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Electromagnetically Actuated Ball Valve Micropumps

presented by

Christophe Yamahata

and

F. Lacharme, J. Matter, S. Schnydrig, Y. Burri, M. A. M. Gijs

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Ecole Polytechnique Fédérale de Lausanne
Institute of Microelectronics and Microsystems

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① Outline

- Lab-On-a-Chip
- State-of-the-art

② Working principle

- External electromagnet
- Multi-layered microchip

3 Microfabrication

- Magnetic membrane
- PMMA microchip
- Glass microchip

4 Results & discussion

- Magnetic membrane actuation
- Micropumps characterization
- Damped oscillator model

5 Conclusion

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Outline

- Lab-On-a-Chip
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Outline ▸ Lab-On-a-Chip

Lab-On-a-Chip:

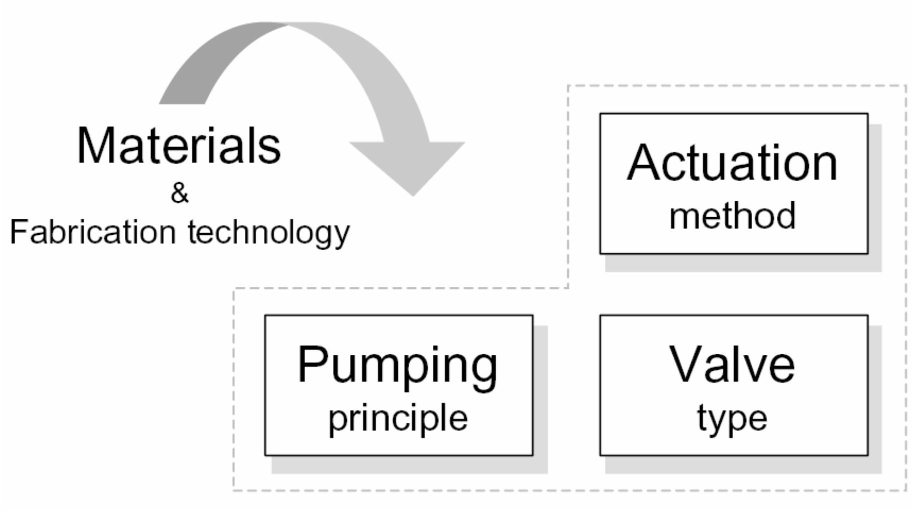
- Microfluidic Laboratory on a chip
- Plastic / glass material

Need for **low-cost** micropumps targeted to biochemical applications:

- **disposable** or **sterilizable**
- with possible **integration** in Lab-On-a-Chip devices

Outline ▸ Lab-On-a-Chip

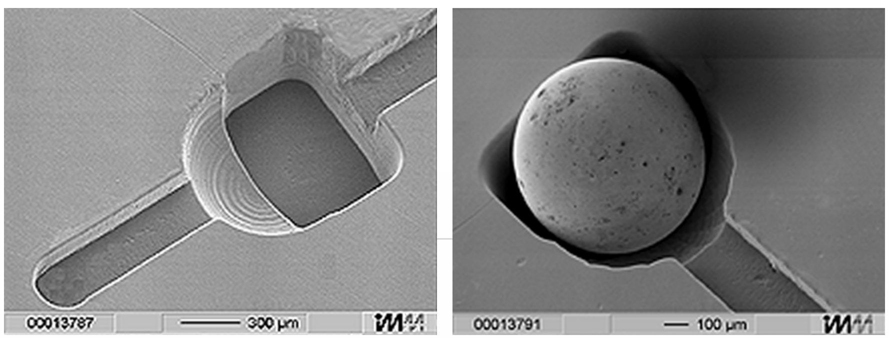
Main aspects to take into consideration in the conception of a micropump:



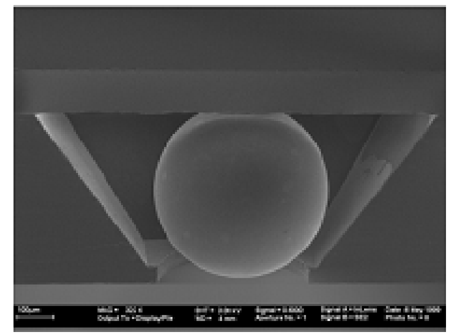
Outline ▸ State-of-the-art (rapid overview)

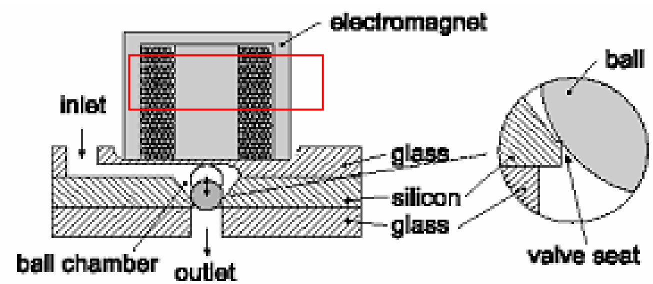
▸ Microvalves

Valves



Injection moulded ball valve fabricated with LIGA technology
IMM Main (Internet website, 1996)





Electromagnetic active ball valve
O. Krusemark

Outline ▸ State-of-the-art (rapid overview)

- Microactuators

Actuators

- Electrical
  - Electrostatic
  - Piezoelectric
- Magnetic
  - Electromagnetic
  - Magnetostrictive
- Thermal
  - Thermal expansion
    (e.g. thermopneumatic, bimetallic)
  - Phase change
    (e.g. Shape Memory Alloys)
- Optical (light direct/indirect interaction)
- Mechanical
  - Linear-rotational conversion/amplification
  - Acoustic (waves, vibrations)
- Chemical / Biological

➔ *Electromagnetic actuation:*

✓ simplicity
✓ force magnitude
✓ deflection amplitude
✗ miniaturization <u>but</u> ✓ external actuation

