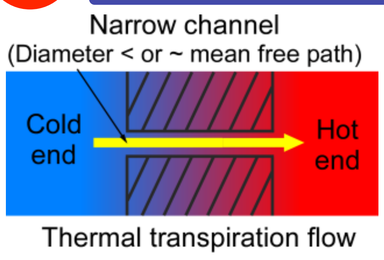
Si-Micromachined Knudsen Pumps for High Flow and Vacuum

Tsenguun Byambadorj, Qisen Cheng, Yutao Qin, Y.B. Gianchandani

Summary: This work presents two families of Knudsen pumps, one for high vacuum generation and the other for high flow generation. These pumps are based on thermal transpiration in narrow channels that have a thermal gradient. Gas is transported from the cold end to the hot end using free-molecular flow without any moving parts. The high-vacuum Knudsen pump uses surface-micromachined elements to form a cascade of 162 stages that are monolithically integrated. It can achieve a vacuum level of 0.9 Torr (0.12 kPa), and a compression ratio of 844. The high-flow Knudsen pump uses dense arrays of vertically oriented through-wafer channels to provide parallel pumping. At atmospheric pressure, it can provide a maximum measured air flow rate of >200 sccm with a response time of <0.5 sec. The high-flow Knudsen pumps are cascaded into multi-stage pumps using stacked and planar arrayed architectures to increase the output pressure head.

1 Knudsen Pump – Concept



Thermal transpiration:
- The hydraulic diameter < or ~ mean free path
- Gas flow from the cold end to the hot end

Mass transport equation for a rectangular channel (Sharipov, 1999)

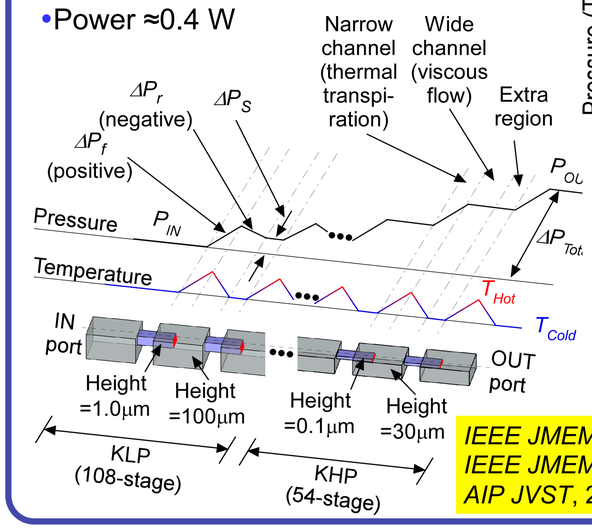
$$\dot{M}_{avg-R} = \left(\frac{Q_T \Delta T}{T_{avg}} - \frac{Q_P \Delta P}{P_{avg}}\right) \frac{a_R^2 b_R P_{avg}}{l} \left(\frac{m}{2k_B T_{avg}}\right)^{1/2}$$

Pressure difference at equilibrium (blocking pressure) $\Delta P_{eq} = \frac{Q_T}{Q_P} \frac{P_{avg}}{T_{avg}} \Delta T$

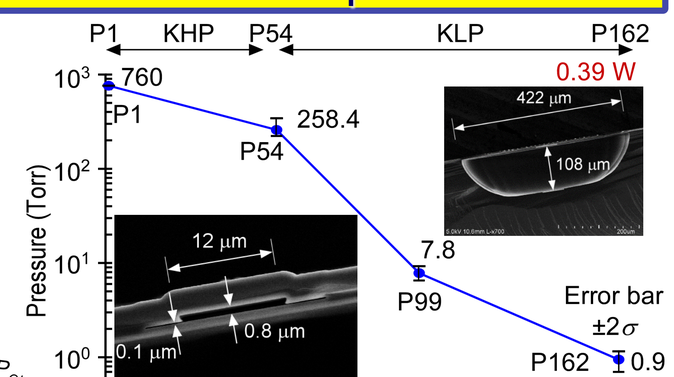
- a_R: channel height
- b_R: channel width
- l: channel length
- m: mass of a gas molecule
- k_B: Boltzmann constant
- ΔT: temperature difference
- T_{avg}: average temperature
- ΔP: pressure head
- P_{avg}: average pressure
- Q_T and Q_P: coefficients dependent on the Knudsen number Kn

