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Simulation of the Measurement of the Impedance of Aqueous Droplets in Segmented Flow

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This work describes the simulation of the operation of an impedance sensor that has been developed at the authors' institute. The sensor measures the conductivity of aqueous droplets in segmented flow and the cell content of such droplets. The sensor consists of two electrodes attached to the outside of a glass capillary. The finite element model of the impedance of the material between these electrodes shows the suitability of the sensor to measure changes in conductivity of aqueous droplets being pumped through the capillary. Until now electrical measurements of droplets in digital microfluidic systems depended only on the dielectric constant of the liquid between the electrodes, this paper shows how the conductivity can also be measured.

1. Introduction

Digital microfluidics is a technique based on the generation of droplets and requires techniques for their handling, and measurement. Standard droplet generation hardware, such as the T-junction droplet generator, generates droplets by injecting an aqueous solution into an immiscible oil in a microfabricated chip. Grodrian et al. (2004) pioneered the use of droplets in cell cultivation as miniaturized bioreactors.

Droplet content is very often analysed optically (Funfak et al., 2009) and often by making use of fluorescent markers and other molecules that act as indicators. Optical measurement offers the advantage of being non-contact. Electrical measurements can in many cases be performed without adversely affecting the object under test. Niu et al. (2007) performed measurements of the capacitance differences of droplets flowing through a microfabricated chip and subsequently could direct droplets through a switching mechanism. Nichols et al. (2009) used capacitative sensing to detect the position of droplets in an electrowetting chip in order to direct the flow of droplets. Capacitative measurement do not measure conductivity and are therefore less suited to full characterization of the liquid within the droplet. This paper presents a simulation of a sensor developed in our institute for measuring the conductivity of droplets. By being able to measure the conductivity of a droplet this opens up the possibility of measuring the impedance and subsequently the cell content of droplets.

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Although most bioimpedance sensors make direct galvanic contact to the medium that they measure, Hofmann et al. (2005) have previously developed a contactless sensor that measured yeast cell growth. In addition the contactless measurement of conductivity has been common in capillary electrophoresis systems (Guijt et al., 2004). In the case of a droplet-based system, it is highly advantageous to provide a continuous hydrophobic surface over which droplets can move freely without breaking up. We suggest the use of a thin walled glass capillary, in this case 25 µm, which separates the measurement electrodes from the aqueous segment within the capillary. Glass surfaces are often coated by a monolayer of hydrophobic silanes for use in droplet-based systems. Grodrian et al. (2004) silanized glass surfaces of a droplet generation chip, so that droplets could move freely across the surface. Cahill et al. (2010) silanized silicon nitride surfaces for performing electrowetting of droplets.

2. Methods

Figure 1 shows the cross-section of the electrode setup. Rotation of this cross-section around the axis of symmetry gives a capillary tube with two electrodes that contact the outer surface of the tube. The ground electrode acts to shield the electrodes from each other so that a maximum of the current that flows between the two measurement electrodes flows through the fluid in the capillary tube. An aqueous droplet is situated between the electrodes within the tube. Otherwise the tube is filled with oil. The tube has an inner diameter of 0.25 mm and the thickness of the capillary wall is 25 µm. The measurement electrodes have a cross-section of 2 mm x 2 mm and are separated by 2 mm.

The simulation was performed in COMSOL 3.5a and Matlab. The electric potential V within the area of the model is described by a modified form of the Poisson equation:

$$-\nabla\cdot\left(\left(\sigma+j\omega\varepsilon_0\varepsilon_r\right)\nabla V-\mathbf{J}^e\right)=Q_j \qquad (1)$$

where σ is the conductivity, ω is the angular frequency, ε_0 is the permittivity of free space, ε_r is the relative dielectric constant, $\mathbf{J}^e$ is the external current density and Q_j is a current source.

