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The Design of an Automated Plasma Diagnostic System and its Applications

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Abstract: The paper deals with the design of a new plasma diagnostic system consisting of a microcontroller based power supply for automatic control of the measurement using Langmuir probe, the communication interface of the power supply and the signal processing program. The utility of the designed plasma diagnostic system is presented through measured U-I curves and a method to measure the relaxation time of the plasma.

The main motivation for the design of the automated plasma diagnostic system was given by our research in different methods of plasma nitriding of steels. During the nitriding process, it is important to get information about the plasma, which is the medium where the heat-treatment process is going on. The new diagnostic system is able to perform measurements during the nitriding process, thus we can analyze the plasma at different temperatures and gas mixtures. The obtained voltage-current curves are recorded and transmitted to the computer, where further signal processing is performed. The paper presents the design of the power supply, the measurement results and the developed signal processing software. Further on, the estimation of the relaxation time of the plasma is presented, based on local measurements using Langmuir probe.

Keywords: plasma diagnostic, Langmuir probe, power supply, microcontroller, data acquisition, IIR filtering, plasma relaxation time.

1. Introduction

In the last three years we have succeeded to rebuild and operate a linear plasma reactor for Direct Current and Active Screen plasma nitriding. The design of the system and the first results were reported in [1],[2], where we

The results of this study were partially presented at the 5th International Conference on Recent Achievements in Mechatronics, Automation, Computer Sciences and Robotics 2015.

focused mainly on the plasma nitriding technology. Beyond the nitriding technologies, it is very important to study the behavior of the plasma, thus the vacuum chamber contains a feedthrough for a Langmuir probe and we designed a measurement device for accurate local plasma diagnostic. Embedding the vacuum diagnostic software in the heat treatment process control software, enables the local plasma diagnostic during the heat treatment process, opening new possibilities in the high temperature plasma diagnostic. To be able to work at high temperatures, we had to rebuild the Langmuir probe, the thermal isolation of the feeding cable was improved and the probe was introduced in a ceramic isolator, thus it can be used in the500-600ºC temperature range.

In the following sections we present the design of the local plasma diagnostic system, starting with a short description of the plasma diagnostic techniques, followed by the design of the power supply, the measurement results and the post processing of the measurements.

2. Plasma diagnostic using Langmuir probe

There are two plasma diagnostics techniques which can be used to explore plasmas [3]. Global techniques are based on the study of the electromagnetic radiation leaving the plasma and provide information on the whole plasma. Local techniques are based on the study of the voltage-current curves of different electrostatic probes inserted in the plasma, which provide local information on the plasma. Both techniques have difficulties, advantages and disadvantages. We designed a local plasma diagnostics setup because we proposed to study the distribution and evolution of local plasma parameters during the nitriding process of steel samples. We use a cylindrical shaped 0,4 mm diameter, 3 mm long probe made of tungsten. The probe is movable, the feedthrough is provided with a computer controlled stepper motor to enable precise control of the probe position. Information on the local plasma parameters can be obtained from the voltage-current curve of the probe. Therefore it is important to ensure proper conditions for these measurements. We designed a complex, computer controlled DC power supply to bias the probe and measure the currents. The power supply is suitable to bias traditional single probes, double probes and emissive probe. All parameters can be adjusted on-demand in the user interface of the program designed for probe measurements. Probe voltage-current characteristics bear information on local plasma parameters. There are different data processing methods which yield information on local electron density, electron temperature (energy). During nitriding these parameters are influenced by the pressure, discharge voltage, temperature, gas mixture and anode-cathode distance.

3. The design of the power supply

The main characteristics of the DC power supply for plasma diagnostics has been defined as follows:

- Output voltage range: -125VDC…+125VDC
- Output current: 0…70mA
- Programmable voltage step resolution 0.01V
- Current measurement accuracy: 1µA
- Output voltage step time: min. 50ms
- Communication interface: RS232 or USB.

The schematic diagram of the designed measurement device is presented in *Fig.1*. A precision linear power supply feeds the low voltage circuits and the measurement modules, while a digital signal controller implements the control and measurement tasks.

