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P. Snögren^{1,2}, M. Berglund^{1,2}, and A. Persson^{1,2,a}

¹Ångström Space Technology Center, Department of Engineering Sciences, Uppsala University, Box 534, 751 21 Uppsala, Sweden

²Division of Microsystems Technology, Department of Engineering Sciences, Uppsala University, Box 534, 751 21 Uppsala, Sweden

Abstract. Monitoring and control of the principal properties of a discharge or plasma is vital in many applications, and sensors for measuring them must be integrated close to the plasma source in order to deliver reliable results. This is particularly important, and challenging, in miniaturized systems, where different compatibility issues sets the closest level of integration. In this paper, a sensor for simultaneous measurement of the pressure and flow through a stripline split-ring resonator microplasma source is presented. The sensor utilize fully integrated electrodes positioned upstream and downstream of the microplasma source to study these parameters, and was found to deliver uniform and unambiguous results in a pressure and flow range of 1-6 Torr and 1-15 sccm, respectively. Furthermore, hysteresis and drift in the measurements was found to be mitigated by introducing a resistor in parallel with the plasma, in order to facilitate discharging of the electrodes. Combined, the results show that the sensor is fully compatible with miniaturized microfluidic systems in general, and a system for optogalvanic spectroscopy in particular.

During the last couple of years, plasma has attracted increasing attention from the microengineering community, particularly in the field of microfluidics. From being mostly central to many fabrication processes, plasma has begun to find more diverse uses through the integration of different kinds of microplasma sources in miniaturized systems¹. Examples of this include gas sensors based on both emission^{2,3} and optogalvanic spectroscopy^{4,5}, microreactors where the plasma is used to initiate chemical reactions⁶, sterilization by UV and/or reactive ions^{7,8}, and sources of photons or ions in, e.g., lasers⁹ and mass spectrometers¹⁰. Together, such use of plasma offers substantially extended functionality in microsystems in general, and microfluidics in particular.

Many of the applications rely on thorough measurement and control of the plasma's physical properties, i.e. the temperature and density of electrons, ions and neutrals, as well as the pressure and gas flow through the discharge. While the electrons and ions are studied by direct electrical probing of the plasma¹¹⁻¹³, the neutrals typically require separate sensors, which still have to be integrated close to the plasma to deliver reliable results. Such close integration may become problematic in microsystems, where thermal, mechanical and electric compatibility issues between different building materials, fabrication processes, and operation requirements often limit how close different components can be stacked. Hence, the integrability of temperature, pressure and flow sensors with microplasma sources is very important if the true potential of plasma-based microfluidics is to be exploited.

^a Electronic email: anders.persson@angstrom.uu.se

In this paper, similar methodology to how the density and density of the electrons and ions are studied, i.e. direct electrical probing, is applied to simultaneous measurement of the pressure and flow through the discharge. The concept of using plasma to measure these entities might not be entirely new, where, e.g., a Penning gauge relies on plasma to measure ultra-high vacuum, and Chua and Pak have demonstrated a flow sensor based on a corona discharge¹⁴. However, the approach of performing these measurements simultaneously and fully integrated with a miniaturized and highly versatile microplasma-source system is. The measurement scheme was first reported in the first author's diploma work, Ref. 15, and this paper represent an extended and more detailed analysis of the same data set.

The design of the sensor is to some extent based on a calorimetric flow sensor scheme¹⁶, in which two sensor elements are positioned upstream and downstream of a heater, and the flow rate is estimated by measuring the displacement of the heat distribution towards the downstream direction. However, in the sensor presented here, a plasma source replaces the heater and the flow is measured by two electrodes, still positioned upstream and downstream of the plasma, under the assumption that a flow will shift the plasma distribution towards the downstream side, and, hence, create a voltage difference between the electrodes. Using a flow to shift the distribution of a plasma is common practice in, e.g., microplasma jets where ionized gas is expelled as a plume from a microplasma source operating at atmospheric pressure^{17,18}. A changing pressure will also affect the plasma distribution, however, independently of the flow direction, wherefore the pressure can, possibly, be measured as the average potential of the two electrodes. In order to balance the measurement, a probe was also inserted into the center of the plasma bulk.

The plasma source was a stripline split-ring resonator¹¹ (SRR) with a resonance frequency of 2.45 GHz, corresponding to inner and outer ring-radii of 4.58 and 6.27 mm with a 2 mm wide gap, figure 1. It was fabricated from a total of six layers of PCB, in a similar way as described in Ref. 19, although with a few exceptions. Firstly, the SMA contact connecting the SRR to the radio frequency (RF) source was mounted out of the plane. Secondly, the gap was fitted with only one electrical probe, since no optogalvanic experiments were performed. Thirdly and most importantly, the fluidic system was equipped with two sets of four electrodes – one upstream and one downstream the plasma source, figure 1. The electrodes closest to the plasma had the same width as the gap, and, hence, covered the whole area that was directly facing the discharge, figure 2. The rest of the electrodes were 0.8 mm wide and extended out through the channel connecting the device to the fluidic system, figures 1 and 2.

