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Application Note Conductivity Sensors

V 1.1

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1 General information

1.1 Theory

1.1.1 Resistance vs. conductance

The resistance represents the opposition to the flow of electric current within an electrical circuit. It determines how much the current is reduced when a voltage is applied. The relation between resistance, applied voltage and current is given below.

$$R = \frac{V}{I}$$

eq. 1-1

where

R [Ω]	resistance
V [V]	voltage
I [A]	current.

Conductance is the reciprocal of resistance and indicates how easily electric current flows through a material. In other words, while resistance measures opposition to current, conductance measures the ease of current flow. This relation is given in eq. 1-2

$$G = \frac{I}{V} = \frac{1}{R}$$

eq. 1-2

where

G [S]	conductance.

1.1.2 Solid conductor

In a solid conductor, electric current is produced through electron movement. Within an electrical circuit, resistance depends on several factors, including the conductor's geometry, temperature, material, as well as frequency of the applied voltage. The material property **resistivity** quantifies how strongly a material opposes the flow of an electric current. Materials with high resistivity offer greater resistance, while those with low resistivity allow current to flow more easily.

At a given temperature and frequency, the total resistance of a solid conductor therefore depends on its material, as well as its geometry. Or in other words, from known resistance and geometry, resistivity can be calculated as

$$\rho = R \cdot \frac{A}{L}$$

eq. 1-3

where

ρ [Ωm]	resistivity
A [m^2]	cross-sectional area perpendicular to current flow

L [m] length of conductor.

A schematic representation of the geometric parameters is given in Figure 1-1.

Figure 1-1 Graphical representation of the geometrical factors of a solid conductor

In analogy to resistivity, a material specific property called **conductivity** can be defined. It defines the material-specific contribution to current conduction. Using the situation introduced in Figure 1-1, conductivity is written as

$$\sigma = G \cdot \frac{L}{A} = \frac{L}{R \cdot A}$$

eq. 1-4

where

σ [Sm^{-1}] conductivity.

1.1.3 Conduction in liquids

Unlike electrons in a solid conductor, electrical currents in liquids are carried by dissolved ions. An example of ionic current in a liquid is illustrated in Figure 1-2. When a voltage is applied between two electrodes, dissolved ions begin to move: negatively charged ions migrate toward the positively charged electrode, while positively charged ions move toward the negatively charged electrode. Under direct current (DC) conditions, this ion movement can lead to effects such as agglomeration or even electroplating on the electrode surfaces. These effects can be mitigated by using alternating current (AC), which periodically reverses the polarity and prevents long-term accumulation of ions at the electrodes.

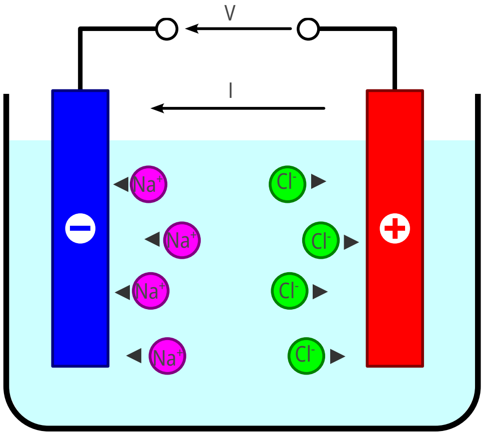

Figure 1-2 Conductivity in liquids

Unlike in solid conductors, the relationship between conductance and conductivity in liquids is less straightforward. The relationship between measured medium resistance and conductivity is still proportional, yet much less obvious compared to solid conductors. Therefore, a proportionality constant is introduced called the **cell constant**, which relates measured resistance to conductivity. Further details regarding the cell constants of iST sensors can be found in section 1.3.1.

$$k = \frac{\sigma}{G} = \sigma \cdot R \longrightarrow \sigma = \frac{k}{R}$$

eq. 1-5

where

k [cm^{-1}] cell constant.

Applying the parameter of cell constant to the solid situation in Figure 1-1 by combining eq. 1-4 and eq. 1-5 we see that the cell constant is defined in simple geometric parameters.

$$k = \sigma \cdot R = \frac{L}{A}$$

eq. 1-6

1.2 Measurement setup

To determine the conductivity of a liquid, the resistance of a conductivity sensor immersed in the medium is measured. Using the known cell constant of the selected sensor, the conductivity can then be calculated according to eq. 1-5.

Resistance can be measured using either a two-wire or four-wire configuration. For liquid measurements, this corresponds to sensors equipped with either two or four electrodes. Schematics of both measurement types are shown in Figure 1-3.