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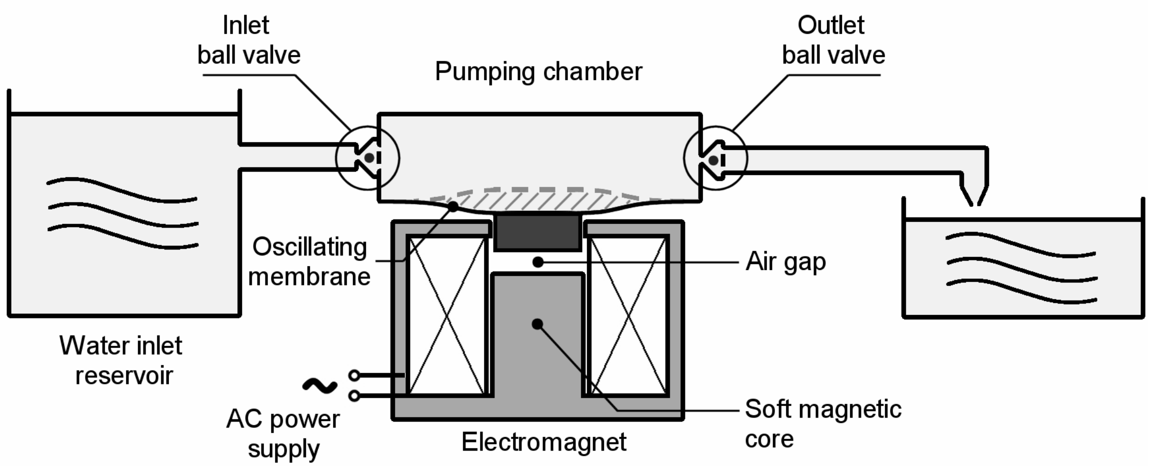
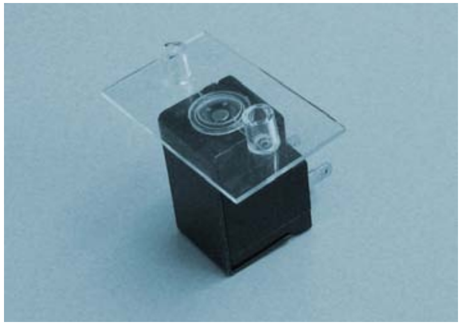
❷ Working principle ▸ External electromagnet

Pumping principle:

- Reciprocating **diaphragm** (“positive displacement” pump)
- Use of passive **ball valves**
- **External** electromagnetic actuation





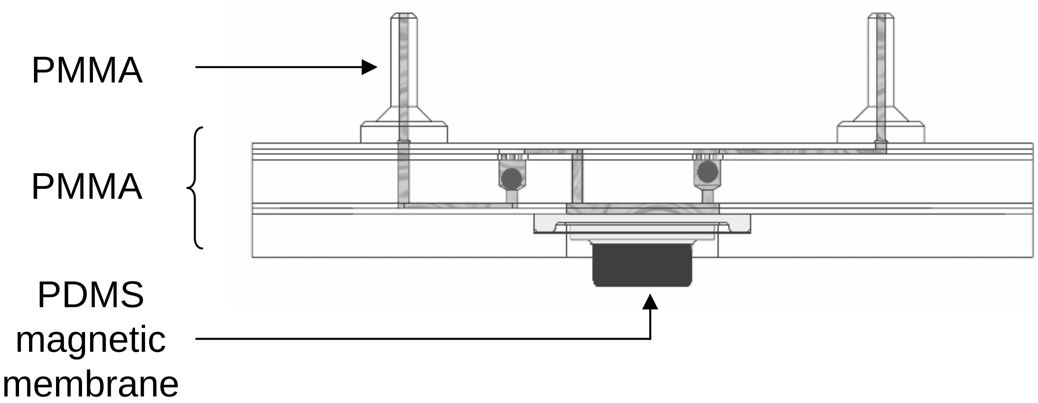
4800 turns coil

(Atam windings s.r.l.)

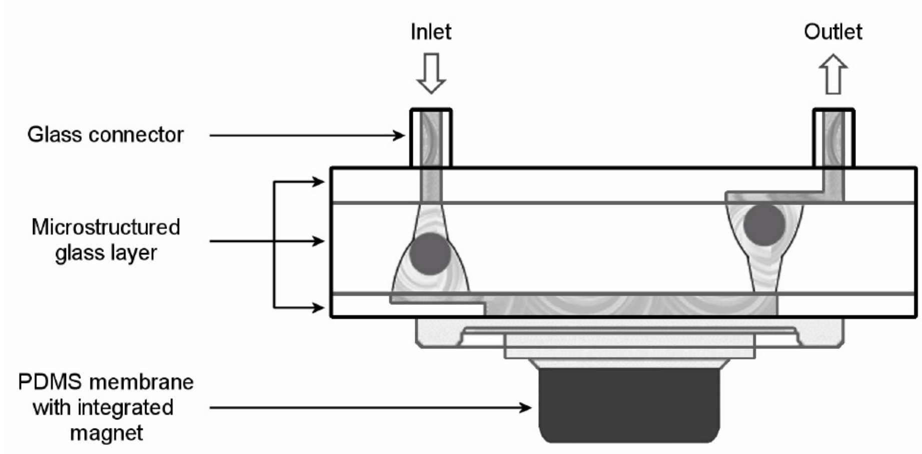
❷ Working principle ▸ Multi-layered microchip

Fabrication method based on **powder blasting** erosion process.

Plastic device
(polymethylmethacrylate)



Glass device
(borosilicate)



