Three Dimensional Numerical Simulations of Synthetic Jet Actuator Flows in a Microchannel

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ABSTRACT

The flow produced by a synthetic jet actuator located in one wall of a microchannel is investigated using computational fluid dynamics (CFD) simulations. In the case of no cross-flow, the ejected vortices travel to the opposite wall and replenish the remains of the vortex left behind from the previous cycle. When cross-flow is added, the vortex penetration increases with both stroke length and frequency. The flow in the cavity appears to be nearly symmetrical, with the greatest effect seen near the orifice. In the orifice itself, three-dimensional effects are more noticeable with decreasing jet-to-cross-flow momentum ratio. The microchannel cross-flow causes the vortices to tumble about their transverse axis, the effect of which also increases with decreasing jet-to-cross-flow momentum ratio.

Keywords: Synthetic jet actuators, microfluidic systems, low Reynolds number, numerical simulation.

1. Introduction

Low Reynolds number flows are a commonly encountered feature in microfluidic systems. One of the most notable characteristics of such flows is the greater relative importance of diffusion compared with macro-scale flows. This means that fluidic pumping and mixing are difficult to achieve at the micro-scale. As a consequence, there have been significant efforts devoted to researching this problem: for example, Tabeling[1] and Siripoorikan et al[2] describe a method whereby a microchannel flow is periodically perturbed by a cross-channel flow to induce mixing, and Bertsch et al[3] and Park et al[4] demonstrate that improved mixing in microchannels can be achieved by judicious use of surface geometry modifications. All of these studies noted that the level of mixing was much less than would be observed in macro-scale experiments.

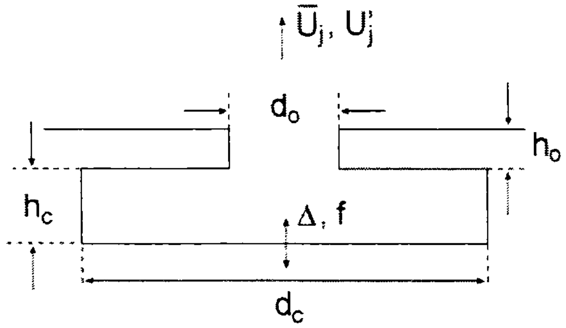

Figure 1. Schematic diagram of main parameters in a synthetic jet actuator flow. d_o = orifice diameter, h_o = orifice height, d_c = cavity diameter, h_c = cavity height, Δ = membrane displacement, f = membrane frequency, U_j = jet velocity, overbar and dash denote mean and fluctuating values, respectively.

Synthetic jet actuators have been proposed as a means of overcoming such barriers to making efficient microfluidic systems. These actuators, depicted in Fig. 1, operate by cyclically ingesting and ejecting fluid from a cavity via an orifice. They represent the idealization of a very old idea, namely the bellows (see Fig. 2 for woodblock prints from the 16th century). The fluidic motion is initiated by oscillating a membrane located in one of the cavity walls. It has been found that, provided the volumetric displacement is the same, the location of the membrane has little effect unless there

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is asymmetry involved[7]. By suitably choosing the forcing amplitude and frequency, several different kinds of jet have been observed experimentally, including a standing vortex pair, a vortex stream and a turbulent jet[8-15]. This is indicated in Fig. 1 by the mean, $\bar{U}_j$, and fluctuating (RMS), U'_j, components of the actuator output flow velocity. When a synthetic jet interacts with a cross-flow boundary layer, it has been found that, in general, the jet penetration and induced turbulence levels increase with jet mean velocity, but when frequency is varied, two distinct interaction types are observed. These interactions have been described as a decaying hair-pin vortex and closed re-circulating zone, with the range for the different behaviours being separated by a critical jet forcing frequency[16-22].

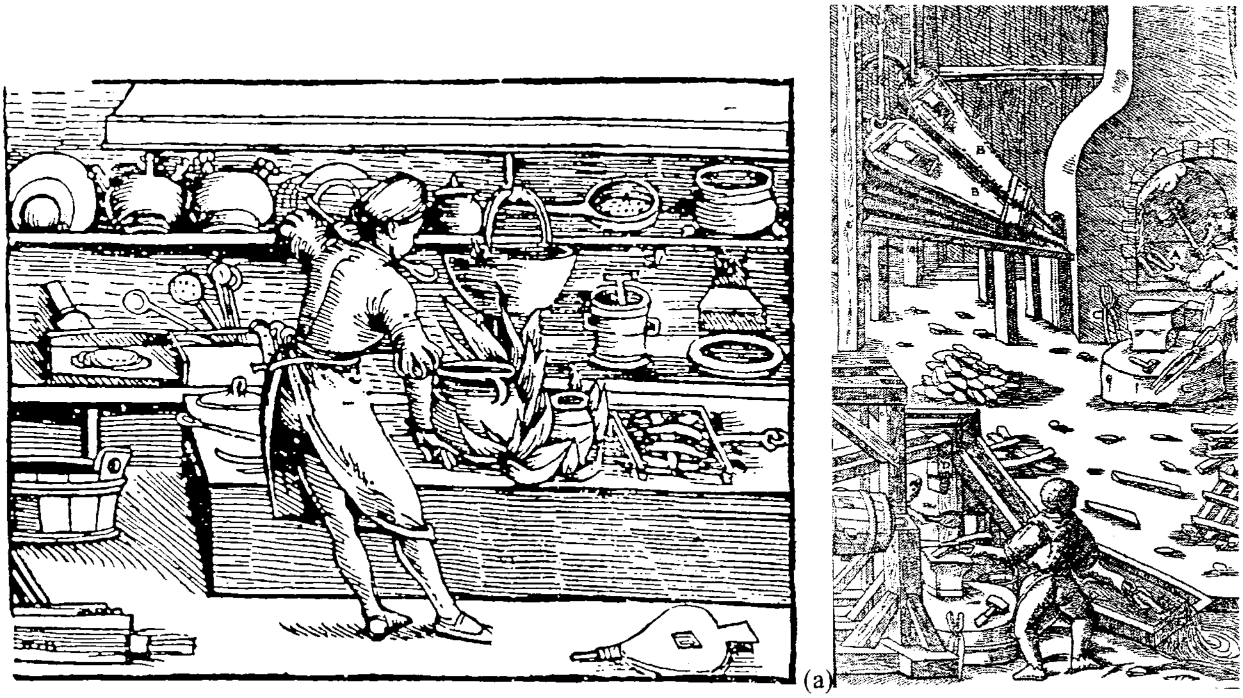

Figure 2. Synthetic jet actuators are the idealization of an old idea, the bellows, which has long been used in both household kitchens (a)[5] and blacksmith workshops (b)[6].

Computational studies of synthetic jets with and without cross-flow have tended to employ either two-dimensional or axisymmetric simulations. Mittal et al.[23] and Utturkar et al[7] used two-dimensional simulations to examine jets with and without cross-flow, finding that jet penetration was greater for low cross-flow Reynolds numbers and high jet forcing characteristics. Lee and Goldstein[24] employed two-dimensional Navier-Stokes simulations to investigate low Reynolds number synthetic jets without cross-flow, finding that jet penetration increased with Reynolds number. Lockerby et al.[25] employed a velocity-vorticity method to examine micro- and macro-scale synthetic jet flows, finding that wave packet formation is delayed in the former when compared to the latter in a suitably non-dimensionalized form. Mallinson and Reizes[26] employed an axisymmetric Navier-Stokes code to examine macro-scale actuators; this work was later extended to the micro-scale[27]. In both studies, it was found that the peak mean centre-line velocity increases linearly with the product of membrane displacement and forcing frequency. This is entirely consistent with experimental observations by Tesar and Zhong[13]. Rizzetta et al[28] examined actuators with high aspect ratio rectangular orifices exiting into a quiescent ambient using two- and three-dimensional Navier-Stokes simulations; however, these did not extend to the case of cross-flow.

