New generation of dew point sensors based on LTCC substrate with decoupled contact system

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Abstract

LTCC is used as a substrate for dew point sensor, e.g. multisensing system consisting of detection system for condensation, temperature sensors, stray field sensor for measurement of condensed water mass. All these components as well as through LTCC vias have been integrated in the LTCC substrate. The mentioned through vias enable the separation of corrosive environment from the electric contact system, the cooling element e.g. peltier element and open new application fields for in line measurement of technical and non-technical processes.

Keywords: dew point sensors, through LTCC vias, condensation, harsh environment, field calibration

1. Introduction

For measurement of humidity a multiplicity of physical relations have been applied in the past to the construction and principles of humidity measurement systems.

Demands of higher energy and material efficiency, quality as well as safety management of technical and non-technical processes require more and more humidity measurement sensors with high accuracy and long term stability, especially in the higher (above 95 % RH.), lower (below 5 % RH and ambient temperature higher 80 °C) humidity range, under the influence of solid and dissolved contamination and in case of higher temperature. Especially the in-line measurement (in opposite to bypass procedure) for the process control needs humidity sensors which work stably enough at higher temperatures and in contaminated air. The CCC* (condensate controlled capacitance according to HEINZE)-dew point sensor presents an absolute measurement device of humidity and allows the dew point measurement of meteorological conditions and in-line technical processes and field calibration.

The existing silicon based product family consists of several configurations such as micro-sensors for the detection of dewing [1] [2], transmitters and more comfortable dew point meters and has industrial interfaces for several applications.

The requirements concerning measurements in corrosive environments have risen continuously [3]. It can be stated generally that the dew point principle (absolute measurement of humidity) due to the measurement at the equilibrium state of condensation and evaporation is the favourable solution for such problems. In opposite to polymer based humidity sensors, the CCC- sensor consists of a mechanical and chemical inertness of the sensor surface (silicon nitride or similar).

LTCC (low temperature co-fired ceramics) as a new sensor substrate was chosen due to its excellent properties such as

- qualified for thin film technology
- chemical resistance
- vertical interconnect access (via)
- back side structuring and contacting
- good thermal conductivity
- good electrical insulation

2. Fundamentals

Dew point sensors belong to the absolute measuring instruments. They measure the dew point temperature and consequently the mass of water vapor within the gas directly. The measuring value is independent of the physical values such as temperature or material constants.

Basis of the dew point sensors is the simple relation between the water vapor pressure and the temperature.

This relationship is represented as a vapor pressure curve in the p, t diagram (figure 1). If the temperature is changed, so does the amount of water vapor. With decreasing temperature water condenses as liquid or ice.

The temperature at which the condensation respectively sublimation and evaporation are in thermodynamical equilibrium is the dew point temperature respectively frost point temperature.

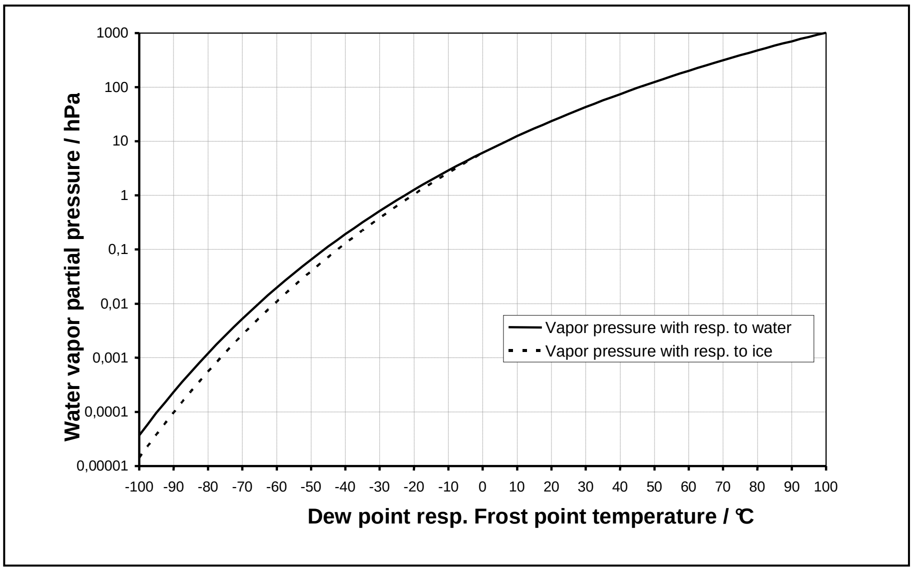

Figure 1: Vapor pressure curve within p, t diagram

The Magnus formula describes the relationship between water vapor pressure (e_w) and temperature (t_F).

$$e_w = e_{ws} \bullet \exp (a_w \bullet t_F)/(b_w + t_F)$$

The equations by Raoult (influences of contaminations) and Thomson (influences of the diameter of water drops) describe the essential relations on the condensation surface regarding accuracy demands [4].