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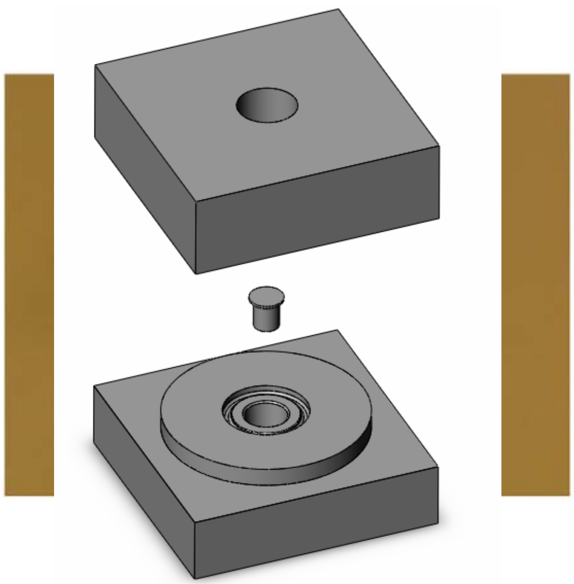
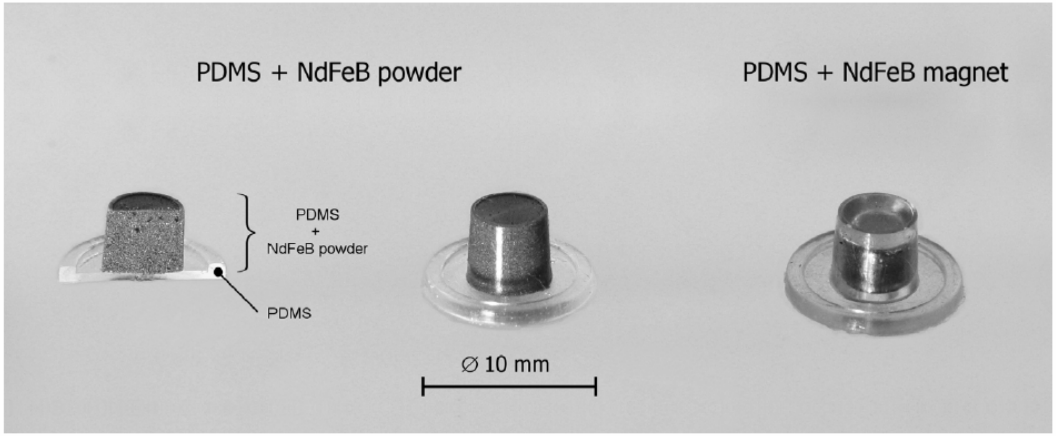
❸ Microfabrication ▸ Magnetic membrane

Integration of a **magnetic material** into the **flexible diaphragm** of the reciprocating micropump



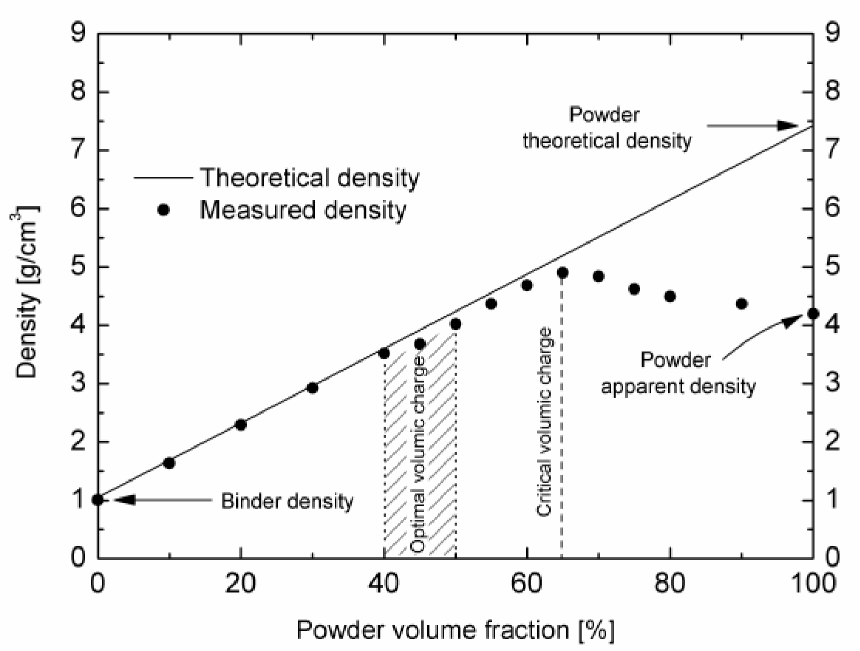


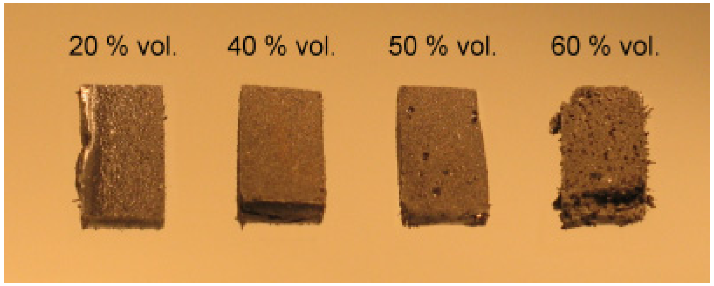
PDMS with NdFeB powder
(MQP-S-11-9 powder, Magnequench)

PDMS + NdFeB commercial magnet

Fabrication of the **composite magnet**:

PDMS matrix + NdFeB powder (typical size ~50 µm)
→ Optimal powder ratio: ~ 50% vol. powder





