A merger of Fresenius' Journal of Analytical Chemistry, Analusis and Química Analítica

ANALYTICAL & BIOANALYTICAL CHEMISTRY

Published in cooperation with
Division of Analytical Chemistry of the German Chemical Society (GDCh – Gesellschaft Deutscher Chemiker)

and supported by
Gesellschaft für Biochemie und Molekularbiologie e.V. (GBM)

Austrian Society of Analytical Chemistry (ASAC – Österreichische Gesellschaft für Analytische Chemie)

Division of Analytical Chemistry of the European Association for Chemical and Molecular Sciences

Division of Analytical Chemistry of the Swiss Chemical Society (DAC/SCS)

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ANALYTICAL & BIOANALYTICAL CHEMISTRY Vol 384 · No 5 · March 2006 · pp xxx–xxx

A 20667

Volume 384 • Number 5 • March 2006

ANALYTICAL & BIOANALYTICAL CHEMISTRY

Co-owned by Gesellschaft Deutscher Chemiker
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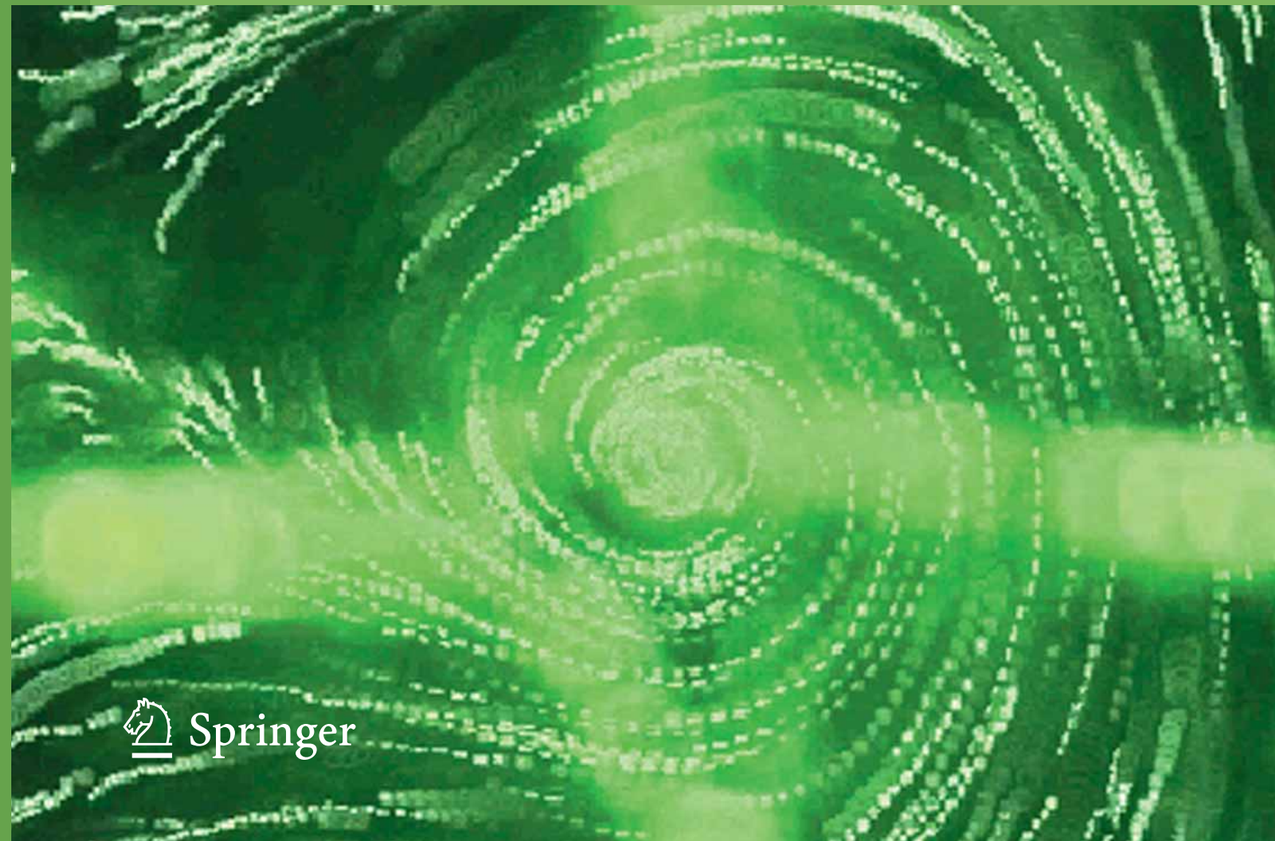
Original Papers



Anal Bioanal Chem (2005) 382: 891–893
DOI 10.1007/s00216-005-3209-1

TRENDS

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Interactions of electric fields with fluids

Published online: 1 June 2005

Technological advances and development of new materials in microfabrication and nano-fabrication have recently led to major research and commercial investment in miniaturised chemical, biochemical, and biological analysis. The advantages of reducing the scale of systems toward the microscale are numerous, in terms of speed, efficiency, reaction control, lower power consumption, less reagent requirements, and so on [1, 2]. Many research groups and companies are involved in the development of microanalysis and microfluidic systems, which are collectively referred to as Micro Total Analysis Systems or the Lab-on-a-Chip [1, 2]. These integrated microdevices have numerous applications in analytical science, the life sciences, healthcare, and separation technology. Mass-produced, parallel microsystems, combining multiple processes in one device have the potential to revolutionise pharmaceutical processing and drug discovery. Low-cost handheld devices could vastly improve diagnosis, providing analytical capabilities currently available only in elaborate, expensive facilities.