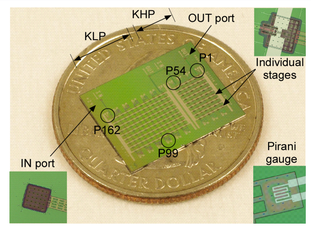
2 Si-Micromachined Knudsen Pump for Vaccum

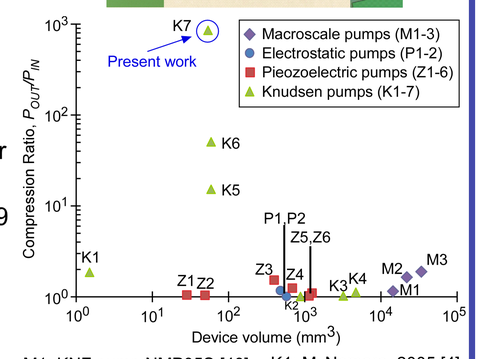
Key Features
- Two-part 162-stage design
- Five-mask single-wafer fabrication
- Integrated Pirani gauges
- 760→0.9 Torr, compression ratio ≈844
- Power ≈0.4 W

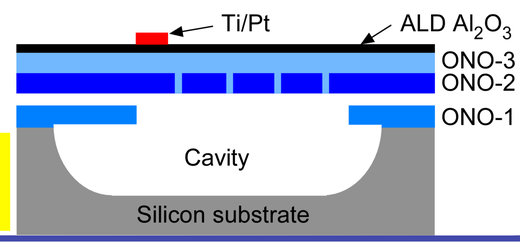


IEEE JMEMS, 2014a
IEEE JMEMS, 2014b
AIP JVST, 2014



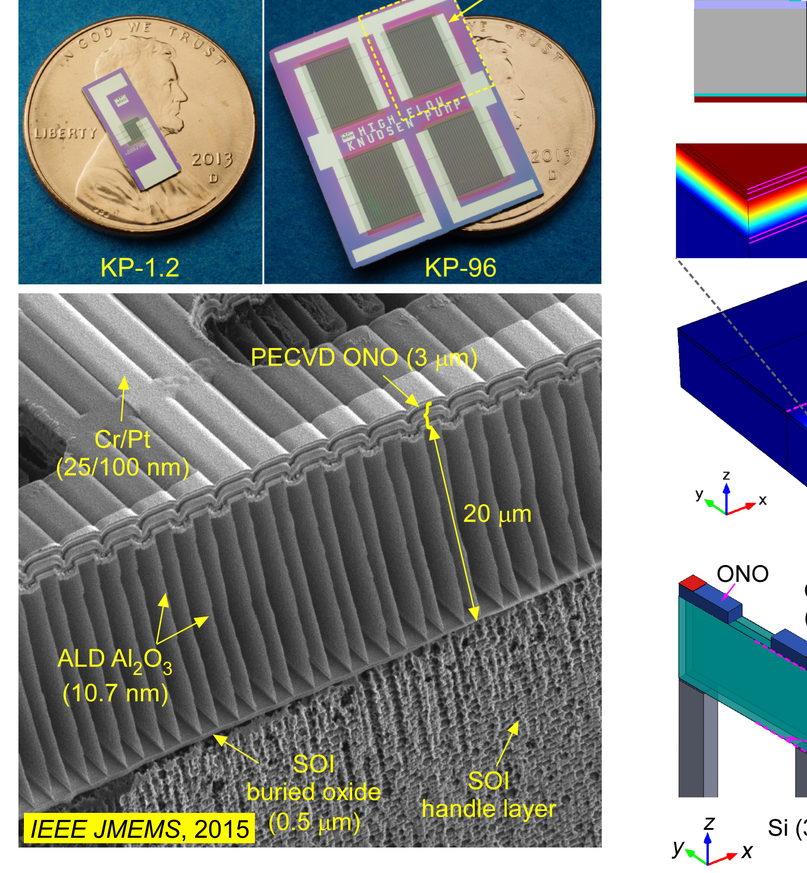






M1: KNF pump NMP05S [40]
M2: KNF pump NMP09B [40]
M3: KNF pump NMP015S [40]
P1: Kim, 2007 [20]
P2: Besharatian, 2012 [43]
Z1: Wijngaart, 2000 [37]
Z2: Gerlach, 1995 [35]
Z3: Kamper, 1998 [36]
Z4: Bartels mp5 micropump [42]
