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A Novel Diagnostic- and Monitoring System for Technological Plasmas Based on the Concept of the Multipole Resonance Probe

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Abstract

Technological plasmas are inevitable in many industrial applications, especially for deposition of layers for high-precision optics or refining of surfaces. An outstanding part of current research is supervision and control of those plasma processes in an industrial environment. The multipole resonance probe (MRP) has already been proposed as a plasma diagnostic based on the idea of active resonance spectroscopy [1]. In this paper we present a complete system, which is able to generate spatially- and temporally resolved measurements with a resolution of about 1 mm and 20 ms, respectively. As can be seen within the theory of the MRP, the probe is insensitive to dielectric coating making it superior to other concepts, while fulfilling all requirements for an industry compatible diagnostic. Furthermore, it is based on a mathematical model, which leads to a very clear and fast analysis of measurement data. Thus, the MRP detects drifts in a deposition process fast enough allowing it to be used for monitoring and controlling tasks. The system comprises the probe, a computer controlled mechanical unit for movability as well as a newly developed electronic measurement device leaving no need for any additional components. Due to the usage of self-designed components, the system features a very reasonable price in terms of financial footprint and upkeep. Several tests in a variety of different plasmas have proven the suitability of the system for common technological plasma applications.

Key words: plasma diagnostic, plasma monitioring, multipole resonance probe, active resonance spectroscopy, plasma process control, industry compatible

Introduction

Within optical coating technology, layer deposition using the PIAD (plasma assisted ion deposition) process is state of the art. Obviously, the surface quality as well as specific surface properties are highly dependent on the plasma parameters. Unfortunately, useful control algorithms that guarantee a high process quality even in the case of malfunction, degradations related to aging or other influences are missing. Existing control algorithms are based upon external parameters like bias voltage or discharge current. Those external parameters only give indirect information about the coating process depending on their associated plasma parameters. A control concept based on the plasma parameters themselves, which allows direct insight into fluctuations and drifts within the plasma would thus be more effective and could increase the productivity of a process. Supervision and control of plasmas require a diagnostic system that allows an exact determination of the inner state parameters of the plasma, especially electron density and electron energy. For the application of such a diagnostic system within industrial processes it has to satisfy high demands. Above all, it has to be (i) robust and stable, (ii) guarantee a simple and unambiguous evaluation, (iii) must not perturb the process, (iv) be insensitive against perturbation by the process itself, (v) be compatible to process integration and (vi) be economical in terms of investment and maintenance. Since nearly all existing concepts do not fulfill these demands within a dielectric coating application we developed a new system based on the well-known active plasma resonance spectroscopy (APRS). In order to guarantee an economical system an optimized electronic measurement unit is integrated allowing a measurement rate that is fast enough to use the system within a process control. Furthermore, an electronically controlled mechanical unit was developed giving the possibility for spatially resolved measurements. This paper describes the complete system starting with the new probe concept followed by two passages dealing with the mechanical unit as well as the electronic measurement unit. It concludes with some measurements that verify the suitability of our system.

MRP Theory

The new probe, called multipole resonance probe (MRP), is an optimized approach based on the concept of active plasma resonance spectroscopy, which uses the universal ability of all plasmas to resonate on or near the plasma frequency ω_{pe}. The idea dates back to the early days of discharge physics and is to couple a rf-signal into a plasma. The absorption spectrum of this signal is measured and on certain frequencies, where electrons resonate, absorption peaks are identified. With these peaks the plasma parameters are evaluated. Many realizations on the basis of the APRS derive very complicated absorption spectra with the need of complex models for evaluation making them inapplicable for online evaluation and thus for monitoring purpose.

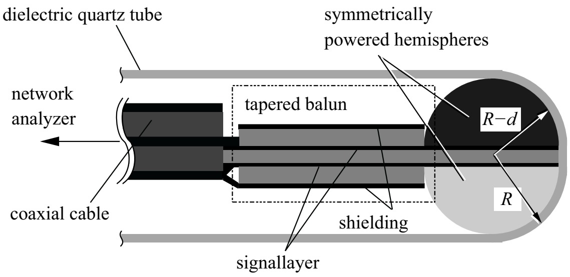

Fig.1: Scheme of the MRP

The probe head consists of two metallic hemispheres mounted on a multilayer printed circuit board serving as a balancing unit as well as holder and feeding device for the hemispheres. The prototype has a total diameter of 8 mm and is realized on three Rogers 4003 laminates – 203 µm thick and 18 µm copper cladding - with two prepreg layers. The multilayer printed circuit board functions as a balancing unit for an unbalanced signal from the feeding device in order to provide the probe with an electrically symmetric signal in the range of approximately 100 MHz up to 6 GHz. Being encased in a quartz-tube the probe is insensitive against dielectric coatings and reactive ion etching. The MRP excites only electrons in the plasma, while mass inertia of heavy particles prevents oscillation of ions making the MRP applicable independent of gas-mixture, power coupling method and reactor geometry.

