# Contamination Guide for Humidity and Temperature Sensors

**Guidelines and instructions around contamination of SHT sensors.**

All humidity sensors, including resistive and capacitive type sensors, are subject to contamination through volatile organic compounds. This guide aims to provide information on the topic of contamination, particularly in relation to capacitive humidity sensors. The first section delves into the technical aspects, providing an overview of the physical principles that govern contamination. This understanding is crucial for developing a robust strategy to combat contamination. The second section introduces a practical framework which helps create an effective contamination mitigation strategy. Following these guidelines is essential in order to guarantee the outstanding performance, high accuracy, short response times and long lifetime of Sensirion's SHT sensors.
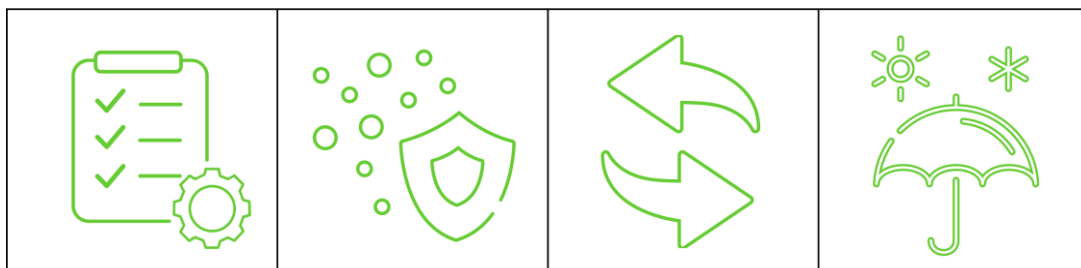
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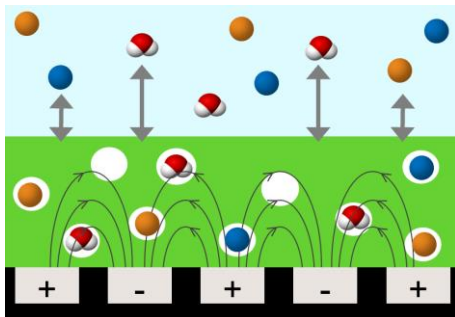
A simple model of contamination is introduced to help understand the various effects which foreign molecules can have on capacitive humidity sensors.
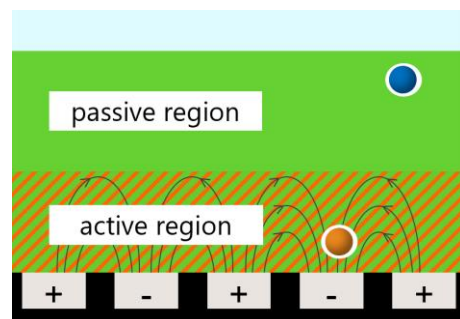
The importance of time dependence is explained with a multilayer diffusion model which focuses on molecules with different diffusion speeds.

The SENS-Framework is introduced as a tool to create a contamination mitigation strategy by dividing it into four steps: Selction, Evasion, Normalization and Setting. It highlights important points which need to be considered throughout the design, production and implementation process.

Contents

1 What is contamination

The working principle of capacitive humidity sensors is based on measuring the change in capacitance induced by the presence of water molecules [1]. It is an intrinsic technological problem that capacitive humidity sensors are affected by contamination. Contamination is characterized by the presence of any foreign substance which affects the humidity-measurement. There are two main types of contamination which can be differentiated, namely **surface and bulk contamination.**

Surface contamination refers to pollutants forming a barrier on top of the sensing unit as illustrated in **Figure 1**. This barrier will partially or completely inhibit the transport of water molecules between the air and the active sensing layer. Sources of surface contamination include particles, conformal coatings, paint and surface films. Surface contamination can easily be avoided by correct handling of the Sensor as well as by using Sensirion's membrane and protective cover options.

Bulk contamination is when a contaminant diffuses into the sensing polymer as seen in **Figure 2**. These foreign molecules will alter the sensor readout negatively affecting performance. Bulk contamination is by far the most frequent form of contamination and is dependent on a multitude of factors such as humidity, temperature, environment, contaminant, exposure time and concentration.
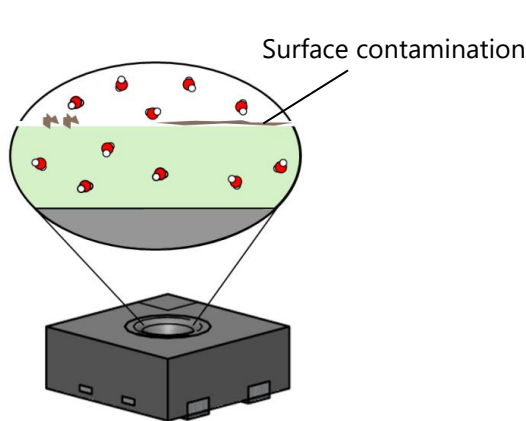

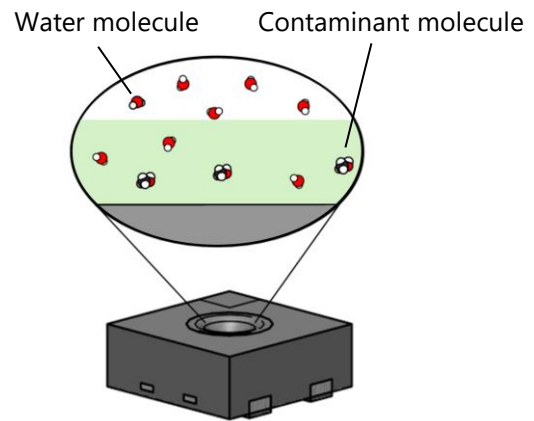**Figure 1**. Illustration of surface contamination

Figure 2. Illustration of bulk contamination

Not all contamination is reversible, certain chemicals might permanently alter the sensor irreversibly.

