

ciency. A microchannel **320**, including a Y-junction **322** and integrated ribbed microstructures, in the shape of herringbones, on the top wall of the channel was fabricated using soft-lithography. A glass support **330** bearing ten pairs of platinum electrodes **332** closed the microchannel. The electrodes were aligned using an optical microscope and were positioned in the microchannel between two consecutive herringbone cycles. Mixing efficiency was determined by flowing an oxidant and a reducing agent through the device and measuring the potential between each pair of dual-facing electrodes after each herringbone cycle.

[0144] A second device, illustrated in **FIG. 27**, was used to mix and dilute a sample solution with a titrant solution. The dilution process produced a series of solutions containing exponentially decreasing redox potentials that were used to generate a titration curve, with a reading from each solution becoming a point on the titration curve. In this example, the microfluidic device included 11 channels (50  $\mu\text{m}$  deep and 100  $\mu\text{m}$  wide, **FIG. 28A**). Two inlet reservoirs **340** and **342** supplied i) the sample that was analyzed, and ii) the titrant solution to inlets **344** and **346**. At the junction **348** (200  $\mu\text{m}$  wide) between the channel supplying the sample solution and the channel supplying the titrant solution (both channels 100  $\mu\text{m}$  wide), herringbone microstructures (nine cycles) placed on the top wall of the junction provided efficient mixing and complete reaction between the sample and the titrant solutions. In the embodiment shown, the serial dilutor provided a dilution factor of  $\sim 2$ ; that is, at each junction, the solution injected into inlet **344** split into two halves. One stream flows to the outlet (waste) without further dilution; the other mixed 1:1 with the solution injected into inlet **346** to produce a solution of lower concentration.

[0145] The electrochemical measurements took place at the end of the channel system, just before all of the microchannels reconnected to produce a waste stream **350** (**FIG. 27**). At these detection points (**FIG. 29**), small apertures **360** (100  $\mu\text{m} \times 100 \mu\text{m}$ ) in a thin layer of photoresist **362** (10  $\mu\text{m}$ ) allowed contact between a platinum electrode **364** and the solution flowing in the channel above it. In all other areas where the electrodes crossed the channels, the layer of photoresist **362** insulated the solution from the electrodes. A silver/silver chloride electrode **368** was exposed to a fluid consisting 100% of the fluid entering inlet **344**. The photoresist **362** was deposited on a 1 mm thick glass support **370**. An optical microscope aided the alignment between the PDMS slab **366** and the electrodes.

[0146] Two solutions were injected into the device depicted in **FIGS. 27 and 28**. One was a strong oxidant,  $\text{Cr}_2\text{O}_7^{2-}$  (Cr(VI)), used as the titrant, and the other a reducing species,  $\text{Fe}(\text{CN})_6^{4-}$  (Fe(II)), used as the sample. To each of the solutions was added  $\sim 0.1 \text{ M}$  KCl and  $\sim 10^{-3} \text{ M}$  HCl (until each solution reached  $\text{pH} \approx 3$ ) to provide an acidic condition for the titrations and for the electrolyte composition required by the Ag/AgCl reference electrode. Reservoirs **340** and **342**, containing the titrant and sample solutions, were placed  $\sim 30 \text{ cm}$  above the device (**FIG. 28B**). These solutions were allowed to flow into inlets **344** and **346** by gravity. The flow rate, measured at the end of the channel system, was  $\sim 1 \mu\text{L/s}$ . The level of fluid in each of the reservoirs was nearly constant during the duration of the experiments (several minutes) as the volume of solution in the reservoir was large ( $\sim 3 \text{ mL}$ ) compared to the volume of

solution in the microchannels ( $\sim 6 \mu\text{L}$ ). The relative flow rates of the sample and the titrant solutions were calibrated before use by adjusting the heights of the reservoirs, as differences in pressure and flow rate in the two channels can change the dilution factor of the device, and may contribute to inaccuracies in the measurements.

[0147] Once the microchannels had filled completely (total internal volume  $\sim 6 \mu\text{L}$ ), the potentials were measured manually at the electrodes using a voltmeter. Simultaneous measurements in each channel could be performed by combining an electronic read-out system (e.g., LabVIEW) to this microdevice. Results may be the same whether potentials are measured sequentially or simultaneously. At the end of the channel network, the fluid in each channel combined into waste stream **350**. The output stream (here, "waste") had the characteristic of a controlled lateral gradient in redox potential.

#### Example 7

[0148] A group of experiments were run to characterize the efficiency of electrochemical mixing using the system illustrated in **FIG. 26**. Mixing efficiency was measured at different points along a single channel that included nine sections of CAM and was compared to mixing along a channel without the herringbone structures. Platinum electrodes **332** were integrated into each side of the channel in both microchannels (**FIG. 26**). These electrodes faced each other and were 100  $\mu\text{m}$  apart across the width of the channel. Each pair of electrodes was separated from the next pair by 2 mm along the length of the channel.

[0149] **FIG. 30** graphically illustrates the potential measured between a series of these dual-facing platinum electrodes when solutions of Fe(II) and Cr(VI) were flowing in a single channel. Without the mixing structures, flow in the channel was laminar and mixing of the reagents occurred due to the diffusion of the ions from one stream to an adjacent stream. The potential thus varied only slightly along the channel, as the rate of reaction of the reagents was slow. Without a CAM, results indicate that complete mixing was not achieved by the end of the channel; the difference in potential between the last pair of facing Pt electrodes reached a value of  $\sim 250 \text{ mV}$ . Incorporating the CAM caused the potential to decrease after each CAM section, and enabled the potential to reach  $\sim 0 \text{ mV}$  at the end of the microchannel, indicating that complete mixing occurred. **FIG. 30** indicates that mixing was substantially complete after five sections of CAM at a flow rate of  $\sim 1 \mu\text{L s}^{-1}$ .

[0150] The microfluidic titration device represented in **FIG. 27** was characterized by allowing fluorescein to pass through inlet **344** and water to pass through inlet **346**, and measuring the changes in fluorescence intensity in each channel (using a fluorescence microscope) after each successive dilution. The device was designed to obtain an exponential dilution pattern at the outlet with a theoretical dilution factor of two. The empirically measured dilution factor was 2.2, averaged over all of the junctions of the device and over three different experiments. The relationship between  $c$  and  $n$  is exponential (eq. 1) where  $c_n$  is the concentration of the analyte in channel  $n$  (where  $n$  ranges from 1 to 11 in this work) and  $c$  is the initial concentration: