Digital microfluidics: Droplet based logic gates

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The authors present microfluidic logic gates based on two-phase flows at low Reynold's number. The presence and the absence of a dispersed phase liquid (slug) in a continuous phase liquid represent 1 and 0, respectively. The working principle of these devices is based on the change in hydrodynamic resistance for a channel containing droplets. Logical operations including AND, OR, and NOT are demonstrated, and may pave the way for microfludic system automation and computation. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2435607]

The promise of combining diverse microfluidic devices to form complex "lab-on-a-chip" systems has inspired many innovations, among them the large scale integration of microfluidic networks.[1] However, the current user is burdened with the task of monitoring and controlling fluid flow in the complex network. Aside from the tedium of manually actuating each valve, the need for external sensors limits its portability and scalability. This problem is exacerbated by the continuous miniaturization of microfluidic chip—as length scale shrinks and device density increases, it will soon become infeasible to detect events and direct decisions manually.

Hence, the key to large scale integration is automation. In electronics, large circuits performing complex operations can be obtained using the basic building blocks known as logic gates. Network control can be built into the circuit using simple Boolean rules, thus eliminating the need for manual intervention. By analogy, logic gates for microfluidic devices would become a valuable tool to automatically direct internal flows in complex networks or even perform calculations without resorting to external processing.

Fluidic logic gates have a history that leads back to the early 20th century, when significant effort was devoted to construct the fluidic equivalent of electronic devices. A notable invention was Nikola Tesla's "valvular conduit,"[2] a channel with different resistances for flows in opposite directions which resembles the nonlinear electrical diode. Although these macroscale fluidic devices provide operational advantage in harsh environment containing electromagnetic interference and radiation, they ultimately lost to semiconductor electronics because they cannot be easily miniaturized. When size is reduced, viscous forces overwhelm nonlinear inertial forces and results in laminar flow. The loss of these nonlinearities renders fluidic logic gates incompatible with microfluidic devices. Moving forward, a microfluidic memory device has been demonstrated using a viscoelastic polymer solution,[3] suggesting that microscale nonlinearities can be introduced via specialized fluid properties. A microfluidic logic device taking advantage of laminar flow to achieve a nonlinear system functional response has also been shown.[4] However, these kinds of logic gates cannot be cascaded, thus limiting direct scaling.

In this letter, we demonstrate microfluidic logic devices using two-phase flow. The presence or the absence of an oil slug in a continuous aqueous phase represents true or false, respectively. Specifically, we show a two-input AND/OR gate as well as a single-input NOT gate; combination of these can theoretically produce all possible Boolean expressions. Our logic devices do not rely on any manual actuation (e.g., external pressure) and have the same input-output type (droplet), so it is possible to feed the output from one gate into the input of the next gate, this cascading capability enables scaling.

The working principle of our logic device is based on the change in hydrodynamic resistance for a channel containing droplet. Theoretical studies[5] and experimental verifications[6] have shown that pressure drop increases across a channel containing two-phase emulsions, particularly at low capillary number. Furthermore, the excess pressure increases sharply when the drop size is comparable to the channel dimensions.[6,7] Another important nonlinearity in our design is attributed to interfacial tension. Below a certain maximum extension, the ratio of the length to circumference of a droplet, droplets do not break up at a T junction.[8] Instead, the entire droplet enters the channel with largest flow rate. Thus, although flow rate of the continuous phase fluid is divided linearly at an asymmetric T junction, the discrete phase droplet is either completely present or absent.

Based on these observations, we designed two separate microfluidic logic gates which perform (1) AND/OR operation and (2) NOT operation. Both gate designs are shown schematically in Fig. 1.

The channel dimensions of the AND/OR microfluidic logic gate correspond to the hydrodynamic resistances R_1, R_2, and R_3. We set the initial resistance ratio such that the flow through R_1 exceeds Q_A. In the laminar flow regime, streamlines do not cross and hence all of Q_A flows through R_1. Resistance ratios are set such that the flow through R_2 exceeds $0.5Q_B$. Therefore, a droplet from Q_B flows towards the OR branch when R_1 is free of droplet. In the case where R_1 already contains a droplet, its hydrodynamic resistance increases by ΔR_1 to R_1'. Flow through R_2 then becomes less than $0.5Q_B$, and a droplet from Q_B preferentially flow into the AND branch. Due to the large channel dimensions, droplets in R_2 and R_3 affect their resistances negligibly.

