Measurement of voltage and current in continuous and pulsed rf and dc glow discharges

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Abstract. Electrical measurements are an important tool for the characterisation of glow discharges and have proved to be useful for a variety of needs in fundamental studies and as control parameter. Therefore, extensive hardware developments and studies of current-voltage (I-U) characteristics in continuous and pulsed, dc and rf modes have been made [1] and will be presented together with new results.

In continuous dc mode, the I-U curves are non-linear and may be characterised by a threshold voltage U₀ and saturation current Iᵌₙₐₓ (both cathode material and pressure dependent). On the other hand P-U curves are to a large extent linear and very similar in the continuous rf mode [2]. The ionic part of time resolved I-U curves of rf discharges however shows almost a linear behaviour and the capacitive component is small. This led to the assumption that gas heating is responsible for the non-linearity between I and U in continuous dc discharges. Consistent with this assumption, a dependence of the I-U curves of pulsed discharges on the duty cycle was found. The comparison of the curves with those at low duty cycle (cold) led to a rough estimation of the gas temperature.

Further investigation and cooperation with modelling groups is needed and planned to explain these results.

1. Introduction

The electrical properties of discharges have always been of interest in discharge physics. Electrical direct current (dc) measurements are easy to perform, and do not disturb the discharge. For dc glow discharges (GD) a lot of documented discharge properties are directly related to the discharge voltage and current [3-5]. Dc discharges used for glow discharge optical emission spectrometry (GD-OES) [6]...
with the aim to measure the chemical composition of solid samples and layered materials [7], require voltage and current measurements for the regulation of the discharge to constant conditions. A radio frequency (rf) generator is required for the measurement of insulating materials or insulating layers. Reproducible electrical rf measurements are necessary to adjust the discharge to constant conditions or to correct the intensities and sputtering rates in order to determine the chemical composition of all samples with sufficient accuracy. Therefore, extensive hardware developments and studies of current-voltage (I-U) characteristics in continuous and pulsed, dc and rf modes have been made [1] and will be presented together with new results.

For any defined glow discharge source and plasma gas there are three main parameters which characterize the glow discharge: voltage, current and pressure. It is known that there are more parameters existing as gas flow [8], temperature of source and gas [9] or source material [10], which influence the discharge. Because they are difficult to measure or to vary they are mostly treated as boundary conditions.

In many experimental results, these boundary effects cannot be distinguished unequivocally, because e.g. the temperature also has an influence on the secondary electron emission [11, 12]. Also wall losses at constricted discharges were taken into account and change the I-U characteristic by a reduction of the effective cathode area [13]. Payling et al. [6, p. 265] e.g. found an increasing sputtering rate with depth at constant voltage and current and assumed that changes in the temperature could be the reason for this effect. Kasik et al. [14] have mentioned that cathode heating lead to changes of the I-U characteristics in GD-MS, mainly to a decrease of the current at the same voltage. Bogaerts et al. [15] confirmed the same effect in modelling calculations and simulations. In this modelling work a nearly linear relation between the cathode and discharge gas temperature was presented. Furthermore, old fundamental measurements about normal glow discharges did show that more than 50 % of the input energy were found in gas heating and heat transport by the discharge gas to the walls [16].

There are some papers about the experimental determination of the discharge gas temperature. Ferreira et al. [17] used line width measurements for the determination of gas temperatures. Li [18] inserted a “thermometer molecule” W(CO)6 in the discharge gas which loses a defined quantity of CO groups at different gas energy distributions and TOF-MS was used for the detection. Wilken at al. [19] estimated surface temperatures of the sample from crater bending. However, many authors have mentioned the lack of experimental data about sample surface and gas temperatures, e.g. [9].

In analytical glow discharges two electrical parameters (e.g. U and I or P and U) are kept constant to get the same sputtering, ionization and excitation conditions for the standard material and the analyzed sample, which is necessary for quantification [20]. Whereas the measurement of voltage and current in continuous glow discharges is reliable and modelling groups can use these data without difficulties, for the analysis of nonconducting materials by RF-GD, a special rf technique for the measurement of voltage and current was developed and used in this work [21]. For continuous analytical glow discharges there is a good agreement between the experimental results and modelling calculations [dc: 22, rf: 23], but the situation is different for pulsed discharges. The difficulty to get reliable data about voltage and current in those discharges becomes clear in the course of some modelling work. At the beginning Bogaerts [24] used the gas temperature as a parameter to fit the measured current in the first time interval of µs pulsed dc discharges, but later it was found that difficulties in the measurement led to wrong results in the experimental data but also at modelling [25]. Our own measurements confirm very high currents at the beginning of dc discharges, but also the difficulties for accurate measurements in the first microseconds. Therefore, we have not focused our work on this problem, but will show that similar problems can arise in the interpretation of afterglow effects, if no clear data about the discharge are given.