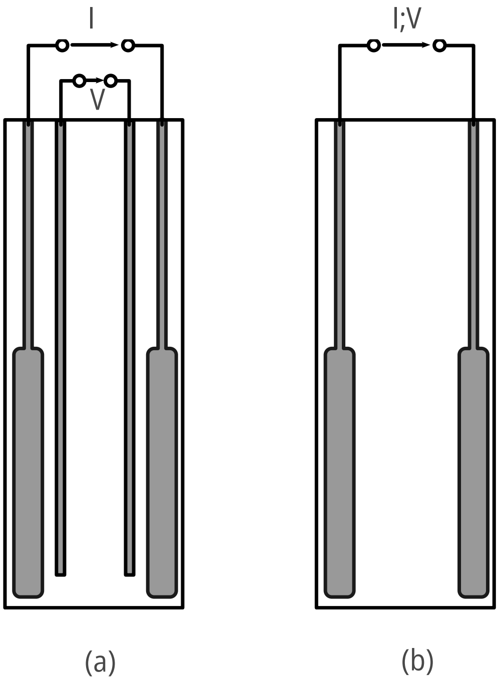

Figure 1-3 Schematics of four-electrode (a) and two-electrode (b) sensor configuration, respectively

In low-conductivity media (below 100 µS/cm), the resistance values are relatively high, and polarization effects are negligible. Therefore, a two-electrode geometry is recommended in this case. Conversely, in media with higher conductivity, a four-electrode geometry is preferred because the liquid's resistance is low. In this case, polarization effects can become significant.

1.2.1 Four electrode geometry

In a four-electrode conductivity sensor (see Figure 1-3 (a)), the current-carrying electrodes are physically separated from the voltage-sensing electrodes. This separation minimizes the influence of contact resistance and electrode polarization on the measurement, as these effects primarily occur at the current electrodes. The voltage electrodes measure the potential drop across the medium without drawing significant current, which enables accurate and stable readings.

The cell constant of the sensor is primarily determined by the geometry and arrangement of all electrodes. It depends on factors such as the effective surface area and positioning of the current electrodes, which define the current distribution through the liquid, and the spacing between the voltage electrodes, which determines the effective measurement path. The voltage electrodes are designed to minimally disturb the electric field and must not draw significant current. Because of the complexity of electric field distributions and interactions between electrodes, the cell constant is typically determined experimentally using calibration solutions with known conductivity. Alternatively, iST has the capability to simulate cell constants reliably to meet specific requirements.

Four-electrode sensors from iST typically feature cell constants between 0.4 and 1.3 cm^{-1}. They are commonly used in applications such as process control in water treatment, marine salinity monitoring, industrial cooling systems, and medical devices including dialysis machines and urine analysis equipment.

To minimize capacitive and inductive effects, especially at high frequencies or in highly conductive media, measurement frequency and signal amplitude can be adjusted. These parameters must be experimentally optimized for each sensor and target conductivity range to ensure maximum accuracy. They are generally application-specific and finally determined by the customer or in collaboration with iST engineering.

1.2.2 Two electrode geometry

In the two-electrode geometry, the same electrodes are used both to supply the measurement current and to sense the voltage. As a result, the measured signal includes not only the resistance of the liquid but also electrode surface transition resistances and capacitive effects from the electrochemical double layer. Two-electrode sensors are mainly used in applications with low ion concentrations, such as coolant monitoring, ultrapure water quality control, or chemical processes with low conductivity.

The two electrode sensors of iST have interdigitated electrodes (IDE), where the cell constant is primarily determined by the geometry of the electrode fingers (width, spacing, length) and the active electrode area. A small cell constant, typically less than 0.3, achieved through narrow electrode spacing and large active areas, enables measurements in very low conductivity ranges.

1.2.3 Temperature influence on conductivity

The resistance is highly dependent on the mobility of the dissolved ions in a liquid. At higher temperatures of the system, the mobility of the ions increases. This results in lower resistance that is detected with conductivity sensor. In first approximation the conductivity depends linearly on the temperature, this is shown in Figure 1-4 for different types of drinking water. In the linear regime the conductivity as function of temperature can be described by eq. 1-7.

