A new concept for liquid manipulation has been developed and implemented in surface-micromachined fluid channels. It is based on the surface tension directed injection of a gas into the liquid flow through micrometer-sized holes in the microchannel wall. The injected gas is directed to an exhaust by a cross-sectional asymmetry of the microchannel and thereby moves minute liquid volumes. Successful pumping experiments were performed with single stroke volumes of tens of picoliters at frequencies around 1 Hz. The minimum actuation pressure is 0.6 bar for a 2-μm channel height, in accordance with theoretical predictions.

One of the major driving factors behind the great success of the so-called lab-on-a-chip concept has been the control of liquid movement on the submicroliter level. Initially, membrane pumps were developed capable of volumes in the range of 0.1–100 μL/s. The use of electrokinetic principles to create a plug-flow in microchannels without using mechanically moving parts strongly accelerated the developments in the field. With the ongoing demands for further miniaturization and associated shrinking dimensions of the fluid channels, principles that use surface tension effects become increasingly attractive because of the increased surface-to-volume ratio. Whereas passive control of surface tension has been demonstrated by chemical modification of surfaces, active control has also been proposed for micro- and nanofluidic systems based on electrical, thermal, and optical or electrochemical principles. A powerful method where surface tension plays a crucial role is the use of gas or vapor bubbles to move liquid in milli- and microchannels. It has found widespread practical application, for example, in ink-jet printing. Recently this principle was implemented on a milliscale in a circular symmetrical configuration, and flow rates on the order of 1 μL/s were obtained. Usually the bubbles are generated inside closed liquid channels by boiling liquid or by electrochemical gas generation, thereby limiting the nature and composition of liquids to be used. In this paper, a more generic pumping mechanism is presented, based on surface tension directed gas injection in a hydrophilic microchannel. The surface tension control is based on geometrical variation of the channel cross section, and therefore, no hydrophobic patches are needed inside the microchannels. The pumping mechanism has been implemented in a thin-film integrated fluidics (IF) technology. Microchannels are fabricated by KOH etching of a sacrificial polysilicon strip, sandwiched between silicon nitride layers. Channels with aspect ratios (length/height) of over 1000 were fabricated using this method.

**Operation Principle.** In hydrophilic, flat channels, water tends to fill the open channel as a result of the capillary pressure (pressure drop across the meniscus) given by

\[
\Delta p = 2\gamma_{lg} \cos \theta / h
\]

where \(\gamma_{lg}\) is the liquid–gas surface tension, \(\theta\) is the contact angle.
Figure 1. Longitudinal cross section of a microchannel explaining the principle of operation, with \( h_1 \) and \( h_2 \) the channel height in the shallow and deep part of the channels, respectively, \( p_0 \) ambient pressure, and \( p_{\text{act}} \) actuation overpressure. (A) The microchannel includes a liquid inlet and outlet and a gas injector. The injector is located at the position where the channel height changes. (B) After adding a liquid droplet to the inlet, the empty channel will by capillary forces. (C) Injected gas will move toward the higher channel part, because there the capillary counter pressure is lowest. (D) Once the gas reaches the outlet, the liquid is ejected, and a temporary gas flow is between gas injector and outlet is maintained. (E) When the gas pressure drops, the microchannel will refill by capillary forces. (F) The starting situation (B) is obtained again.

with the wall, and \( h \) is the channel height. Consider the cross section of a surface-micromachined channel with inlet and outlet openings etched out in silicon nitride containing a height step (from \( h_1 \) to \( h_2 \), with \( h_1 < h_2 \)) just on top of a gas-inlet opening etched from the backside and coated with a hydrophobic) gold coating (see Figure 1A). After adding a “large” droplet (a few microliters) of a liquid to the inlet opening, the empty channel will be filled with liquid by capillary forces (Figure 1B). Subsequently, a gas bubble is injected at the location of changing channel height (Figure 1C), and this bubble will move in the direction of the lowest internal pressure in the liquid, i.e., in the direction of the largest channel height. While neglecting the additional capillary pressures at inlet and outlet (compared to the channel height, the radii of inlet and outlet droplets are much larger), the pressures at the inlet and outlet are assumed \( p_0 \). If an additional (gas) pressure \( p_{\text{act}} \) is applied to the injector, the liquid is pushed in the direction of the outlet if \( \Delta p_2 < p_{\text{act}} < p_0 \), with \( \Delta p_2 \) given by eq 1 after inserting \( h = h_2 \). Neglecting the pneumatic pressure drop in the injector, the net pressure driving out the liquid is given by \( p_{\text{drive}} = p_{\text{act}} - \Delta p_2 \). The liquid in the shallower channel (\( h_1 \)) will not be displaced as long as \( p_{\text{act}} < \Delta p_1 \).

Figure 1A shows a longitudinal cross section of a microchannel including a liquid inlet and outlet and the gas injector. The pump sequence is illustrated in Figure 1B-F. In the initial situation, the channel is filled with liquid (B). After application of an appropriate actuation pressure \( p_{\text{act}} \), a gas bubble starts pushing the liquid out of the channel with height \( h_2 \) (C). The gas bubble reaches the outlet and the liquid volume of channel with height \( h_1 \) is ejected (D). Resetting the injector pressure to \( p_0 \) results in a capillary refill of the outlet channel driven by \( \Delta p_2 \) (E), a process that stops when the initial situation is obtained (F).