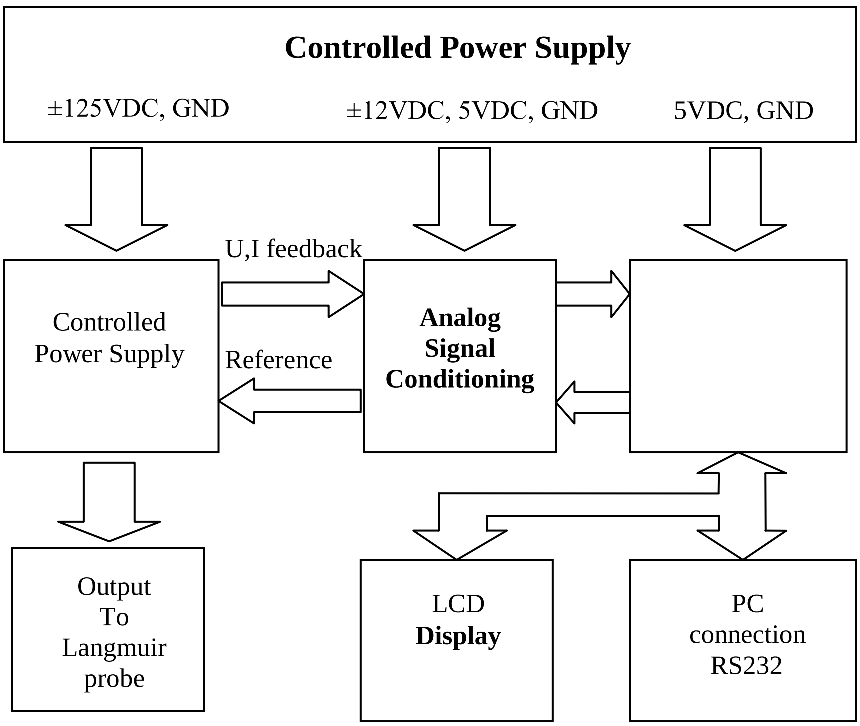


Figure 1: Block diagram of the measurement device

According to *Fig. 2*, the Langmuir probe is supplied with a voltage defined by the measurement software. The output voltage is controlled, thus the probe voltage is kept constant during the measurement. The actual voltages and actual currents are measured with the digital signal controller.

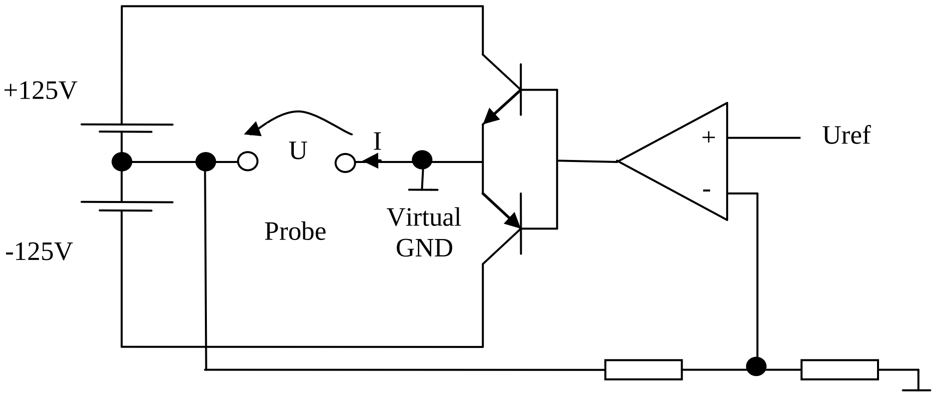


Figure 2: The measurement principle.

During the development several simulations were performed. In *Fig. 3* the pSpice model of the measurement circuit is presented

