»GREEN ICT @ FMD« – Competence Center for Ecologically Sustainable ICT

IoT Current Sensor Nodes for Current Measurement on Cleanroom Equipment for Determining and Optimizing the CO_2 Footprint of Semiconductor Process Tools

A white paper by "HUB 1 – Sensor Edge Cloud Systems and HUB 3 – Resource-Optimized Electronics Production"

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Introduction

As part of the Green ICT @ FMD competence centre, innovative technologies for the ecologically sustainable design of information and communication technology (ICT) are being developed. A central element is the development of sensor edge cloud systems (SEC).

Sensor nodes form a central pillar of the Internet of Things (IoT) by collecting, processing and transmitting data from objects, systems and their environment via sensors. This process takes place decentrally in the so-called sensor edge cloud (SEC). This collected data provides valuable information that is used to monitor and optimize machines, systems and processes in a wide variety of areas. In addition to improving safety, quality, reliability and cost-effectiveness, the focus is often also on increasing sustainability. In view of this fact, however, the important question arises as to the sustainability of the sensor nodes and their operation itself.

In this context, the current sensor nodes are discussed, which are of great importance for precise current measurement and balancing in energy-intensive environments, especially in cleanrooms. The aim is to enable measurement at existing individual systems in order to ensure that their electricity consumption is accurately recorded.

To this end, this white paper analyzes the CO_2 footprint of networked current sensor nodes for the measurement of electricity at cleanroom systems in the production and use phases. The CO_2 footprint for both phases of the current sensor node should be as small as possible so that it quickly pays for itself if the power consumption of the cleanroom system is optimized.
These current sensor nodes make it possible to determine the current at individual cleanroom systems in order to calculate the energy consumption at these systems. In addition to the energy consumption for resources and the cleanroom infrastructure, the energy consumption of the cleanroom system makes a significant contribution to the calculation of the CO_2 footprint of the respective process step. This is particularly important with regard to the overall CO_2 footprint of a cleanroom, as in the case of Fraunhofer EMFT.

The Fraunhofer-Gesellschaft has set itself the climate goal of reducing greenhouse gas emissions to 55% by 2030 and being largely climate-neutral by 2045. For this purpose, it is necessary to carry out an analysis of the current situation at the Fraunhofer Institutes in order to be able to initiate appropriate measures. The semiconductor cleanrooms at the institutes in particular must be subjected to a precise analysis for this purpose, as gases with a high global warming potential (GWP), such as SF_6, which has a footprint 23,900 times higher than the base level of CO_2, are used here.

Two variants of the current sensor are presented here and their CO_2 footprints for the production and use phase are determined. The first variant of the current sensor is a typical shunt solution, in which a shunt for current measurement must be installed in the system installation. The second variant of the current sensor has a splitcore Hall current sensor, which is perfect for installation in brown-field installations.
In addition, the findings from the two investigations will be used to create a concept for an ideal current sensor for brown-field applications.

1. Orienting life cycle assessment for the current sensor nodes

An orienting life cycle assessment (LCA) is a rough analysis of the environmental impact of a product over its entire life cycle. The aim is to look at initial indications of the ecological impacts without carrying out comprehensive and detailed life cycle analysis.

The objectives of life cycle assessment are:

- Identification of environmental aspects such as resource consumption, emissions
- Initial assessments of ecological efficiency
- Support of decision-making processes in product development
- The environmental balance is drawn up for the production phase and the use phase

In the following sections, therefore, a LCA of the production phase and an estimation for the use phase are carried out for both variants of the current sensor node.

1.1 Current Sensor Node with External Splitcore Hall Current Sensor

For the determination of the CO_2 footprint (PCF – Product Carbon Footprint) in the production phase of the current sensor node with external Hall current sensor, the component lists (BOM – Bill of Material) of the individual components were recorded in a bottom-up approach and a potential analysis with regard to the CO_2 footprint was modelled based on environmental database of Fraunhofer IZM. The current sensor node, featuring an external Hall sensor, consists of three main components: the controller unit—specifically a Raspberry Pi—the ADC shield, which records current values by converting analog signals to digital, and the external Hall current sensor, as illustrated inFigure 11.

Figure 1: Block image of the current sensor node with external Hall current sensor

Figure**Fehler! Ungültiger Eigenverweis auf Textmarke.** shows the Raspberry Pi (left), the ADC shield (middle), and the external Hall current sensor (right).

