Silicon Electroosmotic Micropumps for IC Thermal Management

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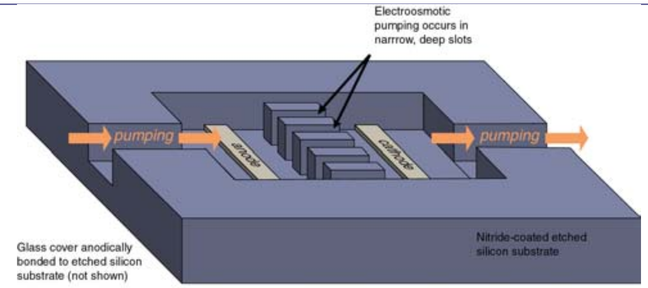
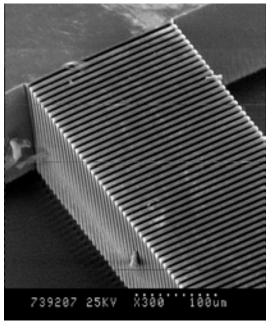
New approaches to thermal management are needed to support continued increases in high-end chip performance. We are developing innovative thermal management systems based on microfluidic networks. Electroosmotic pumping is a key enabling technology for such systems. Electroosmotic pumps scale favorably to the micro regime, require little power, and—having no moving structural elements—are inherently reliable. These pumps leverage electrochemical interactions at a liquid-solid interface to induce flow through the application of an electric field. We have developed a class of novel electroosmotic micropumps, shown in Figure 1, which can be built in to microelectronic devices to provide convective cooling. These micropumps are fabricated entirely through micromachining of silicon substrates in a CMOS-compatible process. Recent prototypes generate flow rates of 110 µL min^{-1} and pressures of nearly 10 kPa while occupying only a 1.5 cm^2 die, performance superior to that of other micropumps that are less robust and much more difficult to fabricate. Our work emphasizes understanding the physicochemical basis of electroosmotic pumping, particularly the dependence of performance on such factors as pump geometry and working fluid chemistry. Pressure generation and flow rate generally increase with reductions in the width and length, respectively, of the pump slots. As shown in Figure 2, however, the finite thickness of the electric double layer at the solid-liquid interface can adversely impact pump performance for slot widths below a few microns. Pressure and flow rate results for several pump design variations have been obtained and compared to expected performance based on theoretical models. Transient response data for the pumps has been obtained using a novel, high-speed, semi-integrated pressure measurement system. This system has allowed measurement of the pump's pressure response during the first few milliseconds after the voltage is turned on, yielding the first experimental results for the fast transient response of an electroosmotic pump of any sort. The fabrication process for our devices includes challenging thick-film photolithography, reactive ion enhanced etching, and LPCVD steps—all of which are supported by Stanford Nanofabrication Facility.



(a)



(b)

Figure 1. (a) Basic structure of the silicon electroosmotic micropump. An axial electric field generates electroosmotic pumping in deep, narrow slots plasma-etched into a silicon substrate. The silicon is electrically passivated. A cover (glass in the prototypes to allow optical access) is bonded onto the silicon to seal the micropump. (b) SEM showing the pumping structure formed by deep etching of silicon. Micropumps with slot widths ranging from 2-4 µm have been fabricated.

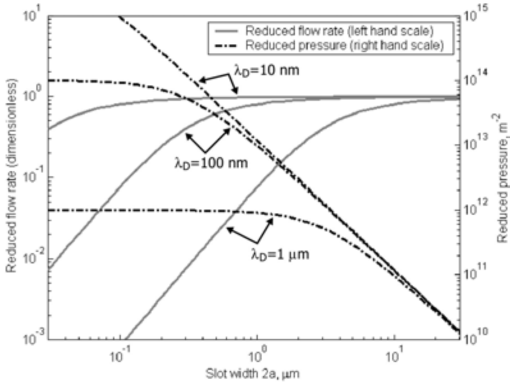


Figure 2. Scaling relations for electroosmotic pumps with narrow slot geometries. Flow rate, normalized by the flow cross-sectional area, the magnitude of the applied field, zeta potential, permittivity, and viscosity, is constant with slot width until the slot width becomes comparable to the Debye length λ_D of the solution. Pressure, normalized by the applied voltage, permittivity, and zeta potential, is proportional to the inverse square of the slot width—again until finite double layer effects become significant.