

Analysis of Geometrical Aspects of a Kelvin Probe

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Abstract:

The presented analysis investigates the capacitance characteristic of a kelvin probe regarding the geometrical transition from a movable electrode plate to a narrow tip. Moreover, predictions can be done concerning optimum geometry, sensitivity and suitable electrical measurement circuitry.

A further aim of this study is to provide optimal tip geometries for different sized kelvin probes. This includes pitching the probes impedance and maximizing the current yield out of the contact potential difference between two metals.

Keywords: Kelvin probe, contact potential difference, work function, non-contact measurement technique, FEM

1. Introduction

A kelvin probe is a non-contact, non-destructive measurement technique to investigate the work function difference of material combinations [1, 2].

It is based on a time varying capacitor where the movable electrode consists of a material A and a fixed electrode of a material B with different work functions [3]. For electrically connected electrodes (e.g. external wire bond) the Fermi levels are equilibrated. Electrons originating from the material with the lower work function flow to the material with the higher work function. Consequently, a contact potential difference establishes and the capacitor is charged.

The vibration of the movable electrode results in a change of the stored electrical energy within the capacitor forcing an electrical current to flow. The work function difference can be determined by measuring this current. Alternatively, a compensated operation can be established by applying an external bias voltage so that the current becomes zero. As a result the bias voltage is equivalent to the work function difference of the electrode material pair [4].

On the one hand, the movable electrode can be a plate in order to form a parallel plate capacitor.

This guarantees a large capacitance change which results in a current that can be directly measured without a sophisticated electrical compensation scheme. On the other hand, the movable electrode can be formed as a narrow tip what gives the ability to get a lateral resolution by scanning over some area [5]. Here, the capacitance change and so the resulting current are quite low what calls for an electrical compensation circuit.

2. Use of COMSOL Multiphysics®

The model is set up with the Electro-mechanics Interface. For numeric efficiency, a 2D axial symmetry is established in order to model a vibrating capacitor with circular plate/tip geometries. The movable electrode is configured to a prescribed harmonic displacement and a defined contact potential difference. The counter-electrode is mechanically fixed and set to electrical ground. The electromechanical field equations used are the electrostatic force equation and the electric flux density equation:

$$\rho \frac{\delta^2 u}{\delta t^2} - \nabla \cdot \sigma = Fv$$
$$\nabla \cdot D = \rho_v$$

The transient behavior is observed and the lateral dimension of the movable electrode is varied by a parametric sweep (cf. figure 1). Furthermore a parametric sweep of probe length is done and an analysis of different tip geometries.

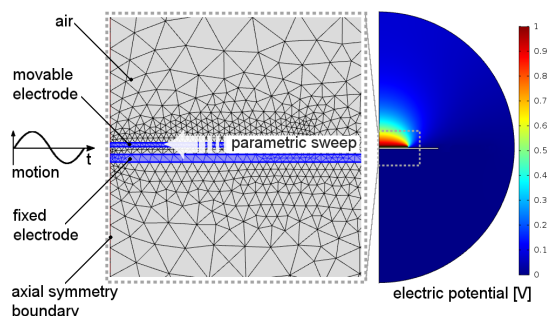


Figure 1. 2D axial symmetric model setup of the kelvin probe.

3. Transient behavior of kelvin probe

Since the motion of the movable electrode is set up as a sine wave, the capacitance gets slightly distorted, like predictable by the well known analytical plate capacitors formula for the capacitance C:

$$C(t) = \epsilon_0 \epsilon_r \cdot \frac{\pi \cdot r_{me}^2}{g_0 + m(t)}$$

$$m(t) = a \cdot \sin(2\pi f \cdot t)$$

in which m is the motion with an amplitude $a=30\mu\text{m}$ and a frequency $f=1\text{Hz}$ (this value has been chosen for calculation purposes – note that a real kelvin probe needs higher frequencies for optimal impedance matching), $g_0=100\mu\text{m}$ is the nominal gap of the movable electrode. These parameters are used in every model for comparability. Figure 2 shows the characteristic transient behavior for a single sine input cycle.