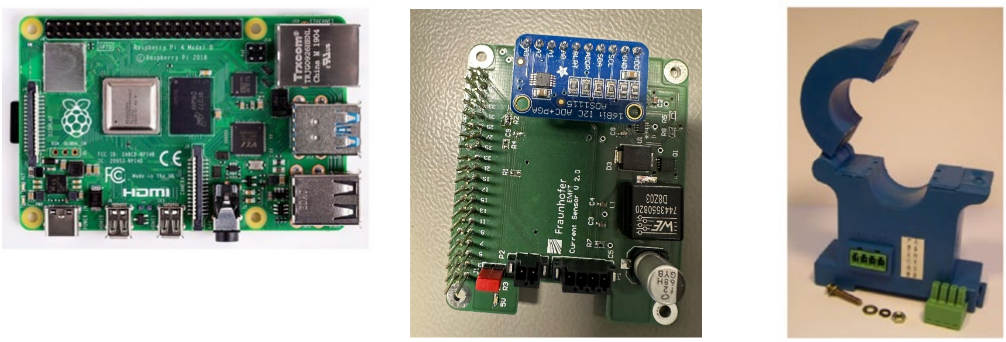


Figure 2: Current sensor node consisting of RaspberryPi (left), ADC shield (middle), external Hall current sensor (right)

Next, a CO_2 footprint is assigned to the components from the BOM (Bill of Material) of all three components of the current sensor node with external Hall current sensor. This is done either via material databases or from existing LCAs. If database values cannot be used, a CO_2 footprint can be estimated based on the material composition. This analysis has been carried out below for all three components.

The total CO_2 footprint for the current sensor system with external Hall sensor is divided as follows:

1. The GWP (Global Warming Potential) for the Raspberrry Pi is 9.46 kgCO_2 eq.

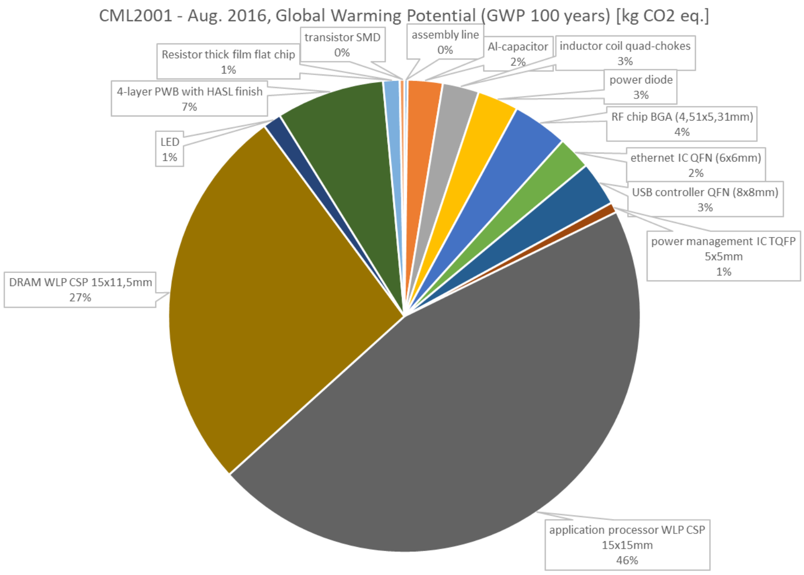


Figure 3: GWP for the Raspberry Pi

2. The GWP (Global Warming Potential) for the ADC-Shield is 0.64 kgCO_2 eq.

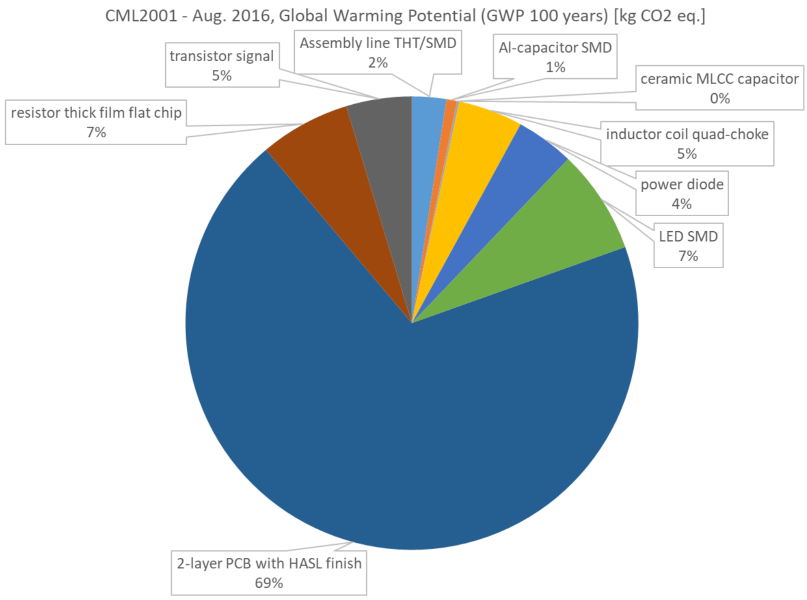


Figure 4: GWP of the ADC Shield

3. The GWP (Global Warming Potential) for the external Hall sensor is approximately 1.57 kgCO_2 eq.

This results in a total GWP of 11.668 kgCO_2 eq. for the current sensor system with external Hall current sensor.