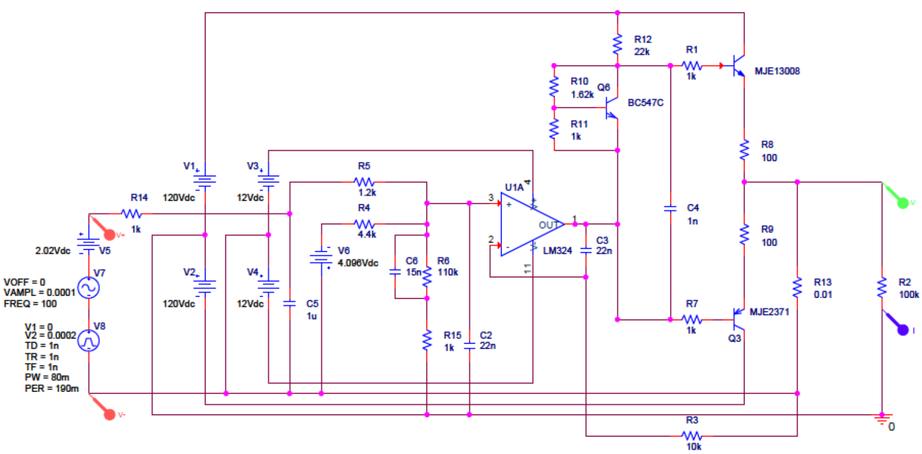


Figure 3: pSpice model of the output voltage control circuit

The most important simulation results are presented in *Fig. 4* and *Fig. 5*. In the first figure the linearity of the output voltage versus the reference voltage is presented. It can be observed that the output voltage is linear in the whole range, thus the control voltage has a unique and linear mapping on the output voltage.

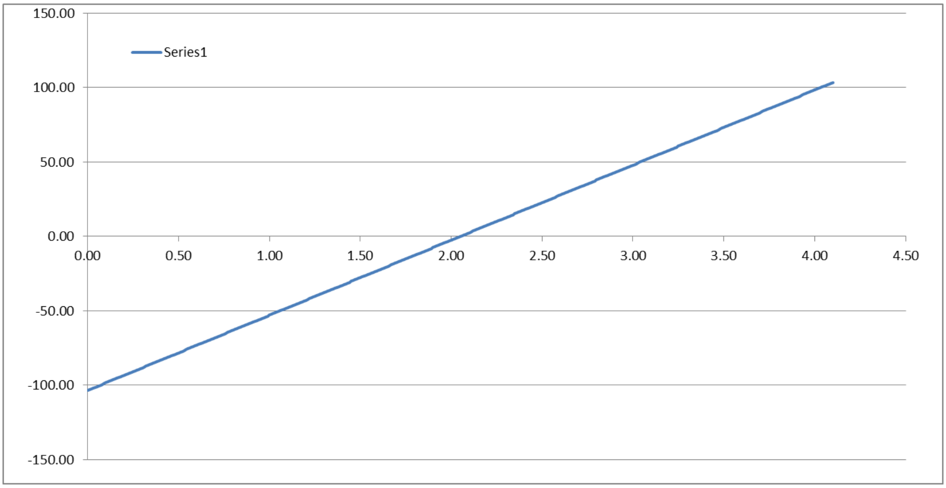


Figure 4: Output voltage [V] versus the control voltage [V]

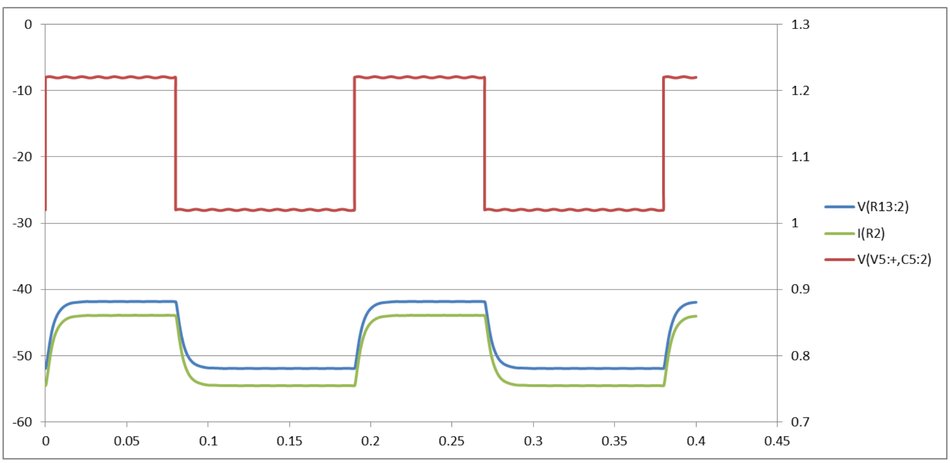


Figure 5: Control and output voltage [V] versus time [s] of the power supply in case square-wave control voltage

In *Fig. 5* the step response of the voltage regulator is presented. The time constant of the closed loop system is about 10 ms, thus the measurement of the output voltage and output current has to start at least with 10 ms delay after the step change on the output voltage. This time constant is acceptable compared to the minimum 50 ms time step defined for the measurement.

4. Practical implementation. Measurement results

The realized power supply is presented in *Fig. 6*. In the front view the operator interface is presented, with an LCD display and the pushbuttons, enabling standalone working of the power supply. In the internal construction one can see the separate modules presented in the block diagram (*Fig. 1*), namely the linear power supply, the analog interface circuit and the control board with the DSP processor.