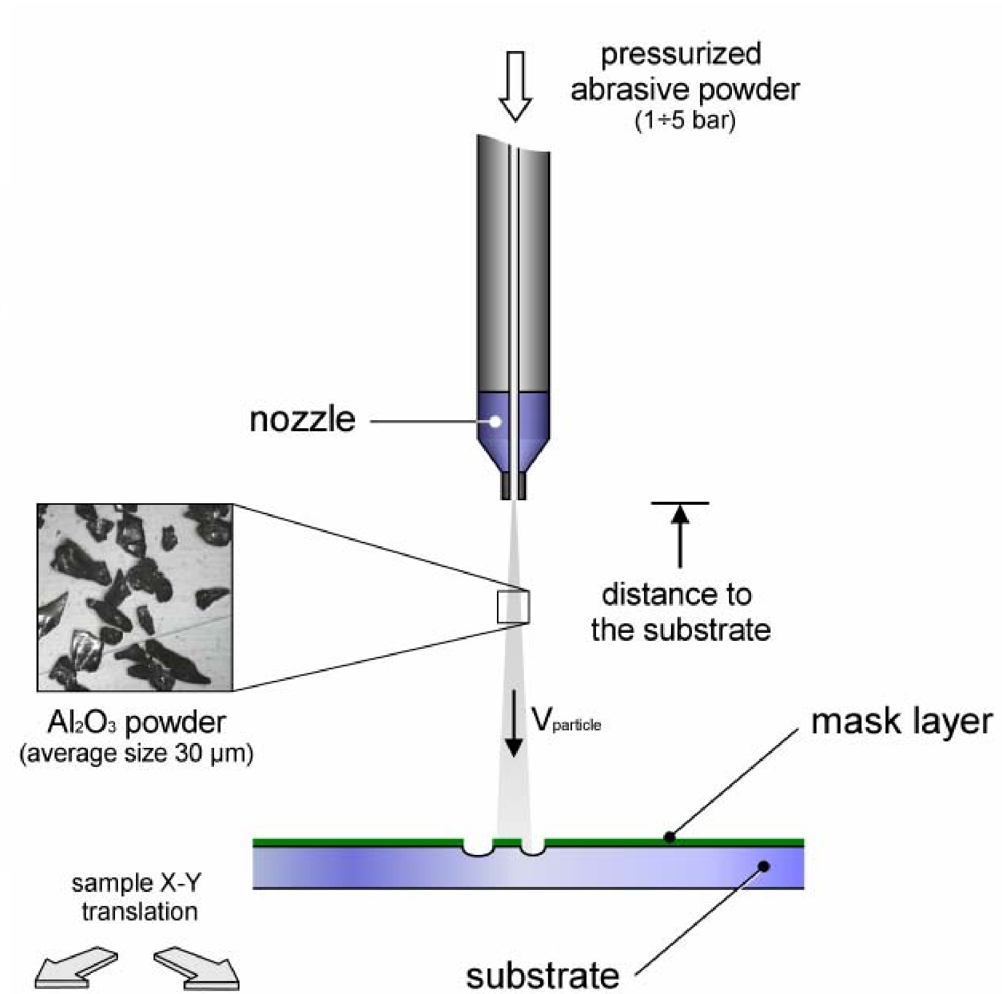
MQP-S-11-9 powder datasheet:

median size: 35 - 55 µm
distribution width: 10 - 30 µm

apparent density: 3.6 - 4.2 g/cm^3
theoretical density: 7.43 g/cm^3

❸ Microfabrication ▸ Powder blasting

Microstructuration of microfluidic chips by **powder blasting**

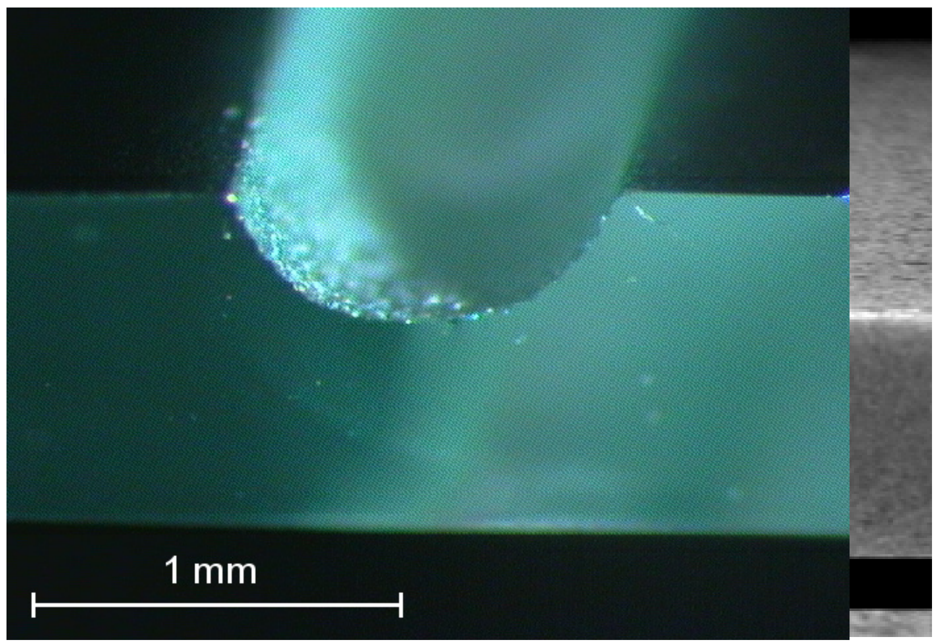


Microstructuration of microfluidic chips by **powder blasting**

Apparent roughness: ~1 µm
Small relative roughness → **hydraulically smooth** microchannels

SEM photograph of a PMMA microchannel fabricated by powder blasting

100 µm wide channel
30 µm Al_2O_3 particles



Fabrication process of the **PMMA** microchip

triethylene glycol dimethacrylate

→

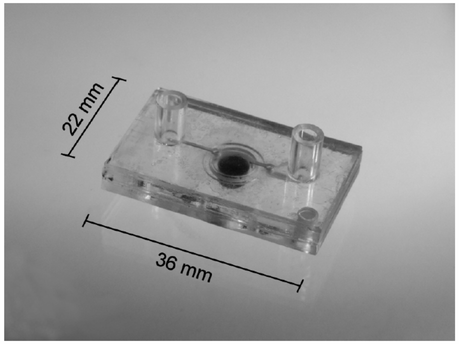
bonding solution applied on each layer

5 min @ 70 °C

Final

→

Microfluidic chip

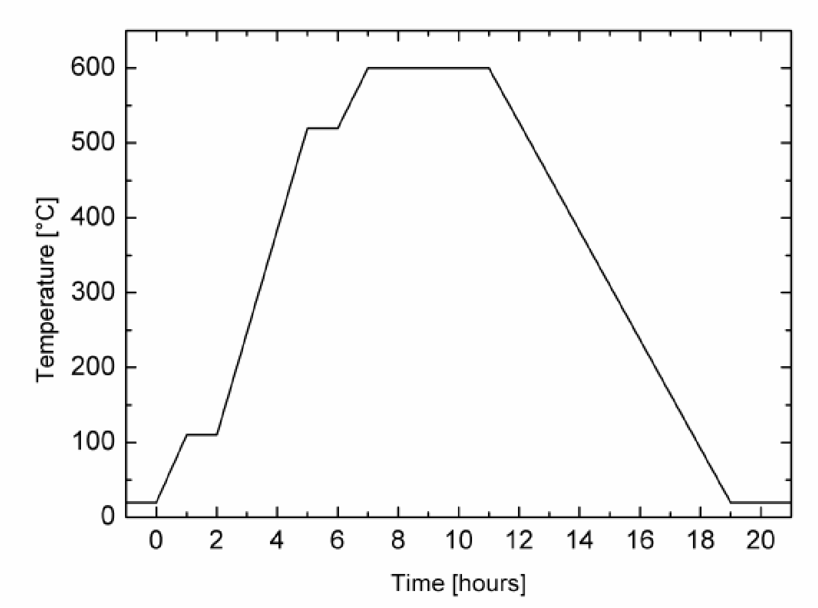


36mm x 22mm x 5mm
(without connectors)

