Radio Frequency CMOS Chem-bio Viscosity Sensors based on Dielectric Spectroscopy

Subhajit Guha and Christian Wenger
IHP, Leibniz Insititute for Innovative Microelectronics, Frankfurt (Oder), Germany

Keywords: CMOS Viscosity Sensor, Dielectric Sensor, RF Viscosity Sensor, High Frequency Viscosity Sensor.

Abstract: This paper presents a CMOS Radio frequency dielectric sensor platform for the detection of relative viscosity changes in a fluid sample. The operating frequency of the sensor is 12.28 GHz. This frequency range has been chosen for high signal to noise ratio and also to avoid other low frequency dispersion mechanisms for future lab on chip applications. The sensor chip has been fabricated in 250 nm BiCMOS technology of IHP. The measurements conducted to show the relative viscosity variation detection capability of the sensor chip, were based on mixtures of glycerol and water as well as glycerol and organic alcohol. The detection limit of viscosity is dependent on the permittivity contrast of the sample constituent. Therefore, it is also shown the choice of frequency inherently aids in the permittivity contrast of the sample constituents.

1 INTRODUCTION

Viscosity sensors are widely developed and utilised primarily for sensing and analysis of oil or fuel (Agoston et al., 2005, Perez and Hadfield, 2011). There is a significant use of such sensors in the automotive industry where detection of contamination or breakdown of oil is of extremely high relevance. Therefore, there is a wide range of commercially available robust viscosity sensors. The working of such sensors are mostly based on mechanical or piezoelectrical sensing mechanisms (Agoston et al., 2005, Thalhammer et al., 1998, Shih et al., 2001, Brouwer et al., 2011). The use and success of viscosity sensors have inspired researchers to use the same principles for various other applications.

In the recent past, there have been efforts to use the principles of viscosity sensors in biosensing applications. Various research groups have designed and developed sensors to estimate glucose concentration in blood (Boss et al., 2012, Zhao et al., 2007) or analyse blood coagulation using the concept of viscosity change (Cakmak et al., 2014). The sensing principle for these developed viscosity based biosensors are also mechanical or piezoelectrical, influenced directly from the established commercial viscosity sensor. The mechanical principle is based on the deflation of cantilevers or beams when a fluid comes in contact with the same. The viscosity of the fluid determines the degree of deflation or deformation of the beam. A significant drawback suffered by this kind of sensors is the relaxation of the beam or the cantilever back to the original position. Therefore, there can be considerable calibration issues for such devices. Piezoelectric based sensors require a piezomaterial, where a variation of mechanical stress on the piezo material leads to an electrical output, such as voltage or current, depending on the read out mechanism. The adhesion or the influence of the biological sample on the piezomaterial pose a serious challenge for such sensors. Recently, MEMS based CMOS compatible viscosity sensor was shown by (Cakmak et al, 2014). working on the same principle of micro-cantilever deformation. Although, reduction in sample volume was achieved, the cantilever approach could still suffer from calibration failures. Impedance spectroscopy method was discussed by (Perez and Hadfield, 2011), where the authors described a viscosity sensor based on the detection of variation of permittivity. The frequency range of operation is in the order of few 1 MHz. Application of this sensor in biological applications will be critical, as there are other dispersion mechanisms of biological samples in this frequency range which could influence the signal to noise ratio for viscosity characterization.

In this work, we propose CMOS on chip dielectric sensor for viscosity characterization. The frequency range of operation is in the order of 12 GHz. In

Guha S. and Wenger C.
Radio Frequency CMOS Chem-bio Viscosity Sensors based on Dielectric Spectroscopy.
DOI: 10.5220/0006151901420148
In *Proceedings of the 10th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2017)*, pages 142-148
ISBN: 978-989-758-216-5

previous works, it was shown that such sensors can be used for the detection of concentration of cells and particles in a suspension (Guha et al., 2015), detection of biomarkers like creatinine and more (Guha et al. 2015). The sensing principle is based on the detection of dielectric change using a capacitive sensor embedded in a resonant CMOS oscillator. In this work, it is proposed that the viscosity variation of fluid samples can be measured by the detection of the change in the dielectric constant of the fluid. Such a sensor can be envisaged for future lab on chip application like characterization of sputum for detection of lung diseases. In this paper we will describe the working principle of the sensor and show the operation of the sensor with mixtures of liquids with different viscosities. The operating frequency of the sensor is chosen to be 12 GHz; this high frequency leads to small chip size and hence small sample volume. Additionally, this frequency range enables a better signal to noise ratio for sensing due to strong contrast in dielectric permttivities.