Figure 6a: Front view of the power supply

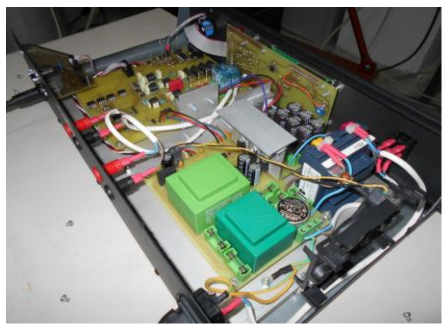
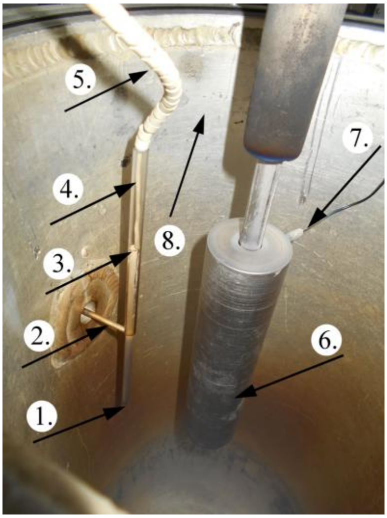


Figure 6b: Internal construction of the power supply

For the local plasma diagnostic the Langmuir probe has been improved, as it can be seen in *Fig. 7*.



1. Cylindrical probe made from wolfram(3mm long, ∅=4mm)
2. Probe holder, allowing radial movement
3. Ceramic isolator introduced in a glass tube
4. Heat-resistant silicon isolated wire
5. Ceramic rings for thermal isolation of the wire
6. The cathode of the discharge
7. Thermocouple for measurement of the cathode's temperature
8. Grounded anode tube, this is basically the water cooled wall of the reactor

Figure 7:The Langmuir probe installed in the linear plasma reactor

The first measurements were made in nitrogen-hydrogen plasma, where the cylindrical probe was heated up to 556ºC and the probe was placed at a distance of 6 centimeters from the cathode. The voltage step applied to the probe was 0.1V and the sampling period was 100ms. The result is depicted in *Fig. 8*.

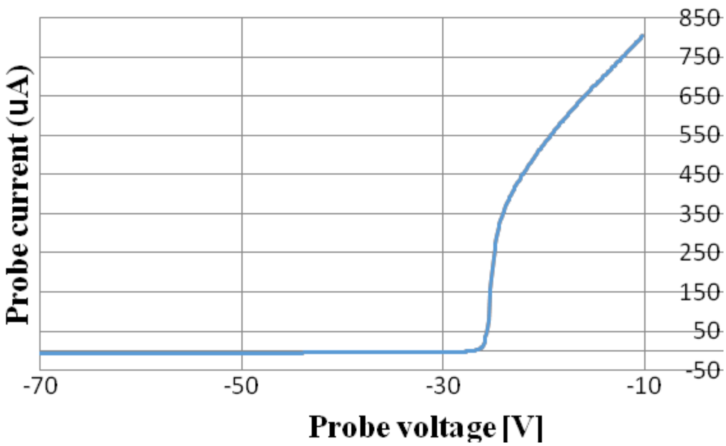


Figure 8: Voltage-current characteristic of the probe measured with the new power supply

For the automated measurements a LabWindows CVI based software has been developed, which has an easy to use graphical user interface (GUI), see *Fig. 9*, and a communication module with the power supply. On the user interface one can set the parameters of the measurement, the measurement results are displayed on a strip chart. In *Fig.10* a set of U-I characteristics is shown, the distance of the probe from the cathode varying from 30 mm to 98 mm.

