The effect of flap parameters on fluid rectification in a microfluidic diode

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We have studied the effect of flap parameters on fluid rectification in a microfluidic diode. We use Navier–Stokes equations and arbitrary Lagrangian–Eulerian formulation to obtain dynamics of fluid flow and motion of the flap. The flap opens during forward flow and seals against a stopper during reverse flow. This allows flow in the forward direction and prevents it in the reverse direction. The rectifier is fluidic analog to a semiconductor diode in function because it rectifies fluid flow. Velocity-pressure (V-P) curves analog to the current-voltage (I-V) curves of the electronic diode has been obtained. The effect of the flap parameters, such as length, thickness, and Young’s modulus has been found out. The transient response of the flap and fluid flow under oscillating pressure driven flow has also been obtained. © 2010 American Institute of Physics. [doi:[10.1063/1.3492403](https://doi.org/10.1063/1.3492403)]

I. INTRODUCTION

The laboratory-on-a-chip applications have been revolutionized by microfluidic technology during the past decade.^{1–3} Microfluidic devices can be used to explore a variety of biological operations, such as fundamental research in protein crystallization⁴ to diagnostic assays.⁵ Fundamental aspects of laboratory-on-a-chip, which are relevant to the field of microfluidics, include pumping, valving, and flow rate sensing.⁶ There are broad ranges of ways to measure and manipulate fluids on a microscale.^{7,8} The incorporation of actively controlled devices, directly in the device or through a fixed interface with external components, often leads to more complex fabrication process and requires complex equipments. The use of passive and autonomous microfluidic components, such as microfluidic diode, can help to eliminate the need for additional equipment.

The process of creating a suitable microfluidic diode is a challenging task. The proposed diode is analogous to an electronic rectifier in function. An electronic diode prevents electronic current flow in one direction; similarly the microfluidic diode prevents fluid flow in one direction. The creation of valves limiting flow in one direction involves a very complex fabrication procedure involving several steps to manufacture the device.^{9–12} A microfluidic diode is a single layer, planar device that can be fully integrated with standard multilayer, soft lithography technology with complex microfluidic circuits.

In many applications, flow rectification is necessary to safely perform tasks, such as drug delivery where backflow must be prevented. The microfluidic diode provides a solution to this problem. The diode can be used to create microfluidic logic gates and in other circuits, which require microfluidic diodes analogous to the diode-diode logic in semiconductor electronics. The microfluidic diode can be a building block for logic devices such as microfluidic OR, AND, NOT, NOR, NOR, an XNOR gates. The development of microfluidic large-scale integration, their design principles to assess the capabilities and limitations of the current state of art to facilitate the applications to areas of biology were reviewed.¹³ An integrated microfluidic valve with a pressure gain much greater than unity was presented.¹⁴ It was shown that this enables integration of fully

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FIG. 1. Schematic of a flap controlled microfluidic diode.

static digital control logic and state storage directly on a chip, ultimately enabling microfluidic-state machines to be designed.

Two microfluidic elastomeric autoregulatory devices: A diode and a rectifier were investigated, exhibiting complex nonlinear behaviors, such as saturation, bias-dependent resistance, and rectification with a Newtonian fluid.¹⁵ Surface tension-based passive pumping and fluidic resistance were used to create a number of microfluidic devices analogs to electronic circuit components.¹⁶ Analytical solutions were presented for a nonlinear pressure-flow for deformable passive valves formed by bonding a deformable film over etched channels separated by a weir.¹⁷ A microfluidic check valve suited for the low Reynolds number flow rate sensing, micropump flow rectification, and flow control in laboratory-on-a-chip devices was investigated using coupling between fluid movement in a channel and a flap suspended in the fluid path to generate a strong anisotropic flow resistance.¹⁸ For low Reynolds number flow, the nonlinear inertial term in the Navier-Stokes equation is small; therefore, the pressure drop in a fixed geometry valve is virtually invariant under flow reversal, regardless of the valve's geometry.¹⁹ An experimental study and theoretical modeling of the device physics of microfluidic valves was presented. The model validated with experimental data offers a useful quantitative prediction for a valve's properties which depend on its dimensions.²⁰

Adams *et al.*²¹ presented a novel elastomer-based microfluidic diode, analogous to an electronic diode allowing flow in forward direction and stopping it in the reverse direction. The device was planar, in-line, and can be replica molded via standard soft lithography techniques. Several geometries of devices, their flow versus pressure characteristics, their behavior, and possible uses were presented.

