Novel Device Solutions against interfering Gas Bubbles in Microfluidic Applications

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Abstract. Unintended gas bubbles in microfluidic systems can significantly interfere with performance and behavior, thus there is a high demand for microfluidic system designs which are capable of preventing gas bubbles efficiently. In this work, we develop two different bubble interference preventing approaches: first a degasser device that actively removes gas bubbles from the liquid based on pressure driven gas permeation, and a second passive micro channel design that provides a guiding mechanism based on the gas bubbles’ effort to minimize their surface energy. The effective performances of the devices are demonstrated using a gravimetric surface acoustic wave biosensor.

Keywords
Microfluidics, Gas bubble removal, Degassing.

2. Materials and Methods

2.1 Degasser

The degasser, shown as schematic drawing in Fig. 1, uses PDMS (Wacker Chemie AG, Germany) as gas permeable membrane material. PDMS is used as biocompatible material in microfluidic systems [4]. The PDMS is used to separate the microfluidic channel from surrounding vacuum channels (see dotted area in Fig. 1). Figures of merit for a microfluidic degasser are the required flow distance until the gas bubble is completely removed (as it determines the dead volume) and the maximum bubble volume that can be removed at a given flow rate.

Therefore, our goal was to maximize the gas flux diffusion through the membrane while keeping the length of the degasser channel as small as possible. The gas flux is equal to:

$$N = \frac{P \Delta p}{h}.$$  

With $N$ being the steady-state gas mass flux, $P$ the gas permeability, $\Delta p$ the pressure difference along the membrane and $h$ the penetrating thickness [5]. To increase the flux the membrane thickness $h$ has to be minimized but still maintain mechanical stability. Our approach contains two vacuum channels beside of the microfluidic channel and one at the bottom of the channel, separated by a thin spin coated PDMS membrane, as shown in Fig. 1. The microfluidic and the vacuum channel have a diameter of 0.3 mm. The final thicknesses of the PDMS membranes are $w = 0.3$ mm and $h = 0.1$ mm.

1. Introduction

Gas bubbles in microfluidic environments are known for causing functional disturbance. This leads to a direct impact on the measured signals due to the different mechanical and electrical characteristics of the gas compared to the liquid analyte. Recently, different approaches have been proposed for handling with gas bubbles. Skelley et al. have introduced a combination of trapping and degassing by capturing gas bubbles with special trap structures in poly(dimethylsiloxane) (PDMS) [1]. However, the obvious disadvantage of these physical traps is their finite volume capacity, which limits the maximal volume of trapped gas bubbles before they flow over. Lochovsky et al. have developed an active degassing process to remove gases solute in the liquid, but their approach requires a rather big dead volume, since they only implement a degassing channel interdigitated with the fluidic channel [2].

Our first approach contains a single active degasser that removes gas solute in the liquid during continuous flow, so that normal device operation is maintained. The degassing is achieved by using pressure driven gas permeation through a porous membrane. Active degassing devices are not suitable for all microfluidic applications, when gas exchange is needed through the PDMS or extreme pH values of fluids are needed [3]. Therefore, in our second design approach a passive guiding channel is realized which prevents any trapping possibilities for gas bubbles within the fluidic channel in order to quickly and directly guide gas bubbles away from the sensitive surface.
Afterwards, the PDMS membrane was spin coated (b), cut and plasma bonded underneath the degasser body (c). The parts were finally plasma bonded onto a glass substrate with a PDMS and cloth layer in between, acting as spacers, thus creating the bottom vacuum channel (d). The casting process was executed as follows: the PDMS was evacuated before it was poured into the casting mold, which was then baked out in a convection oven at 60°C for two hours. The spin coating was performed in a similar way; the mixed and evacuated PDMS was poured onto a silicon wafer and then distributed by spin-coating at 1750 rpm for 30 s before it was baked at 60°C for 20 minutes.

### 2.2 Guiding meander channel

In a second approach, we developed a passive guiding channel in a meander shape that is capable of guiding undesirably introduced gas bubbles directly away from the sensing surface. The working principle of the guiding mechanism is based on the gas bubbles’ endeavor to minimize their surface energy. In order to do so, the bubbles reduce their surface area, leading to the well-known formation of round bubbles. In a microfluidic channel with very limited height this tendency is suppressed (see Fig. 3). Therefore, by adding additional height \( h \) to the channel on a specified path the gas bubbles are forced onto this path.

Since our test application is a gravimetrical sensor, the microfluidic channel design should cover as much of the sensitive area of the chip as possible (gold area in Fig. 4, marked orange) to increase the sensitivity of the sensor. Thus, the rectangular part of the channel overlays the whole sensing surface. Since the height of this part of the channel is limited, the flow resistance \( R_{Fl, Rect} \) is large compared to the one in the elevated part, so that the majority of the flow is guided along the elevated part. In order to maintain an adequate flow over the entire sensing surface, \( R_{Fl, Rect} \) has to be reduced. To do so, the elevated part of the channel is designed in a meander shape, so that the effective length of the rectangular part is minimized.
The guiding channel was also fabricated using PDMS casting as already described in chapter 2.1.