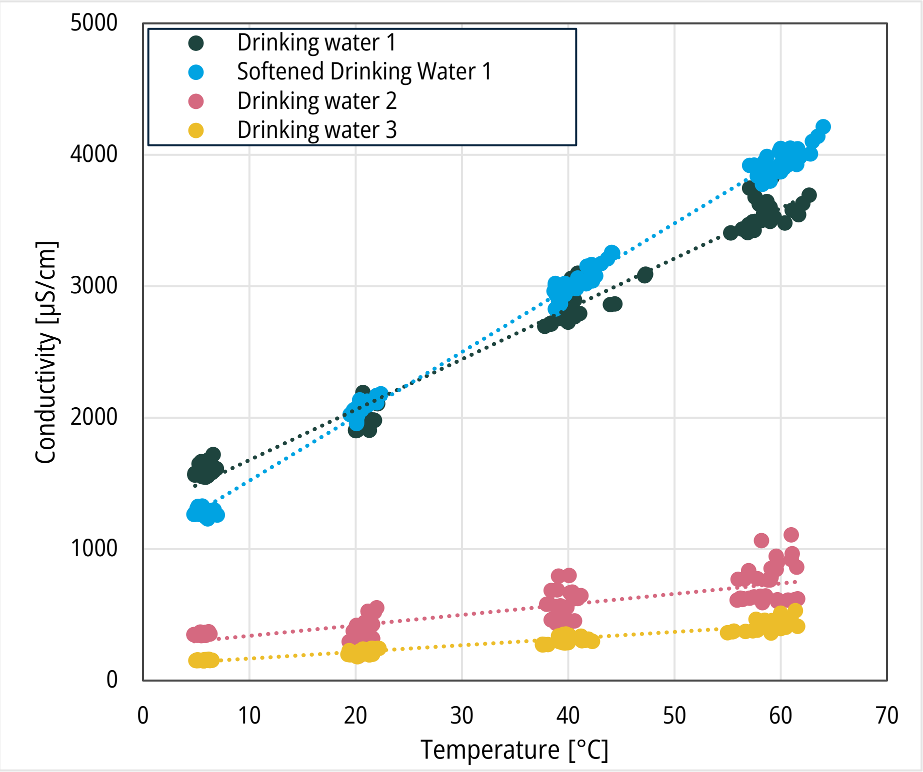

Figure 1-4 Conductivity as function of temperature for different types of drinking water

$$\sigma(T) = \sigma(25°C) \cdot \left(1 + \frac{\alpha}{100}\,(T-25°C)\right)$$

eq. 1-7

where

T [°C]	medium temperature
σ(25°C) [S/m]	medium conductivity at 25°C
α [%°C^{-1}]	temperature coefficient of conductivity

It is important to note that although this equation describes a linear relationship between conductivity and temperature, the specific thermal coefficient of conductivity of a medium, as well as the boundary conditions for which it is valid need to be known for efficient temperature compensation. In other words, not all measurement media share the same change of conductivity with temperature. The temperature coefficient (α) highly depends on the ionic species dissolved in the liquid. Different drinking waters have different ions and quantities of dissolved ions, which results in different coefficients.

1.2.4 Influence of assembly volume

The cell constant of iST's conductivity sensors is determined in a large reservoir under controlled conditions. When the sensor is assembled in a confined volume, the cell constant can be affected by interactions between the sensor's electric field and the surrounding walls. These interactions alter the cell constant and consequently the calculated conductivity. This is schematically drawn in Figure 1-5.

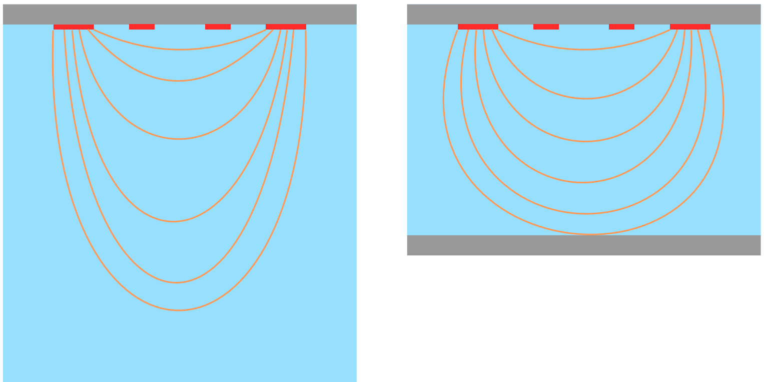

Figure 1-5 Schematic influence of surrounding wall on electric field

This issue can be resolved by calibrating the sensor in its final assembled state. Performing calibration under real installation conditions ensures that the cell constant accurately reflects the actual measurement environment, leading to reliable and precise conductivity readings.

1.3 Characteristics of iST conductivity sensors

iST's standard portfolio of conductivity sensors includes several sensor types, each designed for specific applications. These sensors differ in their cell constants. The choice of sensor depends on the conductivity range of the medium being measured. Figure 1-6 illustrates the relationship between various iST sensor elements and the conductivity ranges of different media, providing guidance for selecting the appropriate sensor.

