

Fast Bonding of Substrates for the Formation of Microfluidic Channels at Room Temperature

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Calculation of Electroosmotic Flow Field

When a microfluidic channel is in contact with an aqueous solution, the channel wall usually becomes charged through various processes such as protonation and deprotonation. These net charges on the channel wall make the electric potential of the channel wall different from that of the solution and subsequently affect the charge distribution inside the channel. The net charge density in the solution follows Boltzmann distribution. In the case of monovalent electrolyte solutions (such as sodium chloride solution), the net charge density at a certain spatial point, ρ_e , can be related to the electric potential, ψ , at that point through:

$$\rho_e = -2ne \sinh\left(-\frac{e\psi}{kT}\right) \quad (\text{S1})$$

, where n is the concentration of the electrolyte, e the elementary charge, k the Boltzmann constant, and T the temperature. This charge density also defines the electric field through the Poisson equation:

$$\nabla^2\psi = -\frac{1}{\varepsilon\varepsilon_0}\rho_e \quad (\text{S2})$$

, where ε is the relative permittivity of the medium and ε_0 the permittivity of vacuum. The combination of (S1) and (S2) is called the Poisson-Boltzmann equation¹. Solving this equation requires the knowledge of electric potentials at channel walls as the boundary condition, which is called the zeta potential, ζ .

When an external electric field is applied along the channel, the net charges in the solution will cause electroosmotic flow. The electrically driven flow field in a channel cross-section, $u(x, y)$, is described by a Poisson equation:

$$\nabla^2u = -\frac{E}{\eta}\rho_e \quad (\text{S3})$$

where E is the external electric field strength, and η the viscosity of the solution¹.

Solving the combination of Poisson-Boltzmann equation and Poisson equation can be achieved analytically or semi-analytically only for certain special channel configurations, such as infinite plate, cylindrical capillary², and rectangular channels with each wall made of the same material³. In our case of a rectangular glass channel bonded using a PDMS layer, the sidewalls have both glass and PDMS, making the analytical solution infeasible. Therefore, we use numerical approaches to solve these two partial differential equations. More specifically, we use Successive Overrelaxation method to

solve the Poisson-Boltzmann equation for charge distribution and Multigrid method to solve the Poisson equation for flow field⁴.

- (1) Kirby, B. J.; Hasselbrink, E. F. *Electrophoresis* **2004**, *25*, 187-202.
- (2) Rice, C. L.; Whitehead, R. *Journal of Physical Chemistry* **1965**, *69*, 4017-&.
- (3) Andreev, V. P.; Dubrovsky, S. G.; Stepanov, Y. V. *Journal of Microcolumn Separations* **1997**, *9*, 443-450.
- (4) William, H. *Numerical recipes in C: the art of scientific computing*, 2nd ed.; Cambridge University Press: New York, 1992.

Other Experimental Details.

Transfer Patterns with Photolithography. Patterns were transferred from photomasks to substrates (glass or silicon) using standard procedures with slight modifications. Patterns for photolithography with features greater than 25 μm were designed using CAD software (Macromedia Freehand 10, San Francisco, CA) and printed on transparency films with a high-resolution (3600 dpi) printer (MediaMorphosis, Mountain View, CA). Photomasks with features less than 25 μm were created by Stanford Nanofabrication Facility with laser beam writing.

For positive photoresists (Shipley series), substrates were spin-coated (600 rpm, 20 s) with hexamethyldisilazane (HMDS) on either a track system spin coater (ASML, Veldhoven, the Netherlands) or a manual spin coater (Laurell Technologies, North Wales, PA). After coating with HMDS, a thin layer (~ 10 μm) of positive photoresist (SPR 220-7, Shipley) was spin-coated (2000 RPM, 40 s) on a 4-in diameter silicon wafer and baked on a hotplate (105 $^{\circ}\text{C}$, 4 min). The photoresist was exposed through a photomask for 18 s and developed. If necessary, the wafer was then baked on a hotplate (120 $^{\circ}\text{C}$, 2 min) to reflow the photoresist to form curved features.