Z5: Stemme, 1993 [34]
Z6: thinXXS micropumps [41]
K1: McNamara, 2005 [4]
K2: Gupta, 2011 [13]
K3: Pharas, 2010 [12]
K4: Gupta, 2011 [14]
K5: Gupta, 2012 [7]
K6: Gupta, 2012 [7]
K7: Present work

3 Si-Micromachined Knudsen Pump for High Flow



Device Features
- Through-wafer narrow channels
- 10 nm-thick Al_2O_3 sidewalls
- 4000 narrow channels/mm²
- Integrated heater and heat sink
- Multi-stage pumps in stacked and planar arrayed architectures

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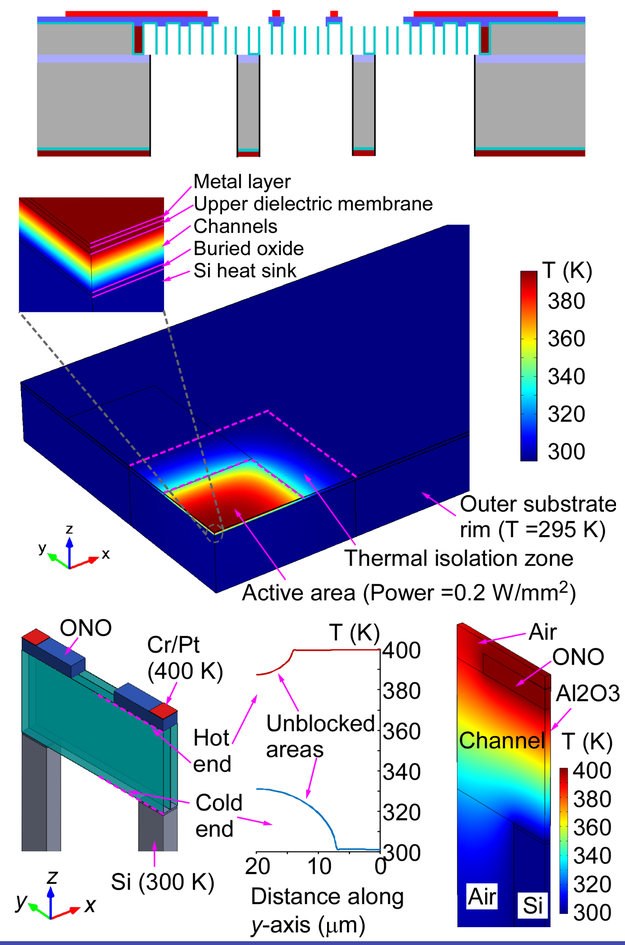
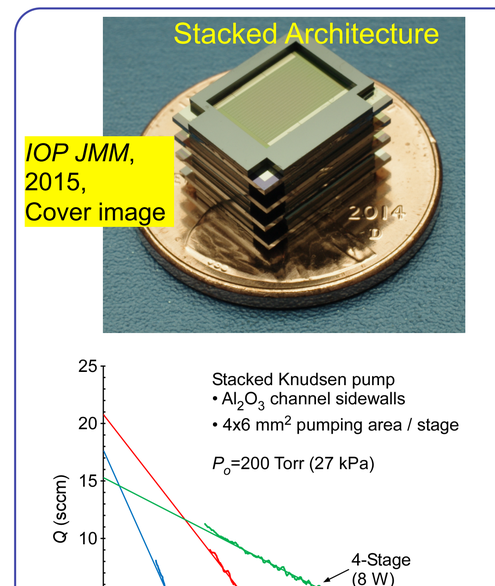
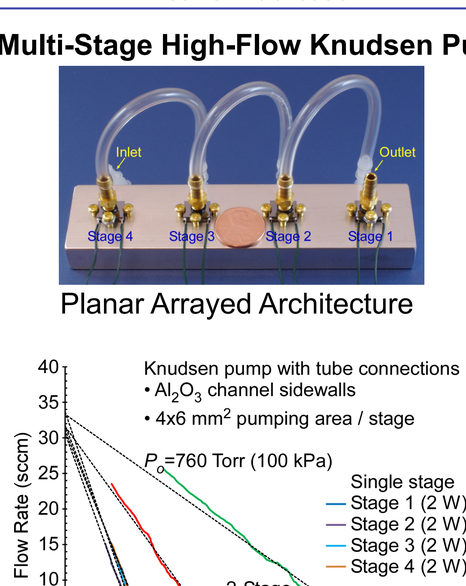