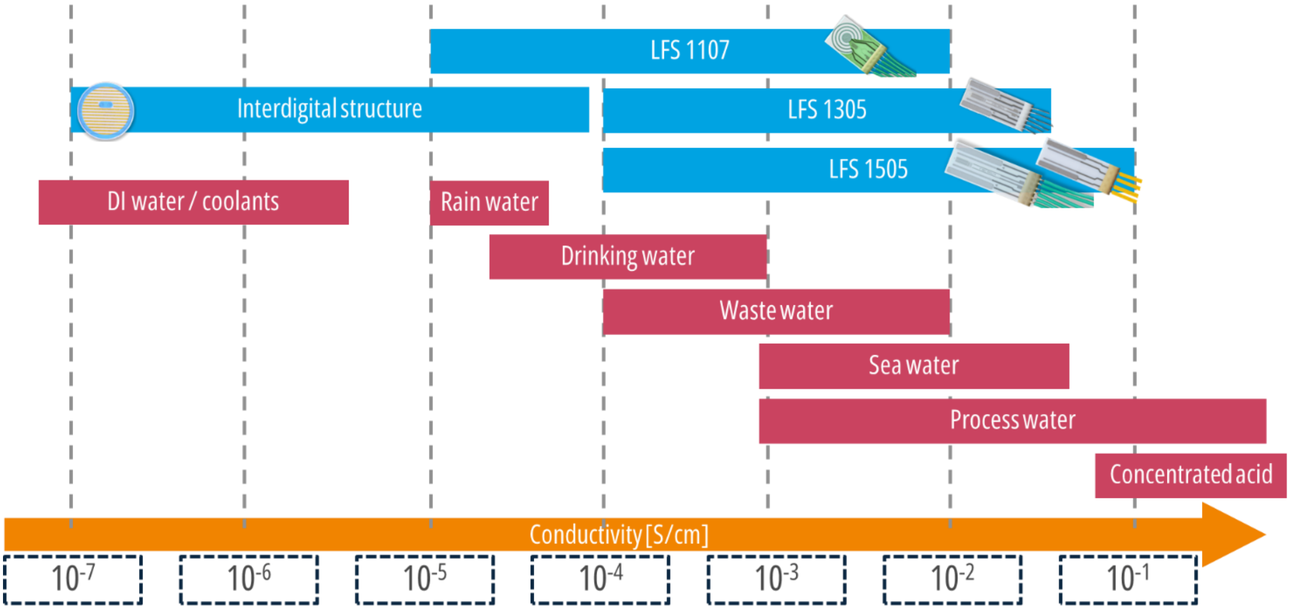

Figure 1-6 iST elements for different conductivity ranges

1.3.1 Characterization of iST conductivity sensors

For most applications, it is essential that the cell constant remain stable. However, measurement frequency can influence the cell constant. To address this, iST specifies the cell constant within a defined frequency range.

To determine these values, sensor elements are tested using various conductivity standards. The measurement volume is selected large enough to ensure that no external influences affect the results. Measurements are performed with an impedance spectrometer, which records resistance while sweeping through frequency values. Using eq. 1-5, the cell constant is then calculated at every data point.

Figure 1-7 presents a typical graphical representation of the average cell constant together with its span as function of frequency for a set of sensor elements. The data are plotted on a semi-logarithmic scale. In this example the cell constant remains stable between 49.1 Hz and 517.3 Hz, defining the suitable operating frequency range for accurate measurements.