In evaluating these correlations, drop sizes in the range of 5 to 10 microns in diameter and an immediate proximity of the temperature sensor to the condensation surface is to be aimed. These fundamental factors are in addition to technological feasibility and signal modulation determining factors for the design of sensors particular for the position of the temperature sensor and the dimensions of the capacitor structures.

3. LTCC based micro system

The state-of-the-art monolithic integrated silicon sensor is based on the thermodynamic principle of condensation and evaporation and utilizes the cost advantages of silicon batch processes. The a.m. CCC*- dew point sensor is a typical micro system solution (figure 2). This sensor unites the sensor chip, the mounting plate including cooling element and the signal processing. The dew point detector is located on the surface of the silicon chip formed as a stray field capacity and is connected with an integrated capacity-frequency converter. The detection area is cooled down by the cooling element. When water vapor condenses at the chip surface, the dew point is reached. At the moment of dewing, the stray field capacity is changing and so is the VCO-frequency. The signal processing guarantees a constant mass of water on the chip surface at the moment of dew point measurement. Using the standard steps of an IC-process, the temperature sensor is located near the water drops. This is absolute necessary for good accuracy.

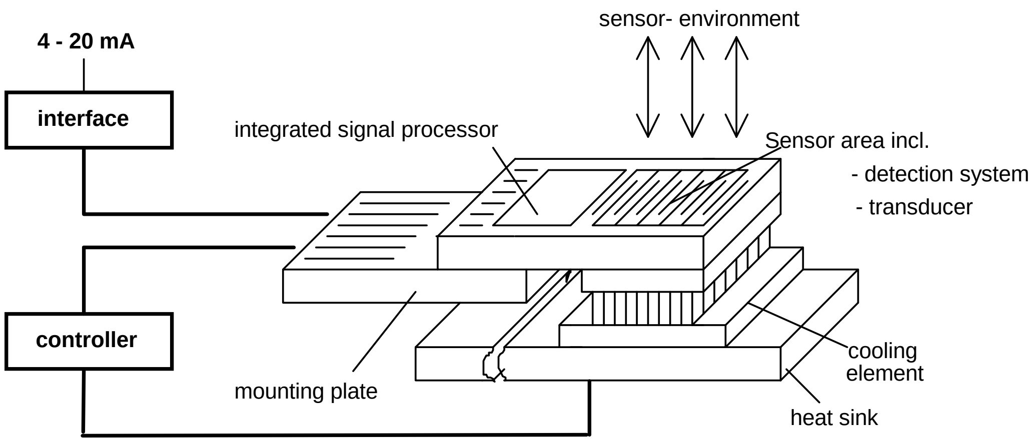

Figure 2: The CCC*-dew point system

The disadvantage of this system consists in the proximity of sensor components and materials such as mounting plate (FR4,) cooling element (Peltier element), signal processor (VCO), encapsulation of the chip to the harsh sensor environment. All these units limit the application field regarding e.g. temperature and contamination. Therefore, the well known features of LTCC were used for a new design of the micro system.

The LTCC substrate in connection with the through vias allows a decoupling of environment and sensor components. Figure 3 shows that all the mentioned components of the silicon-based dew point sensor system have been included in the LTCC micro system. The main difference between the substrates used exists in the electric contact principle. In case of LTCC the contact between the transducer and the controller/interface has been fixed by the back side contact of the substrate.