Figure 1. Exploded view of the six PCB layers making up the device.

Each electrode was connected to a 34970A multichannel data acquisition (DAQ) unit from Agilent Technologies (CO, USA) that measured the voltage between the electrode and the grounded probe. As an option, the probe could be connected to resistors with resistance, R , in parallel with the DAQ, figure 2. Although all electrodes were connected to the DAQ, only data

from the first two, i.e. the pairs closest to any gap, and presented in this paper. In each averaging of record, the flow rate was represented by the voltage difference between the upstream and downstream electrode, $V_U - V_D$, based on the assumption that the flow will offset the distribution of the plasma towards the downstream direction and, hence, create a voltage difference between the electrodes. The pressure, on the other hand, was represented by the average electrode voltage, $(V_U + V_D)/2$, based on the assumption that the average potential of the electrodes only will be dependent on the mean distribution, or rather expansion, of the plasma, which is inherently dependent on the pressure, but, presumably, independent of the flow (see figure 2).

Figure 2. Schematic view of the measurement scheme showing a cross section of the gap through the SRR. The electrical connections to the resistors, R , were optional. The inset shows a photograph of the final device beside a Swedish 10 kronor coin (Ø20.5 mm).

The outer dimensions of the finished device were approximately 30 x 30 x 10 mm excluding the electrical connectors, inset of figure 2. However, it could easily be made much smaller by the use of other materials and fabrication processes as described in, e.g., Ref. 20, making a final size approaching millimeters fully feasible.

In order to connect the device to the external fluidic system, it was mounted with $\frac{1}{4}$ " plastic tubes, inset of figure 2. Upstream of the device was a 275 Mini-Convecton pressure sensor from Granville-Philips (CO, USA) and an F-200 flow controller from Bronkhorst Hi-Tech (the Netherlands), which were used to set up the experiments, and to provide reference measurements. Downstream of the device was a tunable valve that could be used to define the base pressure, i.e. the pressure at the lowest flow rate, before the sample gas was expelled through a vacuum pump. In all other respects, the system resembled that of Ref. 4, and a more thorough description of its schematics can be found in the supplementary material. All experiments presented in this paper were performed with samples of air.

In the experiments, a starting flow of 1 sccm through the system was set using the flow controller. The variable valve was then used to set the starting pressure as measured by the pressure gauge. After stabilization, the flow was first increased to 15 sccm and then reduced back to the starting flow in a total of 20 steps. At each step, the voltage between the electrodes and the probe, as well as the external pressure and flow rate were recorded. These parameters were chosen with respect to the first intended application of the device, which was to monitor the plasma inside a detector for optogalvanic spectroscopy⁵. In this application, pressures below 6 Torr and flows rates below 15 sccm are of particular interest¹². Furthermore, in order to verify a flow dependent signal, the flow through the device could be both blocked and reversed.

Some first results are shown in figure 3, where the voltage between the first pair of electrodes and the grounded probe are shown. Initial observations revealed a significant flow dependency, where the voltage distributions were skewed towards opposite sides depending on the flow direction. The voltage functions also showed a somewhat hysteretic behavior as the flow was cycled from a low, to a high and back to a low rate. This effect was probably inherent to the device, since no similar behavior was found in the external pressure measurement (dashed line and right y axis of figure 3). Here, it is important to note that the pressure and flow rate were mutually dependent in all but one of the experiments presented in this paper, i.e., when the flow rate increased so did the pressure.

Figure 3. Voltage at the first electrodes upstream, V_U , and downstream, V_D , of the plasma as a function of the applied flow rate. The dashed line shows the relationship between pressure and flow. The starting pressure and flow rate in this experiment were 1.1 Torr and 2.5 sccm, respectively.

Figure 4 (a) shows the voltage difference between the electrodes in figure 3, where the flow dependency appears much more clearly, having a uniform and almost linear response with a sensitivity of about 50 mV/sccm. The pressure dependence of the average electrode voltage in the same experiment is shown in figure 4 (b). It had a somewhat stronger but less uniform response (sensitivity ≈ -100 mV/Torr) and demonstrated more of the above mentioned hysteresis. Still, these results were encouraging, and showed that the approach of simultaneously measuring both the flow rate and the pressure was clearly feasible. However, in order to verify this assumption even further, an additional experiment was conducted, where the outlet of the device was blocked and the flow was bypassed directly to the vacuum pump. Hence, no flow passed through the device, while the internal pressure still varied with the external flow. Under these conditions, the flow dependence disappeared while the pressure dependence remained more or less unchanged. This was the only experiment where the pressure and flow rate were not mutually dependent, but where the pressure changed independently of the flow.