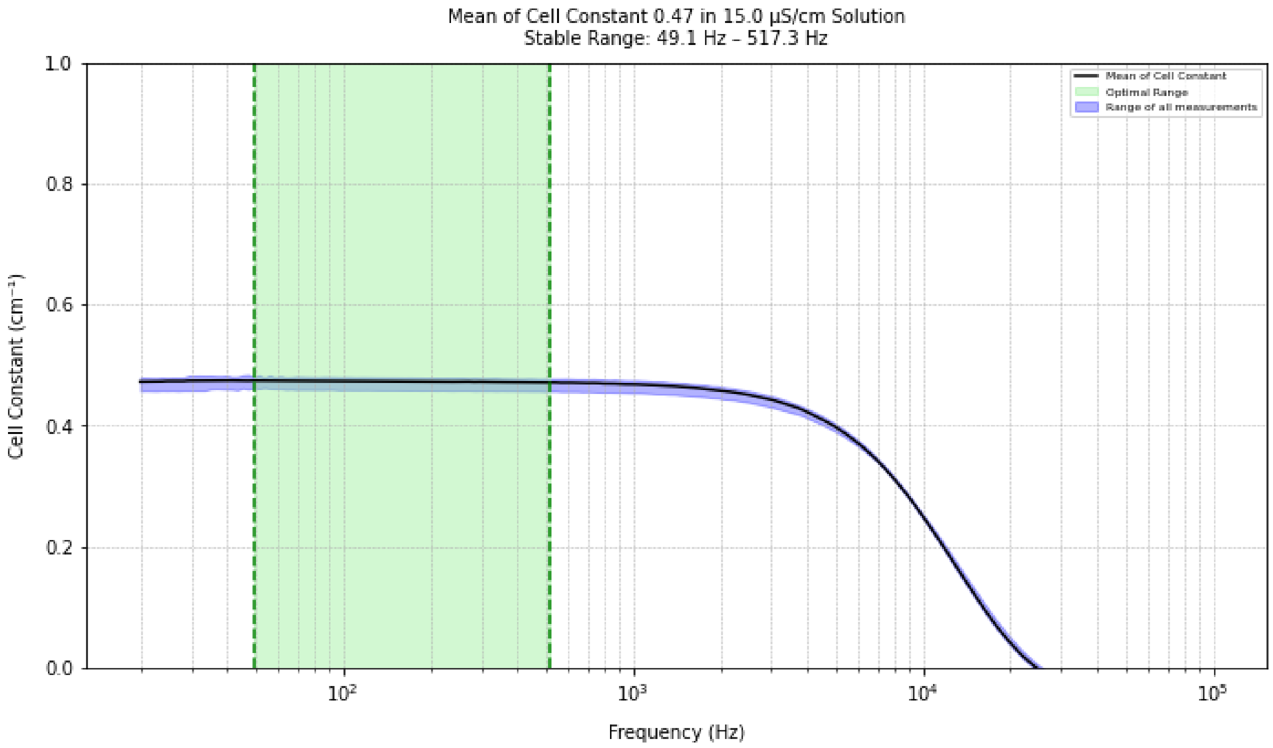

Figure 1-7 Average cell constant and its standard deviation as function of frequency

Depending on conductivity of the media, the frequency range for a stable cell constant can shift. Therefore, the measurement interval of conductivity can be increased by changing the frequency. Whether such an extension of operative conductivity range through changing frequency is possible or not needs to be confirmed in application.

1.4 How to specify your application requirements

1.4.1 Conductivity range

To select the appropriate sensor, the first step is to define the conductivity range of the medium under investigation. For conductivities below 100 µS/cm, iST recommends using two-electrode sensors, as they provide reliable measurements in low-conductivity environments. For media with higher conductivity, a four-electrode sensor is preferred because it minimizes the influence of transition resistance and ensures greater accuracy.

Figure 1-6 illustrates the standard iST sensor elements and their suitability for different conductivity ranges, serving as a practical guide for sensor selection.

1.4.2 Integration volume

As described in section 1.2.4, the integration volume can influence the cell constant of a sensor. This effect becomes particularly noticeable in small volumes, where interactions between the sensor's electric field and the surrounding walls can occur. To ensure accurate measurements after installation, the cell constant must be recalibrated under the actual operating conditions. For larger volumes, the influence of the integration volume can generally be neglected, and the cell constant remains equivalent to that determined in the uninstalled state.

Leveraging iST's simulation expertise, these effects can be calculated in advance, allowing for optimized sensor design and accurate predictions before physical installation.

1.4.3 Supply

Electrolysis of water must be avoided during conductivity measurements. Electrolysis occurs when a direct current or an excessive potential difference is applied across the electrodes, causing water to decompose into hydrogen and oxygen gases.

1.4.4 Connections

Customization is one of iST's core competencies. This includes the ability to connect different types of wires or stranded wires to the sensor elements, ensuring compatibility with various installation requirements. In addition, headers and connectors can be soldered onto a substrate or be connected to the wires.

A detailed overview of iST's customization options is provided in section 2.

1.4.5 Fixation

To measure conductivity, the electrodes must be in direct contact with the medium. It is essential, however, that the mechanical fixation of the chip's lead wires does not come into contact with the medium. Any exposure of these fixation points could compromise measurement accuracy and lead to corrosion or electrical leakage currents.

2 Construction

iST offers two different construction types of conductivity sensors: single-sided and double-sided chip designs. Each configuration provides specific advantages depending on sensor's assembly. Figure 2-1 and Figure 2-2 present exploded views of both versions.