2 Effect of contamination on humidity measurement

When exposed to a contaminating environment, the contaminant will diffuse into the sensing polymer layer along with water molecules until a dynamic equilibrium is reached. This leads to an alteration of the sensor output which is dominated by two different effects. First, the overall relative permittivity seen by the electrodes changes due to the contaminant being present and having a different relative permittivity than the polymer. Second, the contaminant competes with the water molecules for the occupation of the binding sites which limits the amount of water molecules absorbed by the polymer.

2.1 Modelling Contamination

How the relative permittivity and concentration of the contaminant affects the sensor readout at changing relative humidity can be illustrated with a simplified model where the following assumptions are made:

1. The Polymer has a set number of binding sites, which can either be occupied by one water molecule, one contaminant molecule or it can be left unoccupied.
2. The contaminant molecules will fill the binding sites first, proportionally to the ambient contaminant concentration.
   Ex. For 100 binding sites at 50% contaminant concentration, 50 binding sites are filled with contaminant molecules.
3. The water molecules will occupy the remaining free binding sites according to the ambient humidity (Reference humidity).
   Ex. At 40% reference humidity, 40% of the 50 remaining free binding sites will be filled with water molecules (20 binding sites)
4. The resulting measured humidity is calculated from the total relative permittivity of all molecules that occupy a binding site, with the assumption being made that only water has been absorbed.
   Ex. The resulting measured humidity is calculated adding up the relative permittivity of the 50 contaminant molecules as well as the 20 water molecules.

In the following section, the influence of the individual model parameters such as relative humidity, contaminant concentration and contaminant type will be discussed in order to better understand the effect of contamination. The mathematical expression for this model which was used for the following illustrations is presented as equation **(1)** in **section 2.7**.

2.2 Relative humidity

An illustration of an uncontaminated sensor can be seen in **Figure 3**, where the water molecules can diffuse in and out of the polymer creating a dynamic equilibrium. As shown in **Figure 6**, an uncontaminated sensor perfectly measures the reference humidity. However, once the sensor gets contaminated, the measured humidity deviates from the reference humidity.

At low humidity, illustrated in **Figure 4**, the measured humidity is higher than the reference humidity due to the added relative permittivity of the contaminant which simulates the presence of additional water molecules and results in a higher measured humidity.

At high relative humidity a different effect dominates. As shown in **Figure 5**, the large amount of water molecules which want to bind to the polymer exceeds the free binding sites because some of them are occupied by the contaminant molecules. This leads to some water molecules not being able to enter the polymer and instead, the absorbed contaminant molecule will be measured. Since the relative permittivity of the contaminant is generally smaller than that of water (ε = 80.1), this will result in a lower perceived humidity at high RH.
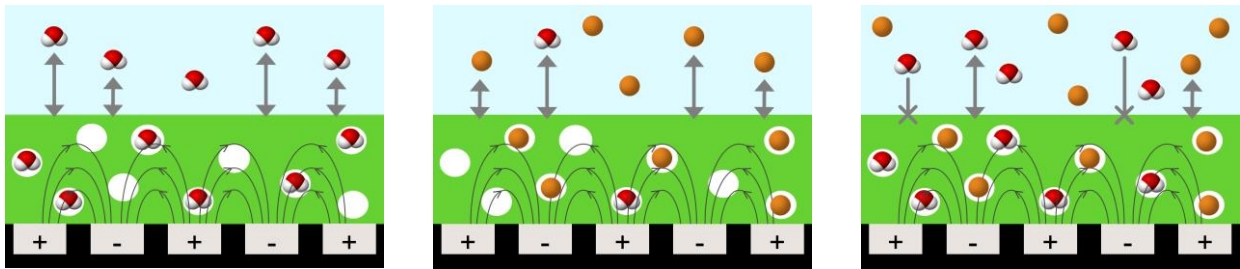

Figure 3. Uncontaminated sensor

Figure 4. Contamination at low RH

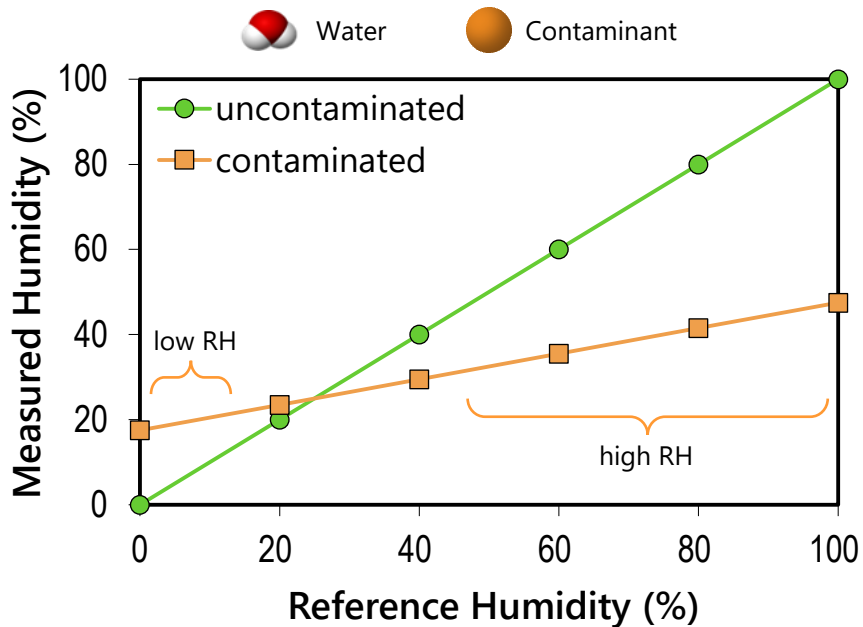Figure 5. Contamination at high RH

Figure 6. Illustration of the difference in measured humidity between a contaminated sensor and an uncontaminated sensor at different reference humidities

2.3 Contaminant concentration

The most important factor in this model is the contaminant concentration. The dependence of the humidity measurement on contaminant concentration can be seen in **Figure 10**, showing three different contamination levels. At low contamination levels, illustrated in **Figure 7**, the caused humidity deviation will be small since there aren't many additional contaminant molecules present which add to the permittivity at low RH and block out water molecules at high RH. At high contamination levels, as shown in **Figure 8**, the slope of the RH-curve decreases and the deviation from the ideal uncontaminated sensor grows significantly. The most extreme case is when all binding sites are blocked by contaminant molecules, not letting any water molecules into the sensor. This is referred to as a "blind sensor" because the measured RH will not change with the humidity but will just be dependent on the contaminant's relative permittivity. This is illustrated in **Figure 9**.
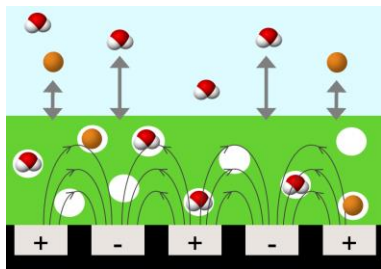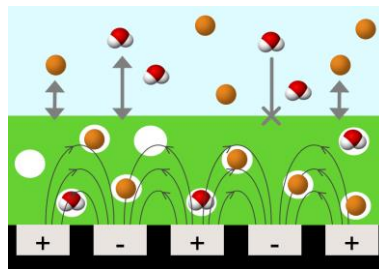

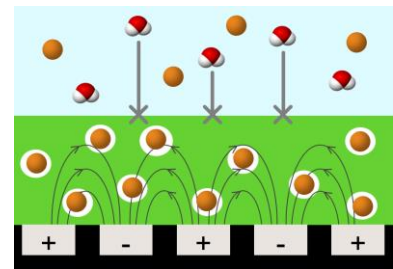**Figure 7.** Low contamination

Figure 8. High contamination

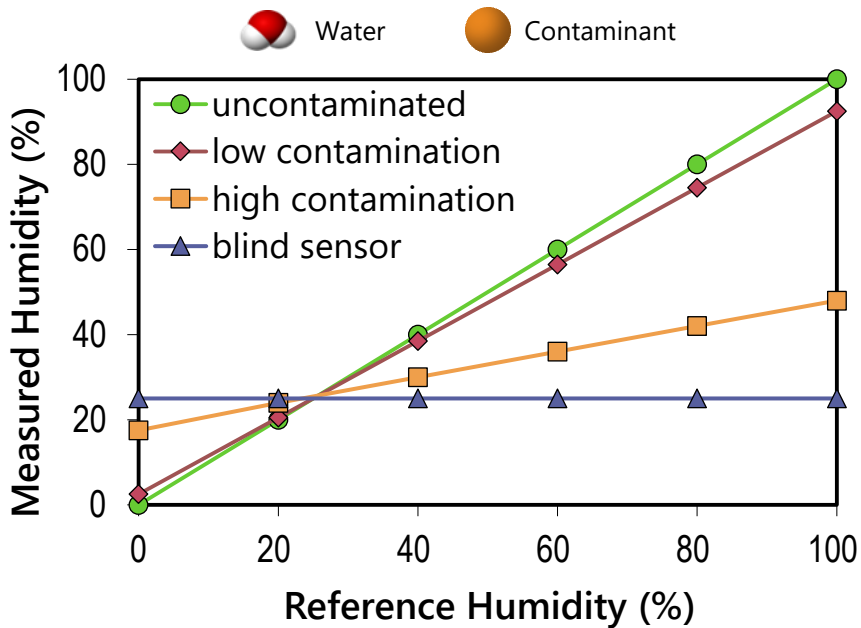**Figure 9.** Fully contaminated sensor (blind sensor)

Figure 10. Effect of contaminant concentration on humidity measurement

2.4 Contaminant type

While the slope of the contaminated RH-curve is determined by the contaminant concentration, intersection point with the uncontaminated RH-curve is determined by the contaminant's relative permittivity. The relative permittivity describes the ability of a material to store electrical energy when subjected to an electric field compared to vacuum. The relative permittivity is low for nonpolar molecules and high for polar molecules. Water is one of the most polar molecules and therefore has a high relative permittivity.

