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Electronic protection methods for conductivity detectors in micro capillary electrophoresis devices

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Abstract

Two level shifting methods are presented to protect the contactless conductivity detector in a micro capillary electrophoresis (CE) device. In the separation channel of a micro CE device an electrical potential is present at the detector area. The conductivity detector with read-out electronics is referenced to ground potential. The potential difference between separation channel and detector causes, at a high enough value (here 2 V), breakthrough of the insulating layer on the detector. By shifting the potential of either the conductivity detector or the separation voltage-supply the difference between the detector electrode potential and the channel potential at the detector area is cancelled. For this compensation system an electrode is integrated in the channel, near the detector, to measure the channel potential.

By compensating for the potential difference between the channel and the contactless detector, lower requirements are put on the breakthrough voltage of the insulating layer. This enables thinning of the insulating film on the conductivity detector, which improves the performance of the contactless conductivity detector and, hence, the overall system performance.

Measurement results of the voltage probe are presented as well as breakthrough voltage measurements of the SiC insulating film covering the conductivity detector.

Keywords: Micro capillary electrophoresis; Breakthrough voltage; DC channel-potential compensation; SiC

1. Introduction

Capillary electrophoresis (CE) is a widely used technique to separate ions in a sample. The sample is brought into a separation channel filled with buffer liquid. After sample injection a high voltage is applied over the separation channel. The injected ions will move through the channel at a different speed, because of their different mobility. In our case, a contactless conductivity detector [1] at the end of the channel monitors the concentration of separated ions. The detector requires a thick enough insulating film to withstand the potential present in the separation channel. This is in conflict with the requirement to achieve a good capacitive coupling to the liquid, thus, a thin layer, necessary for a low detection limit. Electrical compensation techniques are necessary to allow the use of thinner insulating films.

2. Conductivity detection

In traditional CE systems, often optical detectors are used. The required optics are difficult to integrate in an on-chip CE system, making conductivity detection an interesting alternative. The detector used in our device consists of four electrodes on the bottom of the separation channel. The electrodes are covered with a SiC insulating layer, insulating the electrodes from the liquid in the channel, because of the following three reasons [1–3]:

1. A traditional conductivity detector using electrodes in galvanic contact with the liquid will suffer from gas generation in a CE device. The applied separation voltage creates an electric field in the separation channel. Unisolated detector electrodes will cause a constant potential area in the liquid leading to gas generation in the channel at the electrode area. This is avoided by using electrically isolated electrodes.
2. The detector is positioned in the channel at a short distance from the high voltage ground electrode. The electric field strength in the channel causes a potential at the detector area. Using unisolated electrodes in this configuration causes gas-generation at the detector area because of to the potential difference between the channel and detector electronics connected to the electrodes. With isolated electrodes this is avoided.
3. The insulating layer will also protect the electrode-metal for chemical reactions with the liquid.

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The use of isolated electrodes demands an AC-conductivity detector set-up. The SiC insulating film acts as a dielectric of a coupling capacitor between the liquid and the detector electrodes. A thin film will give a good capacitive coupling of the detector to the liquid.

The performance of the system depends, besides the detector performance, on the quality of the separation. The separation process is improved by using a higher separation voltage or a longer separation channel. The chosen chip size (2 cm × 1 cm) limits the channel length to 6 cm (channel width 70 μm, depth 20 μm), making a higher separation voltage the only option. A higher separation voltage leads to higher field strength in the channel causing an increased potential difference between detector and channel, making a thicker insulating layer necessary [4].

At this point, a conflict of interest is created because the high separation voltage is inevitable and demands a thick electrode isolation layer while good capacitive coupling can only be realised with a thin layer.

3. Protection concepts

To prevent break down of the insulating layer, due to a too high voltage drop over the insulating layer, the potential difference between the separation channel and the detector electrodes should be decreased. A commonly used technique is to make a system part electrically floating [5]. Due to the weak coupling of the detector to the liquid the voltage over the insulating layer will be mainly determined by unknown and uncontrollable parasitics, making the system unreliable.