The proceedings of one of the major annual conferences in this field, MicroTAS are published online at the Royal Society of Chemistry web site [2]. Much of the research activity reported is aimed at developing microscale analogues of larger-scale components for handling fluids in microchannels: pumps, mixers, stirrers, etc. Mixing, in particular, is problematic in microsystems, because on this scale, fluids are viscous, flows tend to be laminar, and mixing of two materials is mainly by diffusion [3]. Two DC electric field driven techniques: electrophoresis and electroosmosis [4], are widely used in microfluidic devices and form the mainstays of commercial applications. Electrophoresis is a non-contact method of moving and separating particles by the action of an electric field on the net charge of the particle. Electroosmotic flow in a channel arises from interaction of the electric field along the channel with the electrical double layer near the channel walls. In contrast with pressure-driven flow, which has a parabolic profile in channels, with zero velocity at the walls because of friction, electroosmotic flow has a flat profile across the channel. In electroosmosis, therefore, there is less sample diffusion in the direction of flow—an advantage for sample separations. DC fields applied along the channel can therefore produce particle separation, bulk flow, or both.

Numerous applications have demonstrated the use of electric fields to achieve analytical or separation in microfabricated microfluidic systems; a few of these can be included for illustration. Manz et al. [5] illustrated the basic applications of capillary electrophoresis and electroosmosis in miniaturised systems. Enhanced mixing of fluids has been achieved by use of natural charge imhomogenities and resulting instabilities under the action of applied DC or alternating electric fields to break up fluid streams moving through microchannels [6]. Similar differences in electrical properties between a sample plug and the carrier fluid can be exploited by using an electric field along the channel, both to move the sample and also to compress the sample, reducing sample spreading by diffusion, an effect called sample stacking [7].

A major advantage of electric field-driven pumps or mixers is the lack of moving parts, the field acting directly on the fluid or particles. DC electrophoresis or electroosmosis usually requires the generation of large potentials (~1 kV), however, to generate sufficient flow rate through channels. In comparison, it has been demonstrated that alternating or AC electric fields can produce similar flow rates in microfabricated electrode arrays with much lower voltages (1–10 V). Although this is an advantage in terms of power supply, fabrication of these devices is more difficult. These devices do, however, have relevant applications in microanalysis.

Electrohydrodynamic pumps work by the action of the electric field on gradients of both charge and po-

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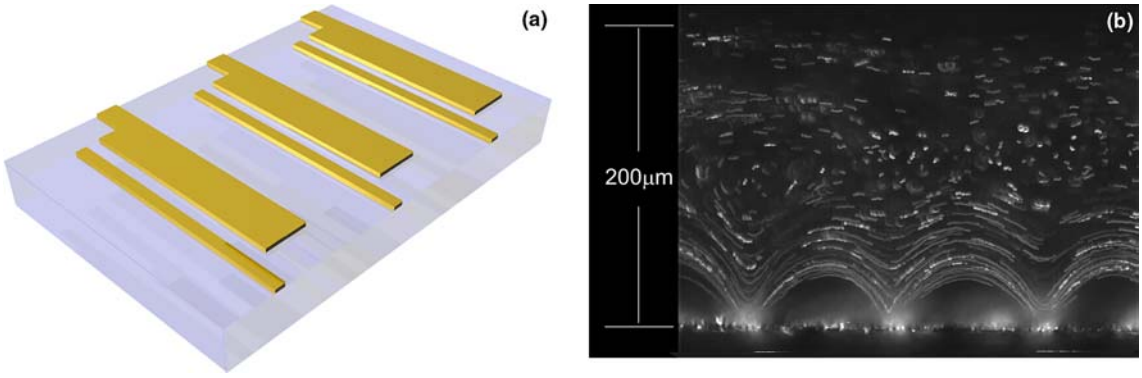


Fig. 1 **a** Schematic diagram of the asymmetric design of microelectrode structure on glass. **b** Streamline plot of the movement of an electrolyte in the asymmetric electrode array looking along the electrodes. This image was obtained by superimposing successive frames of a video sequence showing the movement of fluorescent tracer particles

larisability in the bulk fluid [8]. These gradients can arise from non-uniformities in permittivity and conductivity produced by non-uniform heating of the fluid in the channel. Increases in temperature can result either from Joule heating of the fluid by the field or from external heating. Multilayered microelectrode arrays, which produce travelling AC electric fields, have exploited these phenomena to produce translational flow along the array and the microchannel [9].

