Andrey K. TYAVLOVSKY[1], Anatoly L. ZHARIN[1], Oleg K. GUSEV[1], Konrad KIERCZYNSKI[2]

Belarusian National Technical University, Minsk, Belarus (1), Lublin University of Technology, Lublin, Poland (2)

Kelvin probe error compensation based on harmonic analysis of measurement signal

Abstract. *Reducing of gap-depended errors of Kelvin probe's measurement signal is achieved by harmonic analysis of measurement signal itself, eliminating the need in optical or other distance measurements. Probe-to-sample gap value is calculated via the signal's second to first harmonic amplitudes ratio. Gap-depended error compensation can be made in real-time mode as it is shown in the experiment.*

Streszczenie. *Zmniejszanie błędów szczeliny zależnego od sygnału pomiarowego sondą Kelvina uzyskuje się za pomocą analizy harmonicznej samego sygnału pomiarowego, co eliminuje potrzebę używania optycznych lub innych pomiarów odległości. Wartość szczeliny sondy od próbki oblicza się poprzez stosunek amplitud harmonicznych drugiego sygnału do pierwszego. Kompensacja błędu szczeliny może odbywać się trybie czasu rzeczywistego, jak pokazano w doświadczeniu. (**Kompensacja błędu sondy Kelvina na podstawie analizy harmonicznej sygnału pomiarowego**).*

Keywords: Kelvin probe, contact potential difference, harmonic analysis, measurement errors.
Słowa kluczowe: sonda Kelvina, stykowa różnica potencjałów, analiza harmoniczna, błędy pomiarowe.

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Introduction

A high-resolution Scanning Kelvin Probe (SKP) technique is contactless work function (WF) or contact potential difference (CPD) measurements demands the use of extremely small size capacitor probe [1]. Reducing the probe tip area and therefore the probe-to-sample capacitance leads to the rapid growth of stray capacitance influence [2]. The most common way to solve this problem is to reduce the probe-to-sample gap [3] which can be about the same size as surface roughness. It can lead to additional measurement errors due to non-stability of the gap value. Due to the complexity of theoretical calculations these errors are usually estimated experimentally or even ignored. This approach is appreciable for low-resolution probes, but for high-resolution ones gap-dependent errors must be considered and taken into account.

The present paper is devoted to the study of gap-dependent errors of the vibrating Kelvin probe on a basis of mathematical and computer modeling. A method of real-time measurement of sample-to-probe gap and automatic compensation of its non-stability is also discussed.

Experimental

In a classic Kelvin probe technique a conductive probe is positioned at some distance above a studied sample surface, therefore forming a parallel-plate capacitor. Due to the vibration intentionally applied to the probe, a capacitance C of such a system is modulated under law

$$C(t) = \frac{\varepsilon S}{d_0 + d_m \cos \omega t}, \tag{1}$$

where ε is electric permittivity, S is probe tip area, d_0 is the mean gap between probe and sample, d_m is amplitude of vibration and ω is vibration frequency.

If probe's and sample's work function values are different, an electron transfer between them (e.g. via an external circuit) leads to the potential difference effect between two dissimilar materials. In equilibrium conditions this contact potential difference U_{CPD} (in Volts) is numerically equal to the WF difference (in electron-Volts) [1]. Substitution scheme of probe electrometer's input circuit with vibrating capacitor as a source of a signal is shown on fig. 1. R_L is electrometer's input resistivity that acts as a load resistivity for capacitive source of voltage U_{CPD}. The generalized equation for the current in a circuit containing a vibrating Kelvin capacitor is [1]