Another method makes use of a resistive voltage divider over the high voltage power supply. The resistors are chosen in ratio to the channel length, regarding the position of the detector in the channel. The output of this divider represents the potential in the channel at the detector area. This output biases the detector electronics DC-level, decreasing the potential difference over the insulating layer. However, chemical reactions taking place at the high voltage electrodes in the liquid (redox potential), and changing conductivity in the channel (separated zones), cause a non-linear potential distribution in the system. The error caused by this phenomenon causes a difference between the voltage divider output and the real channel voltage, leading to breakthrough of the insulating layer.

A third method is connecting coupling capacitors (DC-blocking) in series with the electrodes. These capacitors will be charged until the charge at the electrode to liquid interface is equal to the coupling capacitor charge. The ratio of the capacitors determines the division of the total DC potential. Because of the small electrode to liquid coupling capacitance of the insulated electrodes (about 10 pF), external coupling capacitors of about 1 pF are needed. However, this will degrade the performance of the detector, due to the lower total coupling of the detector electronics to the liquid (<1 pF).

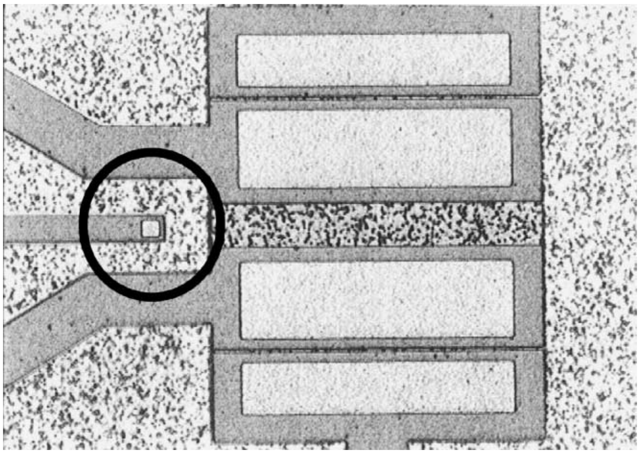

Fig. 1. Close-up of the four-electrode contactless conductivity probe and the potential probe (in circle). All electrodes are isolated with 30 nm SiC (light gray area) except for the 10 μm × 10 μm electrode area of the potential probe. The detector electrodes measure 106 μm × 25 μm (outer electrodes) and 106 μm × 35 μm (inner electrodes).

Other methods using, e.g. a local change in the capillary wall structure [6] are difficult to implement in IC-compatible processes making them less suitable for our devices.

We decided to use a configuration with a potential probe, in galvanic contact with the liquid (see Fig. 1). The probe enables the measurement of the DC potential in the channel at the detector area. This information is used to:

I. Control the DC voltage level of the detector electronics, or
II. Control the potential of the reference terminal of the high voltage source.

The control loop makes it possible to bias the detector system in such a way that the DC voltage difference between the electrodes and the liquid is near zero, putting a lower requirement on the isolation properties of the insulating layer. The layer can be optimised for better coupling of the read-out electronics to the liquid, yielding better system performance. Advantages and disadvantages will be discussed in the next section.

4. Detector level control

Because of the sensitivity of the detector circuitry to parasitics the first stages of the read-out electronics are placed as close as possible to the detector avoiding long cables and minimising parasitics [7,8]. The experimental set-up of the conductivity detector consists of a lock-in amplifier, AC voltmeter, and A/D-converter computer card. The detector DC level is controlled by shifting the GND potential of the detector system (Fig. 2). The ground (GND) terminals of all parts of the read-out system are connected together, which makes it difficult to shift the GND potential of the detector. Shifting of the GND potential of the whole set-up is avoided by using isolation stages between the