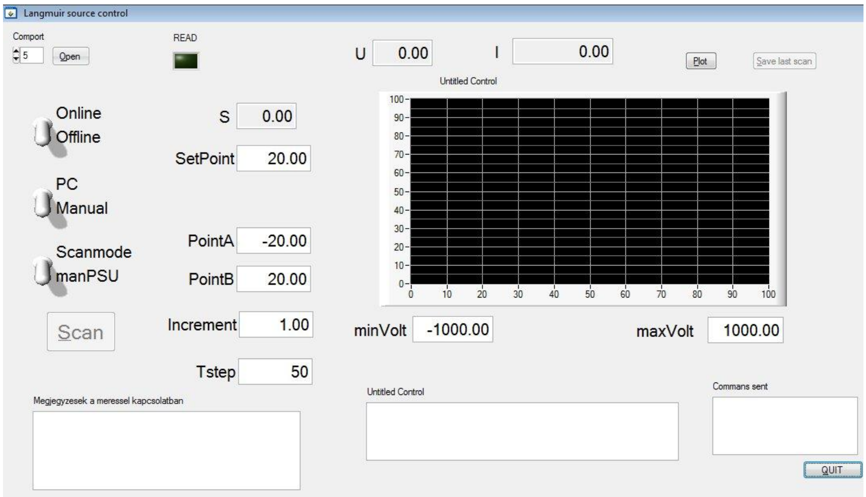


Figure 9: TheGUI of the measurement software

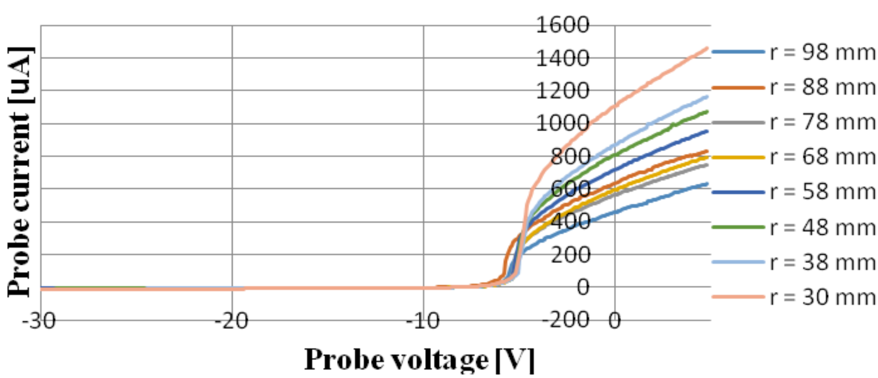


Figure 10: Set of U-I characteristics at 175ºC cathode temperature and different probe distances from the cathode

5. Post processing of the measured data, signal filtering

Although the recorded curves (*Fig. 8*, *Fig. 10*) look smooth, calculating the slope of the curves in different points, the result was unsatisfactory and very noisy. There are two main reasons for the noise of the derivative. The first is the small measurement noise on the curves, and the other comes from the scale changing during the measurement. When the power supply changes the measurement scale, a small step change on the curve can be observed. To be able to use the measurement result, a digital filter was designed to smooth the measured signals [4], [5]. A satisfactory result was obtained with a fourth order Elliptical IIR filter, designed with the sampling frequency of 10 Hz, and the cutoff frequency of 0.4 Hz, see *Fig. 11*.

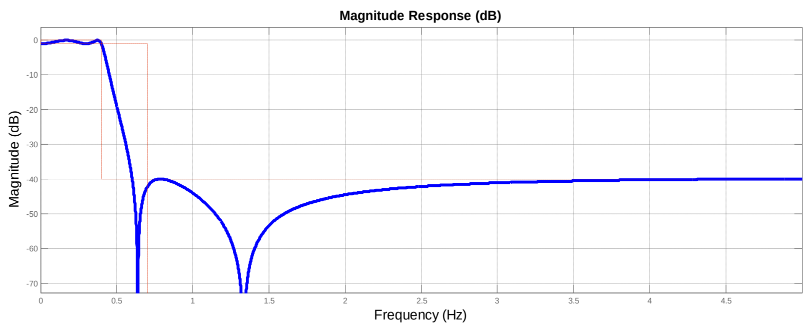


Figure 11: The magnitude response of the fourth order elliptical IIR filter

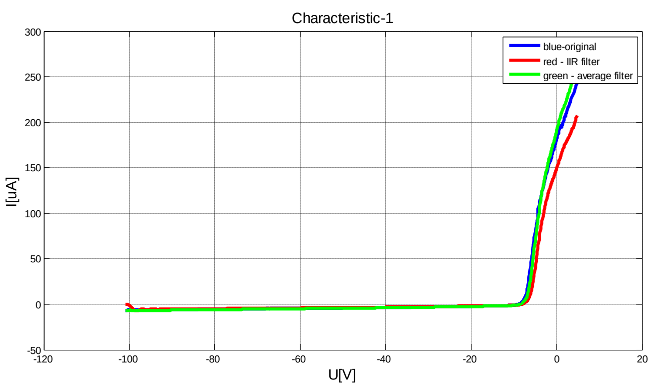


Figure 12: The result of the digital filtering on recorded U-I characteristics

The result of the first filtering of the U-I curve is depicted in *Fig. 12*. The red curve results form the IIR filtering.A phase shift and a magnitude attenuation of the filtered signal can be observed. To assure an accurate interpretation of the derivative of the recorded U-I curves, the phase shift introduced by the digital filter has to be compensated. The phase-shift introduced by the filter can be obtained comparing the derivative of the unfiltered curve with the derivative of the filtered curve. Using a simple shift operation on the filtered derivative, the phase-shift can be eliminated.