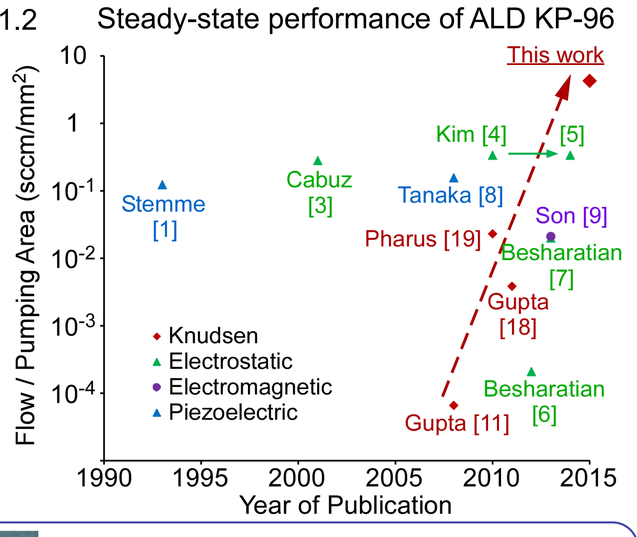


Steady-state performance of ALD KP-1.2



Steady-state performance of ALD KP-96

Performance Features
- >200 sccm flow; >4 sccm/mm²
- <0.5 s response
- >3 year continuous operation
- Highest performance at 200 Torr (27 kPa)
- Pressure head increased by multi-stage architectures



Multi-Stage High-Flow Knudsen Pumps

Planar Arrayed Architecture

Publications:
[1] S. An, N.K. Gupta, Y.B. Gianchandani, "A Si-micromachined 162-stage two-part Knudsen pump for on-chip vacuum," *IEEE Journal of Microelectromechanical Systems*, vol. 23, no. 2, pp. 406-416, 2014.
[2] S. An, Y.B. Gianchandani, "A dynamic calibration method for Pirani gauges embedded in fluidic networks," *IEEE Journal of Microelectromechanical Systems*, vol. 23, no. 3, pp. 699-709, 2014.
[3] S. An, N.K. Gupta, Y.B. Gianchandani, "Vacuum sealing using atomic layer deposition of Al_2O_3 at 250ºC," *AIP Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, vol. 31, no. 1, p. 01A101, 2014.
[4] S. An, Y. Qin, Y.B. Gianchandani, "A Monolithic High-Flow Knudsen Pump Using Vertical Al_2O_3 Channels in SOI," *IEEE Journal of Microelectromechanical Systems*, vol. 24, no. 5, pp. 1606-1615, 2015
[5] Y. Qin, S. An, Y.B. Gianchandani, "Arrayed architectures for multi-stage Si-micromachined high-flow Knudsen pumps," *IOP Journal of Micromechanics and Microengineering*, vol. 25, no. 11, 115026(10 pp.), 2015. (Featured on cover of issue)

Patent: Y.B. Gianchandani, S. An, Y. Qin, "Microfabricated Gas Flow Structure," US 15/006,034, patent pending
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WIMS² University of Michigan
Center for Wireless Integrated MicroSensing & Systems