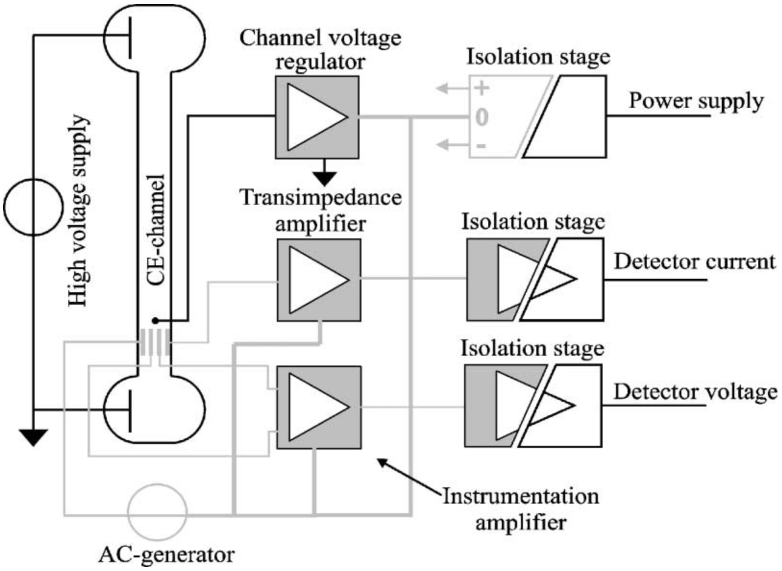

Fig. 2. Schematic overview of a system using level controlled read-out electronics.

detector plus the first stages and the rest of the system. For complete isolation it is necessary to isolate the excitation voltage, AC current read-out, AC voltage read-out and power supply.

The use of isolation stages increases the noise level of the system and adds non-linearity's. The measurement error and detection limit of the system will be increased. The low-level signals used in the detector require shielding of the first stages. The shielding should be biased to the reference level of the detector electronics; detector level control will increase the complexity of the shielding used for the first stages. Also, parasitics which are cancelled when the system reference is at GND potential, will start to cause errors when the reference level is shifted.

Shifting the potential of the read-out electronics puts no extra requirements on the high voltage supply, which is an advantage in existing systems. Usually, high voltage supplies applied in a separation set-up are referenced to ground, shifting their ground potential is not possible. This method is suitable for all types of high voltage supplies.

5. High voltage reference control

Lowering the DC potential in the channel at the location of the detector is achieved by shifting the reference level of the high voltage supply. The reference level is the potential at the negative terminal or the positive terminal of the high voltage supply, respectively, for a positive and a negative separation voltage.

The high voltage supply reference terminal is biased in such a way that the DC level in the channel at the detector remains at ground potential (Fig. 3). This system has the advantage that the conductivity detector electronics are referenced to ground. The signals from the first stages are coupled directly to the rest of the electronics. Furthermore, the shielding of the read-out electronics will be at ground/system reference level, decreasing the influence of some parasitic capacitances. For this system, a floating high voltage supply is required.

A floating high voltage supply is easily obtainable (e.g. Applied Kilovolts Ltd., HP series). Usually a high voltage converter consists of a switching regulator, high frequency transformer, and voltage multiplication stages. The transformer forms an isolation barrier, isolating the high voltage output from its low voltage power supply. The ground terminal of the high voltage output is connected to a regulator,

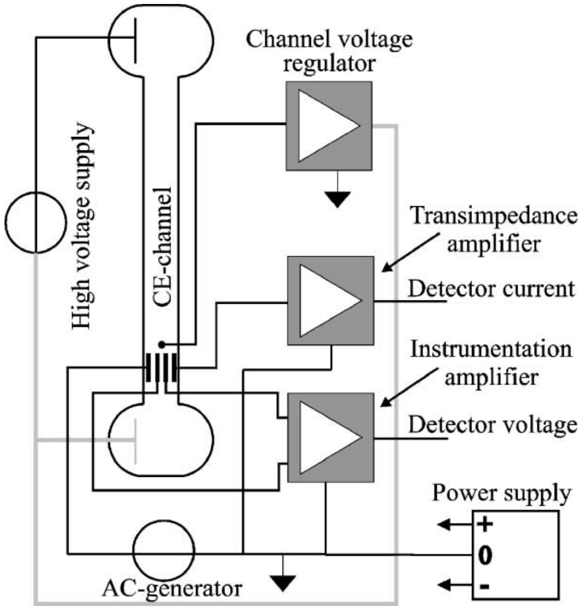

Fig. 3. Schematic overview of a system using a level controlled high voltage supply.