In this paper, we will examine a synthetic jet actuator embedded in a microchannel using a three-dimensional Navier-Stokes solver. The flow interactions are quite different to those encountered in an external flow situation, as has been the almost exclusive focus of earlier work. It should be noted that Yassour et al.[29] and Kercher et al. [30] have employed synthetic jets to cool a metal plate and a microchip, respectively. Also, Mautner[31] used a hybrid two-dimensional Lattice-Boltmann / Navier-Stokes method to examine the mixing induced by synthetic jets in a low Reynolds number microchannel flow. Here, the focus will be on visualizing the three-dimensional flow features that occur during actuator operation in a microchannel.

Square cavity and office geometries are chosen to match our currently available microfabrication capabilities[27], and also to simplify the task of achieving good mesh quality. The membrane is assumed to move normally, that is, like a piston-in-cylinder, to simplify the simulations, thus reducing run-time. Of course, in a real device, the membrane motion will be induced by an externally supplied signal to whichever actuation means is chosen. To accurately capture the complete physics of the device, it will be necessary to undertake coupled simulations. This study represents a first step towards this ultimate goal, allowing us to focus on the fluidics of the problem.

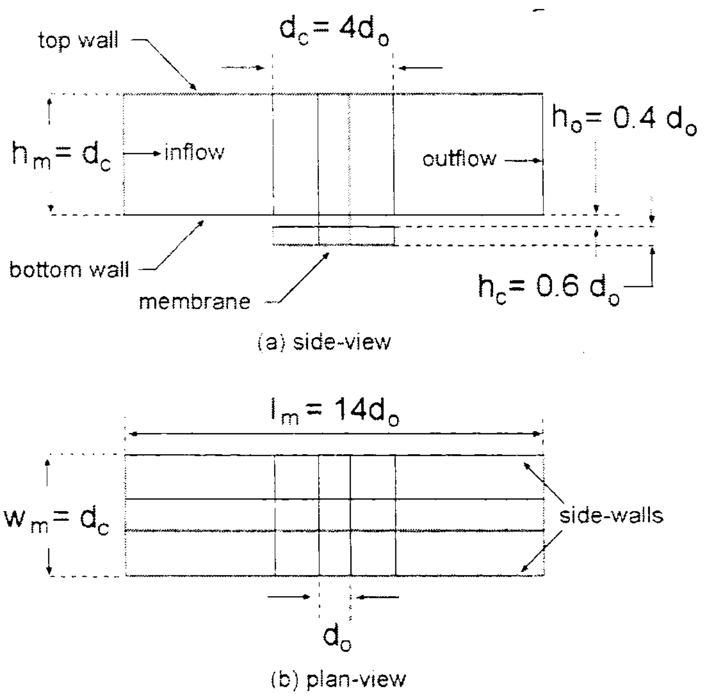

Figure 3. Main features of computational domain. l_m = channel length, h_m = channel height, w_m = channel width. Internal lines indicate subdivision of domain for meshing.

1. Problem Description and Numerical Method

The simulation domain is presented in Fig. 3. The actuator and channel centers are co-located in the computational domain, and the cavity and channel side-walls are aligned. The main dimensions are d_o = 100 µm, h_o = 40 µm, d_c = 400 µm, h_c = 60 µm, l_m = 1400 µm, h_m = w_m = 400 µm. The mesh spacing was set as constant for the actuator chamber and orifice, and geometrically stretched by five percent to the inlet/outlet planes. The actuator membrane motion is simulated as a piston to reduce complexity. The membrane motion, Δ (t), is specified by the membrane maximum deflection, Δ_m, and frequency, f, with:

$$\Delta(t) = \Delta_m \sin 2\pi f t \tag{1}$$

where t is time from the start of the simulation. The test fluid is air with density, ρ = 1.16 kg m^{-3} and viscosity, μ = 18.5 µPa s. We specify the inlet velocity, U_∞ and set the outlet pressure as zero. The four cases considered here are listed in Table 1. In case 1, both the inlet and outlet are set as zero pressure.

The simulations were performed using the commercial finite-volume Navier-Stokes solver, CFD-Ace (www.cfdrc.com). Use of the Navier-Stokes equations is valid for this problem, as the Knudsen number, *Kn*, based on the minimum characteristic dimension, d_{min}, and mean free path of fluid, λ, is:

$$Kn = \lambda / d_{min} \approx 10^{-3} \tag{2}$$

indicating continuum flow. The time-step is advanced using the second-order accurate Crank-Nicholson method. The time step was set as 250 ns, giving 80 time steps per cycle for cases 1-3 and 40 for case 4. The velocity and density are spatially discretized using a second-order method and upwinding, respectively. The equations are solved using the pre-conditioned conjugate-gradient method for velocity and the algebraic multi-grid method for pressure.

Case	Δ_m (μm)	f (kHz)	U_∞ (m s^{-1})	L_s / d_o	S	C_μ
1	10	50	-	3.2	14.0	-
2	10	50	2π	3.2	14.0	1
3	5	50	2π	1.6	14.0	0.5
4	10	100	2π	3.2	19.8	2

Table 1. Forcing and inlet parameters for this study.

To allow this study to be compared with previous efforts, several important parameters are also shown in Table 1. The first is the ratio of the ejected slug-length to the orifice diameter, L_s / d_o. Smith and Glezer[8] define a slug length based on the average measured velocity during the upstroke as:

$$L_s = \int_0^{\tau/2} U_o(t)\, dt \tag{3}$$

where $U_o(t)$ is the measured stream-wise velocity averaged over the orifice area and $\tau = (2\,\pi\, f)^{-1}$ is the forcing period. Müller et al[9] and Smith and Swift[12] showed that a distinct jet is produced for $L_s / d_o > k$, where k is a constant which depends on a number of factors, most important of which is the orifice geometry. Utturkar et al[15] showed that a more general criterion is: $Re / S^2 > K$ where Re = Reynolds number = $\bar{U}\, d_o / \nu$, S = Strouhal number = $(2\,\pi\, f\, d_o^2 / \nu)^{1/2}$, $\nu = \mu / \rho$, and K is another constant which depends on geometry. Utturkar et al defined the mean velocity as:

$$\overline{U} = \frac{2}{A\tau} \int_0^{\tau/2} \int_A U_o(t)\, dA\, dt \tag{4}$$

That is, the criterion is also based on measured quantities. Tesar and Zhong[14] defined a stroke length based on the volume displaced by the membrane, ΔV, as:

$$L_s = \frac{\Delta V}{A_o} \tag{5}$$

where A_o is the orifice cross-sectional area. Tesar and Zhong found that ring vortices are produced for $L_s / d_o \approx 1$ and a clear jet for $L_s / d_o > 5$, whilst no jet is produced for $L_s / d_o < 1$. As this definition of stroke length relies on parameters that define the problem, we have chosen to use it, along with the Strouhal number, to characterize the jet flow in Table 1. The main scaling parameter in the case of cross-flow has been found to be the jet-to-cross-flow momentum ratio[16-22], denoted C_μ. As the cross-flow is confined, the cross-flow momentum will be $\rho\, U_\infty\, A_m$, where A_m = microchannel cross-sectional area = $w_m\, h_m$. For the jet, we can approximate the outflow velocity as $\bar{U}_j = L_s / \tau$, giving the momentum ratio as $C_\mu = 2\, \Delta_m\, A_c / U_\infty\, A_m\, \tau$.

