# Active thermal probe for continuous and direction-dependent measurement of the energy influx in plasma technological processes

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## Abstract

A new calorimetric probe for measuring the energy influx is presented. The probe works according to a compensation principle. The incoming energy influx is compensated on a dummy at a constant sensor temperature by reducing the heating power. The measured value does not depend on the heat capacity or the thermal conductivity of the sensor since the probe operates in thermal equilibrium. This also makes it possible to measure the energy influx during coating processes. A special combination of more than one sensor also allows to record the energy influx depending on the direction, without the need for shielding. The probe is especially suitable for system diagnostics and process monitoring.

## 1. Introduction

Almost all plasma technology applications for surface processing are based on plasma-wall interactions that take place via the plasma sheets that are formed. The influx of energy from the plasma onto the substrate, which can be measured with calorimetric thermal probes, is of great importance for the properties of the resulting layer or the treated surface. So far, probes have been used for this, in which the intensity of a thermal effect depending on the energy influx is measured. Various possibilities for this have been described in detail: measurement of the spatial temperature difference produced by the influx of energy on a substrate [1,2], determination of the temperature increase in the center of a membrane that is exposed to the influx of energy and at the edges cooled [3,4], recording of the heating and cooling curve of a dummy substrate [5-7] and radiation measurement with a thermopile sensor [8].

With these probes, the proportionality factor between the incoming energy influx and the intensity of the thermal effect must be determined by a comparative measurement with an energy source of known intensity and/or by simulation.

This calibration causes measurement uncertainties because in most cases the reflection coefficient of the probe surface is not known [9]. Beside that there are further disadvantages, such as a discontinuous measurement (passive thermal probe), a complicated and/or robust structure or very large compact screens to shield thermal radiation from unwanted directions.

## 2. Procedure characterization

The challenges mentioned above finally led to the development of the active thermal probe, in which the measurement of the energy influx is carried out in thermal equilibrium [10]. With this probe no calibration is necessary and environmental influences as well as the heat dissipation of the probe to the holder are almost completely compensated.

The patented and relatively simple principle of the active thermal probe is as follows: A dummy substrate is used as a probe to determine the energy influx onto a given area. The measuring surface is brought to its working temperature by means of a controlled heating system and the heating power required to maintain thermal equilibrium is measured. The probe is now ready for operation. An influx of energy from outside (plasma, thermal radiation, kinetic energy of particles, condensation heat, etc.) causes additional heating and thus disrupts the thermal equilibrium. In order to keep the working temperature constant, the externally supplied heating power must be reduced. The lowering is then identical to the energy influx, which is displayed directly in mW/cm².

A major difficulty with calorimetric probes to be considered is that the energy balance at the probe changes due to temperature changes in the immediate environment of the sensor. This inevitably happens because the heat flow also changes when the temperature gradient changes. For this reason, the same principle for compensating for heat flows is used with the active thermal probe – similar to the measuring surface – in order to calorimetrically decouple the sensor from the

ISBN 978-3-8007-5835-7

holder and the supply lines. This ensures that the energy balance of the probe remains unchanged when the temperature of the holder and the supply lines changes.

A special version of the probe consists of a combination of more than one heated sensors. This allows separated measurements of the energy influx from the half-space above and from the half-space below the probe. Consequently it is possible to record the energy influx at the probe as a function of the angle of rotation with respect to the normal. Subsequent processing of the measured values using the Laplace transformation can be used to determine the much more interesting dependency: the energy influx at the probe as a function of the angle of incidence. This is particularly important for applications in which the energy influx from the plasma source is overlaid by other heat or energy sources in the reactor chamber.

# 3. Probe structure and recording of measured values

The sensor of the active probe consists of a special platinum element, which is both a heater and a temperature sensor. Its connections and supply lines are protected from the influx of energy and in particular from coating by a ceramic or stainless steel tube. A typical embodiment of the probe is shown in Fig.1.

A special software takes over the adjustment and control of the heating as well as all functions and measuring processes via an AD/DA converter card built into a PC, which is connected to the probe via a signal adjustment. A potential isolation from the plasma is integrated into the signal adjustment as well as a filter specifically to reduce high-frequency interference voltages. Another embodiment operates with an external device in which a microprocessor is integrated to take over the temperature control.