In **Figure 14** the effect of two different contaminating molecules can be seen. A nonpolar contaminant (**Figure 11**) is compared to a polar contaminant (**Figure 12**) of the same concentration. The relative permittivity of the nonpolar contaminant is significantly lower than that of the polar contaminant. As a result, the polar contaminants RH-curve appears shifted upwards from the nonpolar contaminants RH-curve and intersects the uncontaminated curve at a higher point. This leads to the effect that polar contaminants with higher relative permittivities affect the RH-measurement more at lower RH because the measured total permittivity is higher. Contaminants with low relative permittivities affect the RH-measurement more at higher RH where the difference to waters relative permittivity is key.

In **Figure 13** a combined contamination with both the nonpolar and polar contaminant is illustrated. It can be seen in **Figure 14**, that the deviations caused by different contaminants add up by increasing the overall contaminant concentration while the resulting effective relative permittivity is a combination of the individual relative permittivities. The effective combined contamination is a result of all individual contaminant effects which are present in different concentrations with different relative permittivities.
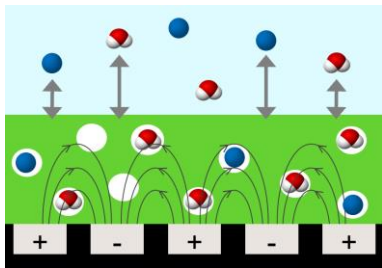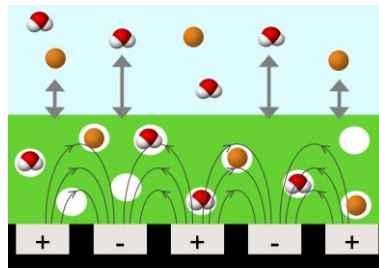

Figure 11. Nonpolar contaminant
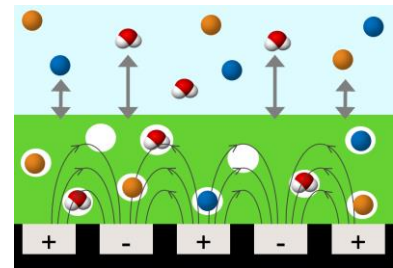
Figure 12. Polar contaminant

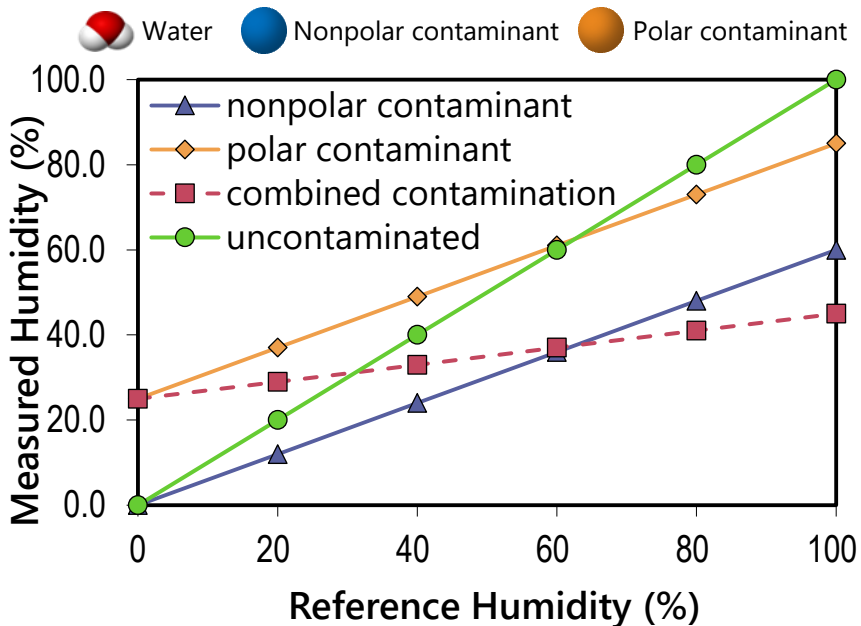**Figure 13.** Combined contamination

Figure 14. Effect of contaminant type on humidity measurement

2.5 Beyond the simple model

In reality, contamination dynamics are a lot more complicated than demonstrated with this simple model, which becomes apparent as soon as the diffusion dynamics are considered. The polymer is a 3D Material with a thickness which is only open to the environment on one side. Simply put, the water and contaminant molecules cannot instantaneously enter the polymer at any place but must diffuse from the top layer to the bottom part. This diffusion depends not only on the concentration of the compound, but also on other factors such as time, molecule size, temperature, other volatile compounds as well as the chemical affinity between the gas molecule and the polymer itself. Temperature itself doesn't only play a role in the diffusion speed, but also in the definition of relative humidity since it is defined through the saturation vapor pressure which is temperature dependent. Additionally, the relative permittivity itself is temperature dependent, where a strong drop of the relative permittivity of water can be observed from 80.1 at 20°C to 61 at 80°C [2].

The complexity of contamination makes it impossible to create a one-fits-all solution for contamination issues. However, there are important measures and procedures to be considered when designing, handling and implementing an SHT Sensor which minimize the risk of contamination in the first place as well as actions that can be taken after a suspected contamination.

2.6   Contamination Dynamics

Contamination in capacitive humidity sensors is a dynamic process, not a static event. This means that the state of contamination is in constant flux, with the contaminant molecules moving in and out of the sensing polymer. When the concentration of the contaminant in the surrounding atmosphere is higher than within the polymer, the contaminant molecules will migrate into the sensor. Conversely, if the concentration is lower outside the polymer, the contaminants will migrate back out. This process is governed by the principle of diffusion. Therefore, the sensor's response to a contaminating atmosphere is largely dependent on the diffusion speed of the contaminant.