1.2 Current sensor node with integrated Hall current sensor

Figure 5: Current sensor system with integrated Hall sensor

For the current sensor system with the integrated Hall sensor (see Figure 5), the CO_2 footprint for the production phase could also be determined based on the BOM (Bill of Material). Fraunhofer IZM has calculated a GWP of **0.45 kgCO_2 eq.** determined. The communication modules represent some uncertainties in the GWP, as it is not clear how many ICs were installed in the modules and thus no clear chip area could be estimated.

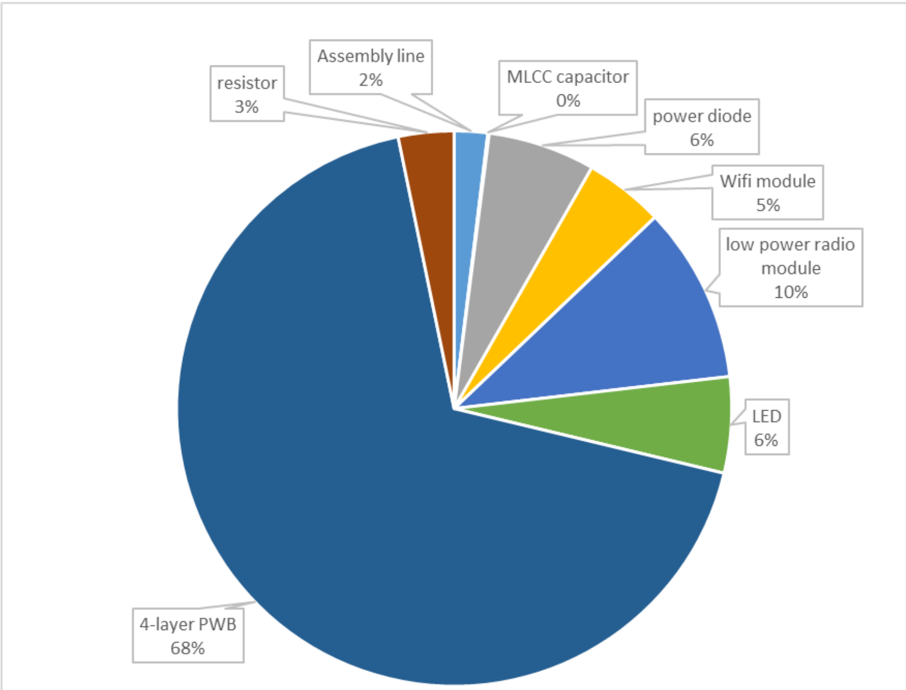


Figure 6: GWP of the current sensor system with integrated Hall sensor

The determination of the CO_2 footprint in the use phase was also determined for both current sensor systems. In the context of recording the usage data of cleanroom systems and equipment, 24/7 operation must be assumed, as such systems are never switched off and are typically only put into standby mode. Therefore, the system current must be permanently monitored.

For the current sensor system with external Hall sensor, this results in the following calculation for the use phase:

	Spannung	Strom	Leistung P [W]	Energie E [Wh]	Energie E [kWh]	
Stromsensor	5	0,7	3,5			
im Sendebetrieb						
			gesamte Leistung	Energie pro Tag	Energie pro Jahr	
			3,5	84	30,66	

	Gesamt Energie [kWh] pro Jahr			Anteil	Anteil Energie [kWh] pro Jahr	
Stromsensor	30,66			1	30,66	
im Sendebetrieb						
			Gesamt Energie [kWh] pro Jahr		30,66	
			Umrechnung in kg CO2 eq. (f. 2022, UBA)			
			0,434	kg CO2 eq./kWh	**13,3064**	**kg CO2 eq./a**

Figure 7: Calculation of the CO_2 footprint in the use phase for the sensor system with the external Hall sensor

Assuming a service life of the sensor system of 10 years, a value for the use phase of 133.06 kgCO_2 eq is obtained.