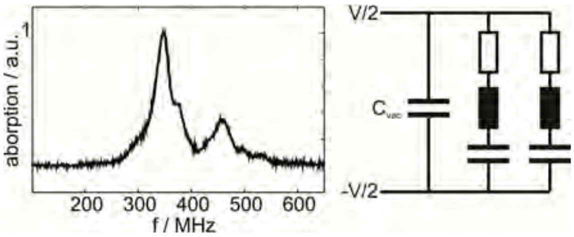

Fig.2: Absorption spectrum measured by the MRP and corresponding equivalent circuit diagram

The system "probe↔plasma" can be converted into an equivalent circuit diagram for every APRS probe. The MRP's circuit diagram consists of direct couplings between the two electrodes, described by the capacitor C_{vac}. The two peaks in the absorption spectrum are related to RLC-elements (see fig.2), which can be used for evaluation. As mentioned before, complex resonance structures of other APRS-probes lead to additional RLC-elements between the electrodes and ground. Due to the MRP's symmetry, these couplings are negligible. Based on the cold plasma approximation - magnetic effects are neglected - the RLC-elements consist of a resistance, characterizing ohmic heating, an inductor, describing mass inertia of the electrons and a capacitor, which is a combination of plasma sheath around the probe and the dielectric medium of the probe itself, the quartz-glass. While the second absorption peak not appearing in every spectrum only the first peak is used for evaluation. This peak is the strongest mode of the MRP in the spectrum, the dipole mode $\Omega_{l=1}$. This frequency is related to ω_{pe} with

$$\Omega_{l=1} = \frac{2}{3}\left(1 - b_{l=1}\left(1+\frac{\delta}{R-d}\right)^{-3}\right)\omega_{pe}^2 \qquad (1).$$

l=1 denotes the dominating dipole-mode, $b_{l=1}$ is a factor, which depends on the probe parameters R, d and ε_R of the dielectric quartz-tube. The electron density n_e is derived by

$$n_e = \frac{\omega_{pe}^2 \varepsilon_0 \, m_e}{e^2} \qquad (2).$$

Due to the MRP's electrically and geometrically symmetry, we are able to identify one distinct absorption peak in the whole spectrum and though a reliable and unambiguous derivation of the electron density.

Kinetic modeling

The application of the MRP in plasmas with pressures of only a few Pa raises the question whether kinetic effects have to be taken into account or not. Measurements to determine the electron-neutral collision frequency show a half peak width at low pressures (p<<1Pa), that cannot be predicted by the fluid model [1]. The difference between measurement and fluid theory is explicable due to kinetic effects that become important in low-pressure plasmas. To verify this interpretation a kinetic model is necessary. A general kinetic model for an electrostatic concept of active plasma resonance spectroscopy has already been presented [2]. This model can be used to describe the dynamical behavior of the MRP, which is interpretable as a special case of the general model. Based on a complete system of orthogonal functions in the angles of the phase space the Boltzmann-Poisson-System can be simplified to the equations of the dipole mode. However, this simplified description cannot be solved analytically. To determine the kinetic dipole part of the spectrum we are working on an approximated expression of the system response. This will allow for an investigation of the influence of kinetic effects on the resonance behavior. We are especially interested in the electron temperature that can be determined by combining the predictions of both: the fluid and kinetic model.

Computer Controlled Mechanical Unit and Monitoring

Fig.3: Mechanical unit for spatially resolved measurements

The MRP is developed in two concepts. For the first concept the MRP is mounted at a fix position for monitoring of plasma processes with time-resolved measurements. The second concept has been developed to investigate and characterize plasma reactors. Therefore the MRP is integrated into a movable system, based on the existing Langmuir probe system APS3, which has been developed at the Ruhr-University Bochum. It consists of a complex ultrahigh vacuum bellow system and allows positioning with millimeter precision in plasma reactors for a thoroughly analysis of spatially density profiles (see fig.3). The system is connected to a PC from which the whole system is operated.