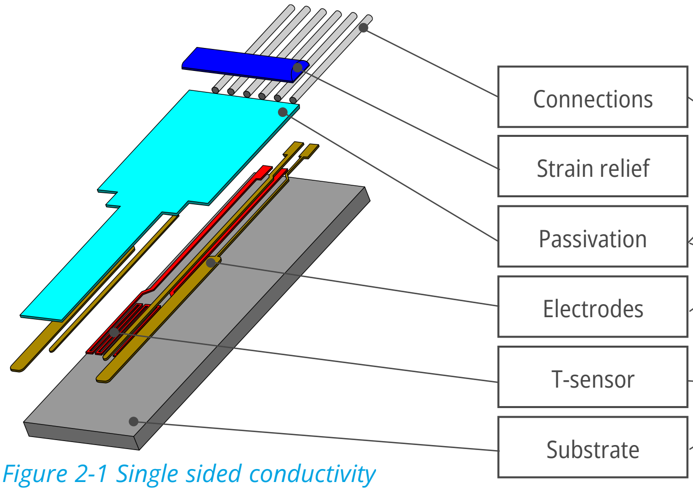

Figure 2-1 Single sided conductivity sensor with lead wires

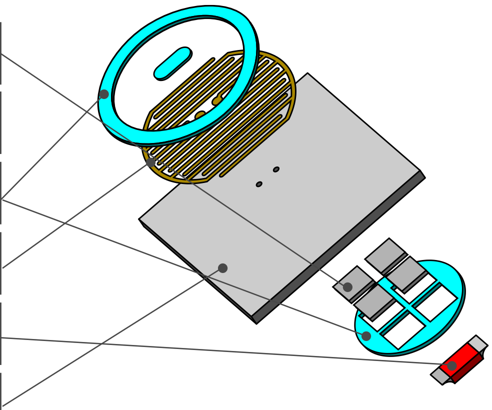

Figure 2-2 Double-sided conductivity sensor with soldered SMD

2.1 Substrate material

The substrate forms the structural foundation on which a conductivity sensor is built. Application requirements, such as chemical resistance, mechanical strength and thermal stability inform the choice of substrate material. Most conductivity sensors are manufactured using alumina (Al_2O_3), a ceramic material that is chemically inert, provides good electrical insulation, is mechanically rigid and offers high thermal stability.

For conductivity sensors with integrated thin-film temperature sensor, a substrate with 99% alumina purity is used. For sensors without an integrated temperature sensor, alumina with 96% purity is typically used. The standard substrate thickness of iST's conductivity elements is 0.63 mm.

If required, other materials, purities and thicknesses can be provided to meet specific customer or application needs.

2.2 Active layer

The active layer is the functional region where both conductivity and temperature measurements take place. The temperature sensor is fabricated from a thin-film layer using photolithography, ensuring high precision and stability. Platinum is used as the active material for iST's temperature sensors due to its excellent temperature coefficient and long-term reliability.

In contrast, the electrodes of the conductivity sensor are applied using an additive manufacturing process. The active materials for these electrodes are typically gold or platinum, chosen for their superior corrosion resistance, electrical conductivity, and chemical inertness, which are essential for accurate and durable performance in various media.

2.3 Passivation material

To insulate the temperature sensor and protect the element from mechanical and chemical influences, an additional layer called passivation is deposited on top of the sensor. In most cases, this passivation layer consists of glass or ceramic materials, which provide excellent chemical resistance and mechanical stability.

However, to measure the conductivity of a liquid medium, it is essential that the electrodes maintain direct electrical contact with the liquid. For this reason, the electrodes of the conductivity sensor are not covered by the passivation layer. In applications involving highly acidic or highly basic environments, special consideration must be given to the choice of materials for both the electrodes and the passivation layer to ensure long-term durability and measurement accuracy.

2.4 Wires

iST's standard conductivity elements without through-hole connections are equipped with silver-coated copper wires or stranded wires, insulated with PTFE to ensure excellent chemical resistance and electrical safety.

In addition to these standard options, iST can provide alternative connection wire materials:

- Enameled copper
- Gold coated nickel
- Silver
- Platinum coated nickel
- Platinum

In case of uninsulated wires, the minimum wire length is 7 mm. Using silver coated copper with PTFE insulation, the minimum wire length is 20 mm.

2.5 Through hole connection

As shown in Figure 2-2, an option with trough hole connection is also available. In this configuration, additional components, for example a temperature sensor, can be soldered onto the backside of the substrate. Furthermore, connectors or headers can be mounted on the backside to facilitate integration into the application. iST also offers the possibility to print landing pads for pogo-pin connection, enabling flexible and reliable electrical interfacing for testing or modular design.

2.6 Dimensions and tolerances

Dimension	**Description**	**Range [mm]**	**Tolerance [mm]**
L	Chip length	-	± 0.2
W	Chip width	-	± 0.2
H	Substrate height	-	± 0.1
H2	Height	-	± 0.3
LW	Wire length	≤ 300	± 1.0
		> 300	± 1.5