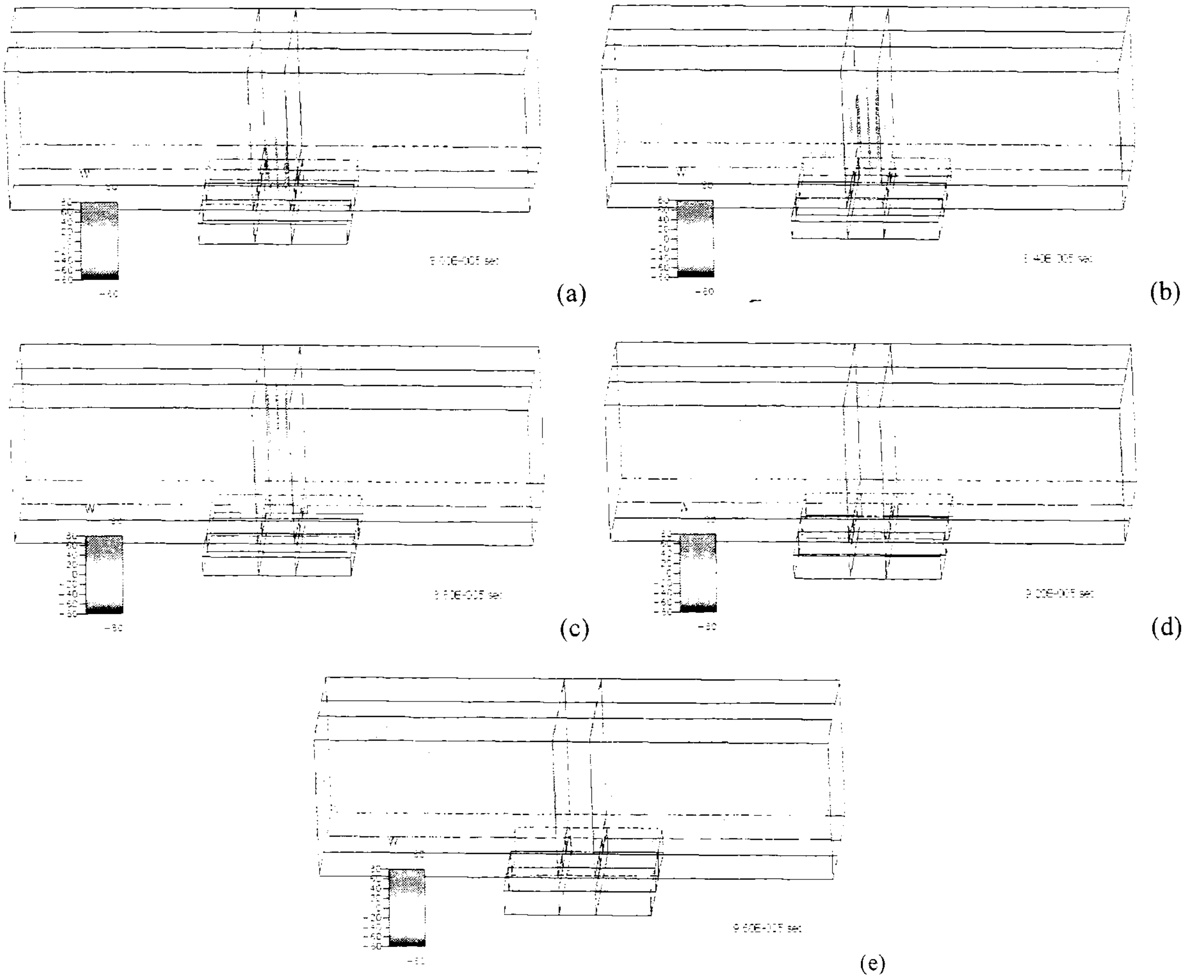

Figure 4. Case 1, velocity vectors on center-line plane, y = 0, mapped with vertical velocity, at five instants in fourth cycle.
(a) $t / \tau = 4.0$; (b) $t / \tau = 4.2$; (c) $t / \tau = 4.4$; (d) $t / \tau = 4.6$; (e) $t / \tau = 4.8$.

3. Case 1: No Cross-Flow, $L_s / d_o = 3.2$, $S = 14$.

The predictions indicate that for this set of conditions, a nearly pseudo-steady flow state is established after the third cycle. Figure 4 presents plots of velocity vectors mapped with vertical velocity at five instants during the fourth cycle, whilst Fig. 5 presents corresponding vorticity contours on planes at y = 0 (centerline) and $z = d_o$ and 3 d_o above the orifice exit plane. The vorticity contours (Fig. 5) are mapped with a sinusoidally varying light-dark colourmap, so that the vorticity variation is represented by "fringe" shifts, in a similar way to density variations altering interferogram fringe patterns in compressible flows (see, for example, Hornung et al.[32]). This allows us to observe the relative strength of vorticity gradients in different parts of the flow domain. On the upstroke, a nearly circular vortex ring emerges from the orifice and heads towards the opposite wall of the microchannel. As the vortex ring reaches the wall, it interacts with the remains of the vortex shed during the previous cycle, spreading outwards and flattening. On the downstroke, fluid is ingested primarily from around the perimeter of the orifice. The ingestion part of the cycle also draws some fluid away from the microchannel top wall, causing further dissipation of the shed vortex system. Subsequent ejections and ingestions give rise to a cyclically replenished vortex system trapped on the microchannel top wall.

