A Passive Micro Gas Regulator for Hydrogen Flow Control

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Abstract

This paper presents the design, fabrication process and experimental characterization of a novel passive micro gas regulator made using MEMS technologies. This device is to be used in a miniature fuel cell for portable electronic appliances. Because it is passive and of small dimensions, it is well-suited for portable applications. To our knowledge, this is the first passive micro gas regulator. However, the structure and working principle of this device is similar to some macroscopic existing devices, for example used in scuba diving. The fabrication uses conventional MEMS technologies to produce complex 3D microstructures, i.e. deep-RIE etching and multiple wafers bonding. The experimental characterization shows that the device works as expected: it passively releases a gas from a high pressure storage tank on-demand and regulates its pressure to about 1 atm.

Keywords: gas regulator, fuel cells, passive device, wafer bonding, deep RIE

1 INTRODUCTION

Fuel cells are now seen as a promising solution to provide miniature energy sources for portable electronic appliances with a high energy density, low pollution and short recharge time [1]. Although the working principle of fuel cells is simple, achieving high efficiencies requires controlling several parameters such as oxygen flow, water production, heat diffusion and hydrogen supply. In the case of portable fuel cells, it is very important to use passive devices as much as possible to control these parameters. This is to save the energy produced by the fuel cell. Therefore, although several micro gas regulators for various applications have been reported in the past (see [2] for example), a passive micro gas regulator is needed for this particular application. Such a device has been developed in this project. Its design, fabrication process and experimental characterization are presented in this paper.

2 DESIGN

The basic structure and working principle of the micro gas regulator (referred to as MGR in the following) are similar to those of some gas or pressure regulators of macroscopic size commercially available: for example some types of pressure regulators used with gas bombs and some types of pressure regulators used for scuba diving [3]. The structure has been adapted to our particular application and to be compatible with MEMS technologies.

2.1 Structure

A schematic cross-section of the MGR is presented in Figure 1.

![Figure 1: Scheme of the cross-section of the MGR.](image)

The device is symmetrical around the central axis except for the exhaust channel that is a parallelepiped. It consists of the stacking of three silicon wafers with an equivalent thickness of 300 µm. A rigid structure of 150 µm height and of 500 µm in radius is suspended by a flexible silicon membrane that is 35 µm thick and 1800 µm in radius. It is connected to a piston that is 130 µm in radius. This last is connected to a stopper that is 250 µm in radius. The bottom and middle wafers are connected through a 1 µm thick silicon dioxide layer. The stopper and the middle wafer are separated by a distance that is the same as this SiO₂ layer. The contact part between the stopper and the middle wafer is around 30 µm in length. The overall size of the MGR is 8×8×1 mm³.

2.2 Working principle

The working principle of the MGR is as follows. The MGR in closed position is shown in Figure 2. The bottom part is connected to a hydrogen tank which pressure is $P_0=2.5$ atm. The exhaust channel is directly connected to the fuel cell which itself supplies a bubble lamp in this example. The pressure of hydrogen in the exhaust...
channel is set to $P_1=1$ atm. Finally, the upper part of the membrane is connected to the ambient air which pressure is $P_2=1$ atm. As the pressure difference on the membrane is zero, the only force acting on the piston is the pressure of the hydrogen tank transmitted via the stopper. It pushes this last against the valve seat and therefore closes the MGR.

![Figure 2: Working principle of the MGR: closed position.](image)

The large arrow shows the pressure difference.

When the lamp is switched on, the fuel cell consumes the hydrogen in the exhaust channel, decreasing the pressure $P_1$ (Figure 3). This pressure difference is taken into account by the membrane and the rigid structure that pushes the stopper away from the valve seat. The MGR therefore opens and more hydrogen is released from the tank to the fuel cell.

![Figure 3: Working principle of the MGR: open position.](image)

The small arrows show the gas flow vectors.

When the pressure of the released gas is back to atmospheric pressure, the stopper closes back as shown in Figure 2. Therefore, this device passively releases hydrogen from a high-pressure tank when needed by the fuel cell and regulates its pressure to the atmospheric one.

3 FABRICATION

The fabrication of this device consists in the successive deep-RIE etching and bonding of three silicon wafers. The use of these two techniques allows the fabrication of complex 3D microstructures [4].

3.1 Process of the first wafer

The fabrication starts with a 300 µm thick double side polished silicon wafer. The process for this wafer is presented in Figure 4.

![Figure 4: Process for the first wafer (see text for details).](image)

Using a patterned Shipley S1818 positive photo resist and deep RIE etching, alignment marks are patterned on one side of the wafer (Figure 4-1). Then follows an original process adapted from reference [5]. Two aluminum layers are successively deposited and patterned on the other side of the wafer (Figure 4-2). A first deep-RIE etching of 150 µm is then performed. (Figure 4-3). Thanks to a time controlled wet aluminum etching, the second aluminum mask is removed (Figure 4-4). Finally, a second deep-RIE etching of 115 µm is performed to form the piston and the exhaust channel (Figure 4-5). The result of this process is shown on a SEM micrograph in Figure 5.

![Figure 5: SEM micrograph of the first wafer.](image)

3.2 Process of the second wafer

A new 300 µm thick double side polished silicon wafer is then directly bonded onto the first patterned wafer as shown in Figure 6-1.