For the current sensor system with integrated Hall sensor, the following calculation results for the use phase:

	Spannung	Strom	Leistung P [W]	Energie E [Wh]	Energie E [kWh]	
Stromsensor	5	0,07	0,35			
im Messbetrieb						
			gesamte Leistung	Energie pro Tag	Energie pro Jahr	
			0,35	8,4	3,066	

	Spannung	Strom	Leistung P [W]	Energie E [Wh]	Energie E [kWh]	
Stromsensor	5	0,1	0,5			
im Sendebetrieb						
			gesamte Leistung	Energie pro Tag	Energie pro Jahr	
			0,5	12	4,38	

	Gesamt Energie [kWh] pro Jahr			Anteil	Anteil Energie [kWh] pro Jahr	
Stromsensor	3,066			0,99	3,03534	
im Messbetrieb						
Stromsensor	4,38			0,01	0,0438	
im Sendebetrieb						
			Gesamt Energie [kWh] pro Jahr		3,07914	
			Umrechnung in kg CO2 eq. (f. 2022, UBA)			
			0,434	kg CO2 eq./kWh	**1,33635**	**kg CO2 eq./a**

Figure 8: GWP in the use phase of the current sensor system with integrated Hall sensor

For the service life of the sensor system of 10 years, a CO_2 footprint of 13.36 kg CO_2 eq. .

To compare the total GWP of the two current sensor systems, the following can be noted:
Production and use phase for the current sensor system with external Hall sensor:

11.668 kg CO2 eq. + 133.064 kg CO2 eq. = <u>144.732 kg CO2 eq.</u>

Production and use phase for the current sensor system with integrated Hall sensor:

0.45 kg CO2 eq. + 13.364 kg CO2 eq. = <u>13.81 kg CO2 eq.</u>

Result:

The environmental assessment of the two current sensor systems shows that the total GWP of the current sensor system with the integrated Hall sensor is about **10 times smaller** than the total GWP of the current sensor system with the external Hall sensor.

1.3 Optimized current sensor node with external splitcore Hall current sensor

To further reduce the CO_2 footprint of a current sensor node, a concept was developed that enables the complete integration of the electronics by means of a selected microcontroller with all necessary interfaces. The sensor system could also be supplied by an energy harvester, e.g. from a partner institute. The current sensor does not necessarily have to be integrated on the board; rather, a Hall sensor with split ferrite for current measurement makes subsequent installation much easier. In addition, this sensor has only a slightly higher impact on the CO_2 footprint over a longer service life.

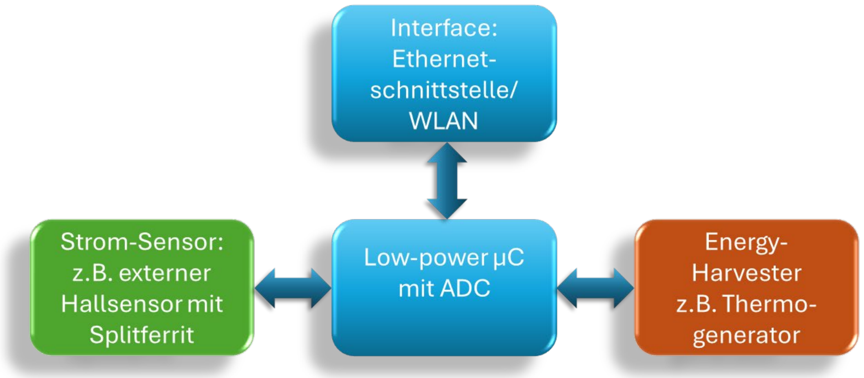
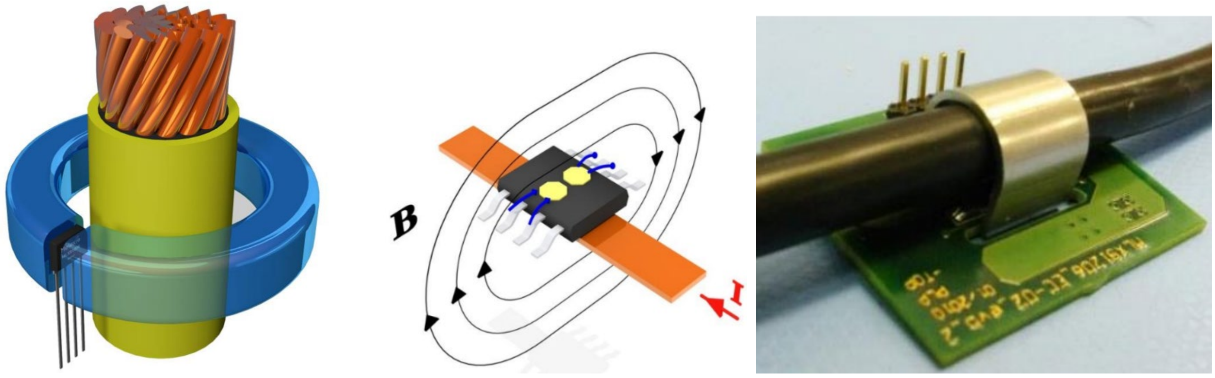


Figure 9. Concept of an optimized current sensor with external Hall sensor with splitcore