The probe can currently be used for energy influxes of up to 2 W/cm² and operates with a resolution of 1 mW/cm². This enables numerous surface technologies such as thermal evaporation, sputtering, electron beam evaporation, hollow cathode arc evaporation, vacuum arc evaporation, CVD, PECVD, MOCVD, etc. to be monitored and controlled.

Other current parameters of the active thermal probe are:

Measurement area: 0,5 cm²

Sensor temperature: <= 400 °C

Temperature consistency: ± 0,03 °C

Max. measured value fluctuations: ± 1 mW/cm²

The special design of the probe also allows measured values to be recorded in the so-called "passive mode". The probe works like the conventional "passive probe". The procedure has already been described in detail in [5]. In this case the Pt100 element of the measuring surface is not heated, but only serves as a temperature sensor. It is designed in such a way that it can be briefly exposed to a temperature of 600 °C without being damaged. Because of the relatively low heat capacity, energy influxes of up to 100 W/cm² can then be measured! However, as with the passive thermal probe, this happens in discontinuous operation.

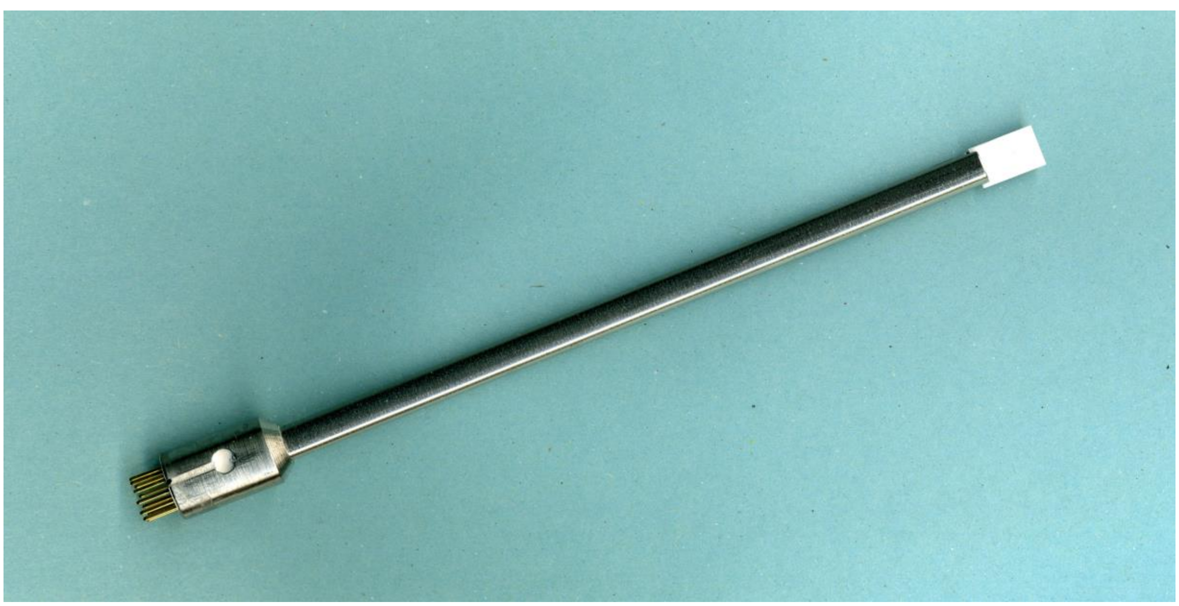

**Fig. 1:** Embodiment of the active thermal probe

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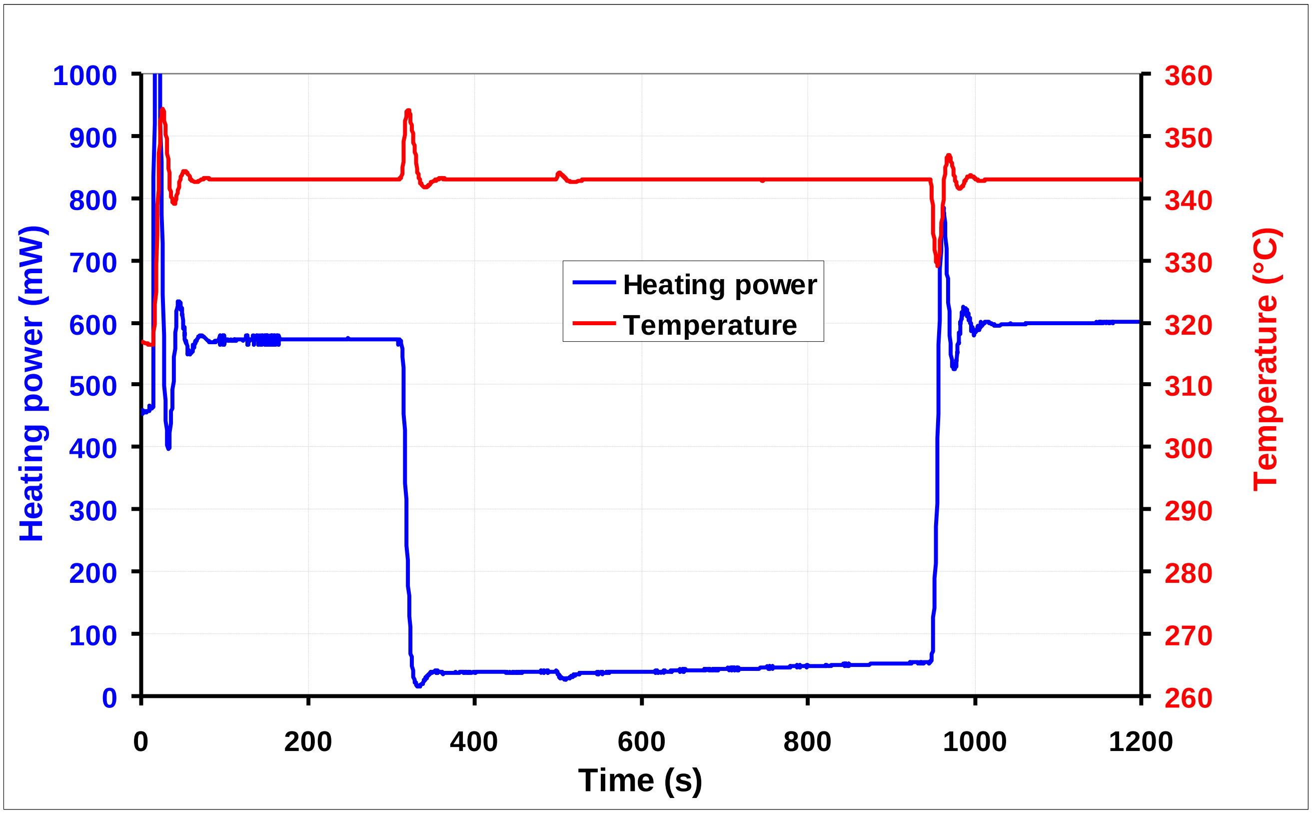


**Fig. 2:** Temperature and heating power at the active probe in an ion beam [12]

## Experimental results

Many measurements were made with the probe in a wide variety of plasmas. A selection of them will be presented here. For example, measurements were made on an ion source (beam diameter 160 mm) at a distance of 225 