A capacitive humidity sensor operates by measuring the change in capacity of the sensing polymer introduced by water molecules. Due to the electric field lines being more concentrated near the base of the polymer where the electrodes are located, a molecule will not have the same effect if it is located near the surface or near the base of the sensing layer. As illustrated in **Figure 15**, the blue molecule will not affect the humidity measurement because it still is in the passive region and has not yet diffused down to the active region. The orange molecule further down will affect the humidity measurement because it is in the active region.
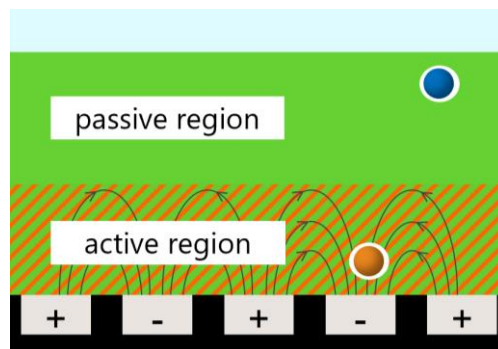

Figure 15. Illustration of the sensing layer of a capacitive humidity sensor. The orange molecule will have a greater effect on the capacitance than the blue molecule because it has diffused further down towards the electrodes.

The distinction between a passive and an active layer has significant implications on the effect of contamination depending on the contaminant's diffusion speed. Fast-diffusing molecules (**Figure 16**, green) will diffuse down into the active layer as soon as the sensor is exposed to the contaminant. The contaminant concentration in the sensor will saturate and reach equilibrium with the contaminant concentration in the atmosphere. As soon as the contaminating atmosphere is replaced with clean air, the contaminant concentration will be higher inside the sensor and the contaminant molecules will diffuse out.

When the sensor is exposed to a slow-diffusing contaminant (**Figure 16**, red) the contaminant molecules will start to diffuse into the top passive layer. Due to the slow diffusion speed, the contaminant will only reach the active layer after some time. In the case shown in **Figure 16**, the contaminating atmosphere is removed before the entire sensor can reach an equilibrium of the contaminant. The newly present uncontaminated atmosphere causes the contaminant which is inside the sensor to diffuse out while it is simultaneously still diffusing into the uncontaminated bottom parts of the active layer.
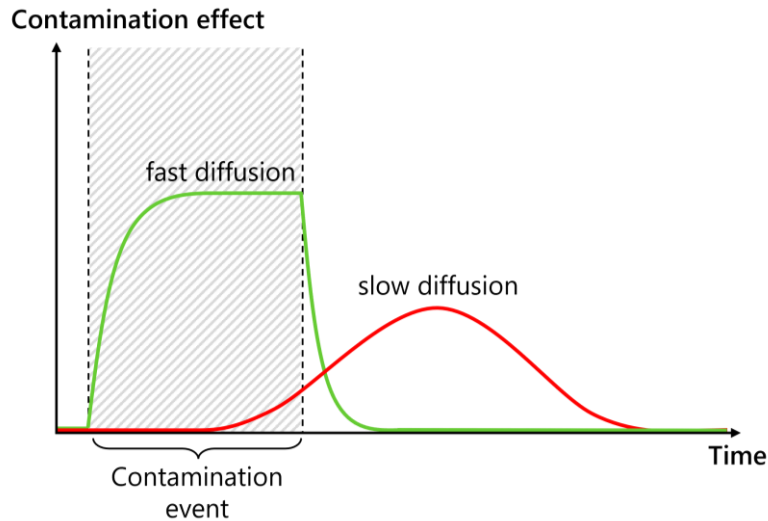
Figure 16. Representation of how different diffusion speeds change the dynamics of contamination. A fast-diffusing contaminant (green) is compared to a moderately diffusing contaminant (red).

In extreme cases with very slowly diffusing molecules, the effect of contamination can appear after the contaminating atmosphere has been removed. Such slow diffusing molecules will not only take time to diffuse into the active layer but will also take time to diffuse out of the sensor. This time delay effect is illustrated in **Figure 17**. Such contaminants can linger in the sensor for extended periods of time. One approach to remove such slow-diffusing contaminants is to leverage higher temperatures in order to accelerate the diffusion process. Higher temperatures lead to faster diffusion speeds which can shorten the time needed for the slow diffusing contaminant to diffuse out of the sensor. This effect is shown in **Figure 18** where temperature accelerated normalization (green) is compared to ambient normalization (red). It is important to note that this temperature elevation must be done in an uncontaminated atmosphere. If the atmosphere is still contaminating, the elevated temperatures will lead to the opposite effect and increase the diffusion of contaminant molecules into the sensor.