1.4 Different Hall sensor installations for current measurement on process plants

Conventional Hall-Sensor | Planar Hall-Sensor | Planar Hall-Sensor with round cable



$B = 1{,}25 * \frac{I}{d}$
d = size of air gap in ferrite

$B = 1{,}25 * \frac{I}{W}$
W = width of the conductor

Figure 10. Conventional (left) and planar Hall sensors (right) [1]

The conventional Hall sensor (seeFigure 10 on the left) is also available as a split-core Hall sensor for current measurement to install the current sensor on existing installations. The planar design of the Hall sensor can also be used to measure current on round cables. For this purpose, a shielding plate made of Mu metal (see Figure 10 on the right). In addition to Hall-sensor-based current sensors, there are also coil-based current sensors available, also with a split-core ferrite. However, a complex calibration must be carried out here until a linear dependence between current and measured value is created.

Both Hall sensor types, conventional and planar, show a very good linear relationship between output voltage and current in the electrical conductor (s. Figure 11).

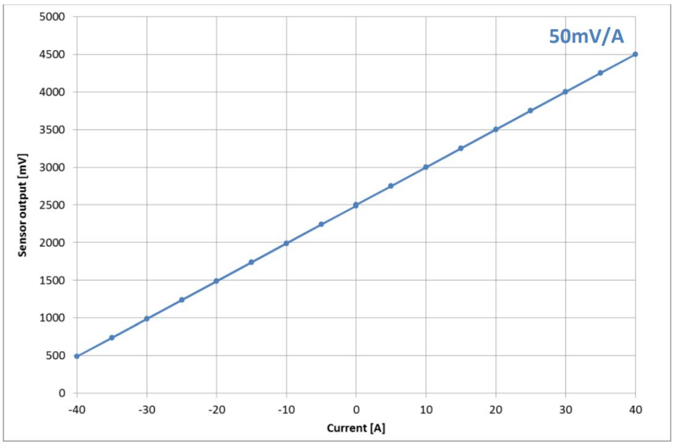


Figure 11. Relationship between the output voltage and the current in the electrical conductor [1]

2. Use of sensors to monitor the power consumption of production equipment in cleanrooms

Selected current sensors were successfully installed on the process systems in the EMFT cleanroom. The EMFT evaluated the current sensors by using them to monitor the Evatec Clusterline sputtering tool and the Tempress diffusion oven. Electricity consumption is recorded and stored in our InfluxDB time series database. The aim is to analyze some standard processes in order to identify possible energy saving potentials.

Figure 12: Current sensor installation on the process systems at the EMFT

2.1 Evatec Clusterline Sputter System

The Evatec Clusterline Sputtering System was used to monitor power consumption in a standard sputtering process of 377 Ohm-TiN (30 nm) on our customer's wafers. The current data is shown in Figure 13 and explains the following phases of the sputtering process:

- (1) Heat the substrate holder from 50°C to 340°C
- (2) Conditioning process
- (3) Break
- (4) Wafer Sputtern (28 Wafer)
- (5) Turn off the magnetron
- (6) Reduce heating to 50°C