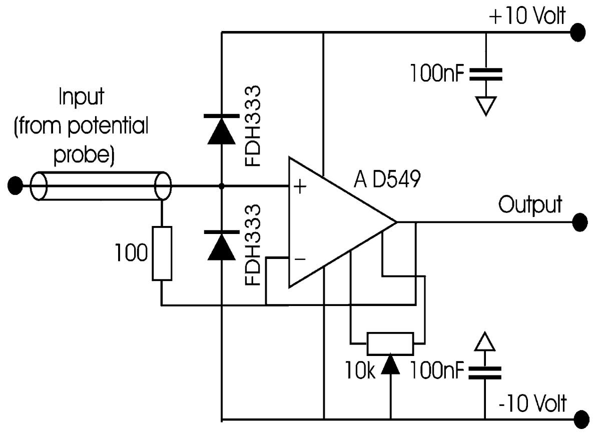

Fig. 4. Circuit used to measure the potential probe voltage.

which will supply the proper offset voltage. However, using this type of compensation might be difficult with an existing set-up, because the ground of the high voltage supply is the system ground.

Besides usage with an insulated conductivity detector this system also enables the use of galvanic coupled conductivity detectors, with respect to the problems caused by the potential difference between the channel and the detector.

6. Probe interface electronics

To obtain an accurate reading of the channel potential and to avoid gas generation at the electrode area the probe is designed as a 10 μm × 10 μm square covered with 300 nm of gold. The gold is evaporated on an aluminium track locally covered with 100 nm of titanium.

To keep current density low on the small surface the probe read-out should draw very little current form the probe. Too high current density might cause chemical reactions taking place at the probe area, introducing measurement errors, damaging the electrode or disturbing the separation process.

The potential probe voltage is buffered with a non-inverting amplifier. The amplifier used is an electrometer OpAmp AD549 of Analog Devices, which has a typical input bias current of 40 fA. The input impedance of the amplifier is typically 10^{15} Ω. The schematic diagram is given in Fig. 4. Special care is taken to minimise the leakage current paths; the input connections are "floating" over the printed circuit board. The input shielding current flow through the parasitics is minimised by driving the shielding of the input. The input protection diodes are selected for low leakage current. The input current of the circuit was measured, in the range of -5 to $+5$ V; the input current was lower than 200 fA.

7. Influence of the contact potential

Interaction between the potential probe and the ions in the liquid will create a potential difference. Therefore, the output voltage of the probe electronics will be different from the potential in the liquid. The voltage difference (value, polarity) depends on temperature and on the type and concentration of ions that react at the electrode surface. Each type of reaction has its own standard oxidation potential under specified conditions (as used in oxidation potential look-up tables). In our application, the situation is subject to changes during the separation process, which makes it difficult to compensate for the generated offset voltage. The generated voltage at the probing electrode induces an error in the compensation system. This error leads to a potential difference over the insulating layer of the detector, which is estimated to be in the order of 1 V [9]. Experiments show an offset voltage of -0.6 V. However, the offset will not change considerably with the separation voltage. The influence of this potential difference can be decreased by subtracting a fixed voltage from the measured channel voltage.

The unknown potential difference between the platinum high voltage electrodes and the liquid is compensated by the control loop. This does not add any additional offset voltage over the insulating layer.

8. SiC measurements

As insulating material a chemically inert material should be used, we investigated SiN and SiC. The chemical properties, electrical properties and technological aspects were taken in account [4]. Based on the higher permittivity of SiC compared to SiN and the possibility to deposit thinner layers of SiC, SiC was used as insulating material (thickness 30 nm). The SiC was deposited using a Novellus Concept One PECVD system. The breakthrough voltage was measured in a dry condition on a testwafer, using a capacitor configuration with SiC as dielectric material. The measurements showed a value of 6.5 V at 30 nm layer thickness. Finally, measurements have been performed in wetted condition. The final device was used, the separation channel was filled with a 2 mM MES/His (pH 6) buffer solution. Platinum wires were inserted in the vials and connected together. The *U–I* characteristic was measured between the platinum wires and the isolated electrode (see Fig. 5). The measurement results show a difference in the breakthrough voltage in dry and wet condition. In wetted condition, the breakthrough voltage is in the order of 3 V. For comparison a 100 nm SiC layer was measured in wet condition, using the same method, showing a higher breakthrough voltage. No measurements were performed to determine the long-term stability of the layer, however, degradation of the layer performance can be expected [10].