Furthermore, I-U or P-U dependences permit to compare dc and rf discharges, to estimate breakdown voltage and to make some theoretical conclusions about the discharge physics. They can also serve as indicators of processes taking place in the discharge. But the aim of this paper is not to
draw those conclusions but to present data of measurement together with experimental details, which are necessary to understand and evaluate these results.

2. Experimental

2.1. Direct current continuous and pulsed discharge

For dc and pulsed dc measurements a 4-mm Grimm type source from Spectrumpa (GDA-750) was used. The discharge pressure was measured in the anode body by a Pirani gauge, calibrated by a baratron manometer (MKS Baratron Type 127; range 0–100 mbar). A high voltage generator (FUG MCN 350-2000) was used to power continuous GD. We used 10 mm thick pure Cu samples (Ø 30 mm) for all electrical measurements and 60 s presputtering time.

The pulsed GD was excited either with the high voltage pulse generator (RUP 3-3a), synchronized by an external TTL pulse generator (HP 33120A) or with a high voltage pulse generator (IRCO M3kS-20N). For evaluation, discharge voltage and current of the pulsed discharge were transferred via a digital oscilloscope (Tektronix 11201) to the computer.

Before the measurement of I-U characteristics of dc pulsed GD, these two pulse generators were compared. The main reason for the comparison of these two pulsers is the significant difference in the electronic circuit. Mainly, the RUP 3-3a, unlike the IRCO M3kS-20N, has an additional high voltage switch, which discharges the load after the termination of the pulse (figure 1).

![Figure 1. Electronic scheme of (a) RUP 3-3a, (b) IRCO M3kS-20N.](image)

The differences in the electronic circuit lead to differences in the current and voltage signal behaviour (figure 2). The discharge voltage signals were measured by the generators itself, using internal voltage dividers. For the electrical current measurements the electronic schemes of the generators provide special outputs where a voltage proportional to the current is formed (figure 1).

With the RUP 3-3a during the pulse, switch 1 is on and 2 is off (figure 1 a). To terminate the pulse the first switch is turned off, but at the same moment the second is turned on and discharges the residual load current. Therefore there are no voltage and current signals after the termination of the pulse. To know this feature is very important for example at the investigation of temporal light emission of pulsed GD. Therefore at the research of the pulsed discharge, especially of the afterglow, it is very important to pay attention to the electronic circuit of pulse generator. The influence of this different voltage and current characteristic on the light emission is shown by Efimova et al. [26]. For the subsequent experiments only RUP 3-3a was used.
2.2. Radio frequency continuous and pulsed discharge
For rf and pulsed rf measurements a standard free standing Grimm type glow discharge source with 4 mm anode tube was used. The glow discharge was excited with an rf generator (Forschungstechnik IFW 3.37 MHz) working in free running regime, i.e. the glow discharge source was a part of the oscillation circuit powered by a dc power supply [1].

For the measurement of the instantaneous signals of voltage and current the glow discharge source was equipped with integrated voltage and current probes. The voltage probe uses a capacitive voltage divider which means that the recorded voltage signal does not contain a dc bias component. The dc bias was calculated (see [1]). The integrated current probe is a current-voltage transformer which converts the measured current into a secondary current. This current is passed through a resistor and the voltage drop over this resistor is measured. Both voltage and current probes are mounted between the cathode plate and the body of the glow discharge source which ensures high mechanical stability and low displacement current distorting the measured current. Nevertheless there is some displacement current which was subtracted numerically.

The signals from the voltage and current probes were fed into a high speed oscilloscope (LC584A, LeCroy). The recorded signals were subsequently transferred into a PC memory where further evaluation was done.