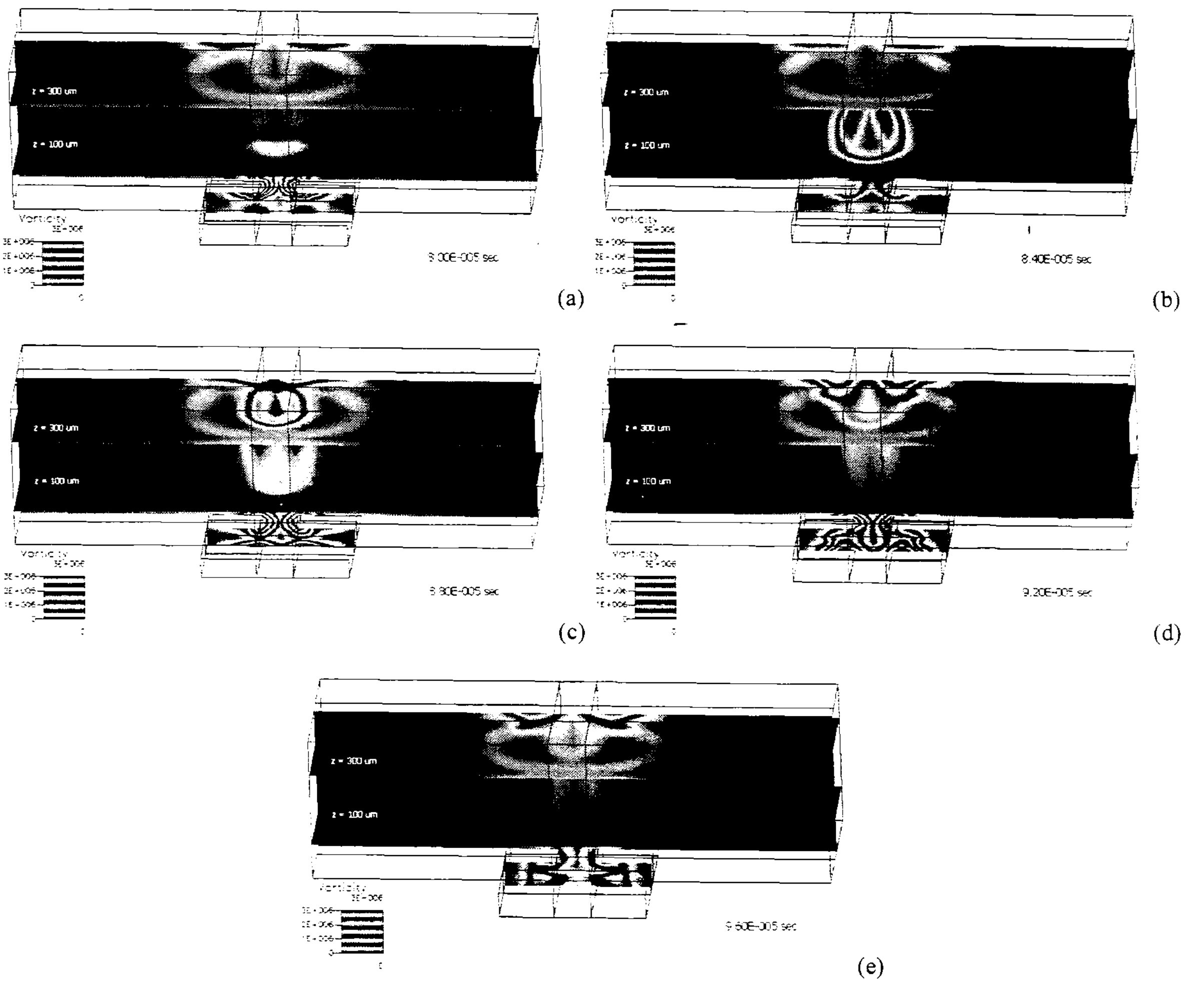

Figure 5. Case 1, vorticity contours on center-line plane, $y = 0$ and vertical planes z = 100 and 300 μm above the channel surface, at five instants in fourth cycle. (a) $t / \tau = 4.0$; (b) $t / \tau = 4.2$; (c) $t / \tau = 4.4$; (d) $t / \tau = 4.6$; (e) $t / \tau = 4.8$.

4. Case 2: Cross-Flow, $L_s / d_o = 3.2$, $S = 14$, $C_\mu = 1$.

Figure 6 presents plots of vorticity contours on planes at $y = 0$ and $z = d_o$ and 3 d_o above the orifice exit plane at five instants during the fourth cycle for the same actuator characteristics as case 1, and with a cross-flow having the same momentum as the jet. Similar to the case of no cross-flow, a cyclically replenished vortex system forms on the microchannel top wall. Here, the center of the system moves downstream relative to the no cross-flow prediction, and the ejected vortices rotate about their transverse axis (out of the page) with the vortex appearing to transform into a hair-pin shape. On reaching the top wall, the vortex spreads further laterally compared to case 1, with the side arms of the vortex reaching the surface later than the apex. The flow in the cavity and orifice appears to be quite symmetrical, apart from near to the end of the suction part of the cycle (see Fig. 6(e)).

5. Comparison of Cases 1-4.

Figure 7 presents plots of velocity vectors mapped with vertical velocity for cases 1-4 at $t / \tau = 0.4$ (near end of ejection), whilst Fig. 8 presents corresponding vorticity contours on planes at $y = 0$ and $z = d_o$ and 3 d_o above the orifice exit plane at $t / \tau = 0.8$ (near end of ingestion). Without cross-flow (Figs. 7(a) and 8(a)), the flow appears quite symmetrical, whereas cross-flow induces asymmetry, with greater asymmetry for smaller jet-to-cross-flow-momentum ratios. For the lowest value of C_μ, case 3, the vortex does not reach the top wall, tumbling and decaying into a hair-pin shape and diffusing before reaching the upper cutting plane in the vorticity plots. For the highest value of C_μ, case 4, the vortex maintains its form and symmetry, with seemingly only small differences from case 1 (no cross-flow). In all three cases with cross-flow, there seems to be little evidence of the wake vortex that has been identified in previous studies.

The vorticity contours at the cavity midplane (z = -70 μm) and near the top wall (z = 350 μm) are shown in Fig. 9 for cases 1-4 at t / τ = 0.8. Again, the greatest degree of asymmetry is observed for the smallest value of C_μ. Nonetheless, the degree of cavity asymmetry is much less than was predicted using two-dimensional simulations with similar values of C_μ[7,23,25]. It is also interesting to note that in both cases 2 and 4, for which the vortex reaches the microchannel top wall, the vortex adopts a hairpin shape.

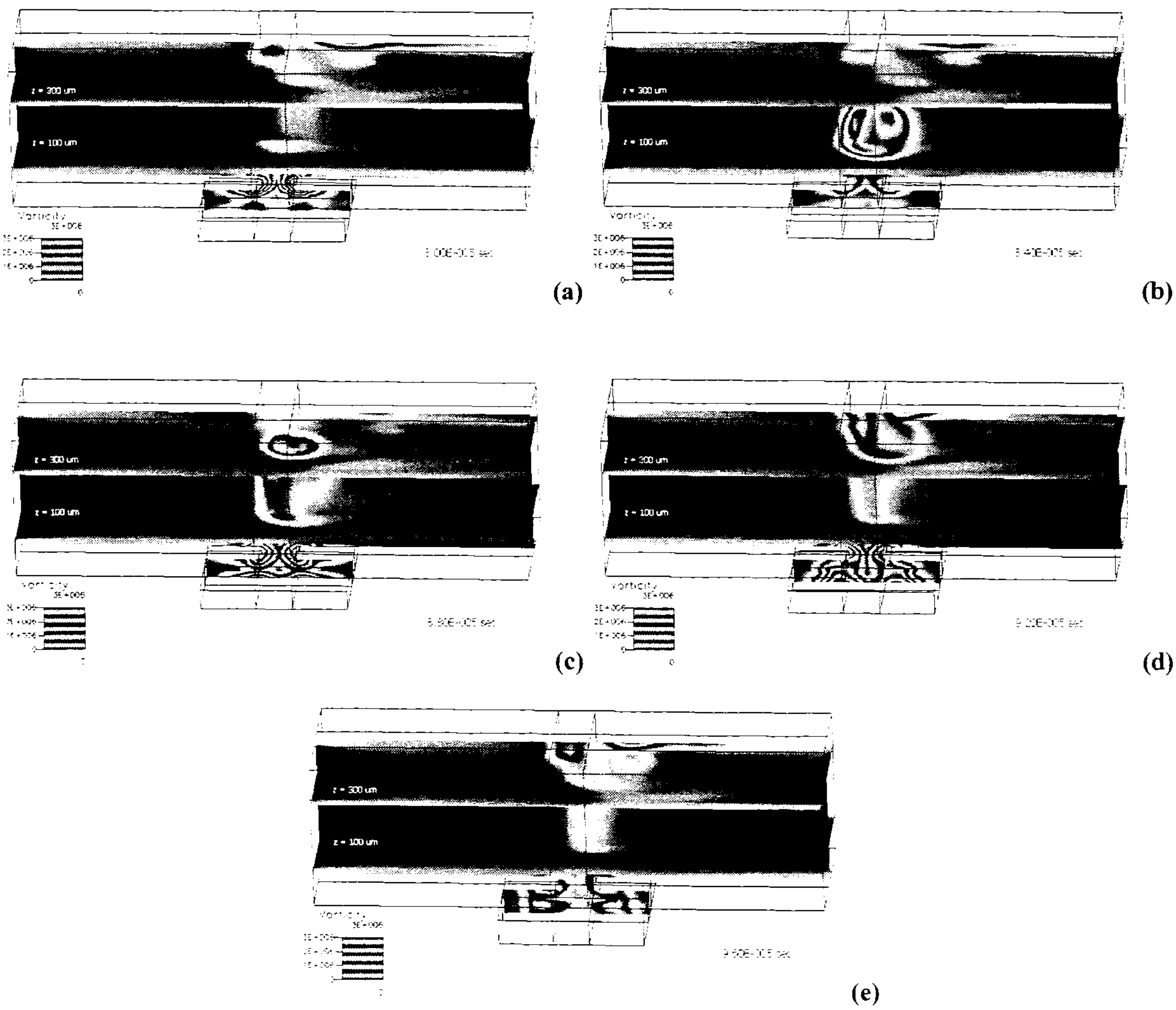

Figure 6. Case 2, vorticity contours on center-line plane, y = 0 and vertical planes z = 100 and 300 μm above the channel surface, at five instants in fourth cycle. (a) t / τ = 4.0 ; (b) t / τ = 4.2; (c) t / τ = 4.4; (d) t / τ = 4.6; (e) t / τ = 4.8.