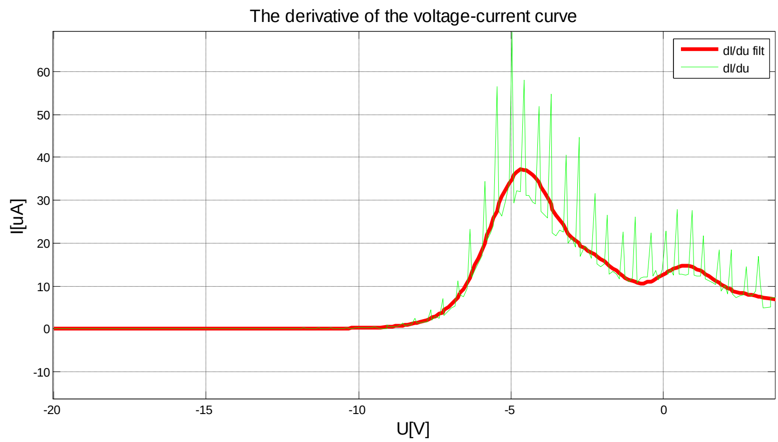


Figure 13: The derivative of the current versus the voltage and the filtered derivative

In *Fig. 13* the derivative of the recorded characteristics is presented. It is imoprtant to notice, that the derivative of the filtered curve is noisy, as it can be seen on the green curve. Appliyng again the same digital filter to the derivative and adjusting the delay caused by the phase shift of the filter, the obtained characteristic is usable for the plasma diagnostic purposes.

6. Estimation of plasma relaxation time

In the linear non-isotherm plasma reactor the plasma is created using direct-current gas discharge and it is necessary to study the physical processes on the surface of the probe (having anodic, cathodic or floating potential), which has direct contact with the laminar streaming gas mixture. Such complex processes are: the well-known direct-current plasma nitriding (DCPN), the most recently developed active-screen plasma nitriding (ASPN) or the anodic nitriding, where the active screen is substituted with a hollow cathode. The control of these complex processes assumes deep understanding of the local plasma parameters, like the electron density, electron temperature, floating potential. All these parameters are measured using Langmuir probes (*Fig. 7, Fig. 8, Fig. 12*). As it is shown in *Fig. 12*, the usual measurement range is 120-150 Vdc, and the resolution is 0.5-0.1 V. The number of the measurements is high, but an automated diagnostic system can handle such a fast measurement when the measurement period is correlated with the properties of the plasma for all characteristic regions (ion-current, electron-current and saturated electron-current). Nearby the probe inserted in the plasma, there is an equilibrium distribution of the particle. This distribution depends mainly on the potential of the probe. When the potential is changed the distribution of the particles change and the spatial arrangement of the particles change. The time necessary for a new equilibrium state formation is called plasma relaxation time. Furthermore, the distance from the probe, where the perturbing effect of the probe cannot be sensed is called relaxation distance [6]. To be able to perform an accurate Langmuir probe measurement, it is necessary to know the relaxation time of the plasma, to be able to set the minimum step time of the voltage applied to the probe. In the followings the measurement of the relaxation time is presented using the plasma diagnostic system and an oscilloscope (*Fig. 14*).

