Producing fluid flow using 3D carbon electrodes

H. A. Rouabah(1), B. Y. Park(2), R. B. Zaouk(2), M. J. Madou(2) and N. G. Green (1)

1- School of Electronics and Computer Science, University of Southampton, S017 1BJ, Southampton, UK.

2- Mechanical and Aerospace Engineering Department, 4200 Engineering Gateway Blg. University of California, Irvine 92617 CA, USA.

Email: ng2@ecs.soton.ac.uk

Abstract. Moving and manipulating bio-particles and fluids on the microscale is central to many lab-on-a-chip applications. Techniques for pumping fluids which use electric fields have shown promise using both DC and AC voltages. AC techniques, however, require the use of integrated metal electrodes which have a low resistance but can suffer from unwanted chemical reactions even at low potentials. In this paper we introduce the use of carbon MEMS technology (C-MEMS), a fabrication method which produces 3D conductive polymeric structures. Results are presented of the fabrication of an innovative design of 3D AC-electroosmotic micropump and preliminary experimental measurements which demonstrate the potential of both the technology and the design.

1. Introduction

Recently, there has been a great deal of research interest directed at microfluidic systems for chemical, biological and medical analysis: the Lab-on-a-Chip (LOC). One of the shared requirements across the numerous application areas are components for the movement and manipulation of fluid based samples. There are many technologies for pumping fluids but one of the most widely used techniques uses DC electric fields to move electrolytic solutions via the interaction between the field and the Electrical Double Layer. Recently, AC electrokinetic methods [1] have been developed which use significantly lower applied potentials but which require metal microelectrodes integrated into the channels used to guide the fluid samples. However, while metal electrodes have a low resistance, unwanted chemical reactions can occur even at low potentials.

An alternative is to use conductive polymers, where the generation of electrochemical reactions is less of an issue. There have been several successful technologies developed in this area, for example: the inclusion of silver nano-particles in photopatternable SU-8 resist (conductive SU-8) [2] and the pyrolysis of polymers at high temperature to produce conductive carbon structures (C-MEMS technology) [3]. Both techniques have advantages and drawbacks. Thick structures and high aspect-ratio (HAR) structures with good resolution are easier to fabricate in C-MEMS than conductive SU-8 but the electrical resistance of the structures is greater. Complicated structures and multilayered patterns are readily achievable using the approach of conductive photopatternable polymers, as each successive layer can be directly patterned over the previous one with no intermediate fabrication steps.

This paper presents details of the pyrolysis of SU-8 structures for the fabrication of 3D microelectrode structures for AC electrokinetic applications. The technique is used to produce the...
existing interdigitated asymmetric microelectrode array design which has been demonstrated to be effective at pumping fluids [1]. A novel design of 3D electrode structure, which is based on the asymmetric electrode array, is then presented and discussed, along with details of the fabrication and the effective limits of the pyrolysis method in this situation. Finally, preliminary measurements of the motion of an electrolytic solution in the microelectrode structures when subjected to an applied AC potential are presented.

2. Fabrication of 3-D conductive electrodes

The different electrode arrays were fabricated in the same way. Layers of SU8 were coated on silicon dioxide wafers to produce the different vertical sections of each design. The patterns of each vertical section were achieved using photolithography, followed by baking prior to the subsequent layer. The final stage of the fabrication was the pyrolysis step: performed in a furnace at 950°C in a forming gas (5% H2:95% N2).

3. Fabrication results

Three different designs of electrode array were investigated. The first design is the basic asymmetric interdigitated microelectrode array, which consists of alternately narrow and wide electrodes [1]. This device was fabricated in order to provide a reference comparison for pyrolysis produced electrodes with previous results from the literature. A thin layer of SU-8 5 (average film thickness 6μm prior to pyrolysis) was used for the electrodes, which had repeat dimensions as follows: 150 μm wide electrode, 50 μm gap, 50 μm wide electrode, 150 μm gap.

The second electrode design used the same base electrode array but had a second layer of thicker raised material to one side of each electrode. This design, first postulated by Bazant [4] has been demonstrated to produce significantly higher flow rates than the basic asymmetric design. The second layer in this design was produced using SU-8 10 (average film thickness 15μm prior to pyrolysis) patterned using soft lithography. Scanning Electron Microscope images of the array and a close up of the electrodes are shown in Figure 1.

![Figure 1. SEM images (whole array and close-up) of the asymmetric interdigitated microelectrode array with the additional raised features to one side of each electrode. The patterned sizes of the base electrode array was electrode: 150μm: gap 50μm: electrode 50μm: gap 150μm, with the raised features originally occupying half of each electrode. Shrinkage during pyrolysis can clearly be observed.](image-url)
the fact that the AC electroosmotic driving mechanism, which produces the fluid flow in this type of microfluidic device, is a surface driven effect. The Electrical Double Layer is a thin layer (~10nm) induced on the electrode surfaces by the applied potential. The electrostatic force moves the ions and they in turn move the fluid through viscous drag but this only has a net effect inside the double layer. As a result, the relatively large volume of fluid (~100µm across) is pulled by lateral drag on the surface, which means that even slight back pressures produce recirculation through the centre of the channel. This design of electrode array extends the surface area of the electrodes vertically into the channel, thereby increasing the surface area significantly for the same volume. This has the effect of increasing the pumping efficiency and increasing the internal hydrodynamic resistance of the pump, allowing it to withstand greater back pressures. For this design, a smaller asymmetric planar electrode array was used (large electrode/gap size 60µm, small electrode/gap size 20µm) as the base. For the pillar HAR structures, a thick layer of SU-8 100 was used (thickness 120µm). Scanning Electron Microscope images of the final electrode array are shown in figure 2.

![SEM images](image)

**Figure 2.** SEM images (whole array and close-up) of the asymmetric interdigitated microelectrode array with the 3D pillar structures. The original sizes of the base electrode array and the pillars were electrode: 60µm: gap 20µm; electrode 20µm: gap 60µm, with the width of the pillars in the direction of flow (across the electrodes) equal to 20µm. Shrinkage during the pyrolysis process can be clearly seen in the reduction in size of the pillars compared to the underlying electrode array.

The effect of shrinkage to the polymer during the pyrolysis process can clearly be seen in the close-up view. The shrinkage is non-uniform and is affected by the topography of the surface, the size and shape of the polymer material and its orientation with respect to the surface. In the case of HAR pillars, a size reduction of up to 50% can be observed, particularly in the height of the pillar: the final height of the pillars was ~ 60µm from an original film thickness of 120µm. Similarly, the width of the small pillars reduced from 20µm to 10µm.

### 4. Results of fluid flow

Preliminary experiments were carried out using a solution of 5µm latex beads in 1 mM aqueous KCl with the beads acting as tracer particles. The behaviour of the particles at different voltages and frequencies can be seen in figure 3, with bubbles being generated at low frequencies.

An applied signal of 20 V peak to peak was applied over a range of frequencies. The voltage was fixed at 16V peak to peak and the frequency was varied from 10 Hz to 100 kHz since the polarisabilities of the particle and the fluid are frequency dependent. A steady fluid flow starts to occur between 4 kHz to 60 kHz. The high velocity of 32µm/s was achieved was at 5 kHz.
5. Conclusion
Two different 3D carbon electrode arrays were made to illustrate the flexibility of C-MEMS in fabricating different structures and geometries. Preliminary measurements of the response of an aqueous electrolyte to an applied AC signal have demonstrated the ability of carbon electrodes to generate AC electroosmotic pumping. The frequency response was similar to that observed for metal electrodes although higher applied potentials were required.

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