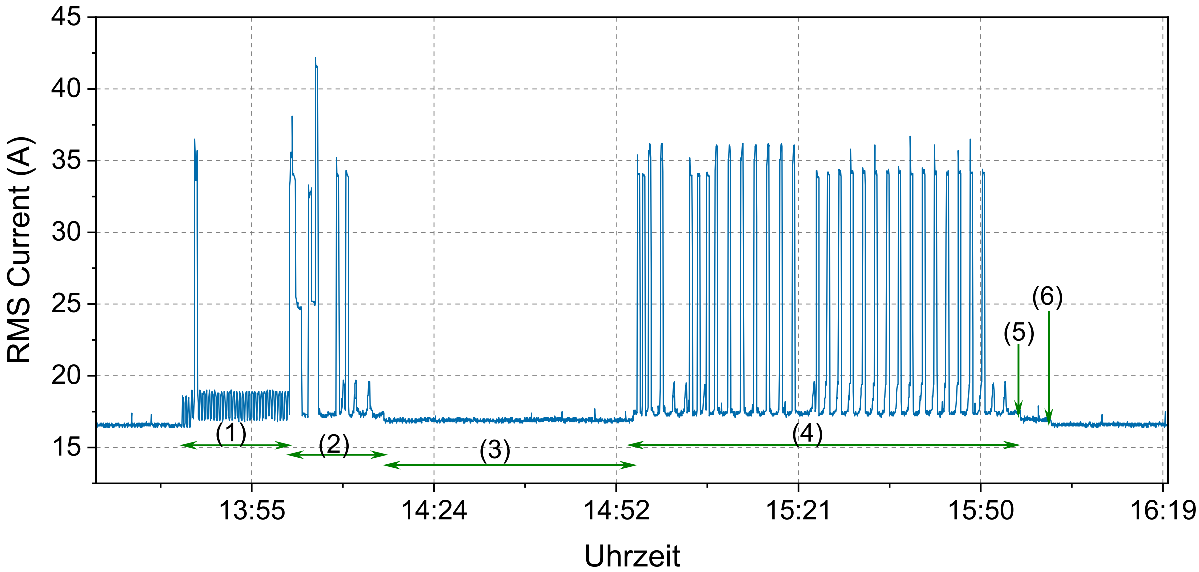


Figure 13: Measurements of current consumption from the Evatec Clusterline during sputtering of 377 ohm TiN on 200 mm wafers

In order to investigate the energy consumption of the individual components of the system, the entire machine was switched off completely and each component was switched on again (see Figure 15). The components of the sputtering plant that contribute to the energy consumption are the cryogenic pumps, the turbopumps and the compressors. The power share of cryogenic pumps is relatively low (0.5-0.8 kW) because we replaced the pumps with energy-efficient pumps a few years ago. The energy consumption of the compressors is high (about 8.3 kW), but they have to be on all the time.

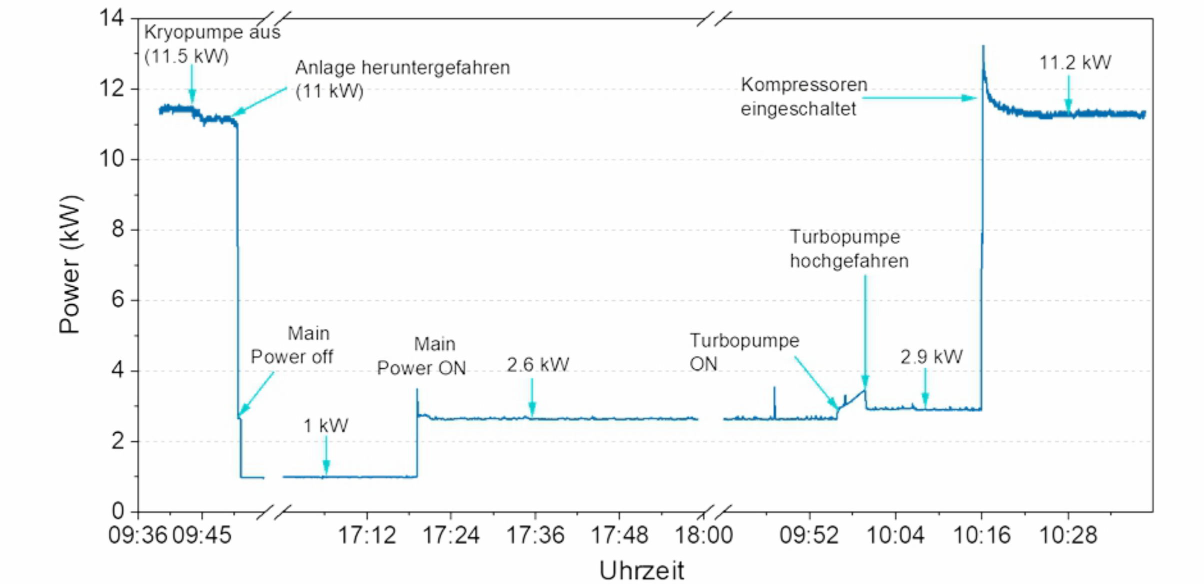


Figure 14: Energy consumption of the individual components of the sputtering system

From a process perspective, energy consumption can be optimized by reducing the temperature of the wafer chuck during the sputtering process. Therefore, TiN's sputtering process was studied in detail for possible energy savings by reducing the Chuck temperature from 340°C to room temperature. The energy consumption was calculated for a batch of 25 wafers. With this value, the energy saving is only about 0.6 percent of the energy that the entire system uses for the sputtering process. So for 25 wafers, we can only save 0.17 kWh. Further possibilities for energy savings are being evaluated.

2.2 Diffusion furnace

The Tempress diffusion furnace was also tested using one of our standard processes, which deposited 530nm of wet oxide on Si wafers. The standby temperature of the furnace was 650°C and the deposition temperature was 1000°C. Figure 15 shows the recording of the entire process, which can be explained by the following phases:

- (1) Opening the furnace and loading the wafers
- (2) Furnace was closed and the temperature was raised to 1000°C
- (3) Oxidation
- (4) Cooling the furnace to standby temperature (650°C)
- (5) Unloading wafers