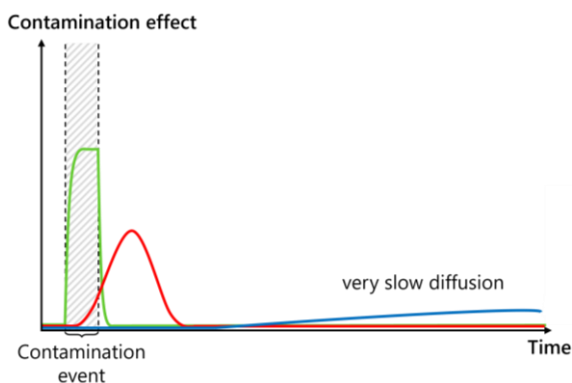**Figure 17.** An example of the time delay in the contamination effect of a very slow-diffusing contaminant (blue).
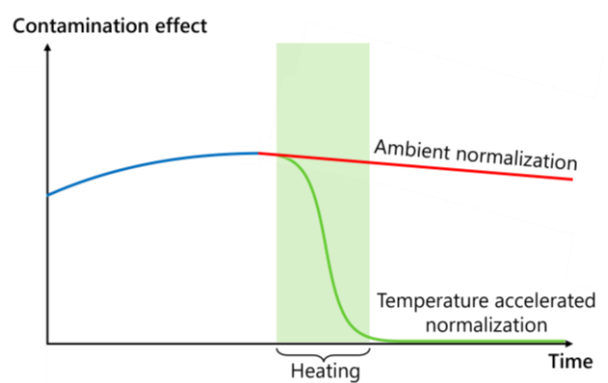

Figure 18. Illustration of how elevated temperatures can be beneficial for sensor normalization with slow-diffusing contaminants.

2.7 Supplementary Equations

Contamination Model

The simplified model introduced in **section 2.1** can be expressed mathematically by (1)

$$RH_{meas} = \frac{\epsilon_{cont} \times c_{cont} + \epsilon_{water} \times RH_{ref}\left(1 - \frac{c_{cont}}{100}\right)}{\epsilon_{water}} \qquad (1)$$

RH_{meas}: Measured humidity [%RH]
RH_{ref}: Actual reference humidity [%RH]
$\epsilon_{cont/water}$: Relative permittivity of the contaminant/water
c_{cont}: Contaminant concentration [%]

Please be aware that this equation offers a basic model for understanding contamination. It is designed to provide a conceptual framework for grasping how contamination behaves. However, it is important to remember that this model is not intended for calculating any deviations in real-world contamination scenarios.

Diffusion

Diffusion is governed by Fick's laws, the first of which can be seen in equation (2).

$$Diffusion = J \times t \times A = -D\frac{dc}{dx}tA = -D_0 exp\left(-\frac{E_A}{RT}\right)\frac{dc}{dx}tA \qquad (2)$$

J: Diffusion flux, amount of substance diffused per time
t: Time
A: Sensing-polymer surface area
D (D_0): Diffusion coefficient (at infinite temperature)
$\frac{dc}{dx}$: Concentration gradient of substance
E_A: Diffusion activation energy
R: Universal gas constant
T: Temperature

Since the sensing polymer surface area (A), the maximum diffusion coefficient (D_0), the diffusion activation energy (E_A) and the universal gas constant (R) are all constants, the diffusion flux can be expressed as a function of the three variables time (t), concentration gradient ($\frac{dc}{dx}$) and temperature (T).

$$Diffusion \propto exp\left(-\frac{1}{T}\right) \times \frac{dc}{dx} \times t \qquad (3)$$

Equation **(2)** includes the diffusion coefficient as predicted by the Arrhenius equation which is a successful model for diffusion in solids. The further simplification from **(2)** to **(3)** ignores the fact that the diffusion coefficient (D_0) actually depends on temperature as well as the diffusion activation energy which considers the local chemical potential. A more accurate and sophisticated model of diffusion may consider the diffusion of a gaseous molecule through a viscous porous material.

3   Contamination mitigation

A lot of different measures can be taken to avoid contamination. Starting from the design-in and storage of the sensor to its handling, processing and implementation in the field. The mitigation strategy can be grouped into four important steps which are described by the SENS-framework.
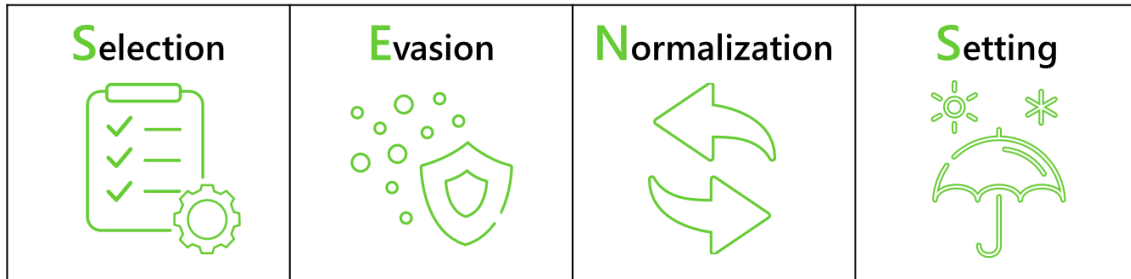

Figure 19. SENS-strategy for contamination mitigation

3.1   Selection

The first step to a comprehensive contamination strategy is selection. There are many different choices to be made which all can help to prevent possible future contamination such as the sensor protective options, which materials will be used throughout production and in the final design as well as general design considerations.

Sensor selection

Sensirion offers a wide range of Sensors with additional protective options which provide protection against contamination. These include a removable protective cover which keeps the sensor opening sealed during processing steps such as conformal coating. An integrated IP67 rated filter membrane which is designed to shield against dust and particles while enabling easier and efficient cleaning. A separate filter cap which allows more efficient design-ins. And Humidity and Temperature sensors with an integrated controllable heater for creep-free operation as well as decontamination possibilities.