The paper is organised in the following manner: Section 2 describes the sensor and the high frequency operation. Section 3 shows the results. The concluding remarks and the application of such a sensor is described in section 4.

2 RF SENSOR OPERATION

The sensor operation is based on the detection of dielectric constant of the sample using a capacitive sensor embedded in the CMOS oscillator. The variation of the capacitance due to the permittivity of the samples leads to the tuning of the resonant frequency of the oscillator. Oscillator based dielectric sensors have been researched upon considerably for the past years and the working principle can be found extensively in literature (Guha et al., 2015, Jamal et al., 2014, Wang et al., 2010). In this work, we extend this sensor platform for viscosity detection.

Although, there are considerable amount of viscosity sensors, CMOS based viscosity sensors are still not well established. Such sensors could be extremely useful for lab on chip applications. For example, sputum samples from different patients have different viscosities and the detection of the same can enable us to detect lung diseases at a very early stage. Viscosity change of a liquid sample can be detected from the permittivity. This is due to the relationship between the permittivity of the overall liquid and the fraction of its various constituents. For example, a glycerol water mixture sample has different viscosities depending on the amount of water in the mixture. At the same time, different water content in the mixture leads to different permittivity of the sample. Therefore, there exists a correlation between the changes in viscosity with the change in the effective dielectric constant of the sample. It should be also noted here, that the knowledge of the fluid constituents of the sample is needed for this kind of indirect viscosity sensing. In this context, the question arises if high frequency sensor is of relevance for the detection of viscosity change. We have seen in literature that high frequency dielectric sensors are extremely useful for the detection of concentration of particles in the suspension (Guha et al., 2015). In the case of viscosity sensor based on dielectric measurements, a high signal to noise ratio can be obtained if the contrast between permittivities of the constituents are considerably high. Considering the glycerol water mixture example again, we find from the literature that the low frequency permittivity of water is around 80 and that of glycerol is 42.5. This provides a considerable amount of contrast in the dielectric permittivities. Therefore, a low frequency detection could be useful. However, if the sensor system has to be a unique platform applied to lab on chip applications, it can be extremely critical at low frequency to obtain a high signal to noise ratio. This is because, the biological samples show dispersion mechanisms at low frequencies and can lead to considerable variation in the results. Therefore, a chosen operating frequency of 12 GHz can be useful. At this frequency considering the glycerol water mixture as an example again, the permittivity contrast is still of the same order.

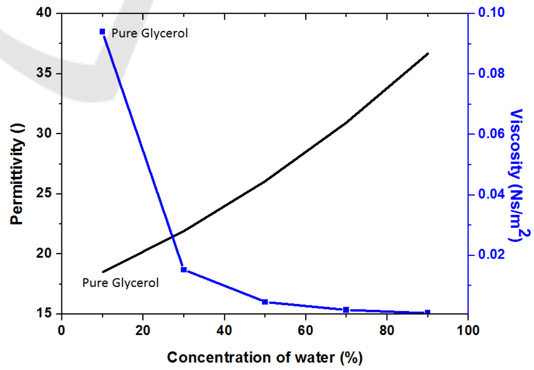

Figure 1: Permittivity and viscosity variation of glycerol and water mixture with respect to water content at 12 GHz.

The permittivity of glycerol is approximately 17 and that of water is 40 at this frequency range. Therefore, operating the sensor in this frequency range provides the advantage of obtaining the permittivity contrast and at the same time avoids the low frequency dispersion mechanisms. Fig 1 shows the variation of permittivity and viscosity as a function of water content in the solution at 12 GHz. Mixture theory was used to calculate the effective permittivity of the mixture and the effective viscosity.