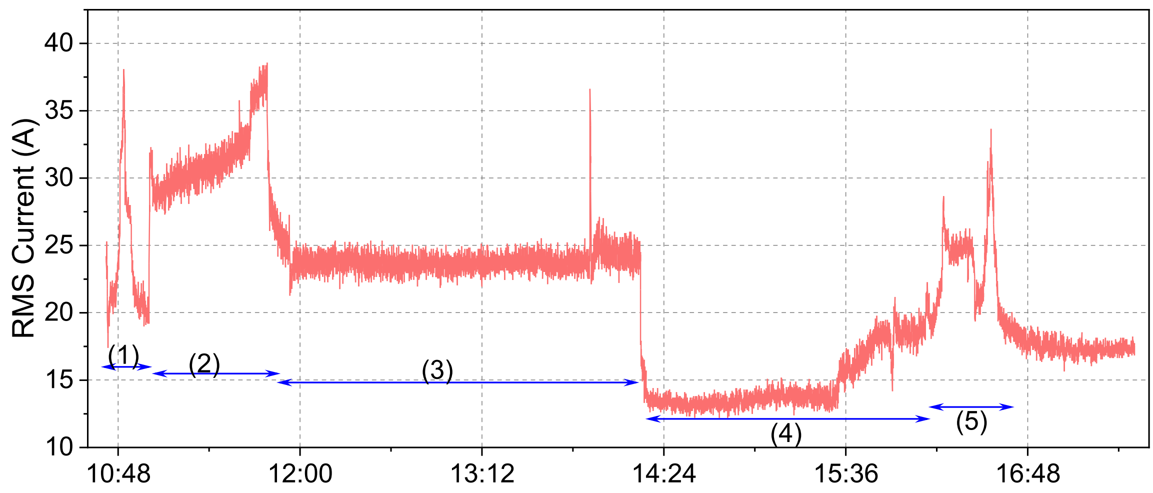


Figure 15: Measurements of the current consumption from the diffusion furnace for a deposition of 530nm oxides on Si wafers

We have tested two energy-saving strategies on our thermal furnace at Fraunhofer EMFT. The first is lowering the standby temperature during the weekend from 750°C to 450°C (Figure 17). With this measure, we calculate an energy saving of 8.2 tCO_2 eq./year. However, with this approach, heating up (from 450°C back to 750°C) takes a few hours. For this reason, this procedure is not very useful, as it takes too long to reach the operating mode for new furnace runs. In addition, you have to set the temperature manually every Friday and Monday so far.

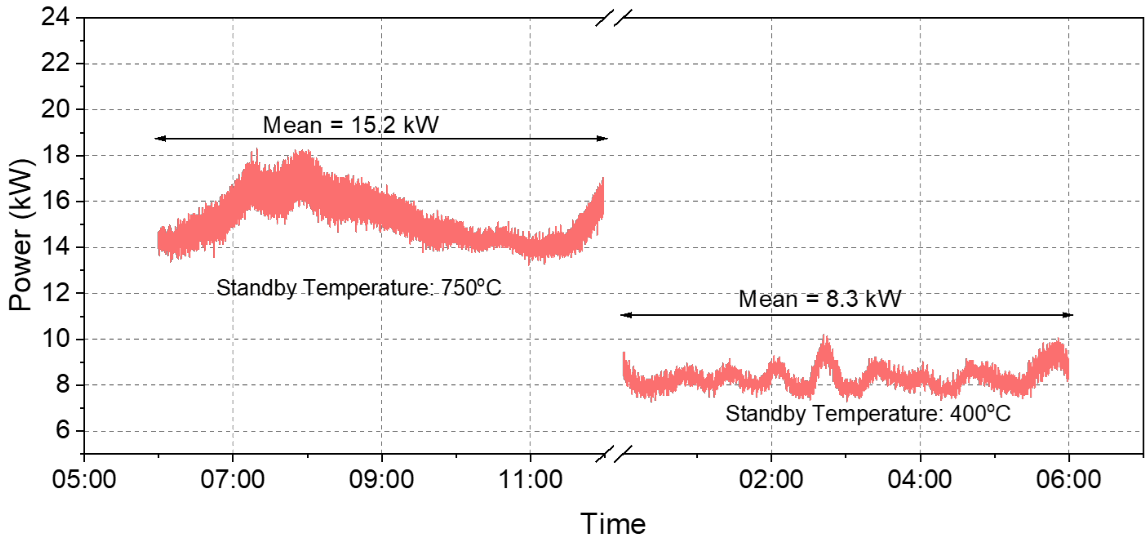


Figure 16: Energy consumption of the thermal furnace by lowering the standby temperature from 750°C to 450°C over the weekend.