mm, at a working pressure of 0.04 Pa and a beam voltage of 500 V. Fig. 2 shows the heating power supplied and the temperature at the probe over time. After switching on the energy source (ion source) at around 300 s, the probe temperature increases, which the controller reacts by reducing the heating power. After about 30 s the temperature equilibrium is restored. At this point, the applied heating power at the probe is approximately 500 mW less than in the “plasma off” state, which corresponds to the incoming energy influx from the ion source.

Based on the fluctuations that occurred and taking into account the size of the measuring area (0.5 cm²), the energy influx can be determined with an accuracy of 1 mW/cm² using the active thermal probe.

The reaction time of the probe was about 30 s for this measurement. This time is needed to restore the temperature equilibrium when the energy influx changes by 100%, in order to be able to determine and display the new measured value of the energy influx. Although this is a respectable size for normal applications, especially for the control and regulation of plasma processes, it can be drastically reduced. Especially as the heating power of the sensor reacts to changes in the energy influx within fractions of a second as shown in the diagram. So if one knows a target value for this variable or the correlation to the properties of the surface of the substrate, a signal can be given to the process within a very short time.

Basically, the reaction time depends on the heat capacity of the probe and the quality of the temperature control. The dimensions of the sensor itself of 7 x 7 mm allow a good local resolution.