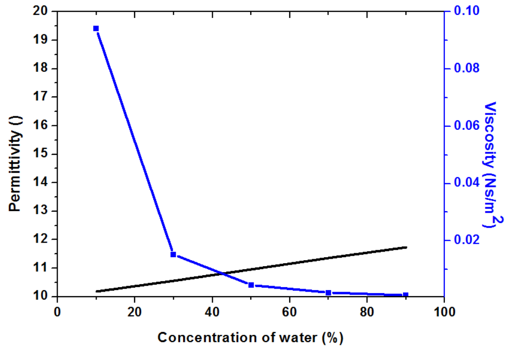

Figure 2: Permittivity and viscosity variation of glycerol and water mixture with respect to water content at 60 GHz.

In case of higher frequency of operation of the sensor, there is a loss on the dielectric contrast. This is shown in Fig. 1 and Fig. 2. At 12 GHz, the variation in permittivity of the glucose water mixture due to water content variation is considerably higher when compared to the variation of permittivity of the same at 60 GHz. However, the variation in the viscosity of the mixture due to its water content is uniform at both the frequencies, as viscosity is a frequency independent parameter.

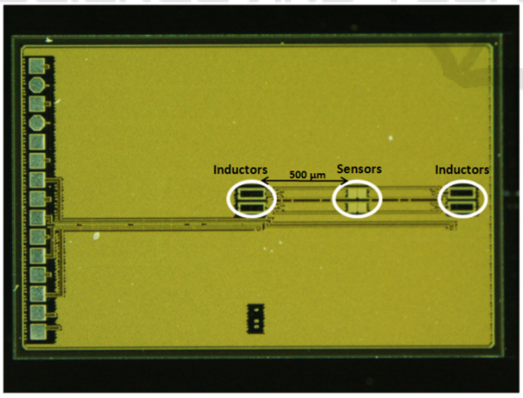

Figure 3: Chip Photograph of sensor chip.

Additionally, the inherent advantage of the high frequency sensor is the sensor chip size and in turn the sample volume required. The sensor chip photo is shown in Fig. 3.

The sensors as seen from a closer look are interdigitated capacitors (IDC) with over-all size of 50 µm x 50 µm. Therefore, sample volume of the order of µl is required for detection. The planar IDC is a fringing field sensor; the fringing electric fields between the adjacent fingers are utilised to detect the dielectric permittivity of the sample placed on top of it. The penetration depth of the fringing fields is the function of the geometry of the IDC structure. For homogeneous solutions, where, the permittivity is uniform all over the solution the penetration depth is not of significance. Therefore, it can be understood that the IDC structures can be used for accurate near field sensing approaches. The sensor chip was fabricated in the 250 nm technology of IHP , with f_t/f_{max} of 180 GHz/250 GHz. The overall chip size 1.8 mm x 3 mm. The larger dimension of the chip in spite of smaller sensor area will be explained in the subsequent experimental and results section.

The sensor architecture details can be found in literature. In Fig. 4, the schematic of the sensor architecture is shown.

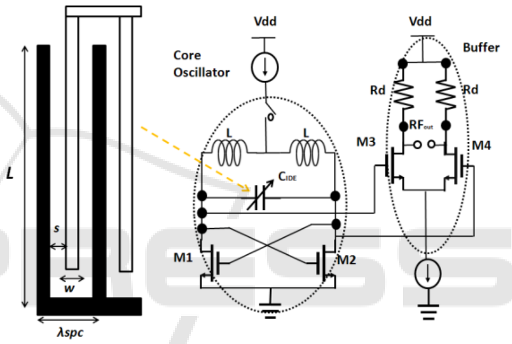

Figure 4: Sensor architecture: Sensor IDC embedded in CMOS oscillator.

As mentioned above the sensor capacitor is embedded in the oscillator and the read out parameter of the sensor is the oscillating frequency of the sensor.

3 EXPERIMENTS AND RESULTS

RF boards were prepared for measurements with viscous liquids. The sensor chip was wire bonded to the board. For the first measurements with the viscous liquid samples no mircrofluidic integration was done. Therefore, one major challenge was encountered while the measurement of liquids, where the bond wires used or the bonding of the chip could be broken due to interaction with the fluid. In order to avoid this scenario, measures were taken to protect the bond wires. This was done by sealing the chip pad area with a dielectric material. This is shown in Fig. 5.