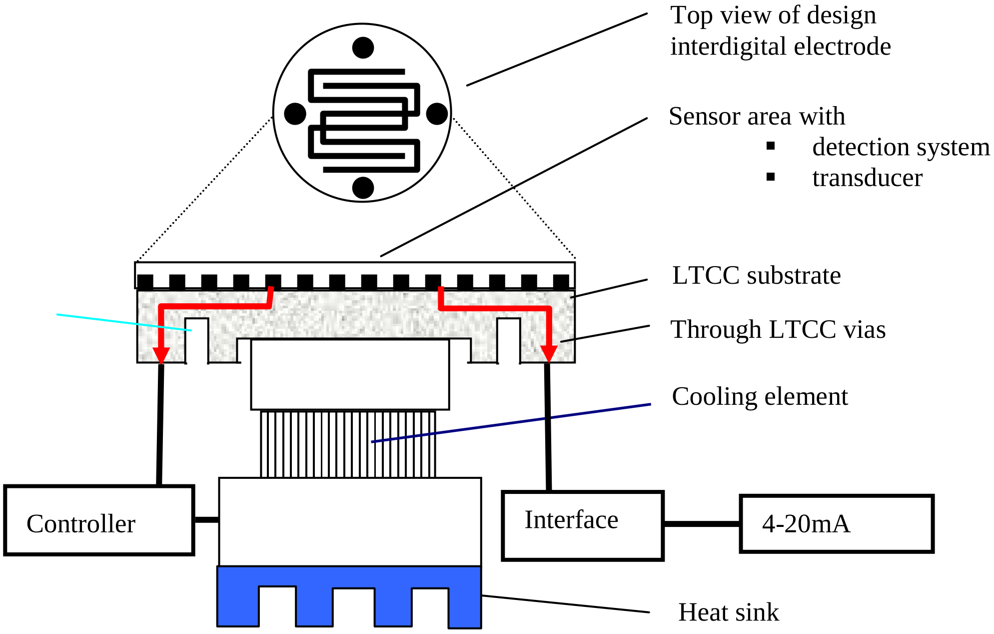

Figure 3: LTCC based CCC* dew point system

4. Preparation of detection system

The LTCC substrate was developed with the aim to improve the performance of standard LTCC significantly with respect to surface roughness, waviness and pinholes in order to make it suitable for the thin film sensor application. Some of them are caused by free sintering process as seen in Figure 4. Whereas the defects on the surface can cause shorts or discontinuities in the electrodes of the capacitances, the waviness is a limiting factor for the contact exposure during UV-lithography and thus for the solution of the structure itself.

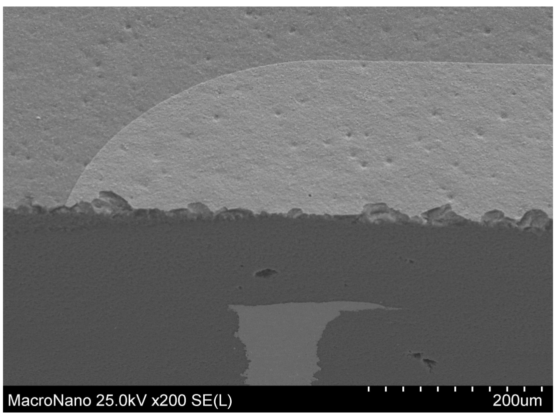

Figure 4: Cross section of LTCC substrate with pinholes inside the material and at the surface

To avoid these effects, the sintering behavior was investigated and evaluated. As a result, the substrate was built by pressure sintering. The remaining release tape on the surface, as shown in Figure 5, was removed by an adapted polishing step. The challenge was to polish the grains of the release tape and to eliminate the undercuts without washing out the glassy matrix of the substrate.

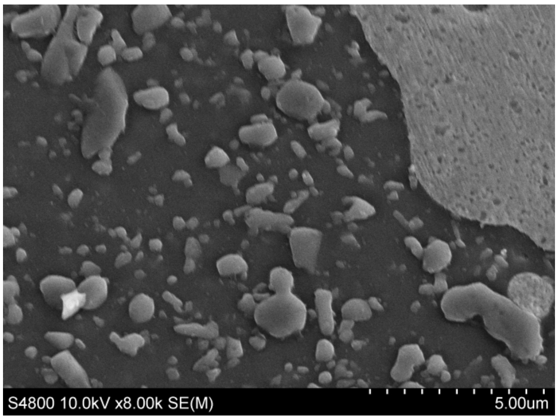

Figure 5: Residues of release tape particles on the pressure sintered surface

The result is shown in Figure 6. The Size of the grain of the release tape is reduced from diameters of up to 3 µm to values below 500 nm and no undercuts can be observed.