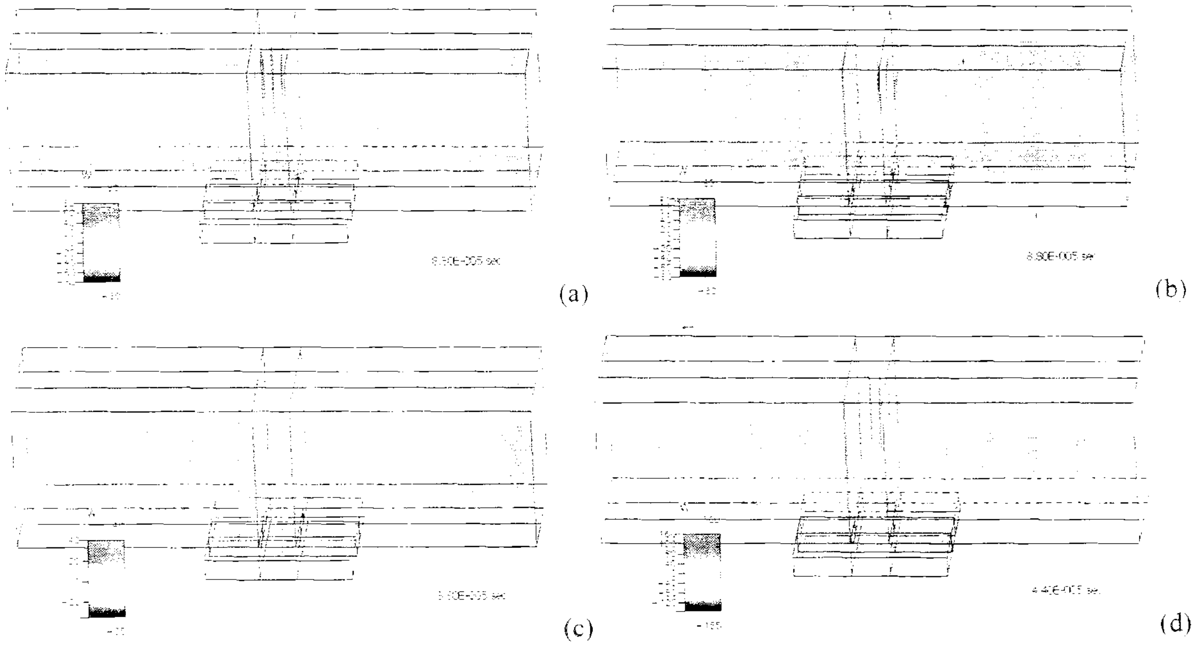

Figure 7. Comparison of velocity vectors on center-line plane for cases 1-4 at same relative point in cycle, $t/\tau = 0.4$.
(a) case 1; (b) case 2; (c) case 3; (d) case 4.

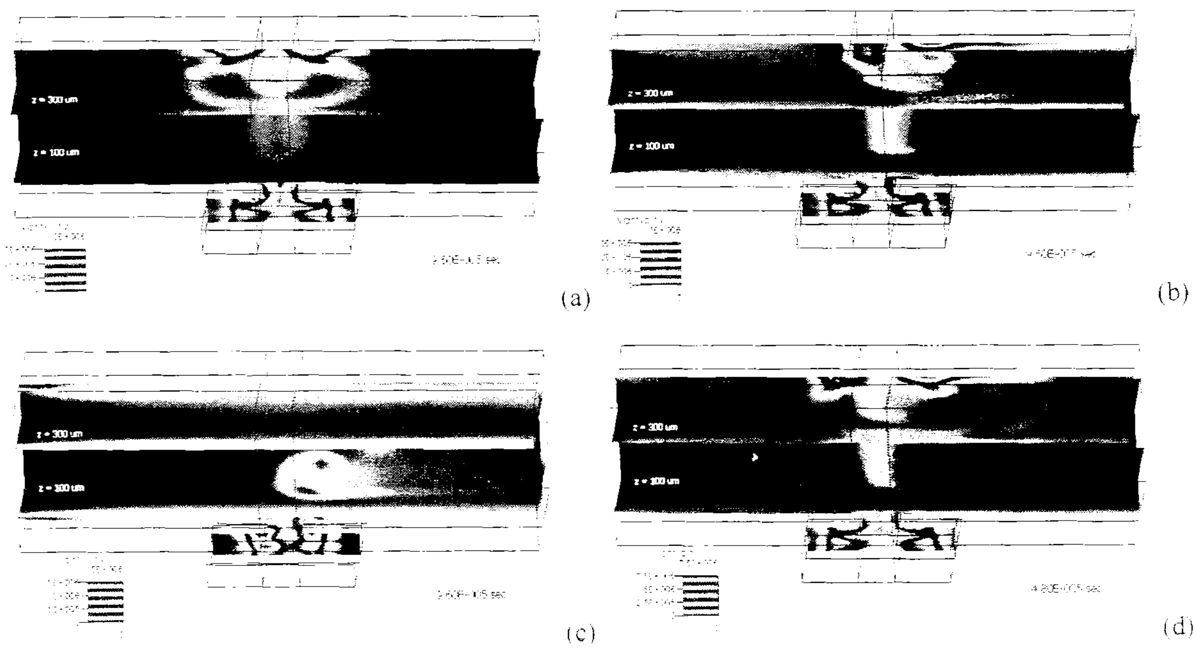

Figure 8. Comparison of vorticity contours in main body of flow for cases 1-4 at same relative point in cycle, $t/\tau = 0.8$.
(a) case 1; (b) case 2; (c) case 3; (d) case 4.

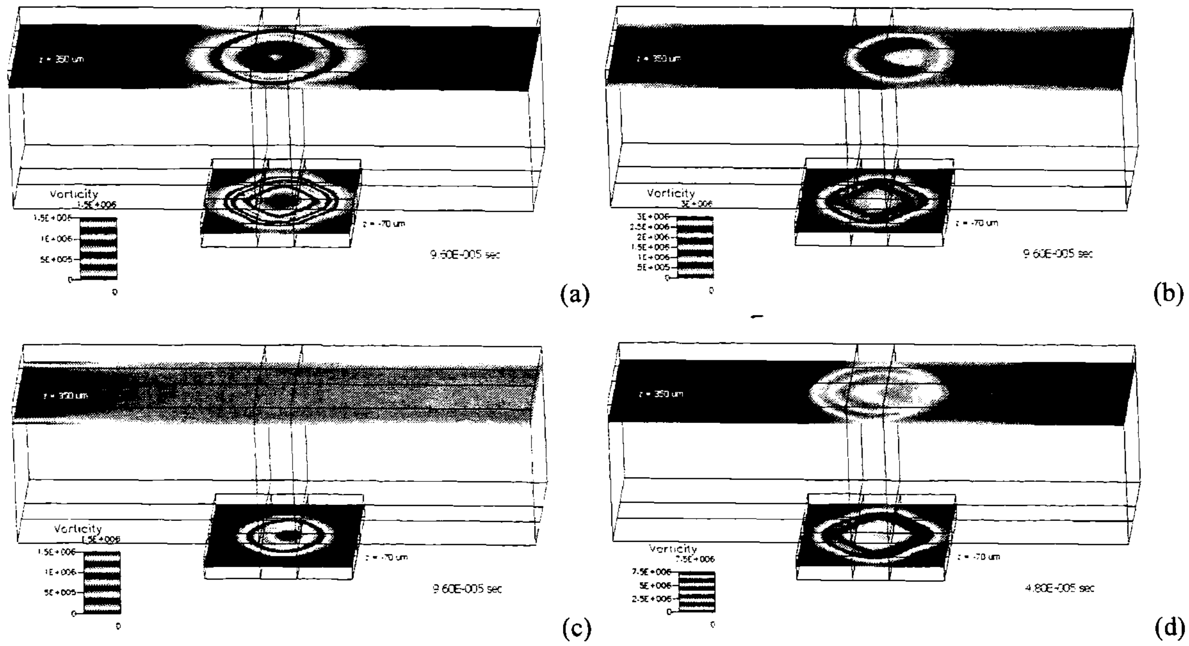

Figure 9. Comparison of vorticity contours in cavity (z = -70 μm) and near top wall (z = 350 μm) for cases 1-4 at same relative point in cycle, t / τ = 0.8. (a) case 1; (b) case 2; (c) case 3; (d) case 4.