To illustrate the measurement of the spatial resolution of the energy influx, Figs. 3 and 4 show the radial profile of the energy influx of the ion source (diameter 160 mm, beam voltage 500 V, source distance 225 mm) and an APS source (power 7.3 kW , bias voltage 133 V, pressure 0.02 Pa). Both sources are used in coating systems for optical layers. [11]

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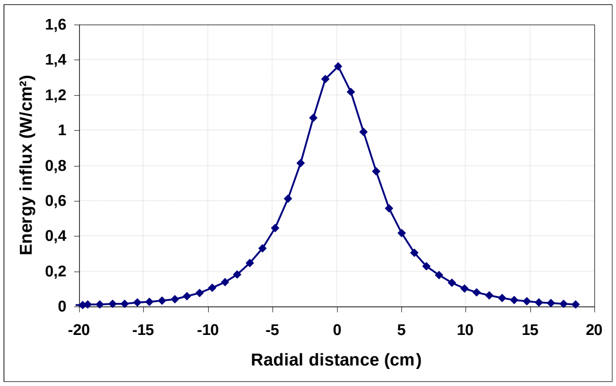


**Fig. 3:** Radial profile of the energy influx of an ion source Ø 160 mm [12]

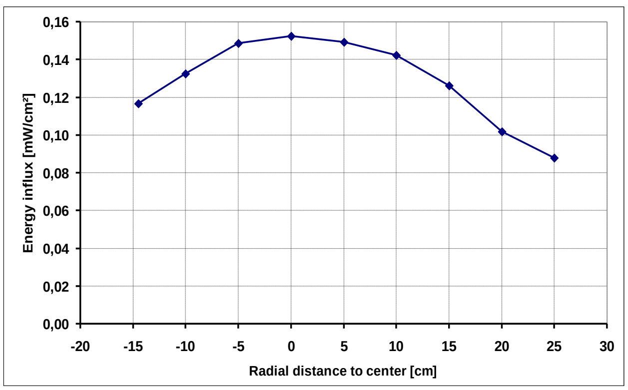


**Fig. 4:** Radial profile oft he energy influx at an APS source [12]

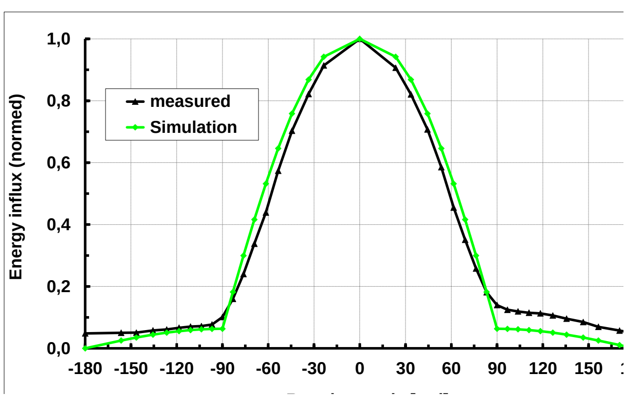


**Fig. 5:** Angle dependence of the energy influx in front of an ion source [12]

Fig. 5 demonstrates the possibility of the probe to determine the energy influx depending on the direction. The angle-dependent distribution of the energy influx was measured at an ion source (type Veeco ALS 340L, working gas Ar) at a distance of 300 mm at a pressure of 0.4 Pa and a beam voltage of 2000 V. (black curve)

In the simulation (green curve), it was taken into account that the edge surfaces of the sensor are also hit by the ion beam when rotating around the longitudinal axis and thus contribute to the measured value.

Therefore, in the range 180° < α < -90° and 90° < α < 180°, an influx of energy is still to be expected, although the back of the sensor is facing the ion source. This is actually shown by the measured values, which show good agreement with the simulation. They also prove that in this plant hardly any background heat radiation reaches the sensor through the mounting parts or the reactor walls. The measured values are only slightly higher than the predicted values in the positive range. This can be caused by the inhomogeneity of the ion beam, which was also observed optically.

Further measurements were made with the probe, e.g. on an RF plasma. For the inductively coupled RF plasma (working gas argon, RF power 300 W, working pressure 0.5 Pa), which is used for plasma etching, the dependency of the energy influx on the RF power is shown in Fig. 6 as an example.