3. Results and Discussion

3.1. Continuous direct current discharge
The discharge in most analytical devices is operated in the abnormal regime. In this mode all cathode surface is fully covered by the discharge and an increase of the current leads to an increase of the current density on the cathode surface and therefore to an increase of the voltage. The plasma behaves electrically rather similar to a resistor. In abnormal mode the operating voltage \( U \) can be described by the equation

\[
U = U_0 + I \cdot R
\]  

(1)

where \( U_0 \) is threshold voltage, \( I \) the current and \( R \) the differential resistance of the plasma [6, p. 193]. \( R \) is considered to be constant, which is not the case in reality (figure 3).
For the low pressures of 3-4 mbar the linear range is wider than at high pressures. Here the convex non linear behaviour becomes more and more pronounced with increasing pressure and at high voltages (and corresponding powers $P$) a saturation of the current can be expected. Even if the determination of the threshold voltage is difficult in this presentation it becomes clear that the threshold voltage decreases with higher pressure according to the law of Paschen \[27\]. The low voltage and current data are not very reproducible and the extrapolation to zero current limit is not possible.

In order to see if the similarity law $I_1/p_1^2=I_2/p_2^2$ is fulfilled, figure 4 shows this presentation, which has also been used for a long time in analytical glow discharges \[28\].

At the low pressures of 3 and 4 mbar the changed threshold voltages have a strong influence and with increasing pressures there are deviations form this law at high voltages and powers. Most probably, these are caused by sample and gas heating, which is known to exist at abnormal discharges \[29\]. Nevertheless, the similarity law is valid over a wide range of pressures and voltages also for the used abnormal discharge in a Grimm type source and deviations from this law can be used to characterize the discharge.

Unlike the I-U plots P-U plots are nearly linear. The power of the dc discharge can be evaluated as

$$P = U \cdot I = I_{\text{max}} \cdot \left( p, \text{matrix} \right) \cdot \left[ U - U_0 \left( p, \text{matrix} \right) \right]$$ \hspace{1cm} (2)

$$I = \frac{I_{\text{max}} \cdot U - U_0}{U}$$ \hspace{1cm} (3)

where $I_{\text{max}}$ is a saturation current, $p$ is a pressure. The meaning of the slope as saturation current becomes clear in equation 3. At very high voltages (e.g. 10 times $U_0 \approx 3000$ V) the quotient becomes nearly one and the current converges to the limiting value $I_{\text{max}}$.

There is no physical background for this presentation, but the difficulty to measure the current in an rf discharge led to this empirical approach. Even if the rf power measured by a reflectometer may be not very accurate and e.g. a subtraction method mostly is applied additionally, these curves can be obtained quite easily. As proved in figure 5, these curves are linear over a wide range and extrapolation to zero power/current limit is possible. Of course also the curves for the reduced power in dependence on voltage in figure 6 obey the similarity law to the same extent as the reduced current (figure 4), but the reduced power curves remain nearly linear.
The threshold voltage can be determined from the P-U plots by a linear extrapolation to P = 0, and delivers objective and reproducible data in the case of the Grimm type sources (figure 7). It becomes clear that the source is operated at the left side of the Paschen curve and a reduction of pressure in the ring slit means a constriction of the plasma inside the anode with direct contact to the wall.

Figure 8 shows that the saturation current depends linearly on pressure. For lower pressures no extrapolation can be done, because the discharge is not stable at these conditions. Of course, threshold voltage and saturation current depend strongly on the applied matrix material and can be used to characterise e.g. the secondary electron emission yield.

3.2. Continuous radio frequency discharge

The measurement system developed at IFW Dresden allows to measure instantaneous voltage U(t) and current I(t) waveforms of rf discharge. These time dependent curves can be converted into current-voltage characteristics. In this paper we mostly present the ionic part of the I-U curves, which can be compared to the dc ones. As in dc mode the impedance of the plasma decreases with increasing pressure. The ionic part of the I-U characteristics of the rf discharge is quite linear and shows hysteresis (figure 9). The hysteresis is caused by the capacity of the sheath at the powered electrode, which is determined by the number of positive charges in the sheath at the powered electrode per volt.
With increasing pressure also the hysteresis is increasing which means an increase of the cathode sheath capacitance too. The ionic part of time resolved I-U curves of rf discharges shows almost a linear behaviour. This led to the assumption that gas heating is responsible for the non-linearity between U and I in continuous dc discharges.