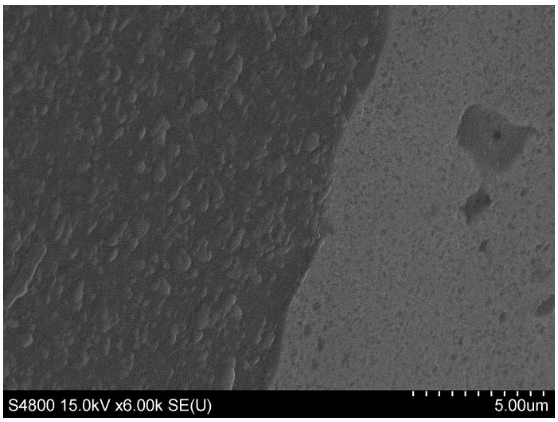

Figure 6: Polished pressure sintered surface

After polishing the surface is coated and structured with CrNi. The structure itself consists of a stray field capacitance and a temperature sensing device in metallization layer. The temperature coefficient is tuned by thermal treatment to the designated value of 3800±200 K^{-1}. Due to the good surface quality ratios of lines and spaces of 10 to 10 µm can be achieved with minimal shorts or discontinuities.

The last step in preparation of the substrate was coating an isolation layer with several specifications realized by using an inductively coupled plasma chemical vapor deposition tool (ICPCVD). At first the isolation has to be free of pinholes to achieve high values for breakdown voltage with a layer thickness of at most 500 nm. The dielectric coefficient of an amorphous silicon nitride layer is about 7 to 7.5 except for electrodes over pinholes, where a frequency depending coefficient can be observed (shown in Figure 7). One possible reason for the frequency dependence is the presence of water adsorbed by the pinhole.

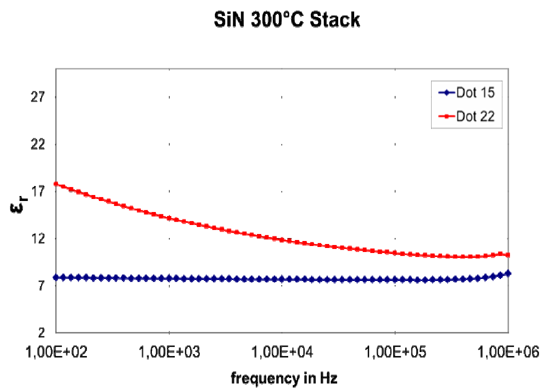

Figure 7: Dielectric coefficient of Si_xN_y with pinholes (Dot22) and without pinholes (Dot 15)

Another demand on the characteristic of the surface was the hydrophobic behavior as an application for humidity sensing devices especially for chemical reactive atmosphere. Silicon nitride is normally hydrophilic with contact angles of about 30°. Due to increasing the silan part in the plasma phase, more silicon can be placed in the nitride layer to achieve a more silicon oxide like contact angle of about 55° (as shown in Figure 8)

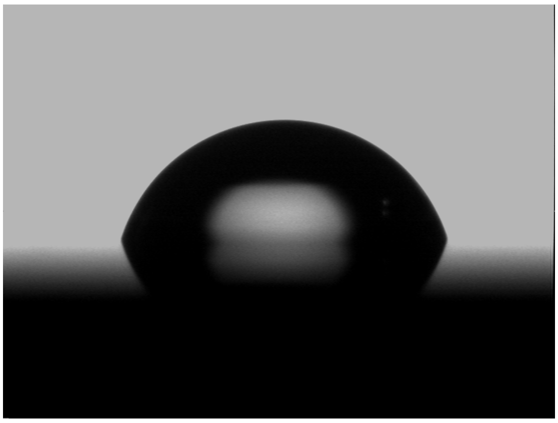

Figure 8: Contact angle of silicon rich Si_xN_y

5. Through LTCC via

The used temperature sensor layer is a special thermal formed CrNi layer. In common use with LTCC as fired substrates with rough surfaces we had good results for contact resistance between CrNi and Au of the via (Figure 9).

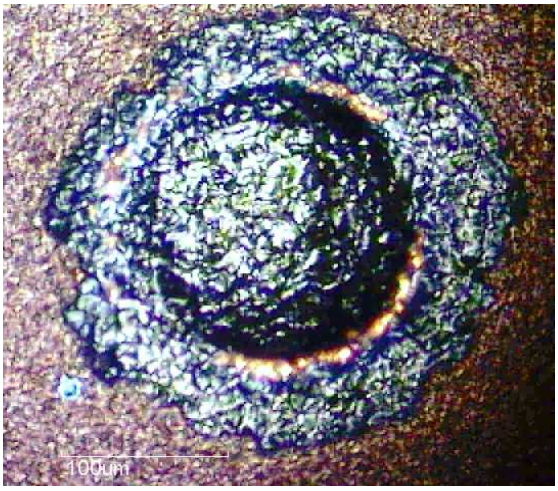

Figure 9: Via on unpolished surface

Better polished surfaces due to a loss of adhesion for CrNi layers after the temper process had bad contact resistance (Figure 10).