The breakthrough voltage determines the maximum allowed error for the potential control. The potential control should keep its error within the range of 3 V to prevent breakthrough of the SiC layer. The allowable error includes the contact potential of the potential probe to the liquid.

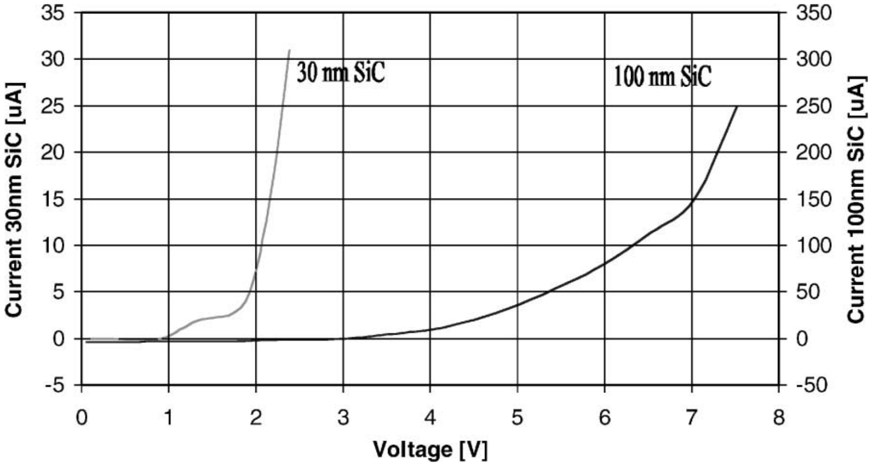

Fig. 5. Measurement results showing the breakthrough voltage of a 30 nm and a 100 nm SiC layer.

9. Experimental results

Measurements were performed with a micro CE device that consists of a separation channel and an isolated conductivity detector integrated in one chip. The method which controls the potential of the reference terminal of the high voltage supply was chosen to enable easy coupling of the conductivity detector to the read-out electronics.

The dimensions of this chip are 1 cm × 2 cm. The channel has a total length of 6 cm, a width of 70 μm, and a depth of 20 μm, the detector is placed at 300 μm from the end of the channel (see Fig. 6). The metal electrodes of the detector are covered with a 30 nm SiC insulating layer.

The channel was filled with a 2 mM MES/His (pH 6) solution. A high voltage was applied (Applied Kilovolts Ltd., HP1R power supply) over the channel and the probe voltage was measured using the described electronics. As can be seen in Fig. 7, the probe voltage is linear to the

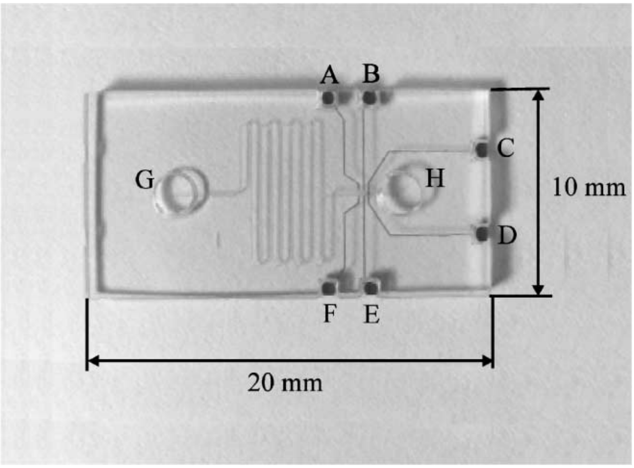

Fig. 6. Photo of a micro capillary electrophoresis device in which the potential probe voltage measurements were performed. (A, F) connections for the potential probe; (B–E) connections for the conductivity detector; (G, H) vials for liquid dispensing.