Electronic Measurement Unit

Former concepts for plasma diagnostics basing on the active resonance spectroscopy as well as our new concept require the generation and evaluation of an ultra wideband rf signal. Since the concept of the active resonance spectroscopy relies on the electron plasma frequency this signal has to cover the full frequency range needed to apply the concept in several different plasma types. Thus, in order to include almost all typical industrial processes, the frequency range can be determined to about 100 MHz up to 6 GHz. Typically, the generation and evaluation of this signal is done using a commercial vector network analyzer (VNA). Since these are generalized instruments for the use in a great variety of applications their costs contradict the idea of an economical diagnostic system for industrial applications. Therefore, our proposed diagnostic- and measurement system includes a specialized electronic unit that is able to generate and evaluate the rf-signal within the complete desired frequency range. Regarding the extremely high bandwidth in conjunction with the very low minimum frequency, a pulse based concept is very promising. Fig. 1 shows the block diagram of such a system that is based on the well known concept of time domain reflectometry systems (TDR). The main idea of this concept is to generate an extremely short electromagnetic pulse whose short pulse width in time domain is correlated to a great bandwidth in frequency domain via the fourier transform. This pulse is sent out to the probe immersed into the plasma where it gets reflected. As the bandwidth of the pulse does not change due to reflection a direct digitization is not possible while fulfilling common dynamic requirements. Thus, the reflected pulse has to be mixed down to an intermediate frequency using a subsampling mixer driven with another extremely short pulse as the local oscillator. Now, a conversion of the signal to the digital domain can easily be done using a standard A/D-converter (ADC) with a following low pass filter. The spectrum of the absolute value of the measured reflection coefficient is then evaluated in terms of resonance frequency within a PC or a microprocessor via a fast fourier transform (FFT). The crucial components of such a system are on the one

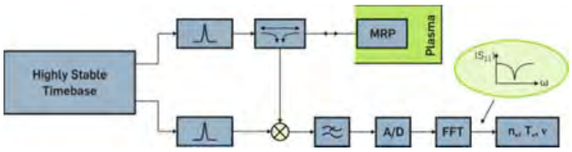

Fig.4: Block diagram of the electronic measurement unit

hand the pulse generators and on the other hand the highly stable timebase. In the following, these components are described in more detail. Since the generated pulse is gaussian shaped the correlation between the pulse width τ and bandwidth B is given by

$B \approx 0{,}62\tau$ (3).

Hence, to achieve the desired bandwidth of about 6 GHz, a pulse width of below 100 ps is necessary. A common concept for the realization of these short pulse widths, which is used within our system, too, is to use turn-off processes of semiconductor devices. As the turn-off time of standard diodes is far too long a step recovery diode (SRD) with a specially tuned dopant profile is used. This profile allows for turn-off or transition times and pulse widths, respectively, of well below 100 ps. For using this diode as a pulse generator, a bias current enables a small forward voltage. Now, a negative voltage step reverses the polarity of the diode and thus a reverse current begins to flow eliminating the charge carriers. Due to the special dopant profile this elimination is not linear versus time but it has an abrupt end. The falling time is given by the transition time of the diode. This quick change in current is converted to a voltage pulse by using a simple inductor. The schematic of such a pulse generator, in a symmetric form, is depicted in fig. 5. The low pass filter prevents that high frequency content from the pulse gets back into the driving circuitry. Furthermore, this filter in conjunction with the output network reduces ringing within the output signal resulting from slight mismatch. Due to the extremely high bandwidth of the pulse a hybrid design, comprising distributed and lumped components, has to be used for the filter.