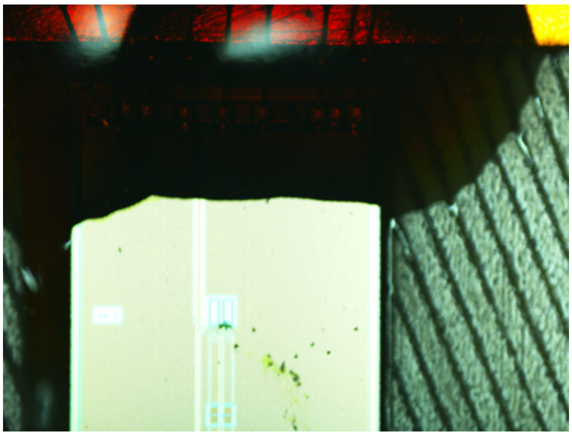

Figure 5: Sensor chip with the dielectric material protecting the bond pads and bond wires.

The dielectric medium prevents the bond wires coming in direct contact with the liquid medium and therefore, no breaking of bond wires can take place. This kind of an approach adds an additional degree of robustness to the chip, wherein, the sensor chip can be dipped in the liquid for accurate calibration of the chip. This method also aids in the cleaning of the chip using ethanol. Therefore, after conduction of every measurement the sensor area can be cleaned for the next set of measurements. This is a significant issue when such kinds of sensors are used for accurate long term usage.

The influence of dielectric packaging of the chip can be seen on the RF output. It is known, that the RF measurement devices are calibrated to 50 Ohms, Therefore, the output lines for the RF signal is designed to have a characteristic impedance of 50 Ohms. The same is done for the RF lines on the board in order to incur minimal losses to the RF signal due to reflection. The bond wires account for some losses. However, encapsulating the bond pad area with the dielectric medium results in additional losses to the RF signal which can reduce the RF output power. However, the RF output power is considerably higher than the noise floor of the measurement device and can be accurately measured.

Fig. 6 shows the measurement setup of the sensor chip with the viscous liquid. A Rhode and Schwarz X-band spectrum analyser has been used for the measurement of the RF spectrum.

It can be seen from the inset view of the spectrum analyser screen (Fig. 7), that the measured RF output power (-27 dBm) is considerably higher than the noise floor of the device. The measurements were conducted in 2 steps. Initially a calibration of the sensor chip was performed with known alcohols with known values of permittivity and viscosity. In the second set of measurements the mixture of glycerol and water was used to measure the oscillator output with varying viscosity. The last set of measurements were performed with the mixture of glycerol and ethanol to show the significance of knowing the constituents of the sample for indirect viscosity measurement.

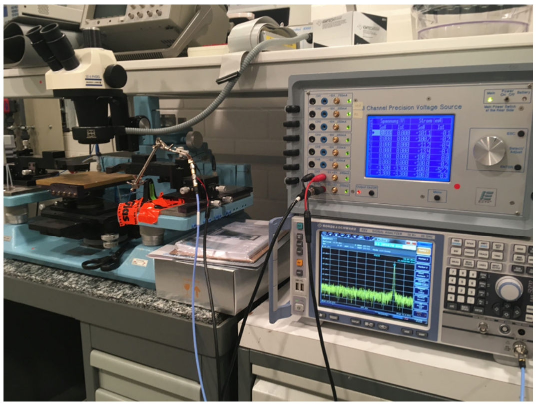

Figure 6: Measurement setup showing Spectrum analyser, power supply and chip holder.

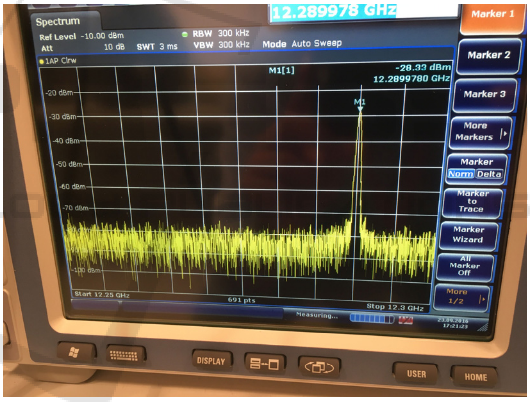

Figure 7: Inset of spectrum analyser. The oscillating frequency with air is 12.28 GHz.