The diode presented in this paper uses coupling between fluid movement in a channel and a flexible solid flap suspended in the fluid path to generate a strong rectification of the fluid flow. The turn off pressure is smaller than the diodes reported previously. This paper is organized as follows. Next section describes schematics and Sec. III presents details of governing equations and numerical details. The results of numerical simulations are described in Sec. IV. Finally, conclusions are drawn in the last section.

II. SCHEMATICS

Figure 1 shows schematic of a flap controlled microfluidic rectifier. It consists of channel and a solid flap. The length of the channel is taken $400\ \mu\text{m}$ and width is taken $100\ \mu\text{m}$ for some cases and $50\ \mu\text{m}$ for other cases simulated in this paper. The channel consists of two structures in the middle: One is used to support the bottom of the flap and other is used to stop the top of the flap during reverse flow to prevent reverse flow. The bottom of the flap is fixed and the top is free to move under the influence of the force exerted by fluid flow. The diode is based on a mechanical effect in which a flap seals to a structure in the channel in reverse flow direction and opens in the

forward flow. This is very similar to a door in the room: Free to swing in the forward direction and has a door stopper in the reverse direction. The properties of the fluidic diode can be adjusted by changing length, thickness, rigidity of the flap, and geometry. The rectification property of the diode changes with applied pressure.

III. GOVERNING EQUATIONS AND NUMERICAL DETAILS

In general, fluid motion can be described in the Eulerian or Lagrangian coordinates. It is slightly more difficult to express the moving boundary by the Eulerian description. On the other hand, the Lagrangian description can treat the moving boundary easily because the fluid particles can be traced by this method. Sometimes the finite elements may be too much distorted during the large deformation of the fluid flow in the computations with the Lagrangian method. An arbitrary Lagrangian Eulerian (ALE) method is realized by combining these two methods. In the ALE description, an arbitrary referential coordinate is introduced in addition to the Lagrangian and Eulerian coordinates. The material derivative with respect to the reference coordinate can be described as

$$\frac{\partial f(X_i, t)}{\partial t} = \frac{\partial f(\chi_i, t)}{\partial t} + (u_i - v_i) \frac{\partial f(x_i, t)}{\partial t}, \quad (1)$$

where X_i is the Lagrangian coordinate, χ_i is the referential coordinate, x_i is the Eulerian coordinate, and u_i and v_i are the material and reference velocities, respectively.

The fluid is treated as an incompressible viscous fluid. The fluid dynamics in the channel is governed by the following momentum and the incompressible continuity equation in the ALE description:

$$\rho \left(\frac{\partial u_i}{\partial t} + (u_j - v_j) \frac{\partial u_i}{\partial x_j} \right) = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho f_i \quad \text{in } \Omega, \quad (2)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{in } \Omega, \quad (3)$$

where u_i is the velocity of fluid particle, σ_{ij} is the stress tensor, p is the pressure, ρ is the density, μ is the viscosity coefficient, and f_i is the acceleration due to external volumetric forces which is taken zero in our study. The stress tensor σ_{ij} is described as

$$\sigma_{ij} = -p \delta_{ij} + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_l}{\partial x_l} \delta_{ij} \right).$$

For incompressible fluid,

$$\frac{\partial \sigma_{ij}}{\partial x_j} = - \frac{\partial p}{\partial x_j} \delta_{ij} + \mu \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} \right). \quad (4)$$

Introducing Eq. (4) into Eq. (2), the momentum equation can be described as follows

$$\rho \left(\frac{\partial u_i}{\partial t} + (u_j - v_j) \frac{\partial u_i}{\partial x_j} \right) = - \frac{\partial p}{\partial x_j} \delta_{ij} + \mu \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} \right) \quad \text{in } \Omega. \quad (5)$$

The reference velocity v_i can be chosen arbitrary in the ALE description. If v_i is equal to zero, Eq. (5) becomes the Eulerian description. If v_i is equal to the fluid particle velocity, Eq. (5) becomes the Lagrangian description.