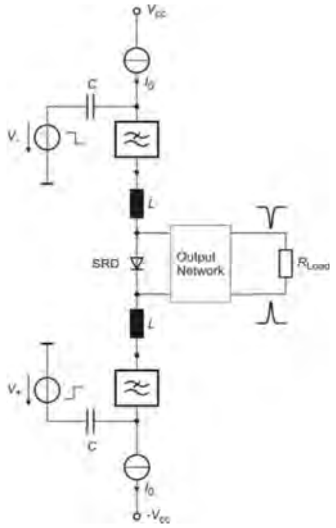

Fig.5: Schematic of a symmetric pulse generator basing on a step recovery diode

Since the pulse amplitude depends on the strength of the reverse current, the driving circuitry has to be able to establish a high current within the minority carrier lifetime of the diode which is only a few nanoseconds. This is realized by a parallel connection of a few buffers. A measurement of the pulse is depicted in fig. 6. As can be seen, a pulse width of about 67 ps and a pulse amplitude of about 3.5 V is achieved fulfilling the aforementioned requirements. Besides the pulse generators, a highly stable timebase is another key component of the whole concept. Due to the working principle of a subsampling unit, this timebase has to provide two driving signals, one for each pulse generator. Having a slight offset in frequency the signals are slid over each other resulting in a timestretched pulse with a heavily compressed spectrum. As the spectral analysis of the measurement signal requires a high stability, the timebase has to have a good phase noise behavior and thus a really low time jitter. In order to realize such signals, different concepts exist. One approach is to take a cascaded phase locked loop [2]. Although the noise performance of this concept is very good it suffers from a high effort in circuit design. Another concept is to take a direct digital synthesizer (DDS), which has an extremely fine frequency resolution. Unfortunately, the time jitter of such a synthesizer is too high making it inapplicable in our measurement system. Nevertheless, the concept of the digital synthesis seems promising and therefore we developed a new concept basing on this idea [3]. A reference signal provided by a crystal oscillator is divided down to the desired frequency using a fractional frequency divider. To avoid the generation of additional phase noise as it is the case using a standard fractional frequency divider, we use division factor sequences with a short periodicity.

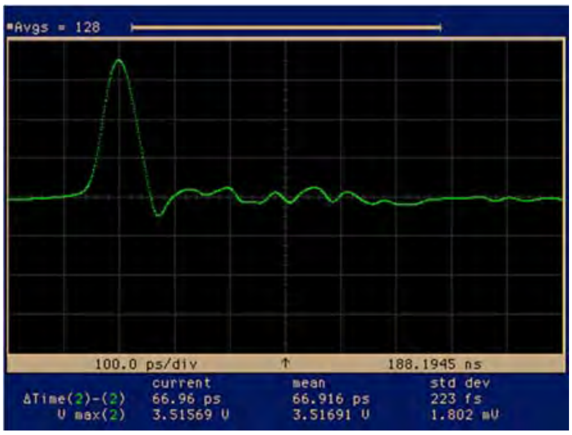

Fig.6: Measurement of the pulse (pulse width ≈ 67 ps, pulse amplitude ≈ 3.5 V)

This periodicity is visible within the spectrum of the output signal as discrete peaks with an offset to the carrier frequency of

$$f_{off} = \frac{f_a}{N_T} \qquad (4),$$

with f_a giving the output frequency of the divider and N_T the number of output cycles within one division factor sequence. Obviously, these peaks degrade the noise performance of the system, thus they have to be filtered out using a bandpass filter with steep filter slopes. Now, before doing this, it is useful to strengthen up the power of the fundamental wave of the signal, because the output of the divider is a pulse train with very low duty cycle. Therefore, a further divide by two frequency divider changes the duty cycle to nearly fifty percent, increasing the power of the fundamental and thus the signal to noise ratio after the bandpass filter. The block diagram used for the timebase is depicted in fig. 7.

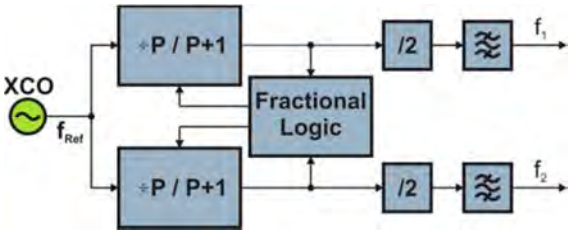

Fig.7: Block diagram of the highly stable timebase

Since the pulse repetition frequency determines the spacing of the dirac comb and thus the frequency resolution of the measurement it is chosen fairly low, to about 5 MHz. The frequency offset between the two signals has to fulfill the nyquist criteria as well as it is the period of the timestretched pulse and thus determines the measurement repetition rate. Within our system, the frequency offset is variable in a large range and is set to about 60 Hz for the following description. The whole measurement unit, depicted in fig. 8, is realized on one multilayer PCB, comprising the timebase, two pulse generators, a subsampling mixer, an A/D-converter as well as the complete digital logic, which is necessary to control the timebase and the ADC. Furthermore, an USB 2.0 highspeed interface guarantees a real-time data transfer to a PC without storing any data on the board. The complete spectral analysis as well as the calculation of the plasma parameters is done on the PC. The offset frequency of 60 Hz determines a minimum measurement time of about 17 ms which is the limit for time resolved measurements. A complete measurement and evaluation cycle takes about 50 ms and is therefore fast enough to use the system for a process control.