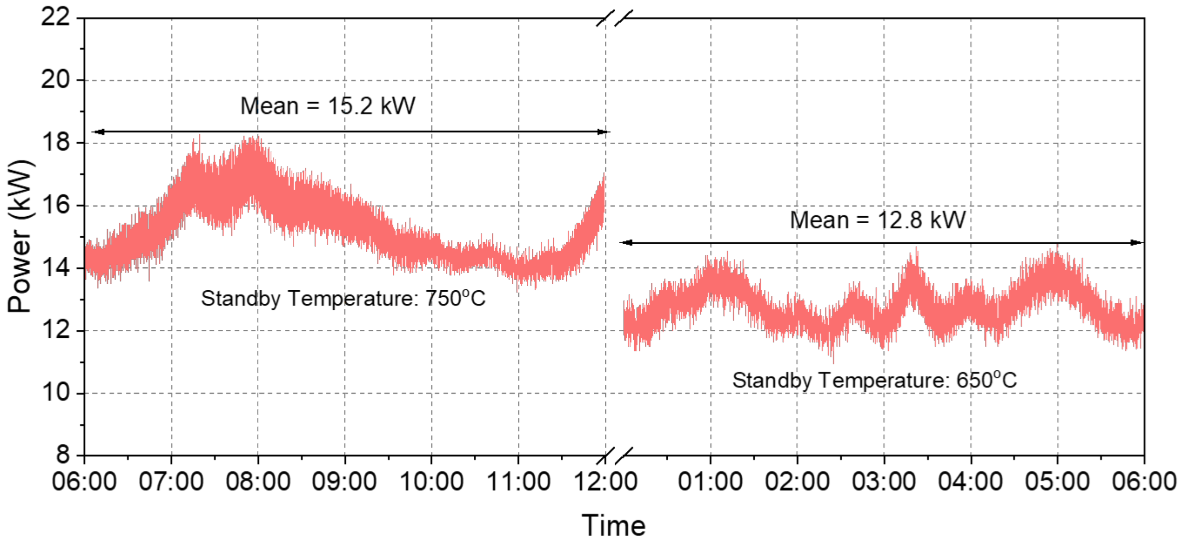


Figure 17: Energy consumption of the thermal furnace by lowering the standby operating temperature from 750°C to 450°C during the weekdays

The second approach is to reduce the standby temperature during operation from 750°C to 650°C (see Figure 17). This results in a saving of 5.1 tCO_2 eq./year. This is cheaper than the first approach, as it only switches to the new standard operating temperature. The calculation is based on current mixture in Germany 2024 (363g in CO_2 eq. per kilowatt hour).

3. Summary

Background and objective
This white paper describes the work of the Green ICT @ FMD competence centre, which develops innovative technologies for ecologically sustainable information and communication technology (ICT). One focus is on the development and evaluation of current sensor nodes for precise current measurement in cleanroom production facilities in order to determine, optimize and reduce the CO_2 footprint of semiconductor processes and components.

Sustainability of the sensor nodes
Sensor nodes are central elements of the IoT and provide data for the optimization of machines, systems and processes – with a focus on sustainability. The question of LCA of the sensor nodes themselves and their CO_2 footprint during operation are essential points that must be estimated at the beginning of a planned optimization, as the savings potential must be higher than the GWP for the sensor nodes themselves.

Variants of current sensor nodes
Two variants are compared, namely current sensor nodes with an external split-core Hall current sensor and current sensor nodes with an integrated Hall current sensor.

Current Sensor Node with External Splitcore Hall Current Sensor
Components: Raspberry Pi, ADC shield, external Hall sensor.
Total GWP (Global Warming Potential) in the production phase: 11.668 kg CO_2 eq.
GWP in the use phase (10 years): 133.06 kg CO_2 eq.
Total: 144.73 kg CO_2 eq..

Current sensor node with integrated Hall current sensor
Total GWP in the production phase: 0.45 kg CO_2 eq.
GWP in the use phase (10 years): 13.36 kg CO_2 eq..
Total: 13.81 kg CO_2 eq.

Cognition:
The system with integrated Hall sensor causes only about a tenth of the CO_2 footprint over its life cycle compared to the external solution.

Optimization concept
An optimized concept provides for the complete integration of electronics with microcontrollers and energy harvesting.
Splitcore Hall sensors make retrofitting easier and have little impact on the CO_2 footprint over the lifetime.

Practical use and energy saving
The sensors have been successfully installed on production equipment in the clean room of EMFT (e.g. Evatec Clusterline Sputtering System, Tempress Diffusion Oven).
The measurements enable the identification of energy saving potentials, e.g. by adjusting the standby temperatures.
Example: Lowering the standby temperature of a diffusion furnace from 750°C to 650°C saves 5.1 tCO_2 eq. per annum.

Overall conclusion
The environmental assessment shows that the choice of sensor design has a significant impact on the LCA.
Targeted technical measures and monitoring can achieve significant energy and CO_2 savings in semiconductor production.

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