Microfabrication ▸ Glass microchip

Fabrication process of the **glass** microchip

- **Powder blasting** of mask protected **borosilicate** glass (borofloat 33, *Schott*)
- Cleaning (isopropanol + piranha solution)
- Glass **fusion bonding** at 600 °C



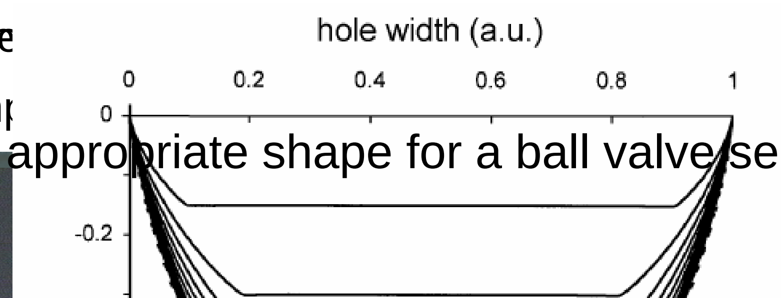
- Membrane assembly: **PDMS/glass** bonding (plasma treatment)
- Connectors gluing: epoxy (Epo-tek)

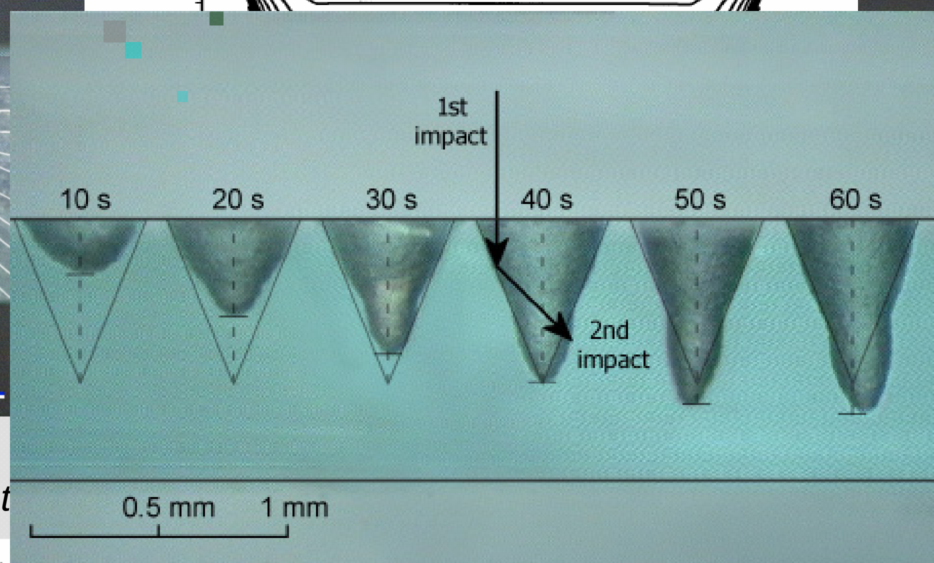
Powder blasting of holes in glass material

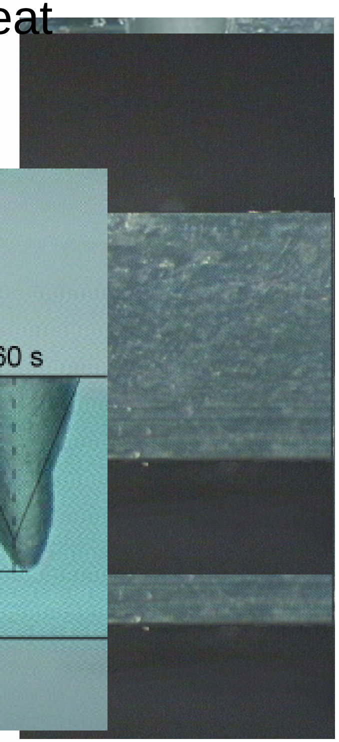
❷ 2nd impact effe

❶ without 2nd imp... fect

→ appropriate shape for a ball valve seat







Evolution of the erosion profile of a hole

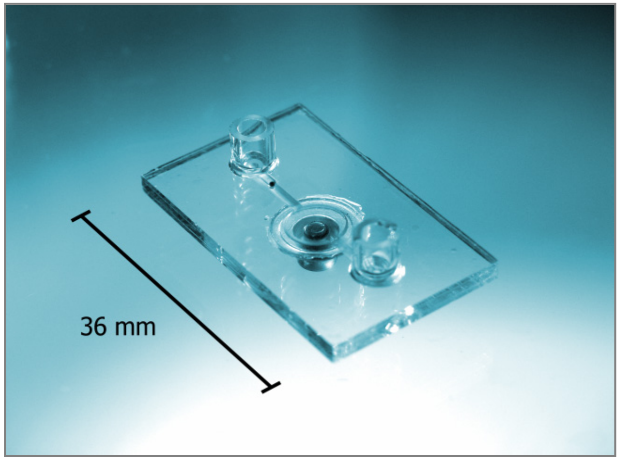
1 mm thick borosilicate

(after P.J. Slikkerveer et al.)