3.1 Calibration

The sensor chip needs to be calibrated with known alcohols of different permittivities and viscosities. With no material on top of the sensor, the output frequency of the sensor is measured to be 12.28 GHz. This can be seen from the inset view of the spectrum analyser in Fig. 7. For the next calibration step the sensor chip was measured with organic alcohols. Four different alcohols were used for the measurement, namely, ethanol, methanol, acetone and isopropanol. Fig. 8 shows the variation of the oscillating frequency with respect to permittivity of the alcohol.

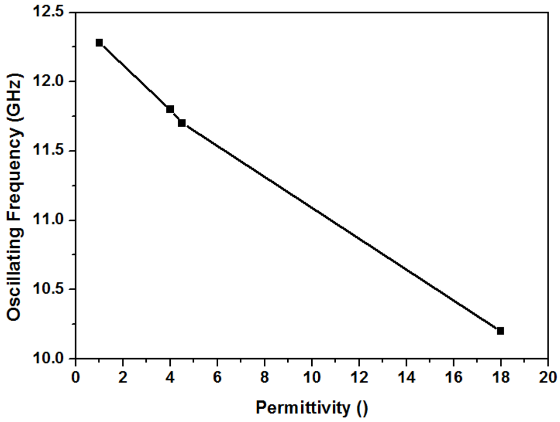

Figure 8: Calibration using different types of organic alcohols.

It is straight forward to understand the variation of the output oscillation frequency with respect to permittivity. As the permittivity increases the capacitance of the sensor capacitor increases as well. The output oscillation frequency which has an inverse relation to the capacitance value of the sensor capacitor decreases with the increase of the capacitance. The relative permittivity values of the alcohols at 12 GHz and at room temperature are given in Table 1.

The corresponding viscosity and permittivity values of the alcohols are also shown in Table 1.

Table 1.

Alcohol	Permittivity	Viscosity(mPa.s)
Isopropanol	4	2.1
Ethanol	4.5	0.983
Methanol	8.2	0.507
Acetone	18	0.30

From Table 1 it is seen that the viscosity values decrease with the increase in permittivity of the acid. However, on the other hand, it is seen water has a permittivity of 42 at 12 GHz and a viscosity of 0.81 mPa.s. Therefore, it can be understood that there is no relation between the absolute values of the relative permittivity and the viscosity. The sensor being ideally a dielectric sensor, can detect variation in the viscosity of a solution based on the permittivity variation. Therefore, it is needed to know the permittivity values of the constituents of a liquid sample in order to detect the viscosity variation. This will be shown in more detail with two different sample mixtures with opposite permittivity trends but same viscosity trends.

3.2 Viscosity Measurement

The operation of the sensor to detect viscosity variation is done using the mixture of water and glycerol. Water being a non-viscous liquid reduces the viscosity of glycerol considerably with its increasing concentration. On the other hand, water has a high permittivity as mentioned in previous section when compared to glycerol. Therefore, increasing the concentration of water in the mixture increases the permittivity of the overall solution. This was also shown in the previous section. The variation of the oscillation frequency with respect to viscosity of the glycerol water mixture is shown in Fig.9.

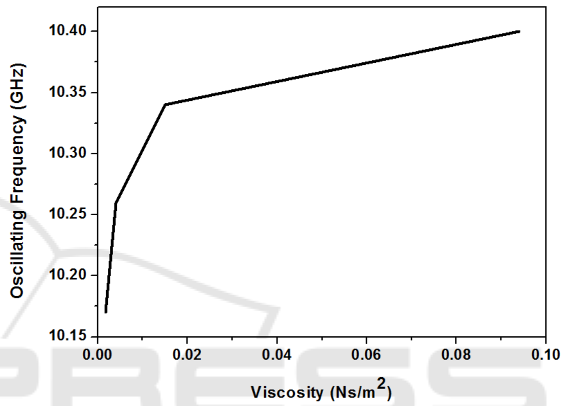

Figure 9: Variation of oscillating frequency of the oscillator with respect to viscosity variation of glycerol water solution.

3.3.1 Discussion

It should be noted here, that the sensor architecture described here is not used to detect an absolute value of viscosity of a given sample. Detection of absolute value of viscosity based on an electrical method is not feasible, unless, there is a direct mathematical correlation between viscosity and an electrical quantity. The sensor architecture in this work is used to detect a relative variation in the viscosity of a fluid sample based on its constituents. This argument becomes clear when a similar experiment was performed with a mixture of glycerol and ethanol. Prior to the that, it is important to understand the exclusiveness of viscosity and permittivity. Fig. 10 shows the variation of permittivity with respect to the percentage of ethanol in ethanol glycerol mixture.