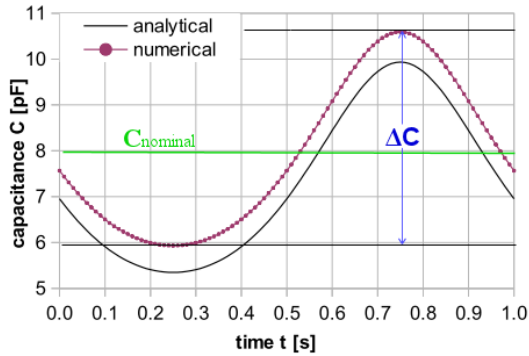


Figure 2. Characteristic transient capacitance behavior of the kelvin probe.

Non applicability of analytical model

For further reviewing the capacitance behavior in downscaling, the radius r_{me} of the movable electrode was swept. By downscaling the plate capacitors radius into a sub millimeter domain, the well known analytical plate capacitor model becomes more incorrect.

That is because the electrical stray capacitance gets a higher influence to the capacitive behavior each step in downscaling. These capacitances are caused by the upper side and the outer sides of the plates geometry, which also contain electrical charges.

Thus the capacitance $C(t) = 2 \cdot W_e(t) / V^2$ has to be calculated out of the electrical energy W_e all over the domain and the contact potential difference V.

This phenomenon makes numerical calculation necessary which also is comfortable. COMSOL AC/DC module uses the energy method to calculate the capacitance out of the electric energy density and makes an easy evaluation for every single time step data possible [6].

The average difference of the analytical results amount at least 8% at $r_{me}=5\text{mm}$ and increases dramatically by downscaling geometry parameters. There is not only an offset in nominal capacitance, rather than an increasing difference of the capacitance change as well. By matching figures 3 and 4 it becomes obvious that a kelvin probe design requires progressive numerical calculation techniques if aimed for high lateral resolution, so that expensive series of experiments can become as short as possible.

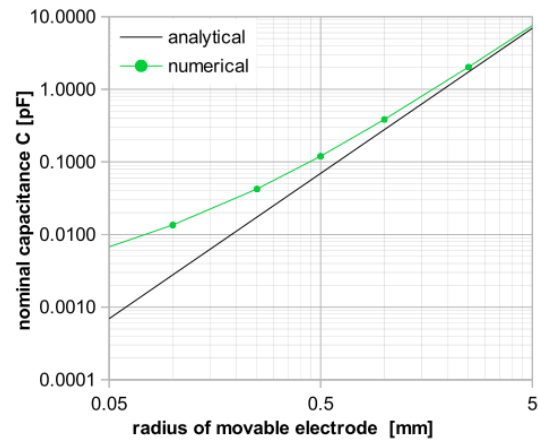


Figure 3. Nominal capacitance as a function of radius.

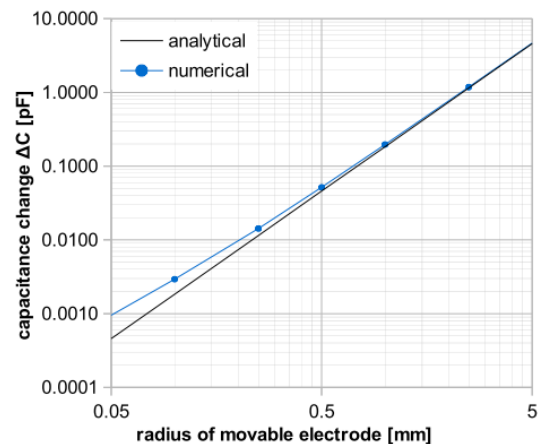


Figure 4. Capacitance change as a function of radius.

4. Geometry scaling of kelvin probe

The geometry scaling was done stepwise to isolate individual effects, by scaling length and radius of the probe separately.

While working on the models it became apparent that the individual effects increase dramatically by downscaling both – radius and length at the same time (cf. figure 7).

4.1 Impact of scaling lateral dimension

The radius r_{me} of the movable electrode was scaled, while the length remains constant at 0.05mm – just to force the impact of scaling the lateral dimension. The simulation results (cf. figure 3 and 4) show, the bigger the movable electrode, the higher the nominal capacitance as well as the capacitance change. The good news is, that surface effects can provide higher capacitances in a real measurement setup. But it also leads to the conclusion, that a higher lateral resolution end at the point where the measurement equipment can not provide reliable values, if just downscaling the lateral dimension.