6. Conclusions and Future Work

The flow generated by a synthetic jet actuator located in a closed microchannel has been examined using three-dimensional computational fluid dynamics simulations. In the case with no cross-flow, the actuator establishes a cyclically replenished vortex on the microchannel top wall, which faces the actuator orifice. When cross-flow is considered, the flow behaviour depends on the jet-to-cross-flow momentum ratio, C_μ. When C_μ = 0.5, the ejected vortices decay very rapidly into a hairpin shape and do not reach the microchannel top wall. For $C_\mu \geq 1$, the vortex reaches the far wall, with the center of the vortex system being offset from the actuator centreline by a decreasing amount with increasing C_μ. Further, the cavity exhibits greater asymmetry with decreasing C_μ, but the asymmetry is seemingly much less than has been observed in earlier studies.

Some key issues that need to be addressed include: whether the solutions exhibit grid and time-step convergence; whether self-similar behaviour is exhibited for a range of actuator input parameters, L_s / d_o, S and C_μ; and, whether there is any effect of orifice and cavity geometries on the flow behaviour.

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Wednesday 10 December

Welcome and Opening Remarks 09.15 to 09.45

Location: Social Science Lecture Theatre

Lorenzo Faraone, The Univ. of Western Australia

Vijay K. Varadan, The Pennsylvania State Univ.

Plenary Presentation 1 09.45 to 10.30

WLAN ICs: a tornado market, Neil Weste, Cisco Systems (Australia) [5274-201]

Morning Tea 10.30 to 11.00

SESSION 1

Room: Engineering Lecture Theatre 1 Wed. 11.00 to 12.30

Materials I

Chairs: John M. Dell, Univ. of Western Australia (Australia); Nico F. de Rooij, Univ. de Neuchatel (Switzerland)

11.00: **Few and single ion implantation for the construction of buried nanostructures in silicon with applications to quantum computation** *(Invited Paper),* D. N. Jamieson, Univ. of Melbourne (Australia); A. S. Dzurak, Univ. of New South Wales (Australia) [5276-01]

11.30: **Fabrication of micromachined ceramic thin-film type pressure sensors for overpressure tolerance and its**

characteristics, G. Chung, J. Kim, Dongseo Univ. (South Korea) [5276-02]

11.45: **Ferromagnetism in transition metal-implanted titanium dioxide films,** S. Wong, Y. Gao, K. H. Cheng, N. Ke, W. Y. Cheung, Q. Li, Chinese Univ. of Hong Kong (China) [5276-03]

12.00: **Use of titanium and titanium dioxide as masks for deep silicon etching,** O. J. Powell, Griffith Univ. (Australia); H. B. Harrison, Griffith Univ. (Australia) and CRC for Microtechnology (Australia); D. Sweatman, Griffith Univ. (Australia) [5276-04]

12.15: **Laser patterning of thin films of TiNiPd deposited on silicon substrate,** V. K. Mathe, D. K. Sood, RMIT Univ. (Australia) and CRC for Microtechnology (Australia); J. P. Hayes, Swinburne Univ. of Technology (Australia) and CRC for Microtechnology (Australia) [5276-05]

Lunch Break 12.30 to 13.30

SESSION 2

Room: Engineering Lecture Theatre 1 Wed. 13.30 to 15.00

Characterization II

Chairs: Peter J. Evans, Australian Nuclear Science and Technology Organisation (Australia); Brett D. Nener, Univ. of Western Australia (Australia)

13.30: **Investigations of ohmic contacts to p-GaN** *(Invited Paper),* G. Parish, G. Umana-Membreno, B. D. Nener, Univ. of Western Australia (Australia) [5276-06]

14.00: **Micro- to nano-domain engineering of LN and LT for new applications,** K. Kitamura, M. Nakamura, S. Kurimura, K. Terabe, National Institute for Materials Science (Japan) [5276-80]

14.15: **Loop closure theory in deriving a linear and simple kinematic model for a 3 DOF parallel micromanipulator,** Y. K. Yong, T. Lu, D. C. Handley, Univ. of Adelaide (Australia) [5276-08]

14.30: **Simple and efficient dynamic model for a compliant micropositioning mechanism using flexure hinges,** D. C. Handley, T. Lu, Y. K. Yong, Univ. of Adelaide (Australia); C. Zhang, Univ. of Saskatchewan (Canada) [5276-09]

14.45: **Performance of a novel non-planar diaphragm and its applications to high-performance devices,** W. Wang, Nanyang Technological Univ. (Singapore) [5276-10]

Afternoon Tea 15.00 to 15.30

SESSION 3

Room: Engineering Lecture Theatre 1 Wed. 15.30 to 16.45

Fabrication I

Chairs: Alex J. Hariz, Univ. of South Australia (Australia); Charles A. Musca, Univ. of Western Australia (Australia)

15.30: **Investigation of SU-8 resist adhesion in deep x-ray lithography of high aspect ratio structures,** R. L. Barber, M. K. Ghantasala, Swinburne Univ. of Technology (Australia); R. S. Divan, D. C. Mancini, Argonne National Lab. (USA); E. C. Harvey, Swinburne Univ. of Technology (Australia) [5276-11]

15.45: **Effect of plume dynamics on the uniformity of excimer laser ablation for microfabrication,** E. C. Harvey, J. Hayes, Swinburne Univ. of Technology (Australia) and CRC for MicroTechnology (Australia) [5276-12]

16.00: **Manufacturing microdroplet generators with laser-LIGA technique,** J. Husny, Univ. of Melbourne (Australia); H. Jin, E. Harvey, Swinburne Univ. of Technology (Australia); J. J. Cooper-White, Univ. of Melbourne (Australia) [5276-13]

16.15: **Quartz crystal microbalance coated with protein self assembly layer to detect organic gases,** M. Mat Salleh, A. Ali Umar, Univ. Kebangsaan Malaysia (Malaysia) [5276-14]

16.30: **Design,** modeling, and fabrication of piezoelectric polymer actuators, Y. Fu, E. C. Harvey, M. K. Ghantasala, Swinburne Univ. of Technology (Australia); G. Spinks, Univ. of Wollongong (Australia) [5276-15]

Thursday 11 December

Location: Social Science Lecture Theatre

Plenary Presentation 2 09.00 to 09.45

Dynamic nano- and micro-devices based on protein motors, Kazuhiro Oiwa, Kansai Advanced Research Center (Japan) [5275-202]

Plenary Presentation 3 09.45 to 10.30

Emerging memory technologies, Sreedhar Natarajan, MoSys Inc. (Canada) [5274-203]

Morning Tea 10.30 to 11.00

SESSION 4

Room: Engineering Lecture Theatre 1 Thurs. 11.00 to 12.30

Fabrication II

Chairs: Erol C. Harvey, Swinburne Univ. of Technology (Australia); Giacinta Parish, Univ. of Western Australia (Australia)