The fluid is taken as waterlike substance with a density $\rho = 1000 \text{ kg/m}^3$ and dynamic viscosity 0.001 Pa s . The fluid enters the channel from the left boundary during forward flow and from the right boundary during reverse flow. We have studied pressure driven flow and the inlet pressure

is assumed equal to p_0 . At the outflow (right-hand boundary for forward flow and left-hand boundary for reverse flow), the boundary condition is $p=0$. On the channel walls no-slip boundary conditions $u_i=0$ are imposed. It is assumed that the flow has fully developed laminar characteristics with a parabolic velocity profile.

The following assumptions are made for the flap surrounded by the fluid. The flap is assumed an elastic rigid body. The motion of the flap is described by the three degrees of freedom, which are the translational displacements X and Y in x - and y -directions, respectively, and the rotational displacement θ defined at the center of the rotation. The equation of motion of the flap can be written as

$$M_{ij}\ddot{X}_j + C_{ij}\dot{X}_j + K_{ij}X_j = F_i, \quad (6)$$

$$X_i = \{X, Y, \theta\}, \quad (7)$$

where M_{ij} , C_{ij} , and K_{ij} denote the mass, damping, and stiffness matrices, respectively.^{22,23} Stiffness matrix K_{ij} contains elasticity properties such as Young's modulus. The X_i and F_i denote displacement and fluid forces, respectively. Each matrix is diagonal with constant coefficients.

The fluid force can be written as

$$F_i = \int (\sigma_{ij}n_j)d\Gamma, \quad (8)$$

where n_j is the unit outward normal vector and the stress tensor σ_{ij} is defined by Eq. (4).

The flap boundary coordinate (x_s, y_s) can be calculated from flap displacement (X, Y, θ) ,

$$x_s = l_x + X, \quad (9)$$

$$y_s = l_y + Y, \quad (10)$$

where l_x and l_y are the distances between a point on the boundary and the center of rotation. The l_x and l_y are calculated by the following:

$$l_x = l_x^0 \cos \theta - l_y^0 \sin \theta, \quad (11)$$

$$l_y = l_x^0 \sin \theta + l_y^0 \cos \theta, \quad (12)$$

where l_x^0 and l_y^0 are the components of the original distance at $t=0$. The flap boundary velocity (u_s, v_s) can be obtained from x_s and y_s as

$$u_s = \frac{\partial x_s}{\partial t}, \quad (13)$$

$$v_s = \frac{\partial y_s}{\partial t}. \quad (14)$$

The self-consistent formulation is solved using a Galerkin variational formulation based finite-element method described and used in Refs. 24 and 25 to study plasma and air dynamics for flow control problems in aerodynamics. The Navier–Stokes arbitrary Lagrangian Eulerian (NS-ALE) finite-element method for direct numerical simulation of the fluid particle system is implemented using programming language C++. The code was run on a system with 64-bit, Intel Core i7-860 processor (8M Cache, 2.80 GHz), which has eight threads, with 8 Gbyte, DDR3, 1600 MHz RAM.

The flap is composed of a flexible material with a density $\rho=965 \text{ kg/m}^3$ and Young's modulus $E=5 \text{ MPa}$. Transient effects are taken into account in the description of both fluid and solid

FIG. 2. The lag factor G as a function of ratio of the particle diameter to the channel diameter, d/r_0 .

flap dynamics. The density and flexibility parameters of flap are in the range of popular material polydimethylsiloxane (PDMS). The PDMS has unique high gas permeability, low loss tangent, low chemical reactivity (except at extreme pH levels), optical transparency (down to 300 nm), good thermal stability, and low interfacial free energy. Therefore, PDMS has been particularly attractive for many applications.

Coupled Navier–Stokes and continuity equations were solved using the arbitrary Lagrangian–Eulerian finite-element technique to study pressure driven transport of particles through a symmetric converging-diverging microchannel.²⁶ The predicted simulation results were in good agreement with existing experimental observations. Electrokinetic transport of cylindrical cells under dc electric fields in a straight microfluidic channel has been studied experimentally and numerically taking into account dielectrophoretic effects.²⁷ The Navier–Stokes equations for the fluid flow and the Laplace equation for the electric potential defined in an arbitrary Lagrangian–Eulerian framework were employed to model the transient electrokinetic motion of cylindrical cells. The numerical results were in perfect quantitative agreement with experimental results. Dielectrophoretic choking in a converging-diverging microchannel was investigated using a finite-element model taking into account the particle-fluid-electric field interactions.²⁸ The capability and versatility of the Navier–Stokes arbitrary Lagrangian–Eulerian were proven from these studies.