For the characterization of the rf discharge and also for quantification it is important to reduce the number of data. Voltage and current depend on time and even if harmonics in the voltage are suppressed, the rf voltage is still superimposed by a dc part, called dc bias. If a sinusoidal rf voltage is applied, the rf current is non linear because of the I-U characteristics of the plasma. Therefore, the cycle root mean square value (CRMS) is used to characterise the rf voltage,

\[
U_{\text{CRMS}} = \left( \frac{1}{t_p} \int_{t_p} U_{\text{bias}} + U_p(t))^2 \right)^{1/2} \text{dt} 
\]  

(4)

where \( t_p \) is a time of one or several periods. The CRMS value of the rf voltage is also called the effective voltage \( U_{\text{eff}} \). Marshall et al. reported for the first time, that the effective voltage in rf mode is comparable to the voltage in dc mode. Sputtering rates as well as emission yields become comparable [30].

The power waveform \( P(t) \) is calculated as the product of the plasma voltage waveform \( U_p(t) \) and the plasma current waveform \( I_p(t) \):

\[
P(t) = U_p(t)I_p(t) 
\]  

(5)

The mean power is the definite integral of the power waveform:

\[
P = \frac{1}{t_p} \int_{0}^{t_p} P(t) dt 
\]  

(6)

At the variation of voltage at constant pressure the impedance of the plasma remains nearly constant in the ionic part of the I-U characteristics also in pulsed rf mode. The P-U plots of rf discharge (figure 10) show a nearly linear behaviour like in dc mode (figure 5). Both curves are also quantitatively very similar, which proves the similar meaning of dc and effective voltage in dc and rf mode, respectively. The reduced power in dependence on voltage (not shown) obeys the similarity law as in figure 6.
The threshold voltage shown in figure 11 obeys also the typical behaviour of the Paschen curve at the left side of the minimum. The values are lower than in figure 7, which could be caused to a certain extent by differences in the source geometry, because the threshold voltage is a function of $p \cdot d$. The distance between anode and cathode is only about 0.15 mm and varies from source to source. On the other hand this result agrees with the fact that rf sources can operate at lower powers than dc sources. Figure 12 shows that also in the rf case the saturation current depends linearly on pressure and the absolute values are similar.

3.3. Pulsed direct current discharge
In the case of pulsed discharges besides current, voltage and pressure the pulse duration $\tau$ and frequency $f$ can also be varied. Additionally, the evaluation of the current value is not as simple as in dc, as the current is not constant. In figure 13 there is a comparison of current signal shapes at constant and different duty cycles. For figure 13 a) the frequency was kept constant and the pulse length was varied resulting in a varying duty cycle as well. For figure 13 b) both frequency and pulse length were varied so that the duty cycle of 1% kept constant. At the beginning and end of each pulse there are artificial signals caused by high currents at ground potential. The data presented in figure 13 were measured with an 8 mm anode and therefore the absolute values cannot be compared with data from the other figures.

Figure 11. Threshold voltage in dependence on pressure from figure 9.

Figure 12. Saturation current in dependence on pressure from figure 9.

Figure 13. Comparison of current signal shapes at different (a) and constant (b) duty cycles at 1000 V and 6.7 mbar.
At a constant duty cycle of 1% (figure 13 b) the currents have the same time dependence and only stop at different times according to their pulse length. But with increasing duty cycle the current decreases at constant frequency 1 kHz (a). This effect is very similar to the decrease of current under higher voltages in the dc case and can also be caused by the discharge gas heating. In order to investigate the influence of pulse length and frequency at the variation of the duty cycle, measurements were done at constant pulse duration of 50 µs, varying the frequency and at constant frequency of 1 kHz, varying the pulse length (figure 13).

For the evaluation of these curves the current of pulses with any length is averaged within a time interval skipping the artificial signals. This algorithm provides the same magnitude of the electrical current for all pulses having the same time dependence, even if the durations of the pulses are different. This algorithm was used to reflect the changes of the current at the first and last 5 µs, which represent changes in the I-U characteristics in this time. The voltage was almost constant during the pulse (see figure 2 a).

![Figure 14](image)

**Figure 14.** I-U characteristics for pulsed dc discharge at constant pulse duration (a, b: 50 µs) and constant frequency (c, d: 1 kHz) at 5 mbar.