Time evolut... the erosion

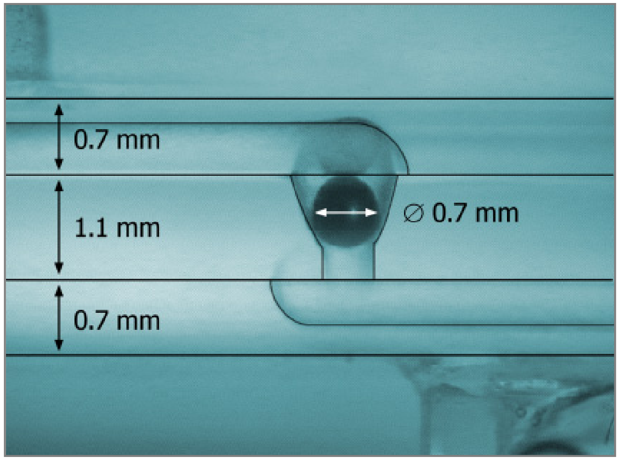
Fig. 5. Three stages in the channel shape

Microfabrication ▸ Glass microchip



Glass prototype of the electromagnetically actuated ball valve micropump

ext. dim. 36 mm × 22 mm



Photograph of the integrated ball valve fabricated in glass

steel ball: Ø 0.7 mm

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⑤ Conclusion

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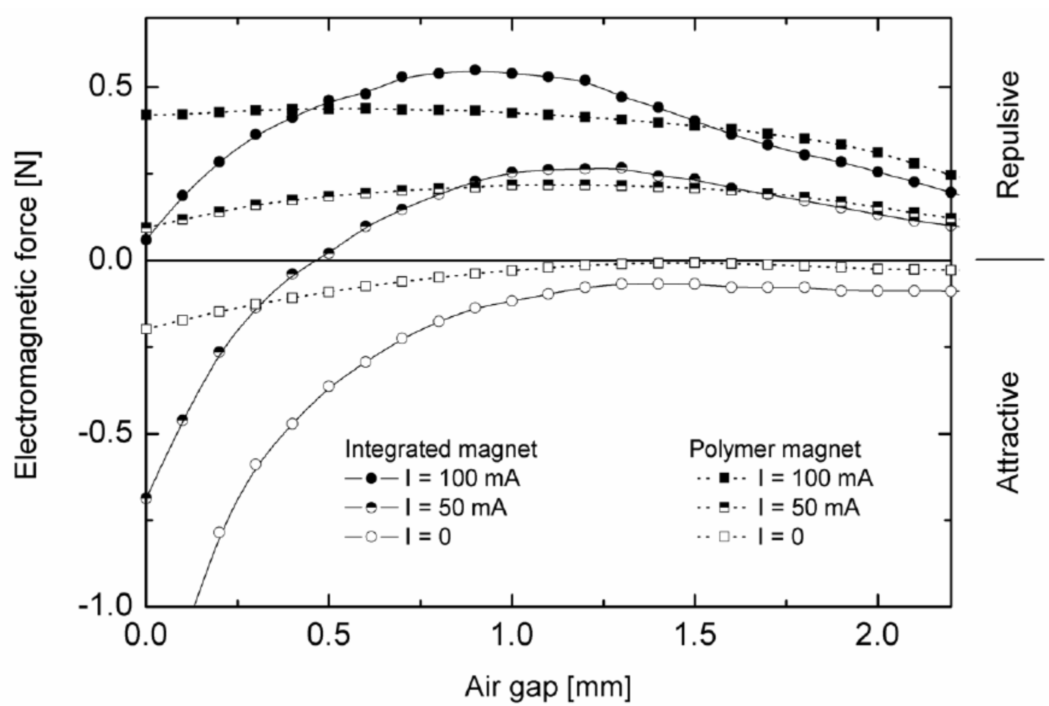
❹ Results & discussion ▸ Magnetic membrane actuation

Characterization of the **magnetic actuator**

→ Force as a function of the air gap, for different currents (DC) in the coil.

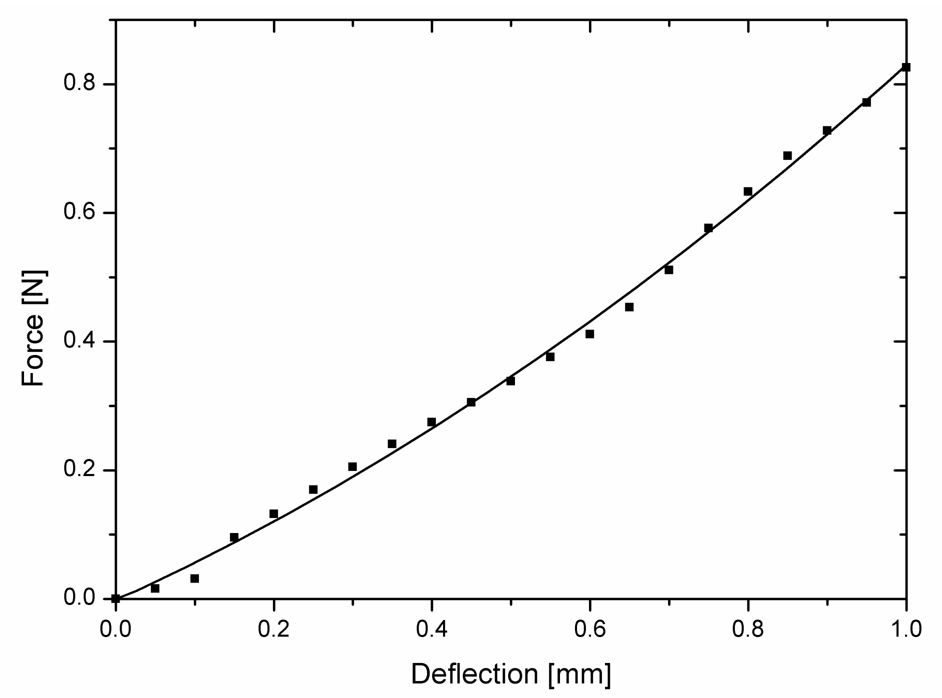


Force max.: ~ 0.5 N

(100 mA DC current)