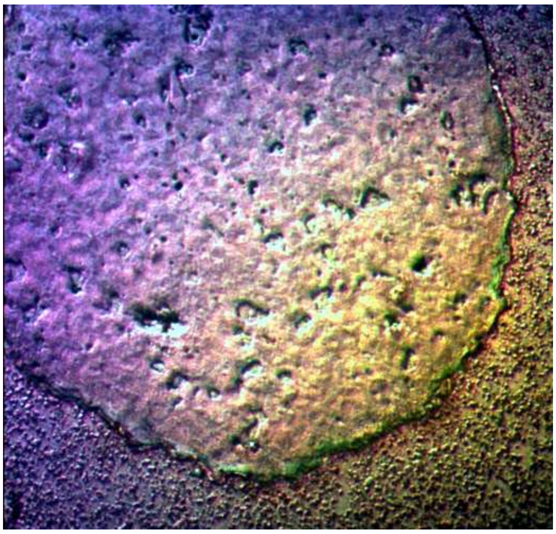

Figure 10: Via on polished surface

Therefore, it is necessary for highly polished surfaces to process the CrNi functional layers without contact to the Au-via and achieve the contact to the via in an additional lift-off process (Figure 11).

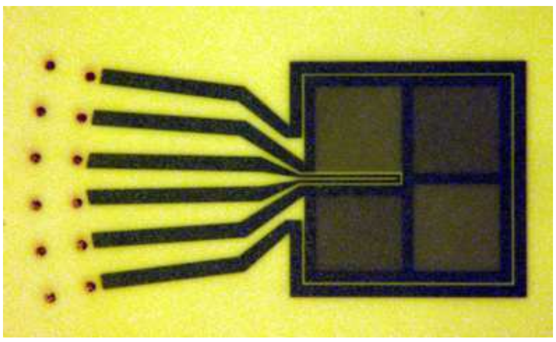

Figure 11: Chip design on LTCC without contact to the vias

Finally, the reliability and the function of the complete system are tested with an impedance measurement at discrete frequencies. The measurement was repeated after every significant process step to assure the functionality during the process chain to detect and stop negative effects of specific parts of the process chain. At the same time, the depositioning step acts as a temperature test for the conductivity between via and CrNi surface layer. In figure 12 one electrical characterization is demonstrated. One substrate with a structure of 15 µm lines and spaces is measured before and after the separation process by a laser and finally after the deposition step at 300°C. It can be seen that only the dielectric behavior changes significantly after the depositioning step, caused by the increasing dielectric coefficient of silicon nitride compared to air. The conductivity between the via and the surface is not damaged.