The boundary conditions are the following:

$$n\cdot\mathbf{J}=0 \qquad (2)$$

$$n\cdot\left(\mathbf{J}_1-\mathbf{J}_2\right)=0 \qquad (3)$$

where equation 2 uses the insulation boundary condition for external boundaries setting the current **J** to zero, equation 3 uses the continuity of current on either side of the boundary for all boundaries between dielectric media. The ground electrode and one of the measurement electrodes are set to ground potential while an AC potential of 1-Volt amplitude is applied to the other measurement electrode. The frequency of the applied potential was varied between 10 kHz and 30 MHz while the conductivity of the aqueous liquid was varied between 1mS/m and 1 S/m. The conductivities and dielectric constant of all other media was set to constant values relating to the chosen materials. The cross-sectional area of the electrode was excluded from the simulation.

The current I passing between the electrodes was measured by integrating the current entering the measurement electrode that was set to ground for one cycle of the AC signal and by integrating around the axis of symmetry. The real and imaginary parts of the current were computed for each frequency and conductivity value simulated. The impedance Z is given by $Z = V / I$, where the impedance modulus $|Z|$ and phase angle θ are given by $Z = |Z| e^{j\theta}$.

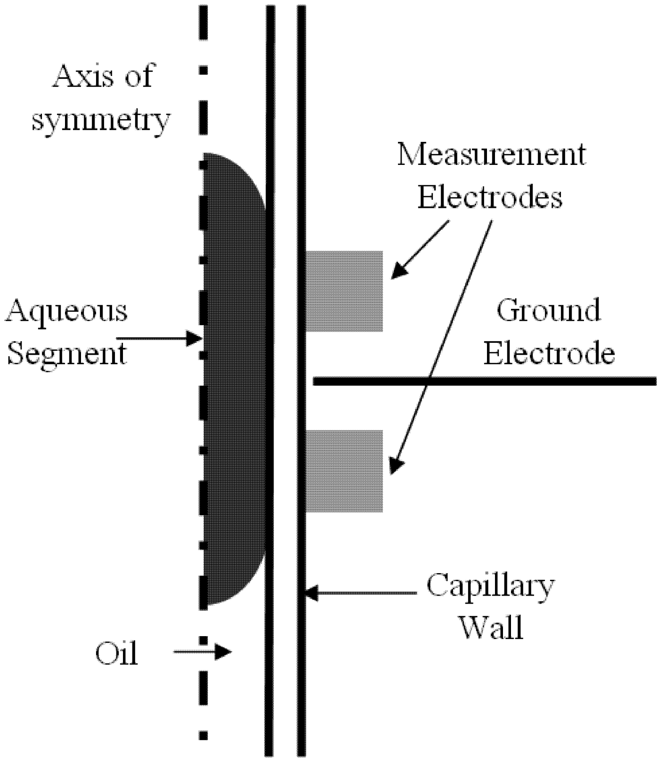

Figure 1: Schematic diagram of a cross section of the sensor. The axis of symmetry allows the simulation to be simplified so that it runs more quickly and efficiently. An aqueous droplet surrounded by oil in a capillary tube passes by two measurement electrodes. The measurement electrodes are shielded from each other by a ground electrode.

3. Results

Figure 2 shows a typical image of the total current density between the measurement electrodes. The current flow through the liquid between the measurement electrodes and depends on the frequency of the applied signal in addition to the conductivity of the liquid in the capillary.

Figure 3 shows the dependence of the impedance modulus and phase angle on the conductivity and frequency. The general form of the curves at fixed conductivity can be divided into 3 distinct regions: (i) at low frequencies, the capacitance of the wall of the capillary tube blocks the flow of current and the phase angle approaches -90°, (ii) at intermediate frequencies, the impedance curve becomes flatter because the impedance is dominated by the conductivity of the fluid in the droplet and the phase angle becomes larger also reflecting the dominance of conduction over capacitance and (iii) at higher frequencies, the capacitance of the water droplet dominates so that the impedance decreases with increasing frequency and the phase angle approaches -90°.