We have simulated flap controlled fluid rectification in a microchannel using a pressure driven flow. Experimental data do not exist for our geometry of the diode to validate our computational results. The developed NS-ALE code has been validated by reproducing wall correction factor of a spherical particle translating along the axis of a cylindrical channel. The wall correction factor is calculated by solving the problem to obtain maximum velocity $V_{\max}$ of undisturbed flow in the channel in absence of the particle and the particle velocity U_p for the pressure driven flow. The lag factor G is then obtained by using $G = U_p / V_{\max}$. Figure 2 shows the lag factor G as a function of ratio of the particle diameter to the channel diameter, d/r_0 . The lag factor predicted by the present NS-ALE model agrees well with the analytical solutions.^{29,30} Haberman *et al.*²⁹ used only ten terms in the Fourier series of the Stokes stream function in their analytical derivations. Their analytical results are valid only when the ratio d/r_0 is smaller than 0.8. Therefore, their results differ from our results for $d/r_0 = 0.8$.

FIG. 3. Contours of magnitude of fluid velocity field during forward flow for flap widths of (a) $4 \mu\text{m}$, (b) $6 \mu\text{m}$, and (c) $8 \mu\text{m}$ for the channel width of $100 \mu\text{m}$.

FIG. 4. Contours of magnitude of fluid velocity field during reverse flow for flap widths of (a) 4 μm , (b) 6 μm , and (c) 8 μm for the channel width of 100 μm .

FIG. 5. Contours of magnitude of fluid velocity field during forward flow for flap widths of (a) $2 \mu\text{m}$, (b) $4 \mu\text{m}$, and (c) $6 \mu\text{m}$ for the channel width of $50 \mu\text{m}$.

FIG. 6. Contours of magnitude of fluid velocity field during reverse flow for flap widths of (a) $2 \mu\text{m}$, (b) $4 \mu\text{m}$ and (c) $6 \mu\text{m}$ for the channel width $50 \mu\text{m}$.

FIG. 7. Streamlines and vectors of fluid velocity during (a) forward flow and (b) reverse flow for channel width of $100 \mu\text{m}$ and flap width $6 \mu\text{m}$.

IV. RESULTS AND DISCUSSION

We describe our results in the following paragraphs. We have carried out numerical simulations for two channel widths. The length of the channel is taken as $400 \mu\text{m}$ and width is taken as $100 \mu\text{m}$ for some cases and $50 \mu\text{m}$ for other cases. We refer the channel with width of $100 \mu\text{m}$ as wide channel and the channel with width of $50 \mu\text{m}$ as narrow channel in the following description. The thickness and Young's modulus of the flap are varied to see the effect on rectification of the flow. The velocity profile of the flow (forward as well as reverse) was parabolic as expected in a pressure driven flow. Figures 3 and 4 show contours of magnitude of velocity $\sqrt{u^2 + v^2}$ during forward and reverse flow, respectively, for wide channel. The flap bends in the direction of flow during forward fluid flow due to the force exerted by the fluid on the flap. This

FIG. 8. Forward velocity u_f as a function of inlet pressure p_0 for (a) wide channel and (b) narrow channel for Young's modulus $E=5$ MPa.

increases the opening between the stopper and the flap, which allow the fluid to flow. During the reverse flow the flap bends toward the stopper under the influence of the force exerted by the fluid. This reduces the gap between the stopper and flap to zero, which prevents the fluid flow in the backward direction. This way, we obtain rectification of the fluid flow. The velocity of the fluid is highest in the opening between the stopper and the flap during forward flow, as well as reverse flow. The fluid has to pass through small opening which leads to an increase in the velocity. The stiffness of flap increases with an increase in the thickness of the flap w_f . This requires higher inlet pressures to open and close the flap during forward and reverse flows, as can be seen from the comparison of Figs. 3 and 4.

We are interested in understanding the effect of flap thickness and length on rectification of

FIG. 9. Reverse velocity u_r as a function of inlet pressure p_0 for (a) wide channel and (b) narrow channel for Young's modulus $E=5$ MPa.

the flow. The length of the flap for narrow channel is half of length of flap for wide channel. Figures 5 and 6 show contours of magnitude of velocity $\sqrt{u^2 + v^2}$ during forward and reverse flow, respectively, for narrow channel. The stiffness of flap increases with a decrease in the length of the flap. Higher stiffness of the flap requires higher inlet pressures to open and close the flap during forward as well as reverse flow as compared to longer flap for the wide channel in Figs. 3 and 4. The stiffness of flap increases with an increase in the thickness. The higher stiffness requires higher inlet pressures to open and close the flap during forward as well as reverse flow as can be seen from the comparison of the Figs. 5 and 6.