4.2 Impact of scaling the length

The length of the probe is scaled, while the radius remains constant at 0.5mm.

The simulation results (cf. figure 5 and 6) show, that the nominal capacitance scales in a different way as the capacitance change. After underrunning a length of approximately 2mm the capacitance change decreases significantly.

Therefore the kelvin probe should have a minimum length. This effect becomes more critical, if scaling down the radius at the same time (cf. figure 7). Bear in mind that figures 5 and 6 show the characteristics at a constant radius of 0.5mm. The logarithmic scale in figure 7 adumbrate the tremendous gain in these characteristics.

Further postprocessing showed, that there is no fixed proportion between length and radius for analytical simplifications. Each single geometry must be reviewed separately.

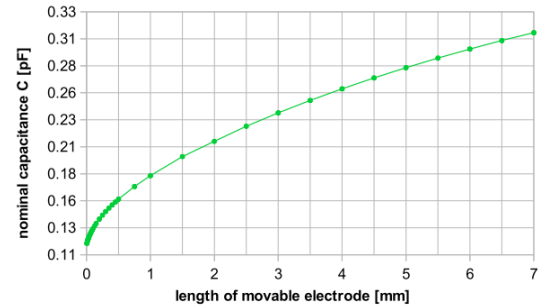


Figure 5. Nominal Capacitance as a function of length.

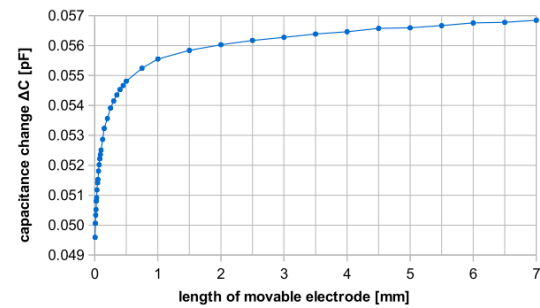


Figure 6. Capacitance change as a function of length.

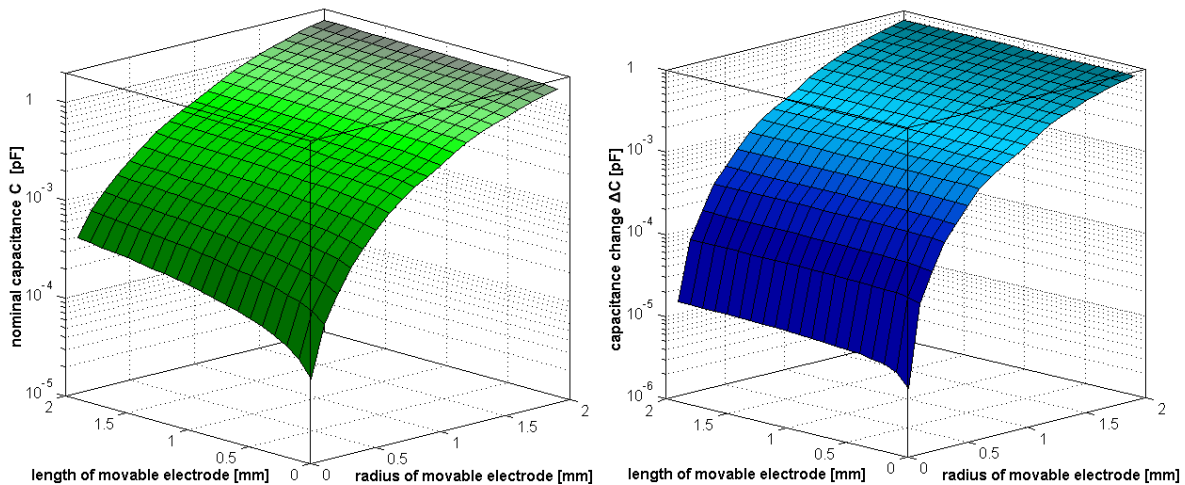


Figure 7. *Left:* The nominal capacitance, *right:* The capacitance change – as functions of length and radius of the movable electrode.