Measurement of the membrane stiffness

Measured stiffness: K ~ 700 N/m



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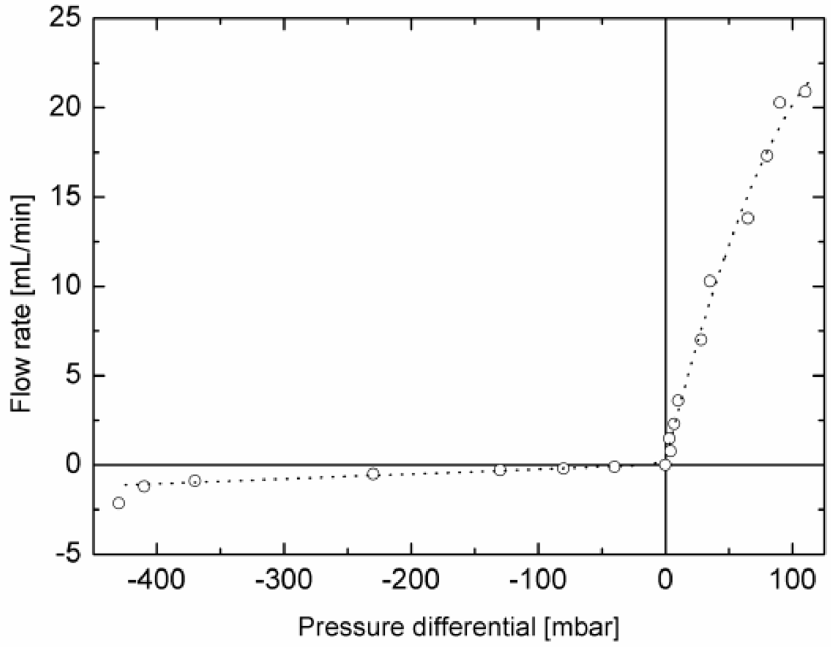
Characterization of the ball valve
(glass device)

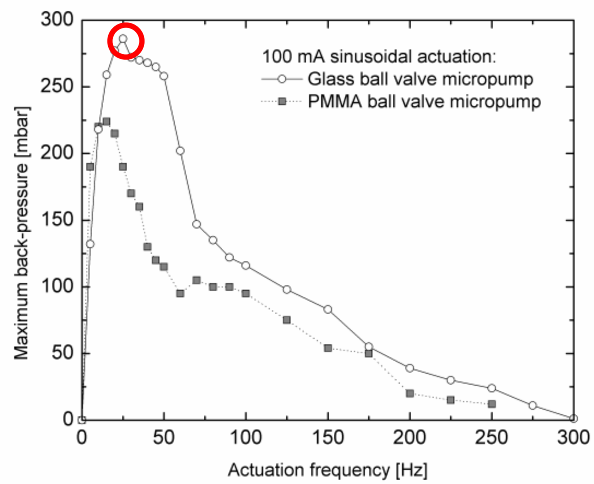
Efficiency of the valve: $\varepsilon = \frac{Q_{+}(P)}{Q_{-}(-P)} \approx \frac{20\,\mathrm{mL/min}}{0.25\,\mathrm{mL/min}} = 80$



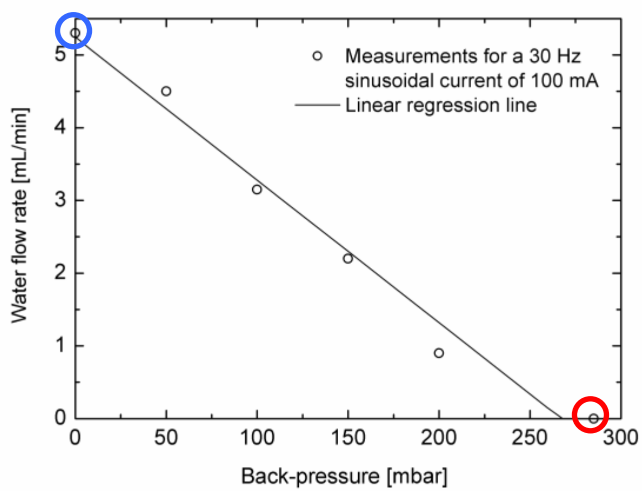
Ball valve integrated in a glass microchip

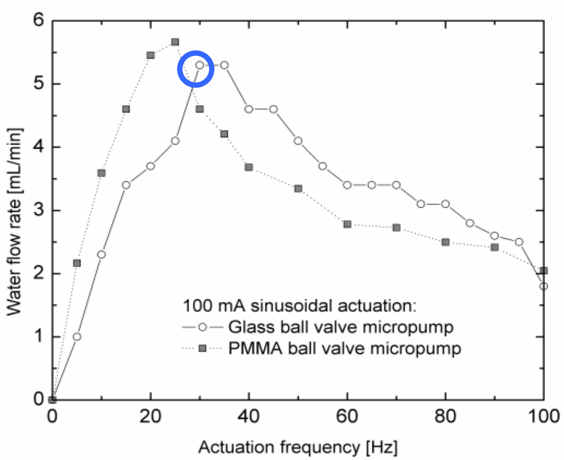
steel ball : Ø 0.7 mm

Characterization of the ball valve micropumps
(glass + PMMA device)



*Flow rate – back-pressure characteristic of the ball valve micropump in **glass***





Equivalence with electrical circuit (RLC electrical model)

Resistance $R = \frac{128\mu l}{\pi D_H^4}$

Inductance $L = \frac{\rho l}{S}$

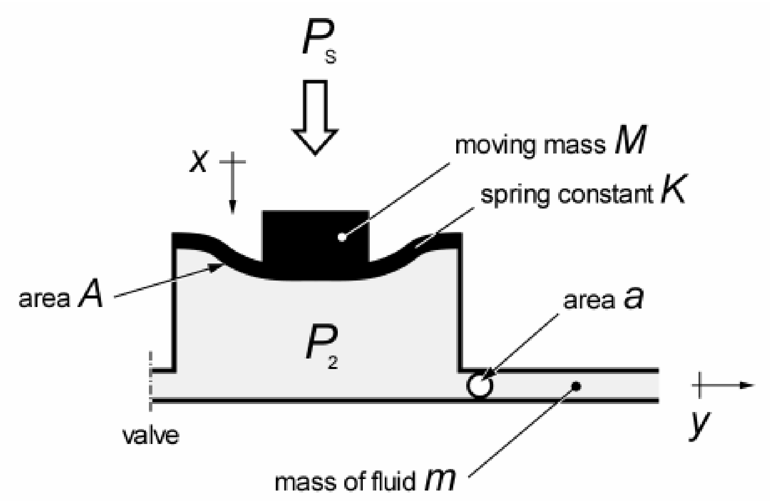
$\Bigg\}$ Liquid flow in microchannels

Capacitance $C = \frac{\Delta V}{\Delta p}$ $\longrightarrow$ Membrane

4 Results & discussion ▸ Damped oscillator model

Equivalence with electrical circuit (RLC electrical model)