Figure 4. Voltage difference between the first upstream and downstream electrodes as a function of flow rate (a), average electrode voltage as a function of pressure (b), both calculated from the experiment shown in figure 3. The drift of the initial voltages (V @ 1 sccm) of the upstream and downstream electrodes as the device is cycled between high and low flows is shown in (c). One cycle corresponded to about 300 s.

Apart from the hysteretic behavior, repetition of the experiment without stabilization showed clear signs of drift. In figure 4 (c), the same experiment was repeated 15 times and the electrode voltages at the start of each cycle were recorded. As can be seen, the electrodes initially drifted in opposite directions, but after about 5 cycles – corresponding to around 25 minutes – the drift of the downstream electrode reversed to a about the same rate as the upstream one. Hence, the drift of the voltage difference, i.e. the flow measurement, leveled out, while that of the average voltage, i.e. the pressure measurement, continued. This behavior was most likely the main explanation to why the pressure measurement in figure 4 (b) showed more signs of drift than the flow measurement, since the setup had been stabilized at the initial conditions for an hour before the experiment.

Both the drift and the hysteresis were probably caused by charging of the electrodes, which is a common issue during electrically probing of a plasma¹³. Even though the electrodes were connected to ground via the DAQ, the latter had an internal impedance of 100 M Ω , which made discharging slow. Hence, in order to mitigate the discharging of the electrodes, resistors with resistance between 100 k Ω and 32 M Ω were connected in parallel with the DAQ, as shown in figure 2. The flow sensor performance was then evaluated based on three parameters – the sensitivity calculated from a linear fit to the sensor response, the linearity based on the goodness of this fit, and the hysteresis corresponding to the maximum difference in the response during a flow cycle. The results can be seen in figure 5. Both the sensitivity and the hysteresis were increasing logarithmically with the resistance throughout the investigated resistance interval, while the improvement of the linearity leveled out beyond a resistance of about 1 M Ω . Here, it should be noted that the reduction of the sensitivity with decreasing resistance was not purely due to voltage division in the circuit, since this would have yielded a linear dependence, but a more complex process involving the impedance of the plasma itself, as well as the capacitance of connecting cables, where, e.g.,

Figure 5. Sensitivity (a), hysteresis (b) and linearity (c) as a function of the resistance of the resistor connected in parallel with the DAQ. Both the sensitivity and the linearity refer to the flow measurement scheme, and the latter is represented by the R^2 value of a linear fit to the data.

The first intended application of the device is in a system for optogalvanic spectroscopy^{4,5,19} where the pressure and flow rate generally is restricted to levels below 6 Torr and 15 sccm. Figure 6 shows the sensor performance in this domain, where the starting pressure was varied in nine steps between 1.1 Torr and 4.1 Torr. As can be seen, unambiguous responses were observed with respect to both pressure and flow. Moreover, the inverse of these graphs, i.e. the dependencies of the pressure and flow rate on V_U and V_D can be found in the supplementary material. The unambiguity of the results proved that the device was capable of sensing these parameters simultaneously and independently, which is very promising with respect to the performance of the optogalvanic detector, where careful monitoring and control of all the plasma parameters are paramount if a stable and reliable spectrometric output is to be achieved. Still, the optogalvanic detector is intended for lab-on-a-chip applications where high levels of miniaturization and mobility are required, meaning that all auxiliary sensors have to be highly integrable with the present system.

Figure 6. Response to flow (top) and pressure (bottom) while operating the device *with different starting pressure in a regime of 1-15 sccm and 1-6 Torr. The lines shows the direction of the nine different flow sweeps, and the contour plots were calculated from linear Lowess fits to the data (span=50). An 32 M Ω resistors connected in parallel with the DAQ in all the experiments.*

From an integrability point of view, some aspects of the design can become problematic if the device is to be included in an optogalvanic detector, since this requires a laser beam to transverse the gap unobstructed¹⁹. This will, in turn, require that at least a part of the first electrode pair (equivalent to the cross section of the beam) is removed. However, the second electrode pair also yielded flow and pressure dependent responses, which were more or less identical to those of the first pair up to a flow of about 6 sccm, after which the flow sensitivity decrease by a factor of ~ 2 , while the pressure dependence remained unchanged. Hence, even if all of the first electrode pair was to be removed completely, the device must be regarded to have all opportunity to fulfil the requirements of the optogalvanic application.

In conclusion, technology and methodology for measuring the pressure and flow inside an SRR microplasma source have been presented, and shown to produce simultaneous and unambiguous results within, and probably beyond, a pressure and flow range of 1-6 Torr and 1-15 sccm, respectively. The device is fully compatible with a miniaturized optogalvanic detector system, in which it will serve the vital function of monitoring the plasma conditions to enable stable and reliable

Supplementary Material

See supplementary material for details of the experimental setup, as well as information on the dependency of the pressure and flow rate on the voltages of the upstream and downstream electrodes.

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DAQ

- Fluidics
- Stripline SRR
- Electrodes
- Plasma
- Probe
- Flow