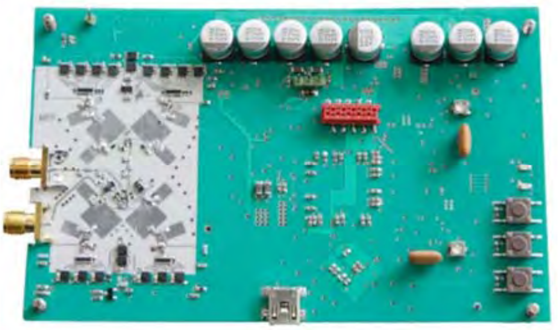

Fig.8: Electronic measurement unit realized on one multilayer printed circuit board

Measurement and Verification

For the investigation of the applicability of the MRP in technical plasmas, measurements were taken in a double inductively coupled Ar-N-plasma. In fig. 9 electron density n_e versus pressure and power variation is shown. The MRP measurements are compared to the established Langmuir probe system. Global trends are noticeable by comparing both diagnostic systems. With rising pressure the gaps between MRP and LP extend, but a decent performance of both diagnostics is observed.

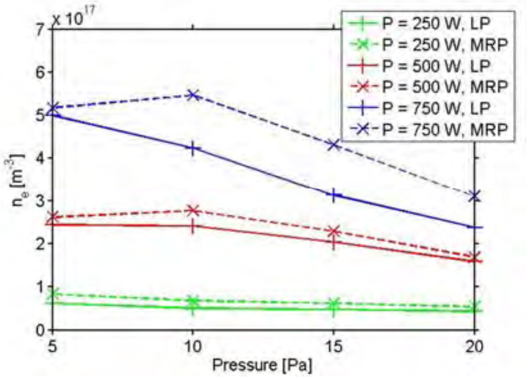

Fig.9: Measurements of electron density versus pressure and power variation in a double inductively coupled plasma in comparison with Langmuir probe

In fig. 10 the monitoring of electron density in a standard process for optical coating is shown. As one can see, the MRP (dotted line) gives smoother density characteristics than the LP (solid black). Due to the insensibility against dielectric coating, the MRP performance is not affected by the deposition process, while the LP performance worsens in this process enviroment. Furthermore, the trend of the electron density differs from discharge voltage (solid red), which is used as a control parameter in the current setup. With this observation, new control schemes on the basis of plasma parameters can lead to much more precise and more effective supervision. For the present case, future work will focus on the relationship of n_e and the parameters of the plasma deposition process. This constitutes a first step towards active control schemes, based on in-situ plasma diagnostics.

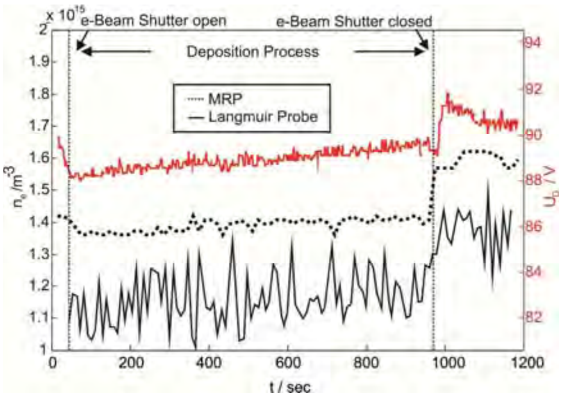

Fig.10: Monitoring of a standard deposition process for dielectric coating on optics

Conclusion

In this work we showed, that the MRP is suitable for monitoring purposes during dielectric coating standard processes as well as for diagnostic investigation for reactor characterization. We developed a complete system comprising a mechanical unit, an electronic measurement and evaluation unit in combination with a unique mathematical model, which allows an unambiguous analysis of important plasma parameters. Due to the fast and precise parameter evaluation the MRP seems to be a promising diagnostic tool for process control.

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