The streamlines and velocity vectors give an idea about path followed by the fluid and the magnitude of the velocity. Figures 7(a) and 7(b) show streamlines and vectors of fluid velocity

FIG. 10. (a) Forward velocity u_f and (b) reverse velocity u_r as a function of inlet pressure p_0 for Young's modulus $E = 1$ MPa. Different lines are for two combinations of channel width and flap thickness.

during forward and reverse flows, respectively, for wide channel, flap thickness $w_f = 6 \mu\text{m}$, and Young's modulus $E = 5$ MPa. It can be seen from the figures that streamlines bend toward the opening between the stopper and the tip of the flap. The velocity vectors show that the velocity of the fluid is highest in the opening during forward as well as reverse flow. This also follows from the contour plots of Figs. 3–6 for forward as well as reverse flow.

Figures 8(a) and 8(b) show forward fluid velocity u_f as a function of inlet pressure p_0 for wide and narrow channels, respectively, for Young's modulus $E = 5$ MPa. The inlet pressure to drive the flow in the forward direction is applied to the left boundary. The forward fluid velocity u_f in the x -direction is taken close to right boundary, at the center of the channel. Different lines correspond to flap thicknesses $w_f = 4, 6$, and $8 \mu\text{m}$ for wide channel in Fig. 8(a) and flap thicknesses $w_f = 2, 4$,

TABLE I. The reverse inlet pressure corresponding to highest reverse velocity and corresponding forward velocity, minimum rectification ratio for different flap thicknesses, and Young's modulus E for 0.1 mm wide channel.

Parameters/flap thickness	4 μm	6 μm	8 μm	$E=1.0$ MPa 8 μm
p_0 (Pa)	26	90	220	42
u_f (mm/s)	0.75	1.5	5.0	0.78
u_r (mm/s)	0.098	0.33	0.8	0.16
Ratio (u_f/u_r)	7.65	4.55	6.25	4.88

and 6 μm for narrow channel in Fig. 8(b). It can be seen that fluid velocity increases nearly linearly with the inlet pressure for both channels. The velocity peaks at some value of inlet pressure for $w_f=8$ μm then decreases for wide channel. A thick flap acts as an obstacle to the flow and induces curly flow at the center of the channel close to the outlet at high pressures leading to decrease in the x -component of the velocity. It was not possible to obtain converging solutions for thin flaps; therefore, some plots do not show whole range of the pressure. Figures 9(a) and 9(b) show reverse fluid velocity u_r as a function of inlet pressure for wide and narrow channels, respectively, for Young's modulus $E=5$ MPa. The inlet pressure to drive the flow in the backward direction is applied to the right boundary. The reverse fluid velocity u_r in the x -direction is taken close to left boundary, at the center of the channel. It can be seen from the plots that reverse velocity peaks at a particular value of the pressure. This value of pressure is not sufficient to close the flap, which results in highest fluid velocity in the reverse direction. The flap starts moving toward the stopper beyond this pressure and the fluid velocity decreases. At sufficiently high pressures reverse fluid velocity is negligible, which means negligible backward flow. This is desirable for practical applications, such as drug delivery where backflow must be prevented to best possible extent. The pressure beyond which the flap starts closing increases with an increase in the flap thickness or reduction in the length of the flap. The stiffness of the flap increases with an increase in the thickness or reduction in the length, which requires higher pressures to close the flap. The fluidic rectifier is an analog of the electronic diode. The current is induced by the voltage in a semiconductor diode. The velocity is induced by the pressure in a microfluidic diode. The pressure in microfluidic diode is equivalent to voltage in semiconductor diode. The fluid velocity in a microfluidic diode is equivalent to the electronic current in semiconductor diode.

Figures 10(a) and 10(b) show forward velocity u_f and reverse velocity u_r as a function of inlet pressure p_0 for Young's modulus $E=1$ MPa. Different lines correspond to two combinations of channel width and flap thickness, which are as follows: Flap thickness is 8 μm for wide channel and 4 μm for narrow channel. We want to see the effect reduced value of Young's modulus on flow. We compare the results of these figures with same channel width and flap thickness in Figs. 8 and 9, which are for higher values of Young's modulus $E=5$ MPa. The opening and closing pressures decrease with a decrease in Young's modulus from $E=5$ MPa to $E=1$ MPa. This leads to higher velocities during forward flow and reduced reverse velocity for a given value of inlet pressure.