11.00: **Novel low temperature CMOS compatible Full wafer bonding process for the fabrication of 3D embedded microchannels using SU-8 photoresist** *(Invited Paper),* F. J. Blanco, IKERLAN S. Koop (Spain) [5276-17]

11.30: **Secret of formulating a selective etching or cleaning solution for boron nitride (BN) thin film,** W. C. Hui, Institute of Microelectronics (Singapore) [5276-18]

11.45: **Comparison of two types of multilayer microcoil fabrication techniques,** A. C. Hartley, R. E. Miles, J. Corda, Univ. of Leeds (United Kingdom) [5276-19]

12.00: **Patterning of SU-8 resist structures using CF4,** K. D. Vora, M. K. Ghantasala, Swinburne Univ. of Technology (Australia); A. Holland, A. Mitchell, RMIT Univ. (Australia) [5276-20]

12.15: **Novel fabrication of 3D silicon photonic crystal structures using conventional micromachining technology,** S. Venkataraman, J. Murakowski, G. Schneider, D. Prather, Univ. of Delaware (USA) [5276-21]

Lunch Break 12.30 to 13.30

SESSION 5

Room: Engineering Lecture Theatre 1 Thurs. 13.30 to 15.00

Materials II

Chairs: David N. Jamieson, Univ. of Melbourne (Australia); Charles A. Musca, Univ. of Western Australia (Australia)

13.30: **Cooling a nanomechanical resonator using feedback: toward quantum behavior** *(Invited Paper),* K. A. Jacobs, Griffith Univ. (Australia); A. Hopkins, California Institute of Technology (USA) and Los Alamos National Laboratory (USA); S. Habib, Los Alamos National Lab. (USA); K. Schwab, Univ. of Maryland (USA) [5276-22]

14.00: **Characterization of thin metal oxide films grown by atomic layer deposition,** P. J. Evans, K. Prince, G. Triani, K. Finnie, C. Barbe, Australian Nuclear Science and Technology Organisation (Australia) [5276-23]

14.15: **Quantum electromechanical system (QEMS),** D. Wahyu Utami, H. Goan, G. J. Milburn, Univ. of Queensland (Australia) [5276-24]

14.30: **Encapsulation of nanoparticles for the manufacture of solid state lighting devices,** S. G. Thoma, J. Wilcoxon, L. Rohwer, Sandia National Labs. (USA); D. Devlin, Los Alamos National Lab. (USA); S. Woessner, B. Abrams, A. Sanchez, Sandia National Labs. (USA) [5276-25]

14.45: **Selective wet etching of fully filtered and partially filtered cathodic arc deposited TiN films,** A. J. Dowling, M. Ghantasala, Swinburne Univ. of Technology (Australia); D. Doyle, Swinburne Univ. of Technology (Australia) and Surface Technology Coatings (Australia); E. Harvey, Swinburne Univ. of Technology

(Australia) and MiniFab (Australia) [5276-26]

Afternoon Tea 15.00 to 15.30

SESSION 6

Room: Engineering Lecture Theatre 1 Thurs. 15.30 to 17.00

Characterization II

Chairs: H. Barry Harrison, Griffith Univ. (Australia); Brett D. Nener, Univ. of Western Australia (Australia)

15.30: **MEMS micromirrors for optical switching in multichannel spectrophotometers,** A. Tuantranont, T. Lomas, National Electronic and Computer Technology Ctr. (Thailand); V. M. Bright, Univ. of Colorado/Boulder (USA) [5276-27]

15.45: **Phase detection scheme for an angular rate sensor,** J. D. John, T. Vinay, L. Qin, RMIT Univ. (Australia) [5276-28]

16.00: **Influence of synthetic jet location on boundary layer separation control,** C. Lee, G. Hong, Univ. of Technology/Sydney (Australia); S. Mallinson, Silverbrook Research (Australia) [5276-60]

16.15: **Large output force out-of-plane MEMS actuator array,** T. Fukushige, S. Hata, A. Shimokohbe, Tokyo Institute of Technology (Japan) [5276-30]

16.30: **Single-spin measurement by magnetic resonance force microscopy: effects of measurement device,** thermal noise, and spin relaxation, H. Goan, Univ. of New South Wales (Australia); T. A. Brun, Institute for Advanced Study (USA) [5276-31]

16.45: **Anodic bond characteristics of Si-wafer and MLCA using Pyrex #7740 glass intermediate layer,** G. Chung, J. Kim, Dongseo Univ. (South Korea) [5276-32]

Posters -Thursday

Posters will be displayed all day Thursday. Poster presenters will stand by their posters from 17.00 to 18.30 pm to answer questions. Posters must be removed at the end of the poster session.

- **Two-way actuation of bilayer cantilever of nickel titanium and silicon nitride thin films by shape memory effect and stress relaxation,** E. Wibowo, C. Y. Kwok, N. Lovell, Univ. of New South Wales (Australia) [5276-44]
- **Electrostatic microrelays with adjustable parameters,** N. I. Mukhurov, G. I. Efremov, Institute of Electronics (Belarus) [5276-45]
- **Identification and elimination of trench crystal defects in sub-0.13-um era,** C. Yeh, C. Chen, Taiwan Semiconductor Manufacturing Co., Ltd. (Taiwan) [5276-46]
- **Lens design issues for the optical structure of a holographic free space optical switch,** K. Lo, D. Habibi, Edith Cowan Univ. (Australia) [5276-47]
- **Fabrication of thin-film transistors on plastic substrates by spin etching and device transfer process,** S. Wang, C.

Hsu, C. Yeh, J. Lou, National Chiao Tung Univ. (Taiwan) [5276-48]

- **New unidirectional interdigital transducers using very thin grating acoustic surface wave substrates and application to wideband low loss filters,** K. Yamanouchi, Y. Sato, Tohoku Institute of Technology (Japan) [5276-49]
- **Comprehensive analysis of InGaP/GaAs heterojunction bipolar transistors (HBTs) with different thickness of setback layers,** S. Cheng, Oriental Institute of Technology (Taiwan); C. Chun-Yuan, J. Chen, H. Chuang, W. Liu, National Cheng Kung Univ. (Taiwan) [5276-50]
- **Mass-productive fabrication method for miniaturized plastic chip devices used in biochemical applications,** T. Fujimura, S. Etoh, A. Ikeda, R. Hattori, Y. Kuroki, Kyushu Univ. (Japan) [5276-51]
- **Formation and its characteristics of PLZT layered film structure for transducer,** M. Ichiki, National Institute of Advanced Industrial Science and Technology (Japan) and Tokyo Denki Univ. (Japan); T. Kobayashi, Y. Morikawa, National Institute of Advanced Industrial Science and Technology (Japan); T. Nakada, Tokyo Denki Univ. (Japan); R. Maeda, National Institute of Advanced Industrial Science and Technology (Japan) [5276-52]
- **Apparent positive resistance and temperature effect on I-V characteristics of RTD,** W. Guo, P. Niu, X. Li, Z. Xu, H. Li, C. Miao, Tianjin Polytechnic Univ. (China) [5276-53]
- **Preparation of PZT films derived by hybrid processing for MEMS application,** Z. J. M. Wang, L. Yan, Tohoku Univ. (Japan); R. Maeda, National Institute of Advanced Industrial Science and Technology (Japan); H. Kokawa, Tohoku Univ. (Japan) [5276-54]
- **Analysis of beam propagation and aberration effects in a holographic free space optical switch,** K. Lo, D. Habibi, Edith Cowan Univ. (Australia) [5276-55]
- **Development of electrochromic sensor using iron-tetraphenyl porphyrins thin films to detect chlorine,** M. B. Yahaya, Univ. Kebangsaan Malaysia (Malaysia) [5276-56]
- **High aspect ratio fabrications of micro journal bearings and microvertical mirrors,** X. C. Shan, Singapore Institute of Manufacturing Technology (Singapore) and AIST (Japan); R. Maeda, National Institute of Advanced Industrial Science and Technology (Japan) [5276-57]
- **Dynamic characteristics of piezoelectric shear deformable composite plates,** R. Kolar, Naval Postgraduate School (USA) [5276-58]
- **Mechanical and optical properties of low temperature PECVD silicon nitride thin films,** M. T. Soh, Univ. of Western Australia (Australia) [5276-59]
- **Novel bistable thermally actuated snap-through actuator for out of plane deflection,** K. Yu, A. Michael, C. Y. Kwok, Univ. of New South Wales (Australia) [5276-61]
- **Modeling and simulation of porous microcantilevers,** G. M. Klass, RMIT Univ. (Australia) [5276-62]
- **Investigation of residual stress in low temperature silicon nitride thin films using diagnostic microstructures,** M. P. Martyniuk, J. Antoszewski, J. G. Wehner, C. A. Musca, J. M. Dell, L. Faraone, Univ. of Western Australia (Australia) [5276-63]
- **Novel 2D MEMS-based optical crossconnect with greatly reduced complexity,** X. Ma, Beijing Univ. of Posts and Telecommunications (China); G. Kuo, National Chengchi Univ. (Taiwan) [5276-64]
- **New method of vibration isolation of scanning electron microscope,** K. Matsuda, Y. Kanemitsu, S. Kijimoto, Kyushu Univ. (Japan) [5276-65]
- **Area-changed capacitive accelerometer using 3-mask fabrication process,** Y. M. Burhanuddin, B. Badariah, T. A.