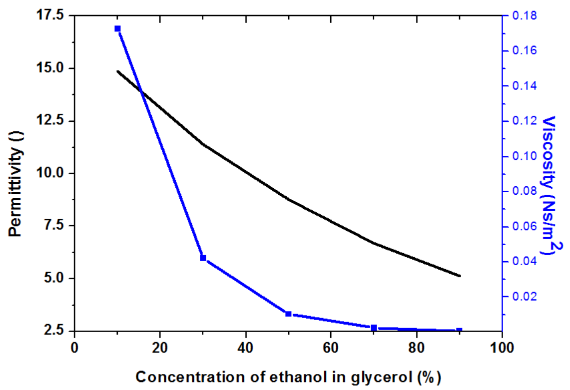

Figure 10: Variation of permittivity and viscosity with ethanol concentration in ethanol glycerol mixture.

It can be seen that as the concentration of ethanol increases in the ethanol glycerol mixture, the permittivity and the viscosity decrease for the overall mixture. This is in contrast to the glycerol water mixture where the increase in water content in the glycerol water mixture increased the permittivity and reduced the viscosity. Therefore, it can be very well understood that the permittivity for a given viscous sample is dependent on the constituents of the sample

The sensor detects only the permittivity and not the absolute value of viscosity of the solution. This can be seen with the experiment on the sensor chip with the mixture of ethanol and glycerol. The results of the same are shown in Fig. 11.

It is observed, that the oscillating frequency reduce with increasing viscosity (reduction in ethanol content in the solution). This is because ethanol has a lower permittivity as compared to glycerol. Therefore, increasing the ethanol concentration reduces the permittivity of the solution. Ethanol also has a substantially low viscosity as compared to glycerol. Therefore, increasing the concentration of ethanol reduces the viscosity of the solution as well. This was not the case for water glycerol mixture, where permittivity of the overall solution increased with increasing water content due to high permittivity of water and viscosity decreased with increasing water content.

Now the question arises about the use of the sensor in lab on chip application like characterization of sputum as was mentioned in the introductory section. From the literature it is known that the viscosity of sputum sample varies with the constituent it for different patients with lung disease (M. Lopez-Vidriero et al., 1973). Especially the water content of the sputum varies for different patients. Knowing the constituents of the sputum, the variation of water content will vary the relative viscosity of the sputum and along with it its permittivity. This sensor architecture can thus ideally be used for the detection of the sputum viscosity variation.

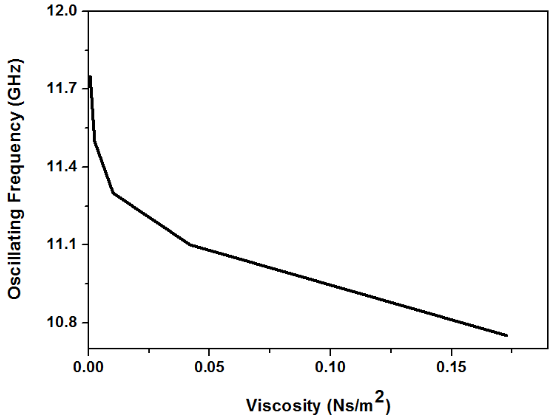

Figure 11: Variation of oscillating frequency of oscillator with respect to viscosity of ethanol glycerol mixture.