TABLE II. The reverse inlet pressure corresponding to highest reverse velocity and corresponding forward velocity, minimum rectification ratio for different flap thicknesses, and Young's modulus E for 0.05 mm wide channel.

Parameters/flap thickness	2 μm	4 μm	$E=1.0$ MPa 4 μm	6 μm
p_0 (Pa)	55	450	90	1600
u_f (mm/s)	1.1	9.0	2.0	33
u_r (mm/s)	0.38	3.0	0.603	11
Ratio (u_f/u_r)	2.9	3.0	3.32	3.0

FIG. 11. (a) Forward velocity u_f and (b) reverse velocity u_r as a function of time. The results are for wide channel with $6 \mu\text{m}$ flap thickness and Young's modulus $E=5 \text{ MPa}$.

Minimum rectification ratio is defined by the ratio of velocities in the x -direction during forward flow u_f and reverse flow u_r at the pressure for which reverse velocity is highest. Table I gives values of the reverse inlet pressure corresponding to highest reverse velocity and corresponding forward velocity, minimum rectification ratio for different values of flap thickness, and

Young's modulus E for 0.1 mm wide channel. Table II gives same values for 0.05 mm wide channel. Default value of Young's modulus is $E=5.0$ MPa in the tables. A flexible, long, and thin flap leads to reduced inlet pressures to open or close the flow for the reasons explained earlier. The minimum rectification ratio (at low pressures) should not be confused with overall rectification property of the diode, which is very high at higher inlet pressures. The proposed design for microfluidic diode has excellent property of allowing flow in the forward direction and preventing flow in the reverse direction.

We have investigated the effect of oscillating inlet pressure on flow and rectification in Fig. 11. Figure 11(a) shows inlet pressure profile for forward and reverse flows as a function of time. Figures 11(b) and 11(c) show forward velocity u_f for $p_0=1000+500\sin^2(2\pi ft)$ and reverse velocity u_r for $p_0=75+75\sin^2(2\pi ft)$ as a function of time for wide channel and Young's modulus $E=5$ MPa. Here f is the frequency of oscillating flow which is taken as 100 Hz. We have represented the form of oscillatory pressure by the square of sin and the effective frequency of oscillations is twice of the frequency f . The figures also show results for static inlet pressures $p_0=1000$ and $p_0=1500$ for forward flow and inlet pressures $p_0=75$ and $p_0=150$ for reverse flow for comparison purpose. The steady state reaches within nearly 10 ms for forward as well as reverse flow. It can be seen that flow responds to the oscillatory pressure. The maximum velocity induced by oscillating inlet pressure is lower than the velocity induced by static pressure of $p_0=1500$ Pa during forward flow. The minimum velocity induced by oscillating inlet pressure is higher than the velocity induced by static pressure of $p_0=1000$ Pa during forward flow. The fluid and the flap have finite response time leading to the difference in the velocities. The highest reverse velocity induced by oscillating reverse inlet pressure is higher than the velocity induced for the static inlet pressure $p_0=75$. Continuous static pressure $p_0=75$ leads to smaller gap between the stopper and the flap as compared to the situation when the pressure drops from $p_0=150$ to $p_0=75$, leading to higher reverse velocity for oscillating inlet pressure.

V. CONCLUSIONS

We have modeled a flexible flap based microfluidic diode, which is analogous to a semiconductor diode in function. The flap opens during forward flow allowing the flow and seals against a stopper during reverse flow preventing the flow which results in flow rectification. The proposed microfluidic rectifier should perform well over a range of pressures and geometries. The rectification will depend on the flap parameters and geometry of the diode. By changing the flap parameters, the turn on pressure of the rectifier and the response time of the flap can be adjusted. Long, thin, and flexible flap requires lower turn on and turn off inlet pressures. It is expected that flexible flap will respond faster during reverse flow. The flow properties of the diode will depend on the channel geometry. The flap parameters as well as geometry of the channel need to be optimized for further enhancement in the forward flow and reduction in the reverse flow. This requires further numerical and experimental efforts.

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