Santoso, Univ. Kebangsaan Malaysia (Malaysia) [5276-66]

- **Micromachined crystal plane on (100) and (110) silicon for reflective mirror applications,** D. Resnik, Univ. v Ljubljani (Slovenia) [5276-67]
- **Development of surface connectors for microfluidic systems,** T. C. Liu, Swinburne Univ. of Technology (Australia) [5276-68]
- **Down conversion of high energy in anatase based TiO2 solar cells,** H. J. Kim, J. S. Song, B. K. Koo, D. Y. Lee, W. J. Lee, J. H. Koh, Korea Electrotechnology Research Institute (South Korea) [5276-70]
- **The MEMS components for front end of direct conversion architecture,** V. J. Vibhute, J. Singh, A. Stojcevski, A. Zayegh, Victoria Univ. of Technology (Australia) [5276-71]
- **Sol-gel deposition of PZT thick film on Pt/Ti/SOI substrate and application to 2D micro scanning mirror,** T. Kobayashi, J. Tsaur, M. Ichiki, R. Maeda, National Institute of Advanced Industrial Science (Japan) [5276-72]
- **Microhot embossing for high aspect ratio used thin polymer sheet,** Y. Murakoshi, National Institute of Advanced Industrial Science and Technology (Japan); X. Shan, Singapore Institute of Manufacturing Technology (Singapore); T. Sano, Chiba Institute of Technology (Japan); M. Takahashi, R. Maeda, National Institute of Advanced Industrial Science and Technology (Japan) [5276-73]
- **MEMS RF-filter for superheterodyne down conversion receivers,** H. H. Pham, J. Chaffey, RMIT Univ. (Australia) [5276-74]
- **Initially buckled,** thermally actuated, and snapping bimorph microbridge, A. M. Michael, K. Yu, K. Y. Chee, Univ. of New South Wales (Australia) [5276-75]
- **Micro/nanomechanical characterization of PECVD fluorocarbon thin film and its application in nanostructure fabrication,** T. Kim, N. Kim, J. Park, Hanyang Univ. (South Korea); E. Lee, Korea Institute of Machinery and Materials (South Korea) [5276-76]
- **Modeling mobility degradation in scanning capacitance microscopy for semiconductor dopant profile measurement,** Y. D. Hong, Y. T. Yeow, Univ. of Queensland (Australia) [5276-77]
- **Finite element modeling of micro-electro-mechanical systems incorporating shape memory alloys,** M. Y. Ahmed, Univ. of Alberta (Canada) and Alberta Ingenuity Fund (Canada); W. A. Moussa, Univ. of Alberta (Canada) [5276-78]
- **Three-dimensional numerical study of steady and pulsed jet/boundary layer interactions,** S. G. Mallinson, Silverbrook Research (Australia); G. Johnson, Univ. of Nottingham (United Kingdom); G. Hong, M. Gaston, Univ. of Technology/Sydney (Australia) [5276-29]
- **Micro- to nano-domain engineering of LN and LT for new applications,** K. Kitamura, M. Nakamura, S. Kurimura, K. Terabe, National Institute for Materials Science (Japan) [5276-80]
- **Surface metalization on the photo-emission,** photo-absorption and core-level shift of nanosolid silicon, C. Sun, L. Pan, S. Li, B. Tay, C. Tan, Nanyang Technological Univ. (Singapore) [5276-33]

Friday 12 December

Location: Social Science Lecture Theatre

Plenary Presentation 4 09.00 to 09.45

Toward smallest possible photonic crystal lasers, Yong Hee Lee, Korea Advanced Institute of Science and Technology (South Korea) [5277-204]

Plenary Presentation 5 09.45 to 10.30

Carbon nanotube field-effect transistors, David L. Pulfrey, Univ. of British Columbia (Canada) [5276-205]

Morning Tea 10.30 to 11.00

SESSION 7

Room: Fri. 11.00 to 12.15

Fabrication III

Chairs: Giacinta Parish, Univ. of Western Australia (Australia); John M. Dell, Univ. of Western Australia (Australia)

11.00: **Wireless MEMS and microsystem for monitoring and control of Parkinson's disease and sleeping disorders,** V. K. Varadan, The Pennsylvania State Univ. (USA) [5276-79]

11.15: **How to prevent a run away chemical reaction in the isotropic etching of silicon with HF/HNO3/CH3COOH or HNA solution,** W. C. Hui, Institute of Microelectronics (Singapore) [5276-34]

11.30: **Study on features of silicon microtrench with inductively coupled plasma etcher,** S. Tietun, Nanyang Technological Univ. (Singapore) [5276-35]

11.45: **Reflowed sol-gel microlens for coupling a laser diode and a single-mode fiber with high efficiency: a cost-effective and high-volume fabrication solution,** M. He, X. Yuan, Q. N. Ngo, J. Bu, S. Tao, Nanyang Technological Univ. (Singapore) [5276-36]

12.00: **Investigation of sample behavior inside on-chip electrophoresis microcapillary using confocal laser scanning microscopy,** S. Etoh, T. Higashi, T. Fujimura, R. Hattori, Y. Kuroki, Kyushu Univ. (Japan) [5276-37]

Lunch Break 12.15 to 13.30

SESSION 8

Room: Engineering Lecture Theatre 1 Fri. 13.30 to 14.30

Fabrication IV

Chairs: Kurt A. Jacobs, Griffith Univ. (Australia); Mu Chiao, Univ. of British Columbia (USA)

13.30: **Atomic Layer Deposition (ALD) of TiO2 and Al2O3 Thin**

Films on Silicon, D. R. G. Mitchell, G. Triani, D. J. Attard, K. S. Finnie, ANSTO Materials (Australia); P. J. Evans, ANSTO Environment (Australia); C. J. Barbé, J. R. Bartlett, ANSTO Materials (Australia) [5276-38]

13.45: **LIGA for Boomerang,** R. A. Lawes, Rutherford Appleton Lab. (United Kingdom) [5276-39]

14.00: **Optically variable devices fabricated by electron beam lithography,** G. C. Rosolen, CSIRO (Australia) [5276-41]

14.15: **Bi-Ti-O thin films for pressure sensors,** C. W. Chong, M. Yahaya, M. Mat Salleh, Univ. Kebangsaan Malaysia (Malaysia) [5276-42]

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