5. Tip geometries of kelvin probe

Different tip geometries provide different capacitance behaviors. That is because of different electric energy densities. To study the consequence of different tip geometries three relatively simple geometries are chosen, in which the flat tip acts as reference (cf. figure 8).

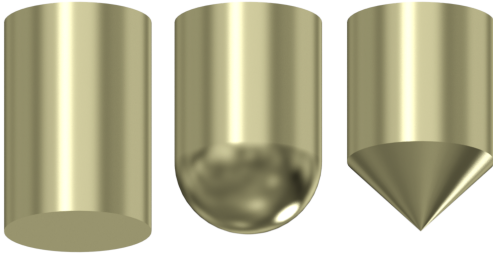


Figure 8. Tips: flat tip, round tip, spikey tip (45°).

To maintain comparability, each geometry length was set to 2mm while the radius was swept. The biggest challenge though is the meshing in COMSOL. Different airspace geometries were set up to provide exact calculations while enabling the sine movement and the parametric sweeps of the different geometries. For instance the meshing which was done for the round tip is shown in figure 9.

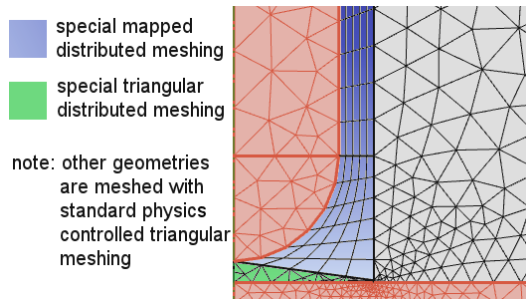


Figure 9. Additional airspace meshing of the round tip model.

The simulation results show that a flat tip has the highest nominal capacitance (cf. figure 10) and capacitance change (cf. figure 11).

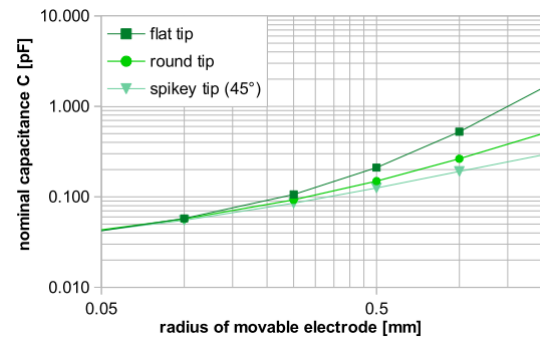


Figure 10. Nominal capacitance of different tips.

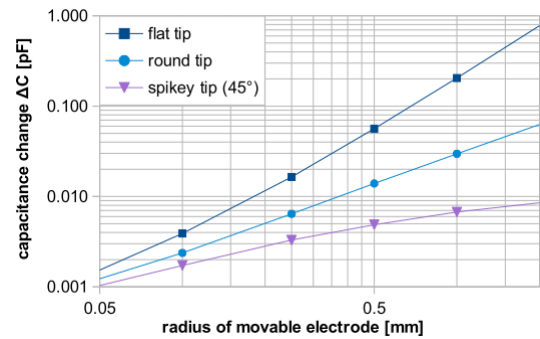


Figure 11. Capacitance change of different tips.

The smaller the lateral tip dimensions are, the closer the capacitance values of the different tip geometries. In case of narrow tips ($r_{me} < 100 \mu m$) the tip geometry (flat, round, spikey) loses importance.

Figure 12 shows the electric potential of the different tip geometries. The electric potential is comparable in the close gap. The vertical boundaries account for the stray capacitances, which have minor influence on the kelvin probe.