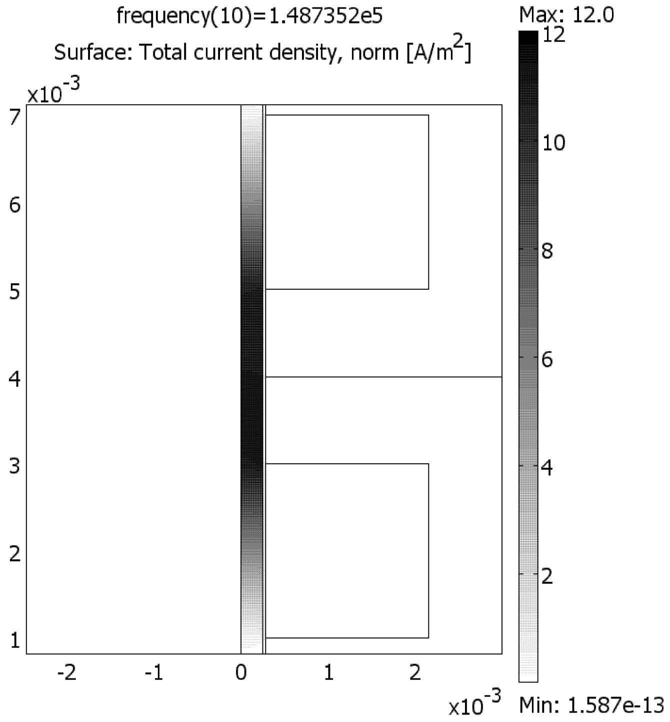

Figure 2: Simulation of the total current density at approximately 149 kHz showing how current flow between the two electrodes through the water in the capillary.

Figure 3 shows that as the conductivity of the liquid within the tube increases that the frequency at which the phases angle maximum is observed shifts to higher frequencies. This shows that the measurement of the impedance of the liquid within the tubing is sensitive to the conductivity of that liquid.

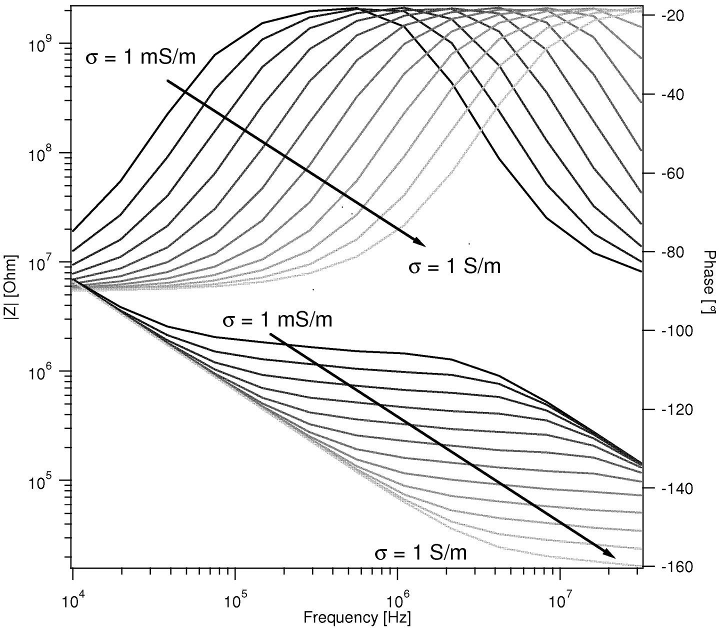

Figure 3: The upper curves show the dependence of the phase angle on frequency for a range of liquid conductivities from 1 mS/m to 1 S/m. The lower curves show the dependence of the impedance modulus on frequency for a range of liquid conductivities from 1 mS/m to 1 S/m.

4. Discussion

The results of this simulation show that an impedance-based measurement can measure the conductivity of a liquid within capillary tubing. By using extremely thin-walled glass capillaries, which are commercially available, the authors can apply low voltage signals that are sensitive to the conductivity of droplets flowing through the tubing. Measurement of the conductivity is the measurement of a variable property of droplets and not a simple measurement of the droplet's presence or absence. Sensitivity to the conductivity of droplets opens up the possibility of measuring the cell content of droplets. The simulation shows the dependence on the conductivity of the impedance modulus and phase as measurable using a gain-phase analyzer

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