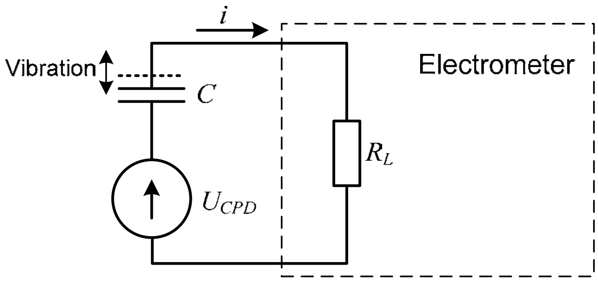

Fig.1. Substitution scheme of a circuit containing a vibrating Kelvin capacitor

$$i = U_{CPD}\frac{dC}{dt} + C\frac{dU_{CPD}}{dt} \tag{2}$$

In the considered scheme U_{CPD} is constant, so the second term in equation (2) is zero and the first term is calculated by differentiation of expression (1). A resulting non-linear differential equation for the output voltage signal U cannot be solved using a traditional approach. In a previous study [4] it was proposed to solve this problem by using a complex-harmonic analysis technique. The solution was found in a form of an infinite sum of complex harmonics U_k written as

$$U_k = kQ_k \omega R_L \sin(k\omega t + \varphi_k), \tag{3}$$

where k is harmonic number and a complex charge Q_k is calculated from the following system of equations:

$$\begin{cases} Q_0^* = \dfrac{j2U_{CPD}}{\dfrac{d_0}{\varepsilon S} - \dfrac{d_m}{\varepsilon S}\dfrac{Q_1^* - \hat{Q}_1}{2Q_0^*}}, \\ Q_k^* = \dfrac{d_m}{2\varepsilon S}\dfrac{Q_{k-1}^* + Q_{k+1}^*}{\dfrac{d_0}{\varepsilon S} + jk\omega R_L} \end{cases} \tag{4}$$

For each harmonic one can introduce a transduction factor A_k that characterizes a relationship between input CPD voltage U_{CPD} and corresponding harmonic voltage U_k:

(5) $$A_k = \frac{U_k}{U_{CPD}} = A_{km}\sin(k\omega t + \varphi_k),$$

where

(6) $$A_{km} = \frac{kQ_k\omega R_L}{U_{CPD}}$$

is amplitude of a transduction factor for the harmonic k. In accordance to (6) A_{km} can be treated as normalized amplitude of the corresponding harmonic of a signal considering U_{CPD} is one.

In most practical schemes the detection of output signal is realized on its first harmonic to avoid noise detection that can persist on higher harmonics so here and below we will consider the first harmonic only despite the following discussion is applicable for other harmonics as well.

A solution of (6) with respect to (4) demonstrates a strong dependence of A_{1m} on the probe-to-sample gap d_0 when d_0 approaches the d_m value. For generality we'll consider a dimensionless normalized value d_0/d_m instead of d_0. In a paper [5] equation (6) was modeled for different vibration frequencies, load resistivity values and modulation factors $m = d_m/d_0$. Probe tip area for calculations was conditionally stated to be 1 mm^2. It was found that for small-sized probes high normalized frequencies of vibration $\omega R_L C_0$ are unattainable. For low normalized frequencies $\omega R_L C_0 \approx 10^{-3}$ medium loads R_L about $10^7 \ldots 10^{12}$ Ohms are inappropriate due to phase instability of output signal so relatively low input resistivity $R_L = 10^7$ Ohm is considered. Under such circumstances a probe-to-sample gap dependence of the first harmonic of a small-sized Kelvin probe output signal takes a look of a graph shown on fig. 2 [5].

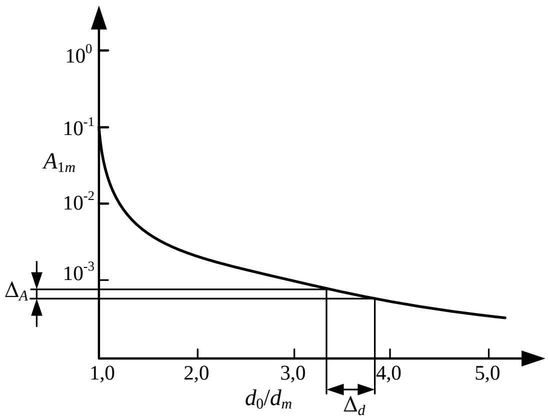

Fig.2. Normalized amplitude of the first harmonic of signal as a function of a probe-to-sample gap [5]

Graf on fig. 2 and corresponding equation for $A_{1m}(d_m/d_0)$ dependence serve as a basis for gap-dependent probe error calculations.