For negative photoresists (SU-8 series), we spin-coated a thin layer (~ 40 μm) of negative photoresist SU-8 (2000 RPM, 40 s) on a 4-in diameter silicon wafer and soft baked it in two steps on a hotplate (65 $^{\circ}\text{C}$, 3 min; 100 $^{\circ}\text{C}$, 5 min). After cooling, the photoresist was exposed through a transparency mask for 25 s in a mask aligner (Karl Suss, Waterbury Center, VT) with a UV-light source (365-405 nm), and developed in an SU-8 developer.

Etching Channels on Patterned Glass Pieces. Glass microfluidic devices were created using standard microfabrication techniques. The glass substrates used for device fabrication were D-263 borosilicate (S. I. Howard Glass Co., Worcester, MA). Rectangular pieces (75 mm x 25 mm x 1 mm) were used for microfabrication, and thin pieces (75 mm x 25 mm x 170 μm) were used as cover plates. Prior to lithography, substrates were rinsed with acetone, methanol, and isopropanol, followed by piranha (4:1 $\text{H}_2\text{SO}_4/30\% \text{H}_2\text{O}_2$ for 30 min.) and RCA (boiling 5:1:1 $\text{H}_2\text{O}/\text{NH}_4\text{OH}/30\% \text{H}_2\text{O}_2$ for 30 min) cleaning. Substrates were rinsed in water and dried. Clean substrates were coated with amorphous silicon (150 nm, Strataglass, Mountain View, CA) as a contact mask.

Photolithography was used to pattern microfluidic designs onto silicon-coated wafers or pieces. Substrates were singed in an oven (150 $^\circ\text{C}$, 30 min) and spin-coated (600 RPM, 20 s) with hexamethyldisilazane (HMDS) on either a track system spin coater or a manual spin coater. After coating with HMDS, Shipley 3612 photoresist was spun onto the substrates (5500 rpm, 30s, 1 mm thick). Substrates were then postbaked (90 $^\circ\text{C}$, 30 s) on a hotplate and allowed to cool. Photoresist-coated substrates were exposed (1.2 s, 17 mW/cm^2) through a chrome-on-quartz mask on a mask aligner (Suss Microtec Inc., Waterbury Center, VT). After exposure, substrates were developed with LDD-26W (~1 min) manually or on nitrogen gas. Appropriate feature dimensions were confirmed visually with microscopy.

After photolithography, glass substrates were prepared for wet chemical etching. Exposed silicon was removed using a Drytek (Lam Research, Fremont, CA) plasma etcher ($\text{C}_2\text{ClF}_5/\text{SF}_6$, ~1 min). Prior to etching, the backside of the substrates were masked with cleanroom tack (Semiconductor Equipment Corp., Moorpark, CA). The substrates

were then isotropically etched with unbuffered hydrofluoric acid (2:1 H₂O/49% HF, 4-5 min). The etch rate was typically 5-8 μm/min; substrates were periodically removed from the HF solution, rinsed with water, dried, and the etched channel depths measured with a profilometer (Sloan Technology Corp., Santa Barbara, CA). Typically, channels were etched to ~30 μm deep. The cleanroom tack was removed, and remaining photoresist was stripped by rinsing in acetone.

After etching, the pieces were immobilized in paraffin, and inlet holes (0.5 mm dia.) were drilled with a microdrill press (Cameron, Sonora, CA). After drilling, paraffin was removed from the pieces by ultrasonication sequentially in acetone and chloroform. The remaining amorphous silicon was stripped from the substrates with the plasma etcher, and the substrates were prepared for bonding to cover plates.

Fluorescent Derivatization. For off-chip derivatization of amino acids, reaction mixtures were prepared in 10 mM sodium borate buffer (pH ~9.2 adjusted with 10 N sodium hydroxide). NDA (DMSO stock solution) and KCN were added so that the final concentrations of NDA, each amino acid, and cyanide were 1 mM, 0.05 mM and 0.1 mM, respectively. The mixtures were prepared such that they contained at least 5% final concentration of DMSO to eliminate precipitation of derivatives. The reaction was allowed to proceed for 15-30 min prior to separation.

The scanning electron microscope (SEM) was conducted with a FEI Siron field emission instrument operated at relatively low acceleration voltages of 1 keV and the thickness of bonding layer was measured with a Dektak IIA Profilometer (Sloan Technologies, Santa Barbara, CA).