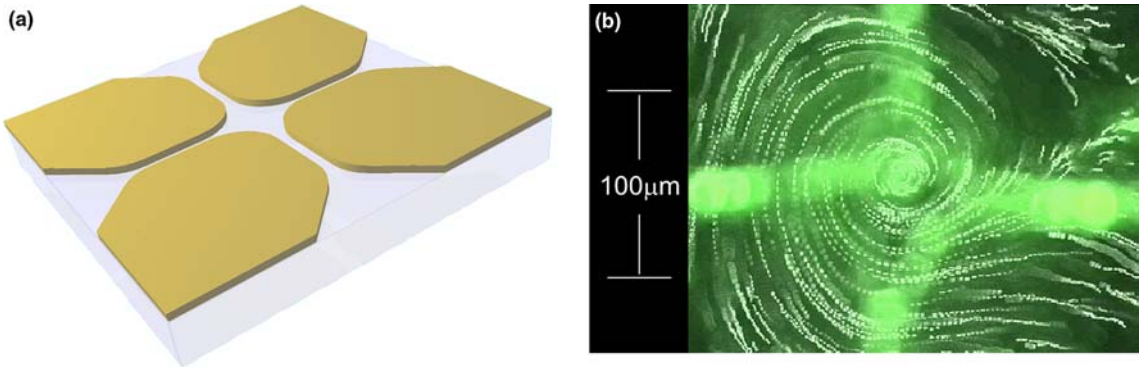
A second AC field effect is AC electroosmosis [8, 10, 11], a second-order electroosmotic effect produced on microelectrode structures fabricated on planar glass substrates. A schematic diagram of one design of electrode array is shown in Fig. 1a. The non-uniform electric field produced by the microelectrodes induces movement in the ionic double layer above the electrode. In an alternating field (typically at frequencies of approx. 1 kHz), both the sign of the induced charge and the direction of the electric field reverse. The direction of flow therefore remains the same producing steady net flow in an AC field [10]. Electrode arrays can be designed to exploit this phenomenon for pumping, using either travelling electric fields or asymmetric electrodes [8, 11].

Figure 1b shows an experimental image of the movement of an electrolyte in a 200 μm high microchannel above an asymmetric array, as described in Fig. 1a. The width of the small electrode and the smallest separation gap was 10 μm and the applied voltage was 6 V peak to peak. The image was obtained by superimposing successive frames of a video sequence of fluorescent tracer particles in the fluid showing the streamlines of the flow. The direction of observation is along the electrodes using the observation system described in Ref. [10]. The velocity of the flow is highest close to the surface of the electrodes and rapidly falls off with height. An improved bulk flow rate can be obtained by reducing the height of the channel.

Electrothermal flow (electrohydrodynamics) at higher frequencies (2 MHz) and higher voltages (15 V peak to peak) is shown in Fig. 2. Figure 2a shows a schematic diagram of the "polynomial" design of microelectrode, with four electrodes arranged in a circle. By applying four phase-shifted AC potentials, a rotating electric field can be generated in this electrode array [8]. As shown in Fig. 2b looking down at the electrodes, this produces a vortex motion in the fluid, which can be used to stir and mix fluids passing over the electrodes.

One further electric field-driven fluid effect, which has recently been demonstrated as a technology for analytical and separation science, is the movement of droplets on surfaces by electrowetting or dielectrophoresis [12]. This technique again uses microelectrodes fabricated on

Fig. 2 **a** Schematic diagram of polynomial microelectrodes on glass. **b** Streamline plot of the movement of an electrolyte in the polynomial electrode array looking down at the centre of the electrodes. This image was obtained by superimposing successive frames of a video sequence showing the movement of fluorescent tracer particles



planar substrates but in this case the fluid is in the form of a droplet on the surface [12]. The application of a DC or AC electric field from the microelectrodes underneath the droplet results in electrical stress on the droplet and movement. Patterned microelectrodes can then be used to pinch off small amounts of fluid or to move the droplet around on the surface. Chemical analysis and reactions can then be performed on the sub-picolitre scale in a controlled manner by using this method to bring droplets together. With advanced microfabrication methods, large arrays of individually addressable electrodes can be fabricated, enabling parallel assays and multiplexing of reactions.

AC field phenomena have advantages and disadvantages in comparison with DC electrokinetic effects. The main advantages are that the power requirements are low and that the effects can be localised to specific points in the microfluidic systems, enabling counterflows to be generated and gating of different flows. Application areas include pumping and mixing in microsystems.

In summary, electric-field-influenced fluidics is a broad area of research which has numerous proven applications as a basic technology in systems for chemical analysis and particle separation. The advances in microfluidic device fabrication and the integration of electrodes and patterned structures into channels for local flow generation and manipulation have led to exciting developments in analytical microsystems.

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