Table 2-1 Conductivity sensor dimensions and respective tolerances

3 Electronic Sensor Frontend

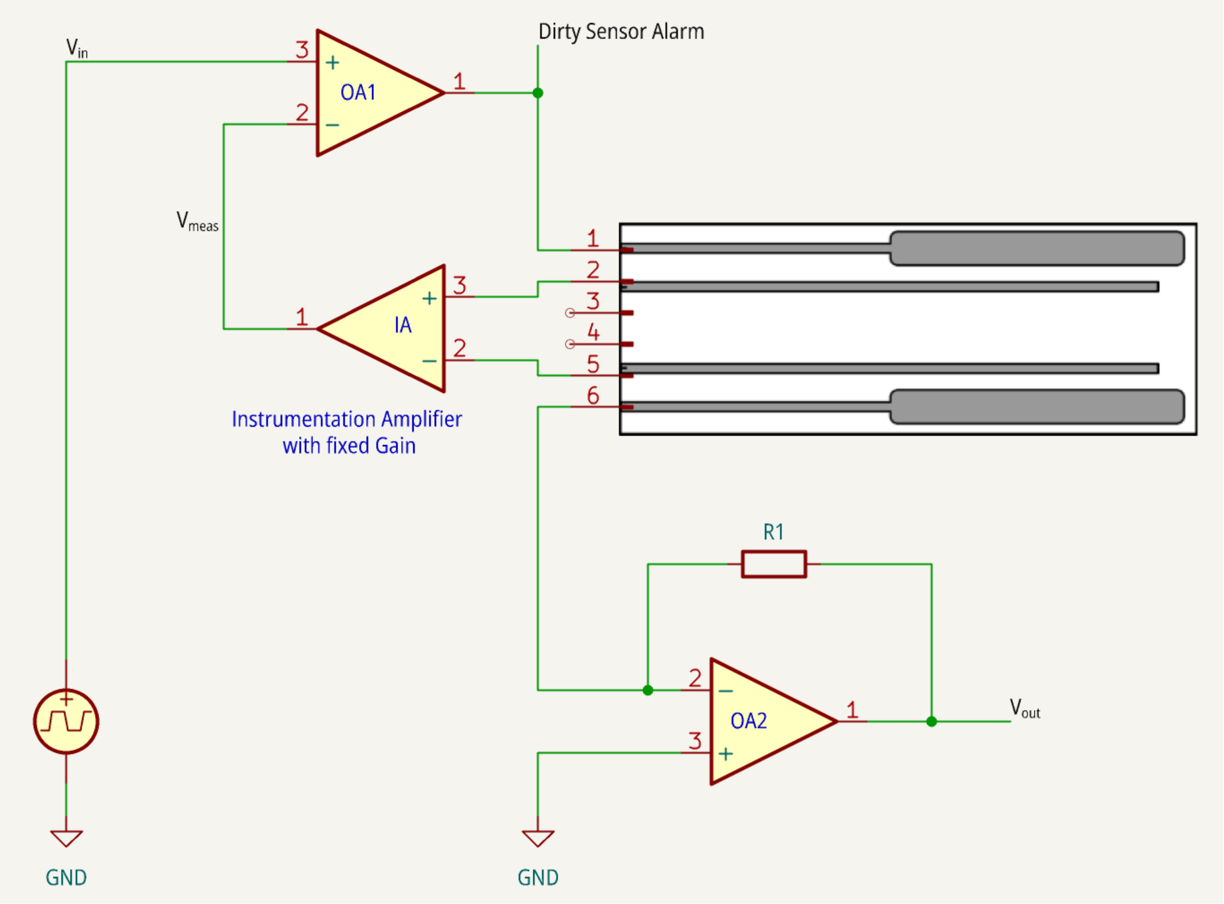

Figure 3-1 Schematic of recommended sensor front-end

The input voltage V_{In} is a rectangular signal with sensor specific frequency (see section 1.3.1) and amplitude $A(V_{In})$. To avoid medium electrolysis, the amplitude should satisfy the criterion in eq. 3-1.

$$A(V_{In}) \leq \frac{0.7\ \mathrm{V}}{2 \cdot \mathrm{Gain}}$$

eq. 3-1

where

A [V]	amplitude of input voltage
Gain [-]	gain of the instrumentation amplifier IA

It is essential to ensure that the DC component of the input voltage (V_{In}) is zero in order to prevent polarization effects at the electrodes, which could lead to unwanted electrochemical reactions, drift in measurement accuracy, or degradation of electrode materials over time.

Combining the cell constant relation eq. 1-5 with the sensor front-end from Figure 3-1, conductivity is calculated as

$$\sigma \approx k \cdot \frac{V_{out} \cdot Gain}{A(V_{in}) \cdot R_1}$$

eq. 3-2

Since the driving signal is rectangular waveform with respect to ground, the measured output voltage (V_{out}) alternates accordingly. However, the movement of dissolved ions is slower than the response of electrons, which can introduce a delay in the development of the measured current. These factors must be considered when evaluating the voltage at V_{out}. One approach to address this is to synchronize the voltage measurement with the excitation signal. Alternatively, some methods rectify the output voltage and utilize a peak hold circuit with a reasonable decay time.

As the measured medium is conductive, additional precautions against unwanted current flows through metallic housing / tubing need to be taken. Such currents influence the measured signal directly and can lead to significant measurement errors. One possible solution against such currents is a galvanic isolation of the complete analog part of the circuit against the remaining electronics and any housing.

