

# A novel thick-film electrical conductivity sensor suitable for liquid and soil conductivity measurements



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## ABSTRACT

Results are reported from an initial evaluation of a novel conductivity sensor that could be incorporated onto a multi-element thick film (screen printed) sensor array designed for soil and water analysis. The new sensor exhibits a repeatable cell constant over a wide range of conductivities and is currently performing very well in an investigation of soil structural properties where its output is being correlated with soil water content in a study of different soil porosities.

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## 1. Introduction

Increasing interest in optimal environmental management, site-specific crop management (SSCM) and climate impact on soil behaviour have all resulted in a rising demand for in situ soil sensing among many environmentalists and soil scientists [1–3]. Floodplain ecosystems are dependent on the specific hydrological regime but the mechanisms controlling species composition of the hydrological regime and related temperature and nutrient levels have not yet been fully understood [4]. SSCM, also called precision agriculture, evaluates variability in soil properties (e.g., pH, temperature, organic matter, water content and soil nutrient levels) to optimise inputs such as fertilizers and herbicides for an optimised agricultural growth [3]. Specific soil parameters and their critical limits are considered to reflect the impact of the climate on soil behaviour [5] and require monitoring to identify changes in soil quality which will provide the basis of understanding some of nature's unknown mechanisms for various agro-ecological zones at district, national and global levels [6]. Low cost, miniaturised electrochemical and physical sensors with modest electronic instrumentation demands that can be buried in the soil allow for an online high density sensor network providing vital data information for the understanding of climate impact on soil behaviour and furthermore on the ecosystem of an area.

Measuring soil conductivity can provide vital information on soil quality as well as distinguishing between different types of soil (e.g. clay, gravel, sand, limestone, coal and several combinations of them) [7,8]. Conductivity readings combined with porosity measurements can give information on the stability of the ground [9,10] which can be extremely important in applications such as monitoring of train rail supporting structures. Electrical conductivity of soil solutions can also be a reliable indicator of ionic concentration and the practice of measuring soil apparent electrical conductivity to evaluate soil salinity has been spreading continuously since the 1970s [11,12]. A significant incentive for the determination of soil solution electrical conductivity from apparent electrical conductivity measurements has developed from the possibility of simultaneous measurements of apparent electrical conductivity and soil volumetric water content [13,14]. The water content and soil solution electrical conductivity are the major factors affecting the apparent electrical conductivity. However, this relationship depends on additional soil and environmental attributes, which limits the predictability of general, theoretical relationships and often necessitates performing laborious, site-specific calibrations. A general model that relies on easily attainable soil parameters has not yet been proposed [10].

Although conductivity probes are available commercially, their cost including the instrumentation required to take readings renders them unfeasible for high density sensor networks [15–17]. Thick film conductivity sensors are of low cost, rugged, miniature and robust design and have the ability to be integrated onto a single substrate with other thick film sensors to form a 'lab-on-chip' sensing array. In a previous design for a thick film environmental sensor array [18], planar conductivity cell electrodes were

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simultaneously printed along with other electrochemical sensor electrodes on the same device such that the conductivity electrodes were produced with no additional cost other than the insignificantly small microgram amount of electrode material used. In addition, due to the sensor design the required electronic interface circuits can be of low complexity providing the opportunity for a higher density sensor network in the investigation area [19].

## 2. Background theory

Although electrical conductivity ( $\sigma$ ) is widely accepted as a simple and well understood principle, if the material of interest is non-homogeneous or non-isotropic it becomes more complicated and more difficult to measure. Electrical conductivity is defined as the reciprocal of resistivity ( $\rho$ ).

Assuming the material to be homogeneous and isotropic then  $\rho$  becomes a scalar defined by Eq. (1):

$$\rho = \left(\frac{V}{I}\right) \cdot \left(\frac{A}{L}\right) \quad (1)$$

where  $V$  is the potential difference (V),  $I$  is the current (A),  $A$  is the cross sectional area through which the current flows ( $\text{m}^2$ ),  $L$  is the distance over which the potential difference is applied (m) and  $\rho$  is the resistivity (Ohm m). Conductivity is defined as the reciprocal of resistivity and is measured in Siemens per metre (S/m) although sometimes it is more conveniently expressed as mS/cm. Therefore, from Eq. (1) conductivity can be calculated as:

$$\sigma = \left(\frac{I}{V}\right) \cdot \left(\frac{L}{A}\right) \quad (2)$$

where  $V$  is the measured voltage (V),  $I$  is the drive current (A) and the term  $L/A$  is the cell constant ( $\text{m}^{-1}$ ) [20]. The specific sensor described here is based on the four electrodes method of conductivity measurement using an alternating square wave current source as the excitation signal. The conventional four electrodes method is very simple and more details on the theory can be found elsewhere [7].