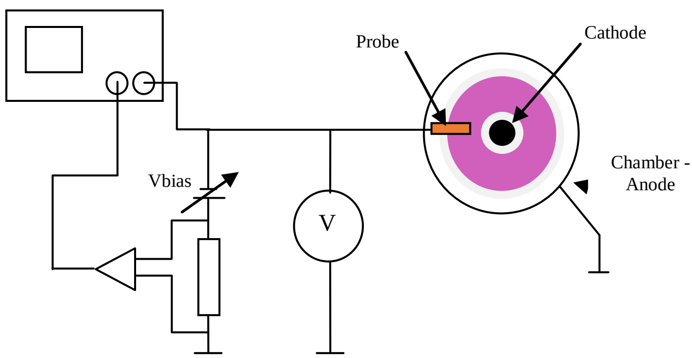
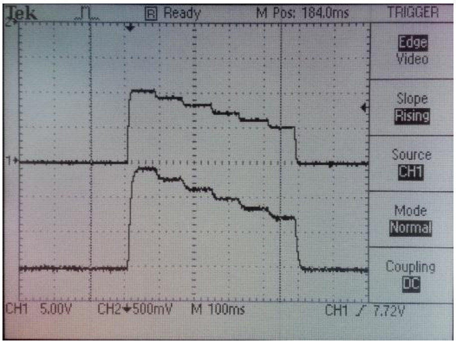


Figure 14: Schematic principle of the relaxation time measurement

Using the automated plasma diagnostic system, during the measurements the bias voltage has been changed in steps and the probe current was recorded using a shunt resistor. The voltage and current waveforms were measured with a digital oscilloscope after the first RC low-pass filter. The effect of the low-pass filter is not significant due to the high cutting frequency (10 kHz). The plasma relaxation time is estimated similarly to the time constant of a first order linear system. From the step response of the system, one can determine the time constant using the graphical method. In *Fig.15*t he measurement results are presented.



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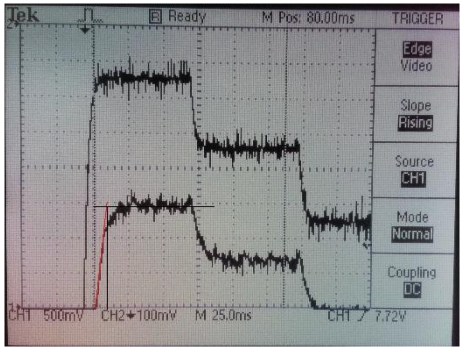
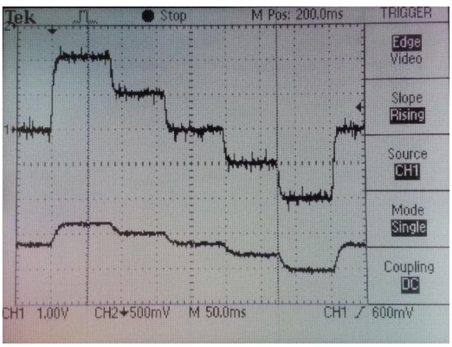


b)



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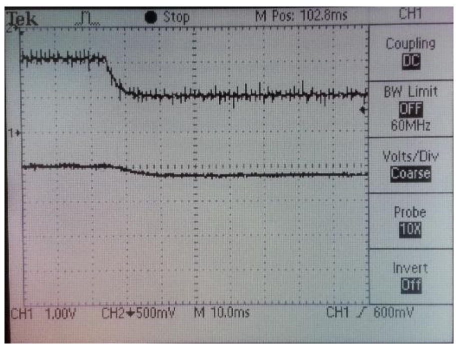

d)

Figure 15: Voltage and current waveforms recorded with the oscilloscope
a) a measurement sequence in the electron-current region. b) the same measurement with higher resolution, the estimation of the time constant is shown. c) Measurement sequence spanning over both electron and ion-current regions. d) The measurement in a 10ms time resolution. The measurements were performed at 200°C of cathode temperature and at 6cm from the cathode in radial direction

According to *Fig. 15.b*,the time constant of the current waveform is about10 ms, and the settling time is about three times the time constant (30 ms), thus an accurate measurement of the current signal has to start at least with 30 ms after the voltage change has been applied. Taking into account the time constant of the voltage controller, which is also about 10 ms (*Fig.5*), the initially defined minimum step time of 50 ms for the applied voltage is correct. In conclusion, the plasma relaxation time is in the range of 10-20 ms in the actual discharge conditions. To have a clear view about the relaxation time in the whole radial region of the plasma (temperature dependence), further measurements will be performed.

7. Conclusion

In the paper we described the design of an automated local plasma diagnostic system. Starting from the design of the power supply we described in detail the steps we made to obtain the desired results. The recorded curves need post processing, thus we designed a software for filter the measured values and the derivative of the curves. The obtained results will be used to collect information about the plasma during different plasma nitriding processes. Using the automated measurement we succeeded to estimate the plasma relaxation time.

Acknowledgements

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