4 CONCLUSIONS

In this work we have shown a high frequency sensor operating in the frequency range of 12 GHz to detect the viscosity change in a fluid. It was shown that the choice of the frequency range was based on high signal to noise ratio due to high contrast in dielectric permittivity. At lower frequencies, the contrast between the dielectric permittivities of the liquids are still high, however, other dispersion effects might influence the use of the sensor in future lab on chip applications. On the other hand, very high frequency operation reduces the contrast between the dielectric permittivities of the samples, and was shown in analytically for glycerol water mixture at 12 GHz and 60 GHz. Solutions with different viscosities were measured and a shift in the resonant frequency of the sensor oscillator was shown in this work. Two solution mixture was characterized: glycerol water mixture and glycerol ethanol mixture. For glycerol water mixture, the increase in water content increased the mixture permittivity and reduced the mixture viscosity. On the other hand, for the ethanol glycerol mixture, the permittivity and viscosity decrease with increasing ethanol content. The sensor architecture is suitable to detect the permittivity change based on which the solution viscosity of known constituents can be obtained. It was highlighted that this method is an indirect way of detection of viscosity. This is due to the fact that viscosity being a mechanical quantity, cannot be measured directly with an electrical quantity. Therefore, knowing the characteristics of the constituents is extremely important. This kind of sensor architecture is suitable for future lab on chip applications like sputum characterization based on viscosity variation of the sample.

ACKNOWLEDGEMENTS

The authors would like to thank BMBF, Germany for funding the project under the grant no: 13U13862. The authors would also like to thank the technology department of IHP for fabrication of the chip.

REFERENCES

Agoston, A., Otsch, C., Jakoby, B., 2005. Viscosity sensors for engine oil condition monitoring-Application and interpretation of results. *Sensors and Actuators A: Physical*. 121 (2), 327-332.

Torres Perez, A., Hadfield, M., 2011. Low-cost oil quality sensor based on changes in complex permittivity. *Sensors*. 11, 10675-10690.

Thalhammer, R., Braun, S., Devicic-Kuhar, B., Groschl, M., Trampler, F., Benes, E., Nowotny, H., Kostal, M. 1998. Viscosity sensor utilizing a piezoelectric thickness shear sandwich resonator. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*. 45 (5), 1331-1340.

Shih, W., Li, X., Gu, H., Shih, W-H., Aksay, I. 2001. Simultaneous liquid viscosity and density determination with piezoelectric unimorph cantilevers. *Journal of Applied Physics*. 89(2), 1497-1505.

Brouwer, M., Gupta, L., Sadegi, F., Peroulis, D., Adams, D. 2011. High temperature dynamic viscosity sensor for engine oil applications. Sensors and Actuator A: Physical. 173, 102-107.

Boss, C., Meurville, E., Sallese, J.M., Ryser, P. 2011. A viscosity-dependent affinity sensor for continuous monitoring of glucose in biological fluids. *Biosensors and Bioelectronics*, 30 (1), 223-228.

Zhao, Y., Li, S., Davidson, A., Yang, B., Wang, Q., Lin, Q. 2007. A MEMS viscometric sensor for continuous glucose monitoring. *Journal of Micromechanics and Microengineering*. 17, 2528-2537.

Cakmak, O., Ermek, E., Kilinc, N., Baris, I., Kavakli, I.J., Yaralioglu, G.G., Urey, H. 2014. Microcantilever based LOC system for coagulation measurements. In Proceedings, *18th International Conference on Miniaturized systems for chemistry and Life Sciences*, Texas, USA.

Guha, S, Wolf, A., Lisker, M., Trusch, A., Meliani, C., Wenger, Ch. 2015. 12 GHz CMOS MEMS lab-on-chip system for detection of concentration of suspended particles in bio-suspensions. *In Proceedings, Biodevices*, Lisbon, Portugal.

Guha, S., Warsinke, A., Tientcheu, Ch.M., Schamlz, K., Meliani, C., Wenger, Ch. 2015. Label free sensing of creatinine using 6 GHz CMOS near-field dielectric immunosensor. *Analyst* 140, 3019-3027.

Jamal, F.I., Guha, S., Eissa, M.H., Borngraeber, J., Meliani, C., Kissinger, D., Wessel, J. 2016. Comparison of microstrip stub resonators for dielectric sensing in low power K-Band VCO. In Proceedings *IEEE Topical Conference on Biomedical Wireless Technologies, Networks and Sensing*, Texas, USA.

Wang, H., Sideris, C., Hajimiri, A. 2010. A frequency shift based CMOS magnetic biosensor with spatially uniform sensor transducer gain., IEEE; Custom Integrated Circuit Conference, USA.

Lopez-Vidriero, M., Charman, J., Keal, E., De Silva, D., and L Reid, L. 1973. Sputum viscosity: correlation with chemical and clinical features in chronic bronchitis. Thorax, 28, 401- 408.