![Image of two guiding meander channels placed on gold sensing areas of a surface acoustic wave biosensor chip. The orange frame shows the sensitive surface and the blue frame indicates the area covered by the fluidic channel.](image)

**Fig. 4.** Image of two guiding meander channels placed on gold sensing areas of a surface acoustic wave biosensor chip. The orange frame shows the sensitive surface and the blue frame indicates the area covered by the fluidic channel.

### 3. Results and discussion

#### 3.1 Degassing

The experimental setup was such that a continuous flow of a DI-water air bubble mixture was controlled via two syringe pumps (HLL Landgraf LA-110, Germany), one with a syringe filled with DI-water and one with a syringe filled with air. Their outlets were connected using a T-junction, which was then connected to the inlet of the degasser. With this setup the flow rate as well as the composition of the mixture, or better to say the bubble length, was precisely controllable [7]. Fig. 5 shows the microfluidic degasser at work. The Water-Air mixture was introduced from the bottom left. The flow rate of the mixture was 5 ml/h, the relation between water and air was 1:1 leading to a bubble size of about 1.5 cm when entering the degasser. Apparently the bubble size gets smaller with increased progress of the mixture in the microfluidic channel, indicating a continuous degassing process.

![Image of the microfluidic degasser at work. The water gas bubble mixture enters the degasser at the bottom and follows the meander channel to the top. The degassing leads to a continuous reduction of the bubble size.](image)

**Fig. 5.** Image of the microfluidic degasser at work. The water gas bubble mixture enters the degasser at the bottom and follows the meander channel to the top. The degassing leads to a continuous reduction of the bubble size.

As indicated in Chapter 2.1 the figures of merit for a microfluidic degasser are the introduced dead volume and the bubble volume that can be removed sufficiently at a given flow rate. The microfluidic channel has a diameter of 0.3 mm and a length of 30 cm resulting in a dead volume of about 20 µl. At a flow rate of 5 ml/h the longest bubbles that can be removed are about 1.5 cm long, indicating a gas volume of approximately 1 µl. This result is highly dependent on the type of solute gas, as the diffusion constants in PDMS differ for different gases [5]. However this result was obtained with solute air, which is the most frequently occurring gas mixture solute in liquid analytes. The chosen flow rate of 5 ml/h is ten times higher than the actual one set in our standard experiments [8] and the removed gas volume of 1 µl clearly exceeds the usual occurring ones. Thus the performance of our improved degasser shows its capability of reliably removing all interfering gas bubbles before they reach the sensitive part of the sensor.

#### 3.2 Guidance

The sensor used in all following experiments is a gravimetric surface acoustic wave (SAW) sensor that is typically used to sense mass adsorption processes on its surface. The output signal is the frequency shift of the resonance frequency (about 130MHz). To illustrate the importance of the guiding principle in a microfluidic sensor application, where no online degassing is possible, Fig. 6 shows the correlation of bubble behavior inside the microfluidic channel above the sensing area and the sensor output signal. The microfluidic channel used in this experiment has a rectangular base of 8 mm by 5 mm and a height of 0.3 mm. Gas bubbles inside this channel are marked red. The dotted lines indicate at which point of time the pictures were taken in relation to the number of performed measurements. In the first picture, one can obviously see that there were no gas bubbles inside the channel at the beginning of the measurement leading to a stable output signal. At about measurement number 200 the output signal starts to change significantly due to an agglomeration of gas bubbles on the sensing area, as one can see in the following pictures. The gases solute in the liquid keeps enlarging this agglomeration, until measurement number 1950 (s. picture five). At this point of time the agglomeration of gas bubbles engrosses the whole channel, so that the fluid flux pushes it out of the channel. This leads to an abrupt change in the output signal at measurement number 2000 to its initial value, because of no further gas bubble disturbance, as apparent in picture six.
Fig. 6. Correlation between gas bubble formation in the microfluidic channel and its impact on the SAW sensor’s resonance frequency. a) Photographs taken during the measurement. b) Plot of SAW sensor’s resonance frequency shift versus the number of performed measurements.

Obviously, the presence of gas bubbles on the sensing surface causes an unwanted great impact on the resonance frequency, which would overlay true measurement results. However, when the gas bubbles are pushed out of the channel the resonance frequency shifts back to its initial value. Fig. 7 shows the same measurement performed with the guiding meander channel. Clearly, the gas bubbles reaching the sensor still have an impact on its resonance frequency, but the duration of this impact is reduced to a very short time of a few seconds which it takes the bubbles to pass the whole channel, thus not overlaying the signal change expected by a mass adsorption process, which would take several minutes.

Fig. 7. The same measurement as shown in Fig. 6 performed with the new meander guiding channel. The controlled guiding of the gas bubbles through the channel leads to a negligible short interference with the output signal.

4. Conclusion

We have improved an active degasser device by doubling its performance due to an additional vacuum channel at the bottom of the fluidic channel. This is eminently important for the miniaturization of the microfluidic system, since the dead volume within the degasser device is significantly reduced. Additionally, we developed a new guiding meander structure in order to quickly guide any unwanted gas bubbles away from the sensitive part of the microfluidic device. Compared to the degasser the guiding structure is suited for any oxygen sensitive application. Furthermore its working principle is not material dependent. So the PDMS can be replaced with a chemical inert material.

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References


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