For the case where $Q_A=Q_B$ (using the normalized resistances $\bar{R}_1=R_1/R_3$ and $\bar{R}_2=R_2/R_3$), these two requirements are captured in the following inequalities:

$$3\bar{R}_1+\bar{R}_2-1<0 \quad \text{(no droplet in } R_1\text{)}, \tag{1a}$$

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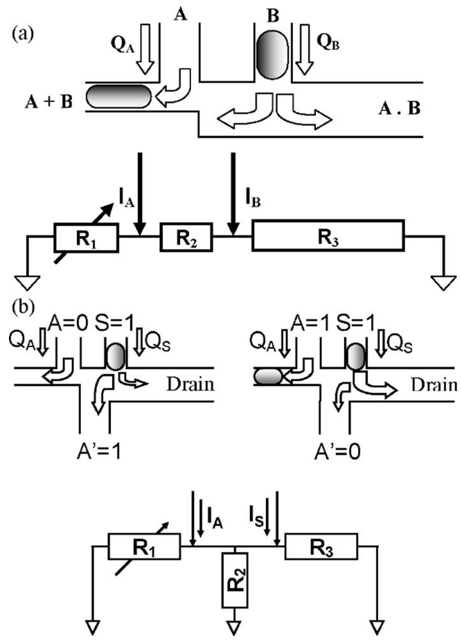

FIG. 1. Microfluidic logic gates and their electrical equivalent circuits for (a) AND/OR operation and (b) NOT operation. Current (flow rate) distribution at the T junction is governed by Kirchoff's current law. Outlet voltages (pressures) are maintained equal and constant.

$$3\bar{R}_1' + \bar{R}_2 - 1 > 0 \quad (\text{droplet in } R_1). \tag{1b}$$

Overall, droplets from Q_A always flow into the OR branch, and droplets from Q_B flows into the OR branch except when the OR branch contains another droplet from A. Therefore, the Boolean expression for the OR branch is $A+BA'=A+B$, whereas the expression for the AND branch is AB.

Next, we present a microfluidic NOT gate design. Unlike the AND/OR gate design which routes the input to the output, our NOT gate derives its output from another source. Our microfluidic NOT gate is a variation of the first AND/OR design. By observing that the Boolean expression for the OR branch is $A+BA'$, we can readily obtain BA' by tapping into the channel region in between inputs A and B in Fig. 1(a). Replacing input B by a "true" source, we get $1A'=A'$.

In the case of NOT gate, if there is no droplet from A, the flow through R_3 is less than $0.5Q_s$ to prevent droplets from entering R_3. Droplets enter R_2 by default since a larger flow from S enters R_2 compared to R_1. However, when a droplet from A is present, the increase in resistance $R_1'=R_1+\Delta R_1$ causes the flow through R_3 to exceed $0.5Q_s$; hence droplets from S flow to R_3. For $Q_A=Q_S$, these constraints yield the following inequalities:

$$\bar{R}_2 - \bar{R}_1\bar{R}_2 - 3\bar{R}_1 < 0 \quad (\text{droplet enters } R_2 \text{ by default}), \tag{2a}$$

$$\bar{R}_2 + \bar{R}_1 - 3\bar{R}_1\bar{R}_2 > 0 \quad (\text{no droplet in } R_1), \tag{2b}$$

$$\bar{R}_2 + \bar{R}_1' - 3\bar{R}_1'\bar{R}_2 < 0 \quad (\text{droplet in } R_1). \tag{2c}$$

Figure 2 shows a theoretical guideline to designing a microfluidic AND/OR and NOT logic gates. The regions of operation are bounded by the inequalities noted above. Intuitively, large ΔR_1 corresponds to strong nonlinearities, which lead to more robust logic operation.

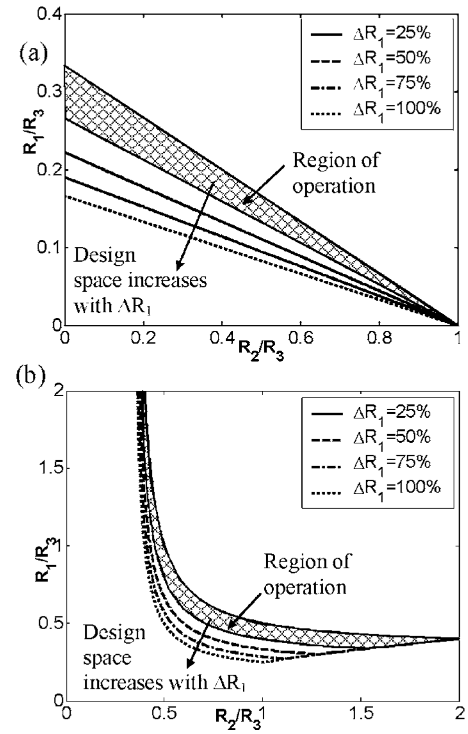

FIG. 2. Theoretical operating region of the microfluidic (a) AND/OR gate and (b) NOT gate. As ΔR_1 increases, the range of admissible channel geometry increases.