It is apparent from the all plots in figure 14 that the averaged current value decreases with increasing duty cycle. This indicates that there can be a different temperature. But unlike the I-U plots for the continuous dc mode in the case of pulsed dc discharge most of the I-U characteristics are not curved. This means that the discharge gas temperature for a defined duty cycle remains nearly constant. For high pulse length, frequencies and duty cycles the current of pulsed dc discharges also starts to saturate at the end of the pulse (figure 14 b, d), because these conditions are similar to a continuous discharge.
The comparison of the I-U characteristics acquired at the beginning and at the end of the pulse shows clearly that at the beginning the current is higher than at the end. This agrees with the effect of gas heating, which however may not be the main reason for these different currents. In the case of pulses with short durations of 10 µs in figure 14 d) the times for current integration nearly overlap and no difference is possible.

I-U characteristics measured at constant pulse duration (figure 14 a, b) begin to change only at duty cycle 0.1 (2000 Hz). This means that cooling is efficient between the pulses, if there is more time than about 500 µs.

From figures 14 b) and d) follows that at 50 µs pulse length and 1 kHz frequency there is more influence of the pulse length on the discharge gas temperature than of the duty cycle at fixed pulse length. A similar effect was observed by D. Fliegel [31] for the breakdown voltage. His experiments showed that the breakdown voltage of pulsed discharge remains the same at different delays between two plasma pulses, but with increasing pulse duration the breakdown voltage decreases.

Measurements at varying pressure were also done and show the expected correlation between pressure and current. This correlation can be used for temperature estimation as shown in [26].

3.4. Pulsed radio frequency discharge

![Figure 15. Ionic part of the I-U characteristics at different pressures and duty cycles (50 µs constant pulse length, cycle during last µs).](image)

Equivalent measurements to the dc pulsed case were also performed for the pulsed rf discharge. However, 25 % was the highest duty cycle which could be applied, because the rf generator needs about 20 µs to become stable (dc bias development) and to switch off. More details about these results are presented in [26] and only some comparisons are done here.

All I-U characteristics were measured at constant rf generator anode voltage of 1100 V. Figure 15 shows the ionic part of the I-U characteristics at different pressures and duty cycles measured at the end of the pulse. Two I-U plots with the same slope can correspond to the low duty cycle and low pressure and to the high duty cycle and high pressure. For constant frequency and at 6 mbar the same effect is visible in figure 16. This phenomenon gives an approach to estimate the discharge temperature (see [26]). Figure 16 shows also changes in the electronic part. At high duty cycles the maximum current reduces and the hysteresis increases.

![Figure 16. I-U characteristics for pulsed rf discharge at constant frequency (400 Hz) at 6 mbar (25 µs – 625 µs pulse length).](image)
The difference between the beginning and end of the pulse is not as pronounced as in the dc case, because there are no high currents in the first microseconds at rf discharges. Similar to the dc case, the weakest effect occurs at the beginning of the pulse at constant frequency and the strongest effect is visible in this mode at the end of the pulse (see figure 16).

Additional experiments with varying anode voltage, constant pressure (6 mbar) and constant pulse length (50 µs) have shown that the voltage has nearly no influence on the slope of the ionic current, even if the power changes by a factor of 2.

4. Summary and Conclusion
Accurate measurements of voltage and current support the interpretation of analytical results and are necessary as input or fit parameters for modelling groups. From the comparison of different hardware for dc pulser, it becomes clear that several microseconds after pulse termination current may still flow, because of discharging capacities.

In continuous dc and rf mode, the transformation of I-U into P-U curves simplifies the determination of threshold voltages and saturation currents. From the comparison of those curves it was confirmed that in rf mode the effective voltage corresponds best to the voltage in dc mode.

In pulsed mode, the variation of pulse length and frequency influences the I-U curves and complicates the evaluation and presentation of the data. In general, a higher duty cycle reduces the current at the same voltage. The similarity of this effect with a reduction of pressure or gas density most probably is caused by gas heating.

In pulsed dc it was found that the time behaviour of voltage and current is independent of frequency and pulse length, if the duty cycle is kept constant. The current within the first 5 µs decreases during the pulse. This effect is less pronounced in rf mode, because the strong currents at the beginning are missing. The current decrease because of gas heating is similar and after about 500 µs off pulse the gas cools down. An increase of voltage does not change the slope of the current voltage characteristic to the same amount as a corresponding change of the duty cycle. Also the changes in the electronic part of the I-U characteristics need further attention. Therefore, continued cooperation with modelling groups is needed and planned.

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