

# Micropumping of liquid by directional growth and selective venting of gas bubbles

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We introduce a new mechanism to pump liquid in microchannels based on the directional growth and displacement of gas bubbles in conjunction with the non-directional and selective removal of the bubbles. A majority of the existing bubble-driven micropumps employs boiling despite the unfavorable scaling of energy consumption for miniaturization because the vapor bubbles can be easily removed by condensation. Other gas generation methods are rarely suitable for micropumping applications because it is difficult to remove the gas bubbles promptly from a pump loop. In order to eradicate this limitation, the rapid removal of insoluble gas bubbles without liquid leakage is achieved with hydrophobic nanopores, allowing the use of virtually any kind of bubbles. In this paper, electrolysis and gas injection are demonstrated as two distinctively different gas sources. The proposed mechanism is first proved by circulating water in a looped microchannel. Using  $\text{H}_2$  and  $\text{O}_2$  gas bubbles continuously generated by electrolysis, a prototype device with a looped channel shows a volumetric flow rate of  $4.5\text{--}13.5\text{ nL s}^{-1}$  with a direct current (DC) power input of  $2\text{--}85\text{ mW}$ . A similar device with an open-ended microchannel gives a maximum flow rate of  $\sim 65\text{ nL s}^{-1}$  and a maximum pressure head of  $\sim 195\text{ Pa}$  with  $14\text{ mW}$  input. The electrolytic-bubble-driven micropump operates with a  $10\text{--}100$  times higher power efficiency than its thermal-bubble-driven counterparts and exhibits better controllability. The pumping mechanism is then implemented by injecting nitrogen gas bubbles to demonstrate the flexibility of bubble sources, which would allow one to choose them for specific needs (*e.g.*, energy efficiency, thermal sensitivity, biocompatibility, and adjustable flow rate), making the proposed mechanism attractive for many applications including micro total analysis systems ( $\mu\text{TAS}$ ) and micro fuel cells.