Materials selection

A careful material selection helps avoid contamination coming from materials integrated alongside the sensor as well as materials that the sensor may temporarily be exposed to during processing. Certain chemicals and groups of substances that are known to have an increased risk of causing contamination or even irreversible damage to the sensor. Special attention should be given to the following substance groups:
- Volatile (polar) molecules e.g. methanol, ethanol, acetone, isopropanol
- Cleaning agents, conformal coatings and board wash which are applied in a liquid state directly to the sensor
- Materials such as glues, adhesives, plasticizers which may release volatile molecules by outgassing

Material handling instructions may be found in Sensirion's "Handling Instructions" [3].

Process selection

During manufacturing the sensor is especially exposed which is why special attention should be paid to minimizing potential contamination sources. The processes which the sensor goes through play an important role in determining whether and to what extent a contamination source will contaminate the sensor. By selecting production processes which allow the flow of fresh air around the sensor opening and limiting the time exposed to elevated temperatures, additional contamination can be avoided.

Special attention should be paid to the use of board wash and conformal coatings

Design selection

A good design-in will enable the sensor to function according to its highest precision specifications and avoid possible contamination issues throughout its lifetime. For all the information regarding design-in, please refer to Sensirion's "Design Guide for Humidity and Temperature Sensors" [4].

3.2 Evasion

Evasion is the most important step in the SENS-framework and describes the actions which can be taken to minimize any contamination caused during processing by sources which cannot be avoided as described in section 3.1. In order to be implemented correctly, a basic understanding of contamination dynamics and the factors which promote contamination is necessary.

As explained in depth in section 2.6 and by equations (2) and (3) in section 0, the three main parameters that control diffusion are **contaminant concentration, exposure time and temperature**. These parameters can be leveraged to minimize any possible contamination.

Concentration

Diffusion naturally occurs, moving particles from an area of higher concentration to one of lower concentration. This means that if an uncontaminated sensor is exposed to a contaminating atmosphere, the contaminant will diffuse into the sensor. The higher the contaminant concentration is in the air, the more contaminant will diffuse into the sensing polymer. On the other hand, if a contaminated sensor is exposed to a clean atmosphere, the contaminant molecules will diffuse out of the sensor. Therefore, it is important to provide a circulation of fresh uncontaminated air locally around the sensor throughout processing as well as avoiding high contaminant concentrations at all times.

Exposure time

The longer the sensor is exposed to a contaminating atmosphere, the more contaminant will diffuse into the polymer. This means that it is very important to keep any exposure to contaminants as short as possible.

Temperature

Diffusion speed increases with temperature. This has two big implications. If the sensor is exposed to a contaminating atmosphere, low temperatures will reduce the severity of contamination by keeping diffusion speeds low. However, the effect of temperature dependent diffusion can be taken advantage of in case of decontamination. By increasing the temperature in a controlled manner while exposing a contaminated sensor to a clean atmosphere, will increase the speed at which contaminant molecules diffuse out of the sensor. This can be done by using the built built-in heater in Sensirion's humidity and temperature sensors for decontamination which is explained further in section 3.3 and follows the principles explained in section 2.6.
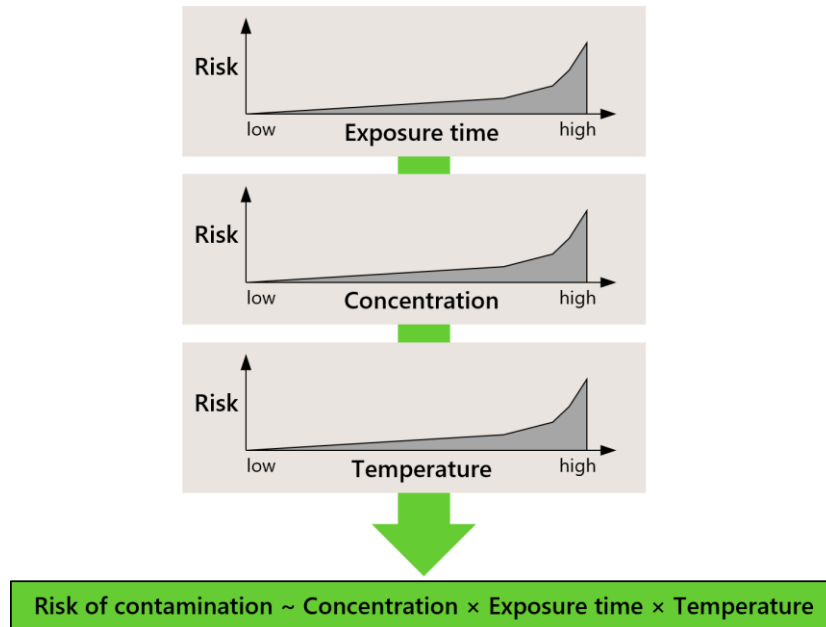
Figure 20. Increased contamination risk with high exposure time, contaminant concentration and temperature.

As illustrated in **Figure 20**, the total risk of contamination can be minimized by keeping exposure times, contaminant concentrations and temperatures low during storage and integration of the sensor.

3.3   Normalization

The third step of the SENS-framework is normalization. Normalization includes actions that can be taken after a contamination event or after the sensor has been integrated and before it is deployed in the field. There are multiple actions which can be taken with increasing effectiveness and effort.