4 Handling and assembly

4.1 General remarks

To measure conductivity, the electrodes must be in direct contact with the medium under test. Consequently, the sensitive layer is not protected by any coating, which must be considered when handling conductivity sensor from iST. iST recommends handling the elements only with clean gloves to avoid electrode contamination. Additionally, tweezers should touch only side edges of the sensor to prevent scratches on the electrode surface. Ideally, plastic tweezers should be used.

Furthermore, wire bending should be minimized to reduce the risk of wire breakage and ensure long-term reliability.

4.2 Shelf life

The shelf life of the elements is minimum one year from iST shipment date, when the sensors are properly stored in iST original packaging.

Taking into consideration our experience, in most cases the products can be used beyond 1 year if they are properly stored.

4.3 Storage

iST recommends the following storage conditions:

- Temperature: 10°C – 30°C
- Humidity: 40% - 60% rH

Furthermore, the sensors must not be exposed to etching or corrosive environments and should not be directly exposed to sunlight. Mechanical stress such as mechanical shock, top load or vibrations must be avoided.

4.4 Laboratory assembly recommendations

For sensor elements with lead wires, the mechanical fixation must not come into contact with the media. At the same time, the electrode geometry should be fully immersed to ensure accurate measurements. For our standard elements the recommended immersion depth is shown in Figure 4-1.

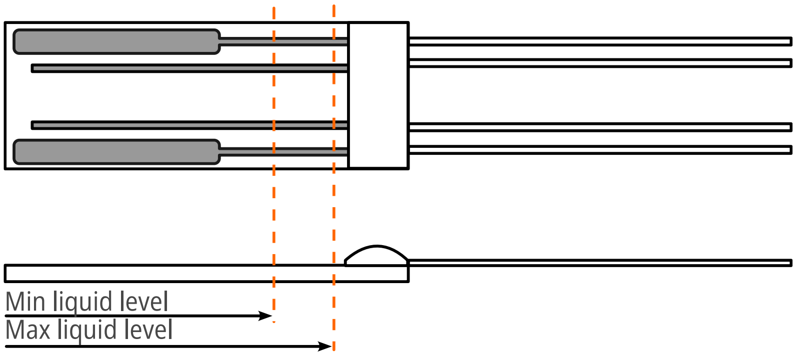

Figure 4-1 Recommended immersion depth for standard sensors between min and max

For sensor elements with electrical contacts on the back side, the entire front surface may be exposed to the medium. However, proper sealing is essential to ensure that the back side remains completely insulated from any liquid. Failure in adequate sealing can lead to electrical short circuits or corrosion.

4.5 Application assembly recommendations

For single-sided sensor variants, to ensure proper insertion depth and insulation of wires from the measurand medium, a potting or overmolding process is used in most applications. If sensors are potted or overmolded, the electrodes must not come in contact with the potting material. Since contamination impacts the electrical contact between the media and the electrodes themselves.

4.5.1 Epoxy Resins

It is crucial to use an epoxy with low moisture absorption, since the elements are mostly used in aqueous solutions and adsorption of water may lead to shorts between the contacts. iST has already used type 301 successfully in water applications. Nevertheless, the material has a low viscosity which makes the handling difficult.

4.5.2 Silicone (RTV)

Alternatively, silicone (RTV) can be used. This material is more viscous and therefore the handling is easier. In contrast, the material has a longer curing time. iST has used the material in high humidity applications in the past, where it showed satisfactory performance. Nevertheless, the stability of the material in contact with liquid water has not been evaluated.

4.5.3 PPSU

iST does not recommend using PPSU in a distance less than a few millimeters as housing or potting material, since PPSU close to the electrode geometry may influence the measurement.

4.5.4 PUR

In iST applications PUR has not been in direct contact with the medium. Instead, it has primarily been used as a potting material to protect electronics against moisture and to provide additional mechanical fixation.

4.5.5 Overmolding

There are some experience with overmolding sensors with soft silicone material for use in aqueuos solutions. Silicone bonds to the sensor well and can also be used as seal to a housing. Materials area available which meets test requirements regarding ISO 10993 and USP Class VI.

4.5.6 Double-sided sensors

In case a double-sided sensor is used, face sealing using an appropriate O-ring, or a custom flat sealing gasket are usually used.

4.6 Cleaning of the element

SIP cleaning of the elements is possible as well as gamma sterilization. Some electrode configurations can get harmed by an extended ultrasonic cleaning step. Mechanical cleaning, for example with a brush, may scratch the surface of the electrodes, which influences the cell constant of the sensor.

4.7 Calibration in assembly

As described in section 1.2.4 the volume of the sensor can highly influence the cell constant of the element. Therefore, iST AG recommends calibrating the electronics in the desired assembly for optimal accuracy. For this standard solution with a given conductivity value can be used. With measured resistance the cell constant can be calculated with the aid of eq. 1-5. For best results, the conductivity value of the standard solution shall be as close to the real application value as possible.