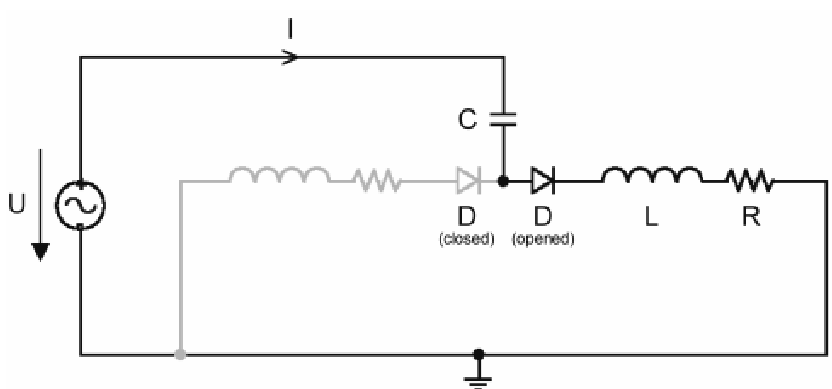
*Reciprocating pump with **ideal valves**:*



$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{\left(\frac{A}{a}\right)^2 m}}$$

$$\Updownarrow$$

Equivalent electrical model of the reciprocating pump

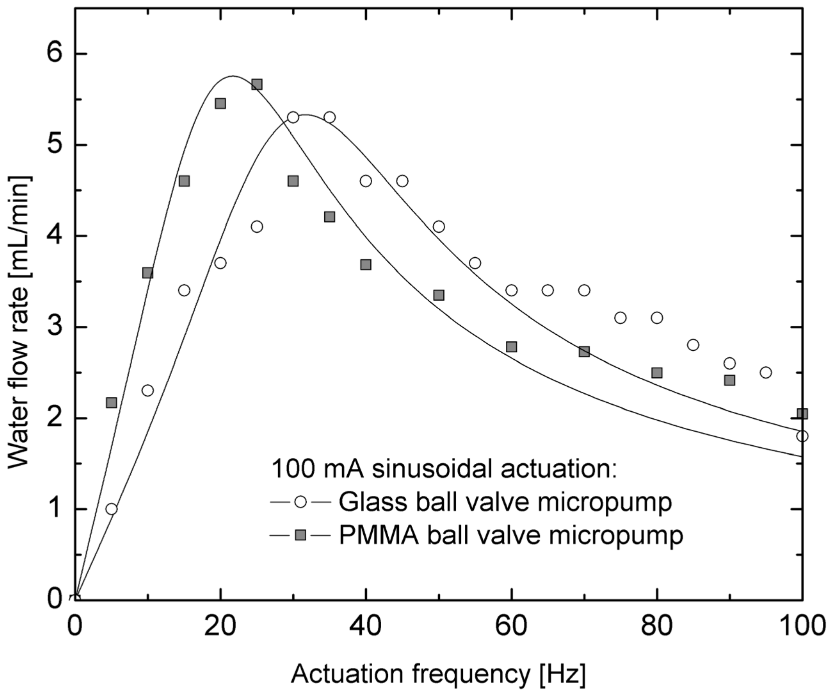


$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Results & discussion ▸ Damped oscillator model

Equivalence with electrical circuit (RLC electrical model)

→ Good **estimation of the resonance frequency** with this hydrodynamic model of the ball valve reciprocating micropump.



Flow rate – frequency characteristics of the ball valve micropumps

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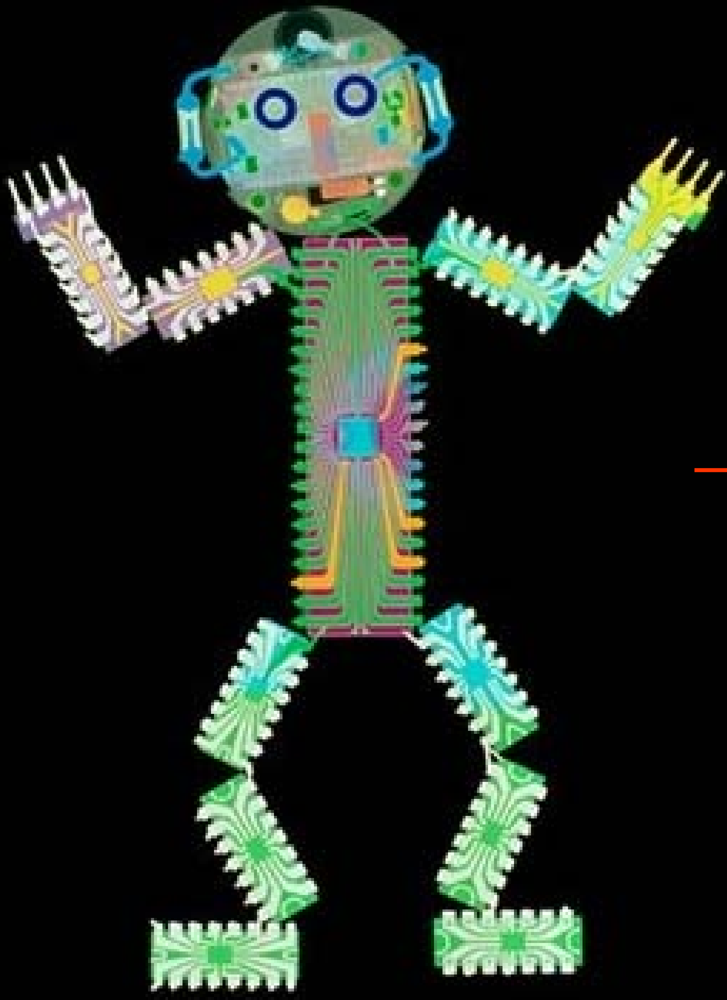
5 Conclusion

Summary of the performances of the different prototypes:

Pump type (ball valve micropump)	**Maximum back-pressure**	**Maximum water flow rate**	**Typical operating frequency**
PMMA	225 mbar	~ 5 mL/min	f_o ~ 30 – 40 Hz
Glass	280 mbar		

Main results:

- Flexible membrane → high compression ratio (bubble tolerance & self-priming)
- ball valve → high efficiency (limited reverse flow)
- External electromagnetic actuation → high forces achievable



Thank you!