Ambient Normalization

The working principle of ambient normalization is that the contaminant will exit the sensor over time if the sensor is exposed to an uncontaminated atmosphere. This decontamination behavior is governed by the same diffusion dynamics which are presented in equation (2) except for that providing a clean atmosphere reverses the contaminant concentration gradient and therefore the contaminant molecules will diffuse out of the sensor. The most important aspect is that the clean air must be able to move to allow the transport of the contaminants away from the sensor. It should be noted that the timeframe for such a decontamination varies strongly depending on the severity of contamination as well as the contaminants binding energy to the polymer. Strongly binding contaminants may not be removable at room temperature or in extreme cases may not be removable at all. Due to the diffusion rate of the contaminant out of the polymer decreasing with a decreasing contaminant concentration, this method will reduce the contamination rather than removing it completely.

Heater assisted decontamination

A more sophisticated method is to use the integrated heater of SHT4x sensors to temporarily increase the temperature which strongly increases the outgassing speed of the contaminant out of the polymer. For further information on this topic, please consult the Application Note "Heater Decontamination SHT4xX" [5].

Reconditioning

As a last resort, reconditioning will return the sensor to its calibration state removing any temporary contamination. The procedure involves two steps:

- Baking: 100 – 105°C at <5 %RH for 10 h
- Re-Hydration: 20 – 30°C at ~75 %RH for 12 h

The time required to return to the calibration state is strongly dependent on the exact conditions which the sensor was exposed to. Please note that the reconditioning process must be applied to the bare sensor without contact with any possible contaminants, such as additional packaging.

3.4 Setting

The final step in the SENS-framework is "Setting", which encompasses considerations that should be made to guarantee contamination-free accurate humidity measurements throughout the sensor's lifetime.

In addition to a good design-in, the sensor placement is almost equally important. Even a well-designed device which is misplaced will not return the best possible measurement. The sensor placement should allow airflow around the sensor opening which not only ensures that the local conditions are representative, but also avoids standing air which can be harmful in contaminating atmospheres. More information on this topic can be found in Sensirion's "Design Guide for Humidity and Temperature Sensors" [4].

4 Contamination testing services by Sensirion

Sensirion offers material contamination tests which determine whether a specific material may pose a contamination risk to the sensor. This test based on accelerated contamination offers support for material related design decisions as well as diagnostic investigations.

Please contact Sensirion for further information.

5 Bibliography

[1] Sensirion, "Introduction to humidity," August 2009. [Online]. Available: https://www.sensirion.com/products/downloads.

[2] C. G. Malmberg and A. A. Maryott, "Dielectric Constant of Water from 0° to 100° C," *Journal of Research of the National Bureau of Standards,* vol. 56, no. 1, p. January, 1956.

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[5] Sensirion, "Heater decontamination SHT4xX," February 2024. [Online]. Available: https://www.sensirion.com/products/downloads.

[6] University of Washington, "Dielectric Constant of Common solvents," [Online]. Available: https://depts.washington.edu/eooptic/linkfiles/dielectric_chart%5B1%5D.pdf. [Accessed 03 2024].

6 Revision History

Date	Version	Pages	Changes
June 2024	1	all	Initial release
September 2024	1.1	5 7	Updated **Figure 5** for better clarification Adapted coloration in **Figure 14**

Important Notices

Warning, Personal Injury

Do not use this product as safety or emergency stop devices or in any other application where failure of the product could result in personal injury. Do not use this product for applications other than its intended and authorized use. Before installing, handling, using or servicing this product, please consult the data sheet and application notes. Failure to comply with these instructions could result in death or serious injury.

If the Buyer shall purchase or use SENSIRION products for any unintended or unauthorized application, Buyer shall defend, indemnify and hold harmless SENSIRION and its officers, employees, subsidiaries, affiliates and distributors against all claims, costs, damages and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if SENSIRION shall be allegedly negligent with respect to the design or the manufacture of the product.

ESD Precautions

The inherent design of this component causes it to be sensitive to electrostatic discharge (ESD). To prevent ESD-induced damage and/or degradation, take customary and statutory ESD precautions when handling this product. See application note "ESD, Latchup and EMC" for more information.

Warranty

SENSIRION warrants solely to the original purchaser of this product for a period of 12 months (one year) from the date of delivery that this product shall be of the quality, material and workmanship defined in SENSIRION's published specifications of the product. Within such period, if proven to be defective, SENSIRION shall repair and/or replace this product, in SENSIRION's discretion, free of charge to the Buyer, provided that:

- notice in writing describing the defects shall be given to SENSIRION within fourteen (14) days after their appearance;
- such defects shall be found, to SENSIRION's reasonable satisfaction, to have arisen from SENSIRION's faulty design, material, or workmanship;
- the defective product shall be returned to SENSIRION's factory at the Buyer's expense; and
- the warranty period for any repaired or replaced product shall be limited to the unexpired portion of the original period.

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Headquarters and Subsidiaries

Sensirion AG
Laubisruetistr. 50
CH-8712 Staefa ZH
Switzerland

phone: +41 44 306 40 00
fax: +41 44 306 40 30
info@sensirion.com
www.sensirion.com

Sensirion Taiwan Co. Ltd
phone: +886 2 2218-6779
info@sensirion.com
www.sensirion.com

Sensirion Inc., USA
phone: +1 312 690 5858
info-us@sensirion.com
www.sensirion.com

Sensirion Japan Co. Ltd.
phone: +81 45 270 4506
info-jp@sensirion.com
www.sensirion.com/jp

Sensirion Korea Co. Ltd.
phone: +82 31 337 7700~3
info-kr@sensirion.com
www.sensirion.com/kr

Sensirion China Co. Ltd.
phone: +86 755 8252 1501
info-cn@sensirion.com
www.sensirion.com/cn

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www.sensirion.com/distributors