To test this approach, we built microfluidic logic gates using soft lithography.[9] Rectangular channels with constant height are created in poly(dimethylsiloxane) (PDMS) by first lithographically patterning 60 μm thick SU-8 photoresist spun on a silicon wafer. A 10:1 mixture of PDMS is then cured upon the SU-8 master and bonded to another flat PDMS layer after oxygen plasma treatment. The devices were baked at 150 °C overnight and treated again with oxygen plasma for 5 min to render the surface hydrophilic. Fluidic resistance for a uniform channel height is approximately proportional to channel length/width ratio. We designed the device geometry such that the channel length/width ratios for the branches R_1, R_2, and R_3 correspond to 1600/100, 200/200, and 12800/200 in the AND/OR gate and 1000/100, 1550/120, and 2300/120 in the NOT gate, all units in micrometers. As a result, the fluidic resistance ratios ($\bar{R}_1$ and $\bar{R}_2$) for both AND/OR and NOT gates are 1/4 and 1/64 and 12/23 and 31/46, respectively. These ratios fall within the region of operation (with ΔR_1=50%) indicated in Fig. 2. Droplets of silicone oil (Dow Corning 200® Fluid 20CST) are generated at an upstream T junction and suspended in water containing 2% SPAN 80 surfactant. Fluorescent dye is added to one inlet to illustrate the flow profile during operation. A high speed camera (FASTCAM APX-RS, Photron) captures the operation of these logic gates at 1000 frames/s.

A sequence of images demonstrating the operation of the AND/OR logic gate is shown in Fig. 3. Figures 3(a) and 3(b) show that when *one* droplet arrives from either A or B, the droplet enters the OR branch. Figure 3(c) shows that when droplets from A and B arrive simultaneously, droplet from A enters the OR channel, increasing its local resistance, and forcing the incoming droplet from B to enter the AND chan-

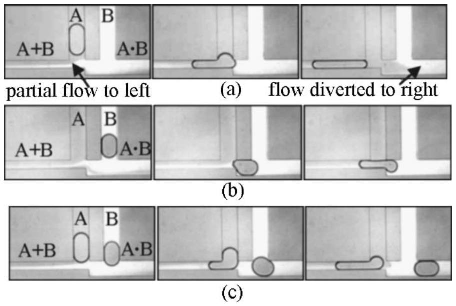

FIG. 3. Operation of a microfluidic AND/OR gate (a) $A=1$, $B=0 \rightarrow A+B=1$, $AB=0$. Note also that flow from B is completely diverted to the right when the OR channel contains a droplet. (b) $A=0$, $B=1 \rightarrow A+B=1$, $AB=0$. (c) $A=1$, $B=1 \rightarrow A+B=1$, $AB=1$.

nel instead. The fluorescent dye flow profile further shows that after a droplet from A enters the OR channel, the flow from B is diverted to the AND channel, thus verifying our model.

Figure 4 shows experimental observation of the NOT gate operation. When there is no droplet from channel A, droplets from the source are routed by default to the A' outlet [Fig. 4(a)]. On the other hand, in the presence of a droplet from A, droplet from the source is diverted to a drain channel [Fig. 4(b)], hence A' outlet is devoid of droplet.

Nonlinearities in the system can be further improved to increase device sensitivity. For example, by increasing the viscosity of the dispersed phase, flow resistances due to presence of a droplet increases.[5] Channel geometry can also increase nonlinearities. A droplet moving from a wide inlet into a narrow channel would have a larger leading curvature compared to its lagging curvature. A net Young-Laplace pressure drop across the two menisci contributes to additional droplet resistance.[10]

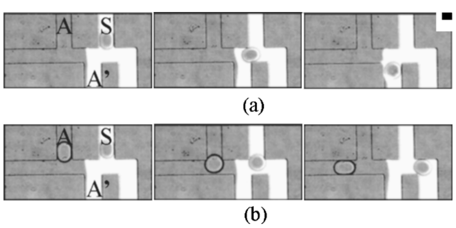

FIG. 4. Operation of a microfluidic NOT gate (a) $A=0$, $S=1 \rightarrow A'=1$. (b) $A=1$, $S=1 \rightarrow A'=0$.

Finally, we note that droplets based microfluidic logic gates are large (hundreds of micrometer) and operate at low frequency (Hertz to kilohertz). They do not replace electronic logic gates, but serve a complementary role in integrated microfluidic applications. For example, these gates can be combined to form a microfluidic multiplexer. Given a certain input pattern, the multiplexer selectively routes the corresponding reagent droplets to the output. One can simultaneously achieve automation and miniaturization in combinatorial chemistry using droplet based microfluidic logic gates. The challenges to devise a reliable synchronization scheme for droplets generation and for independent control of droplet size and frequency remain.

In summary, we have demonstrated a droplet based microfluidic AND/OR and NOT logic gates. Logic operation is based on the nonlinear change in hydrodynamic resistance for channels containing droplets. This approach shows that the fluid-structure interactions in two-phase flow can be harnessed to produce systematic nonlinearities in low Reynold's number microfluidic applications. Devices utilizing such phenomena might find applications in flow control, computation, and automation in microfluidic systems.

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