3 mW). With this setup a TEG will be enough to power the system. The PC software calculations prove that it is required to take this parameter dependency into consideration, because of the difference (factor 100) between the structures.

The future work will focus mainly on creating the whole system with an NFMI and a TEG as power supply. Also, different sensor types have to be evaluated, which will give additional information about the production process and the life time monitoring of a PCB product. Also the interaction of calculations in the layout phase, like the thermal parameter calculation and the placement with the microcontroller of the sensor system, and the control PC of a manufacturing process with these informations, will require further research and tests.

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