**EXPERIMENTAL SECTION**

**Bubble Pump Fabrication.** Test structures were fabricated by standard silicon micromachining techniques (Figure 2). First a 1-μm LPCVD silicon nitride layer is deposited and patterned by reactive ion etching (RIE) to define the gas injector. Next, two layers of polysilicon are deposited subsequently by LPCVD and patterned by RIE to form the sacrificial layer, which defines the microchannel. The channel cover plate is formed by 1-μm LPCVD silicon nitride, which is patterned by RIE to define the inlet and outlet holes. The sacrificial polysilicon and the injection holes in the substrate wafer are etched simultaneously in a 25 wt % KOH solution at 74 °C. After cleaning and drying, a hydrophobic coating is deposited into the gas injector hole at the backside through a shadow mask. Figure 3A shows a microscope picture of a

![Image](image-url)
fabricated pump and SEM closeup pictures (Figure 3B–D). Figure 3D shows a SEM picture of the microchannel that has been cut open by focused ion beam (FIB) etching at the location of the gas injector. Note the change in the channel height halfway to the injector. In the tested devices, the channel height was 2 \( \mu \text{m} \) in the thicker part and 1 \( \mu \text{m} \) in the thinner part, as defined by the thickness of the polysilicon. The size of the fabricated microchannels is 1 mm from inlet to outlet and a width of 40 \( \mu \text{m} \).

**Experimental Setup and Procedure.** Chips of 1 \( \times \) 1 cm\(^2\) containing 24 microchannels were glued on top of a hollow sample holder, which can be pressurized for the pneumatic actuation. The sample holder contains a pressure sensor to record the actuation pressure during the experiments. Pressure is switched from high (compressed air) to low (air, atmospheric pressure) by means of a three-way solenoid valve (The Lee Co., LFYA series). The compressed air pressure is adjustable between 0 and 1 bar overpressure through an Omnifit reduction valve. To follow the experiments, the sample holder was placed under an optical microscope (Nikon). Pumping cycles were recorded by a Kodak Fastcam 1000C high-speed camera connected to the microscope. To fill a microchannel, a filtered droplet of deionized water is deposited on the microchannel inlet by a standard medical syringe with needle, by hand. Positioning is done using the focused microscope light spot as a reference. The water droplets typically have a diameter of 1 mm and allow pumping experiments for 5–10 min before evaporation.

**RESULTS AND DISCUSSION**
Clean hydrophilic microchannels immediately fill by means of the capillary forces. To find the capillary counter pressure of liquid

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(25) The images are formed from scattered electrons generated while scanning with the FIB in a low-energy mode. The apparatus used is a FEI 200.

(26) Water is deionized (\( > 15 \text{ M} \Omega -\text{cm} \)) using a Millipore Elix 3 system. Before filling the microchannels, the water is filtered (Gelman Acrodisc 0.2 \( \mu \text{m} \)).
in the higher part of the microchannel, the amplitude of the actuation pressure was gradually increased. Although formation of a small initial bubble was already observed at time $t_0$ ($p_{act} = 300$ mbar; see Figure 4A)), actual pumping only started for actuation pressures above 0.6 bar (see Figure 4A, picture pneumatic pump stroke). This difference may be partly attributed to the fact that, before ejection of the channel volume, a tiny droplet with small radius ($\approx 15\mu m$) has to be formed at the outlet, which needs additional pressure. In addition, the pictures in Figure 4A, pump stroke sequence, at $t_0$ and $t_0 + 0.25$ s, suggest that at these times there is still a liquid connection between inlet and outlet channels. Thus, for real displacement of the meniscus in the outlet channel, it seems that 300 mbar is insufficient. This is in correspondence with eq 1; the fabricated structures have $h_1 = 1\mu m$ and $h_2 = 2\mu m$, and for polysilicon with a native oxide, the surface tension term $2\gamma_{lg} \cos \theta$ is estimated in the range of 0.1–0.2 J/m$^2$. With this value, eq 1 predicts a minimum actuation pressure between 0.5 and 1 bar. Experiments with several devices have demonstrated a reproducible operation of the bubble pump.27 Figure 4A shows microscope high-speed images for a pneumatic actuation at 0.5 Hz at 0.84 bar. The corresponding applied pressure wave, as measured at the sample holder, is shown in Figure 4B. At $t = t_0$, the gas pressure has started to increase, and air just enters the channel. As the actuation pressure further increases, air moves to the left into the higher part of the channel. At $t = t_0 + 0.25$ s, the whole left part has been emptied, and ejected water starts to evaporate. For the structure used in this experiment, the total displaced liquid volume is 40 pL as calculated from the volume of the emptied channel. In the right column of Figure 4A, the refill cycle is shown step by step. Once the actuation pressure is reduced, water reenters the higher channel part, driven by capillary forces. The linear refill speed by the capillary action can be estimated at 2 mm/s. The presented pumping method has a potential for precise dosing of picoliter aliquots and may have several analytical applications. First, it may be used as a picoliter pipet, whereby also integrated electrochemical actuation (formation of an oxygen bubble) can be considered, as we have experimentally verified in preliminary experiments. Alternatively, the device may be used as an injector for a gas chromatograph or a mass spectrometer. Finally, with a modification of the design, picoliter-volume segmented flow may be generated, with the liquid volumes separated by any inert gas. Such a system may have interesting applications in drug discovery, as they may facilitate the storage of extremely small amounts of chemicals in chemical libraries. Future research will focus on generating continuous flow by addition of a second gas exhaust membrane and increasing the speed of operation by further reduction of the dimensions and optimization of the design.

CONCLUSIONS
Gas bubble injection is a simple and generic method for the displacement of picoliter amounts of liquid in surface-micromachined hydrophilic channels. The experiments show that the surface tension directed injection of gas and fast capillary refill in a hydrophilic channel are reliable and strong effects on the microscale. Reproducible dispensing of $\approx 40$ pL of water has been demonstrated. The desired actuation pressure can be estimated by a theoretical calculation.

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