![Figure 6: Process for the second wafer (see text for details).](image)

Using a patterned aluminum mask, this second wafer is completely etched using deep-RIE etching in order to form the piston (Figure 6-2). The result of the process for this
second wafer is shown in Figure 7, where the central piston and the exhaust channel can be seen.

Figure 7: SEM micrograph of the first two wafers.

### 3.3 Process of the third wafer

Finally, an oxidized 300 µm thick double side polished silicon wafer is directly bonded onto the first two patterned wafer as shown in Figure 8-1.

![Process for the third wafer](image)

Figure 8: Process for the third wafer (see text for details).

Using a patterned aluminum layer, this third wafer is completely etched using deep-RIE etching to form the stopper (Figure 8-2). Using a time controlled HF etching, the buried SiO₂ layer is partially removed in order to release the stopper from the valve seat (Figure 8-3).

![SEM micrograph of the cross-section of the MGR](image)

Figure 9: SEM micrograph of the cross-section of the MGR (cut is not centered).

The result of the whole fabrication can be seen in Figure 9. This SEM micrograph shows a cross section of the MGR obtained by dicing saw. In order to protect the device from excessive heating during the dicing, the cut is not centered.

### 4 EXPERIMENTS

The characterization of the MGR consists of controlling the input pressure \( P_0 \) in Figure 2) and the regulated pressure \( P_1 \) in Figure 2) while measuring the flow rate through the MGR and the displacement of the membrane.

#### 4.1 Experimental set-up

A homemade testing bench has been developed specifically for this device. It uses nitrogen as the testing gas. A picture of this experimental set-up is shown in Figure 10.

![Experimental set-up](image)

Figure 10: Experimental set-up.

The whole experimental set-up is placed on an optical bench with pneumatic suspensions. The micro valve is packaged in a homemade chamber made of machined SUS and sealed with Viton sheets. It is seen on the left part of Figure 10. Above the chamber is placed the laser head used to measure the membrane displacement (Keyence LC 2430). The input pressure is measured with a SUNX DPH-A02 pressure transducer, and the flow rates are measured with STEC SEF 4400 flow meters. After the MGR, the pressure is regulated using a STEC UR-7340 pressure regulator and a vacuum pump. The pressure regulator also serves to measure the output pressure. All measurements have been made at equilibrium states.

#### 4.2 Behavior of the MGR

The pressure \( P_0 \) was set to 2.43 atm in order to simulate the pressure of the gas tank. The pressure \( P_2 \) was naturally at atmospheric pressure. At first, the pressure \( P_1 \) was also set to atmospheric pressure. The measured flow was 0.0 sccm, which is the limit precision of our mass flow meters. The MGR was therefore closed and the leakage was below 0.1 sccm nitrogen. Using the pressure regulator, the regulated pressure \( P_1 \) was progressively reduced below atmospheric pressure. The nitrogen flow rates before and after the valve were recorded, as well as the displacement of the membrane. The results are shown in Figure 11. The flow rates before
and after the device are almost the same, which indicates that there was little leakage from the system with the outside. Only the flow rate after the MGR is shown in Figure 11.

![Flow in the valve and Membrane displacement](image)

**Figure 11:** Experimental characterization of the MGR.

The MGR behaves as follows. When the regulated pressure $P_1$ is at atmospheric pressure, the MGR is closed and no gas is flowing through it. The situation remains the same until the regulated pressure $P_1$ decreases below 0.93 atm. At this time, the MGR starts to open as the membrane moves, and the nitrogen starts to flow. At the end of this experiment, when the regulated pressure $P_1$ reached 0.88 atm, this pressure was increased to 1 atm and we could verify that the MGR was closed again.

The principle of this device has therefore been demonstrated: a high pressure from the tank closes the MGR; the opening and closing of the system are commanded by the pressure $P_1$ in the exhaust channel.

### 4.3 Cracking pressure

Several mechanisms can be chosen in order to store the hydrogen in the final fuel cell system: metal hybrid, compressed gas or liquid hydrogen. Whatever the mechanism chosen, the pressure $P_0$ of hydrogen in the tank is dependant on the temperature. In some cases, this pressure $P_0$ can be multiplied by a factor 10 in the temperature range 25-60°C. It is therefore important to have a gas regulator that can operate at higher input pressures. Moreover, it is important that the pressure at which the gas regulator opens (called the cracking pressure) is not much dependant on the input pressure.

In order to investigate this situation at higher temperatures, the MGR was tested at higher input pressures. The results of these experiments are presented in Figure 12.

![Cracking pressures of the MGR](image)

**Figure 12:** Cracking pressures of the MGR.

It can be seen that although the input pressure is increased by a factor 5, the cracking pressure is only diminished by 25%. Therefore, the sensibility of the MGR to the input pressure, and therefore to the temperature, is limited.

### 5 CONCLUSIONS

This paper has presented the design, fabrication process and experimental characterization of a novel passive micro gas regulator. Thanks to their small sizes and high functionality, MEMS devices are well suited for portable applications. However it is very important to produce passive or self-powered devices in the case of portable applications in order to save the embarked energy. Because they require several fluidic and mechanical devices in order to achieve high performances, fuel cells for portable electronic appliances are seen as a good application field for MEMS technologies, especially if the MEMS devices are passive or self-powered.

### ACKNOWLEDGMENT

This work is supported by VLSI Design and Education Center (VDEC), the University of Tokyo, with CADENCE Corporation, including for photo mask fabrication.

### REFERENCES