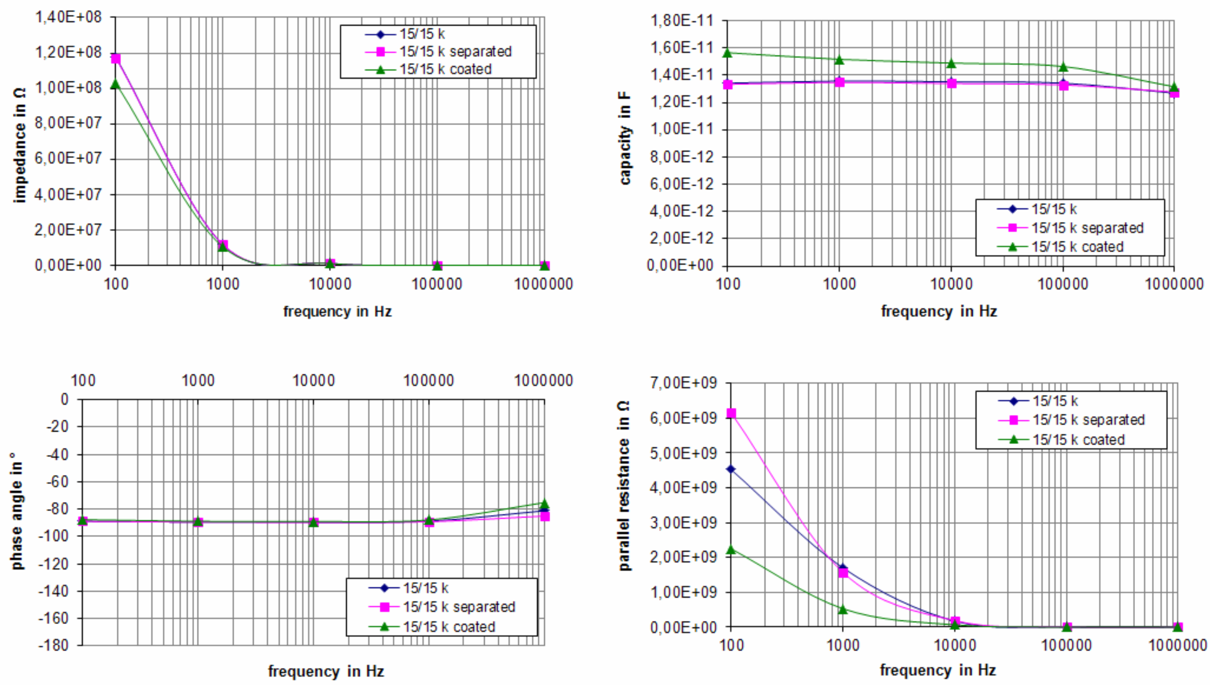

Figure 12: Impedance measurement of a LTCC substrate with 15 µm finger with and space between the finger structure

6. Results

On the basis of scientific investigations a thermal model was developed and verified for the estimation of the thermal conduction and heat transfer resistances for a probe design. After different construction concepts, material investigations and thermal simulation models, a new structure of a dew point probe for applications in contaminated air was developed. In figure 13 the differences in principle between the silicon and LTCC based sensor are evident. To emphasize are a temperature-stable and heat insulating probe head made of plastic material and the temperature heat sink of the peltier element over heat shunts, heat pipe, probe foot and heat sink. The structure of high temperature test stands and the development of an evaluating LabView program were conditions for the practical tests of the different technological development steps.

Figure 13: Comparison of CCC* silicon (left) and LTCC (right) dew point probe

The characterization of the sensor elements or probe assemblies is based on the characteristic curve. The curve shows the dependence of the capacity of the temperature of the sensor surface, the behavior of the sensor during the condensation. Parameters such as run of the curve, hub and rise are evaluated. Based on the sensor characteristic curve, the working point of the adjustment control is established.

In figure 14 the characteristic curve is shown for a probe assembly.

The recording of the curve was determined by measuring the capacitance and temperature settings for different operating points in the unregulated state.

Shown are the dewing pictures of the sensor surface with an indication of the measured capacity.

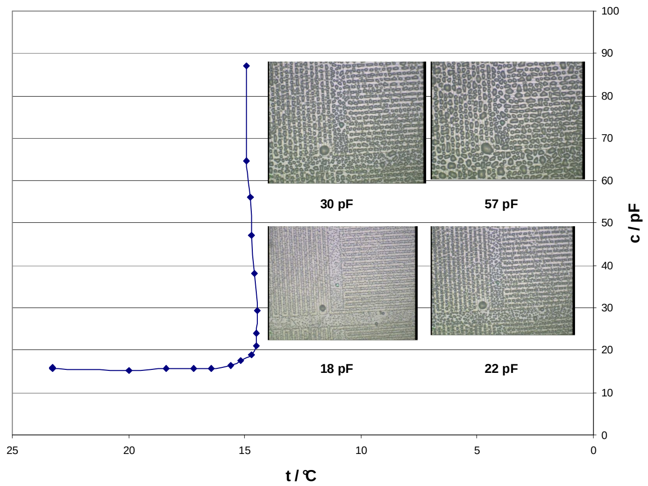

Figure 14: Sensor characteristic including dewing pictures of sensor surface

The wetting behavior of the surface was adjusted so that uniform and reproducible condensation is generated on the surface. First tests to control behavior show that in case of an LTCC-based sensor compared to a silicon-based dew point sensor, a greater mass of water in the balance of condensation and evaporation can be regulated with adequate time constants.

To assess the quality of the passivation layers, leakage measurements were carried out. Only a leak-free passivation current guarantees a sufficient lifetime for the sensor.

7. Summary

The LTCC substrate was successfully integrated in the CCC dew point sensor system. The design of a stray field and temperature sensor was realized. The surface of the sensor - important for the detection system of condensation - allows contact angles of about 60°. The fabricated sensors showed a good dependence of the condensation vs. electric parameters. The prepared vias were stable enough within the tests.

8. Acknowledgement

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