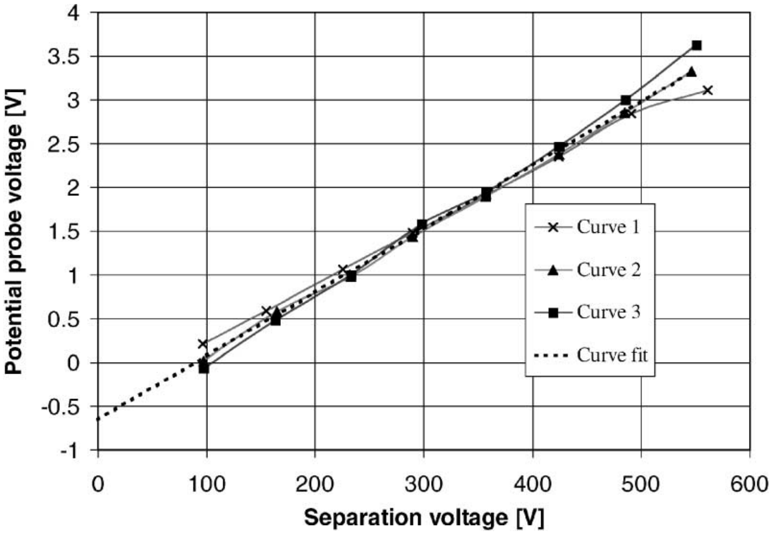

Fig. 7. Measurement results showing the probe potential voltage vs. the applied separation voltage.

applied separation voltage, following the 1/200 ratio of the relative detector position to the channel length. The dotted line is a fitted curve, from which can be seen that there is an electrode to liquid potential difference of -0.6 V. During the measurements the conductivity electrodes were floating.

10. Conclusions

Two methods are presented to lower the potential difference between the separation channel and the conductivity detector, putting less stress on the detector insulating film. Both methods require a potential probe in the liquid near the detector. The read-out electronics necessary for the channel potential measurement are described and measurement results with the system are reported. The SiC layer covering the detector was evaluated in dry and wet condition showing a lower breakthrough voltage in wetted condition. Better coupling of the detector to the liquid, achieved by a thinner insulating layer, and the low breakthrough voltage of the SiC justify the use of an electronic protection system.

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Biographies

Jeroen Bastemeijer received a BSc degree in Electrical Engineering in 1997. After a short period as a telecommunications specialist at the Royal Dutch Telecom organisation (KPN-Telecom) he joined the Delft University of Technology, also in 1997. He is involved in electronics design and sensor system research as a member of the Integrated Physical ChemoSensor group of the DIMES Electronic Instrumentation Laboratory (Microelectronics Department, Delft University of Technology).

G.W. Lubking was born in 1944 in Rotterdam, The Netherlands. He received the MSc degree in 1967 from the Delft University of Technology and worked there since 1969. He was a senior electronics designer responsible for the design of electronic circuitry for various sensors. Tragically, G.W. Lubking has passed away suddenly on the 18 December 2000.

Frederic Laugere was born in 1974 in Angouleme, France. In 1998, he received the MSc degree in Electrical Engineering from the National School of Electronics and Radioelectricity from Bordeaux (ENSERB) with a specialisation in microelectronics. He joined the Electronic Instrumentation Laboratory of the Delft University of Technology as a PhD student in August 1998 and is working on a miniaturised liquid-conductivity detector for capillary electrophoresis.

Michiel J. Vellekoop was born in Amsterdam in 1960. He received the BSc degree in Physics in 1982 and the PhD degree in Electrical Engineering in 1994. In 1984, he joined the Delft University of Technology to work in the field of acoustic wave sensors. In 1988, he co-founded Xensor Integration B.V., a company specialised in the development and production of integrated sensors, where he was managing director from 1988 till 1996. From 1996 till the summer of 2001 he was leading the Integrated Physical Chemosensors group of the DIMES Electronic Instrumentation Laboratory (Microelectronics Department, Delft University of Technology), since 1997 as an associate professor. Since the summer of 2001 he is a full professor at the Institute of Industrial Electronics and Material Science at the Vienna University of Technology, Austria, in the field of Industrial Sensor Systems.