In this four electrode method the outer electrodes, which are in contact with the sample measurand, are the current carrying electrode pair and the inner electrodes are the voltage ( $\Delta V$ ) measuring electrode pair. Assuming that the current passing between the two outer electrodes is equal to the current passing through the inner ones, the electric field developed between the voltage electrodes depends on the electrical impedance of the sample. Using Ohm's law, the impedance of the measurand can be calculated and

if a constant current source ( $I$ ) is used then that impedance is equivalent to the impedance of the measured sample. If the cell constant ( $L/A$ ) is also known the conductivity of the solution can be calculated using Eq. (3). However due to fringing of the electric field between the electrodes, these two currents are not the same and hence the cell constant becomes a function of the fringing. The fringing in turn is a function of the conductivity of the measurand, giving rise to non-linearity in the measurement of conductivity. There are however, several advantages to using the four electrodes method including the minimisation of polarisation effects as well as a longer electrode lifetime and a wider measuring range. The use of an alternating current source also minimises any polarisation effect and in particular, the use of low frequencies minimises any errors that might arise due to the effective capacitance of the measurand. The commonly used frequency range is from about 100 Hz to several kHz, because at lower frequencies electrode polarisation interferes with the readings and at higher frequencies apparent conductivity is no longer constant at the dc value, but increases with frequency (a phenomenon termed dispersion) [10].

## 3. Sensor fabrication and geometry

Planar arrangements for conductivity sensors, such as those used in some previous studies [18,19] have several disadvantages, especially for soil. The most important drawback is that for soil sensing it is often desirable to monitor over a relatively large volume of soil (as compared to liquids) to compensate for any lack of homogeneity in the sample. This requirement generally dictates a much larger spacing of the electrodes, which can further exacerbate the problems of fringing as a result of increased electrical path length. One way around this is to also increase the effective cross-sectional area of the measured sample by increasing the surface area of the electrodes thereby maintaining the cell constant; however this simple expedient can still prove sensitive to electrode alignment issues. An alternative strategy has been adopted here that exploits ratiometric symmetry in the electrode arrangement to overcome some of these issues.

An initial design for a previously described multi-element sensor array [18] utilised a simple four electrode planar conductivity cell where the electrodes were made of a high purity platinum ink (Heraeus RP 10001-145B) printed on a ceramic substrate (96% alumina, Coors Tech). However due to significant issues with variable fringing at different analyte conductivities the cell geometry was changed in a subsequent design to that of the three dimensional model depicted in Fig. 1, using a supporting structure that was

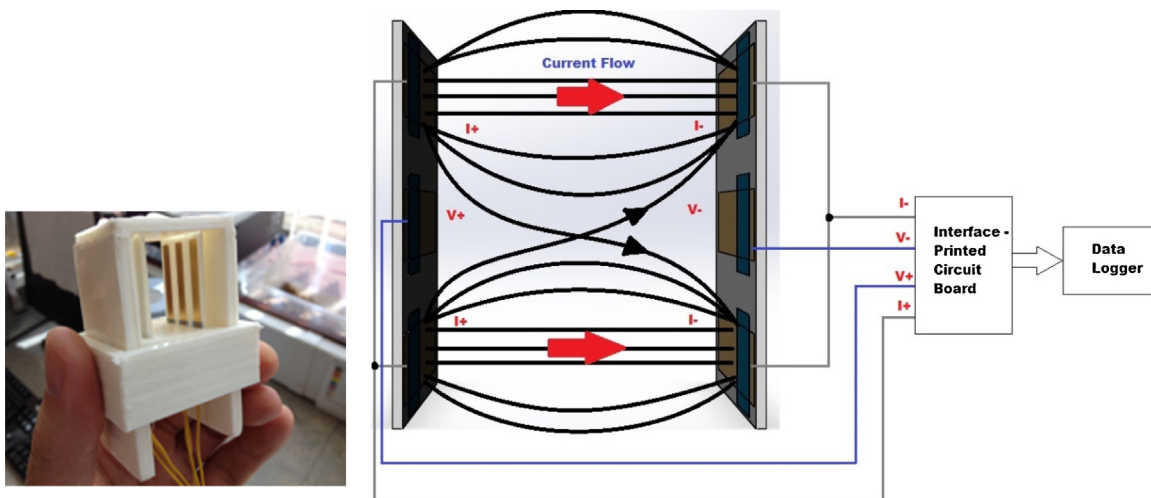


Fig. 1. Conductivity cell electrode configuration and geometry.

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