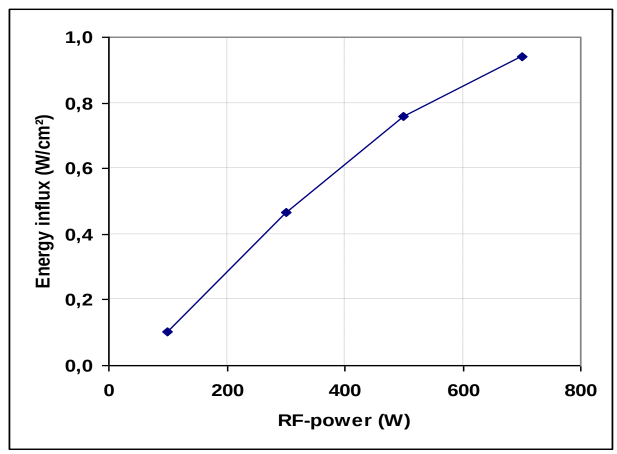


Fig**. 6:** Energy influx versus power in an RF plasma **[12]**

## 4. Summary

A continuously working active thermal probe for the determination of the energy influx at plasma-technological processes is presented. The principle of measurement is based on the compensation of the incoming energy influx. Key benefits are the application for continuous measurement and the suitability for thin film deposition. A cost intensive or complex calibration of the probe is no longer needed.

At selected positions of the reactor the energy influx to the probe can be measured depending on the direction and the correlation with properties of the growing layer or the treated surface, respectively, can be determined. Since the thermal probe reacts sensitively to the process parameters at the substrate surface it is very well qualified for control and monitoring of layer growth or surface treatment processes. Main advantage of the probe is the high sensitivity, good resolution and low efforts for application.

The probe is a cost-efficient, particularly suitable device for quality control in plasma-technological applications.

## 5. Literature


[1] H. Kersten, D. Rohde, H. Steffen, H. Deutsch, R. Hippler: Die Bestimmung von Energieflüssen bei Plasma-Oberflächen-Prozessen, Fachzeitschrift Galvanotechnik 12 (2005) 2996-3007

[2] H. Steffen, H. Kersten, H. Wulff: Investigation of the energy transfer to the substrate during titanium deposition in a hollow cathode arc, J. Vac. Sci. Technol. A 12 (1994 ) 2780

[3] K. Ellmer and R. Mientus: Calorimetric measurements with a heat flux transducer of the total power influx onto a substrate during magnetron sputtering, Surf. Coat. Techn. 116-119 (1999)1102-1106

[4] R. Gardon: An Instrument for the direct measurement of intense thermal radiation, Rev. Sci. Instrum. 24 (1953) 366

[5] J.A. Thornton: Substrate heating in cylindrical magnetron sputtering sources, Thin solid films 54 (1978) 23

[6] H. Kersten, D. Rohde, J. Berndt, H. Deutsch, R. Hippler: Investigations on the energy influx at plasma processes by means of a simple thermal probe, Thin Solid Films 377-378 (2000) 585-591

[7] H. Kersten, H. Deutsch, H. Steffen, G.M.W. Kroesen, R. Hippler: The energy balance at substrate surfaces during plasma processing, Vacuum 63 (2001) 385-431

[8] P.A. Cormier, M. Stahl, A.L. Thomann, R. Dussart, M. Wolter, N. Semmar, J. Mathias, H. Kersten: On the measurement of energy fluxes in plasmas using a calorimetric probe and a thermopile sensor, J. Phys. D, Appl. Phys. 43 (2010) 465201

[9] M. Stahl, T. Trottenberg, H. Kersten: A calorimetric probe for plasma diagnostics, Rev. Sci. Instr. 81 (2010) 023504

[10] R. Wiese, H. Kersten: Einsatz einer aktiven Thermosonde zur Diagnostik von Prozessplasmen, Galvanotechnik 6 (2008) 1502-1507.

[11] K. Matl, W. Klug, A. Zöller: Ion-assisted deposition with a new plasma source, Materials Science and Engineering A140 (1991) 523-527.

[12] R. Wiese, H. Kersten, G. Wiese, M. Häckel: Aktive Thermosonde zur Messung des Energieeintrages, VIP Vol. 23 Nr.3 (2011) 20-23


## 6. Acknowledgment


Dipl.-ing. (FH) E. Brunner, Zirox-GmbH Greifswald

Dr. R. Bartsch, neoplas GmbH Greifswald

Dr. rer. nat. H. Steffen †, INP Greifswald

The project for the development of the active thermal probe was funded by the BMWI (FKZ VP2046504DF9)