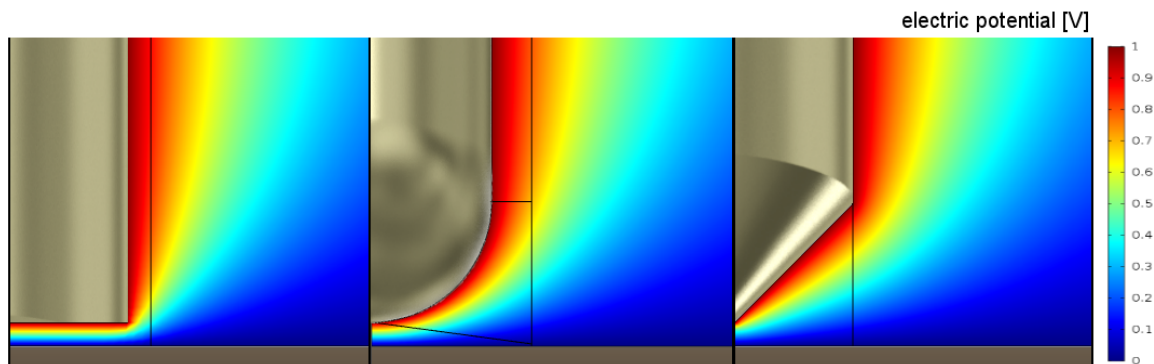


Figure 12. Electric potential of three different tips: flat tip, round tip, spikey tip (45°).

6. Equivalent electrical circuit of kelvin probe

In order to find a suitable equivalent electrical measurement circuit, the model was exemplarily extended by a simple load resistor (cf. figure 13).

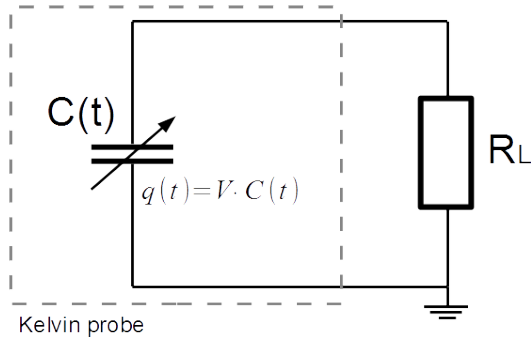


Figure 13. Equivalent electrical circuit of kelvin probe with simple voltage measurement application.

For comparison purposes the model was set up in COMSOL (Electrical Circuit) and in Spice. Figure 14 shows the capacitance characteristic at a frequency of 100Hz for two periods.

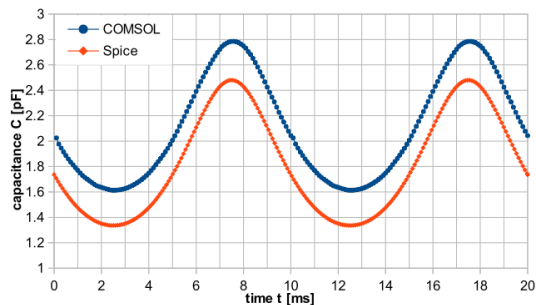


Figure 14. Characteristic transient capacitance behavior of the kelvin probe including electrical circuit.

Figure 15 presents the voltage drop over the load resistor ($R_L=10M\Omega$).

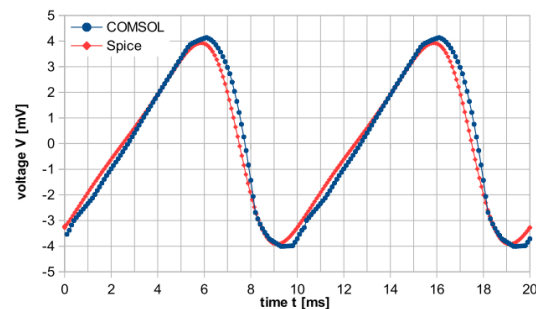


Figure 15. Characteristic transient voltage drop over load resistor.

The Spice model is based on the analytical equations of a plate capacitor (see section 3.) and shows a good correlation.

7. Conclusions

A COMSOL model of a kelvin probe was successfully established and different probe geometries were investigated. Moreover, the model was expanded by a simple electrical measurement circuitry to demonstrate a complete kelvin probe setup.

Future investigations should lead to a highly sensitive electrical circuit (e.g. compensated scheme or differential amplifier scheme) in order to optimize performance.

8. References

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9. Acknowledgements

Supported by the foundation for the promotion of the Reinhold Würth University of Heilbronn University in Künzelsau.