Results and Discussion

To study the dependence of transduction factor error Δ_A on the probe-to-sample gap uncertainty Δ_d (see fig. 2) one can use a well-known equation

(7) $$\Delta_A = \left|\frac{\partial A_{1m}}{\partial(d_0/d_m)}\right|\Delta_d .$$

The derivative $\left|\frac{\partial A_{1m}}{\partial(d_0/d_m)}\right|$ can be treated as sensitivity factor Δ_A/Δ_d of the output error Δ_A on input uncertainty Δ_d dependence. This sensitivity factor also depends on probe-to-sample gap value as it can be seen on fig. 3 where derivative values plotted vs. normalized probe-to-sample gap values.

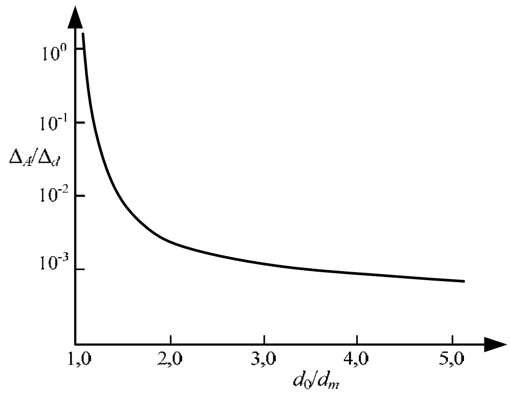

Fig.3. First harmonic error sensitivity on probe-to-sample gap uncertainty plotted vs. normalized gap value

As it is easily predicted, an output signal error sensitivity on probe-to-sample gap uncertainty raises dramatically when normalized gap falls under d_0/d_m = 2,0 i.e. for gap values less than two amplitudes of vibration that corresponds to highly non-linear regime of Kelvin capacitor [4]. Besides this regime is the most interesting for high-resolution Kelvin probes [3, 6]. It means that probe-to-sample gap must be controlled in this regime in real-time mode to avoid additional errors due to gap variations when scanning non-flat surface. It can be done by using additional optical sensors [2] but an accuracy of optical method for very small gaps is limited. Moreover, optical distance measurements depends on absorption and reflection factors of the surface that could vary across the scanned area and are not applicable for surfaces under optically transparent coverings. An alternative method of probe-to-sample gap measurement is based on analysis of Kelvin probe's output signal itself. As it was found in previous study [5], harmonic contents of output signal depends on the modulation factor of vibrating capacitor and therefore on d_0. Particularly it was found that the ratio between the second and the first harmonics amplitudes can be used to measure the probe-to-sample gap value. A dependence of the second-to-first harmonic amplitude ratio on the normalized gap value as it was calculated in paper [5] is shown on fig. 4.

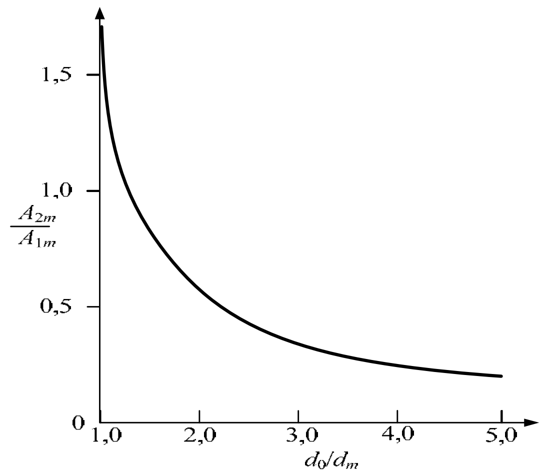

Fig. 4. Second-to-first harmonic amplitude ratio plotted vs. probe-to-sample gap [5]

The second and the first harmonics amplitudes could be measured in real-time mode with the aid of two different narrow-band filters coupled with phase-lock detectors. Then a signal proportional to these amplitudes ratio could be used as a negative feedback signal to maintain a constant mean gap value d_0. An error of this feedback signal depends on uncertainty of harmonics amplitudes ratio measurements. A value of this error can be calculated by equation similar to equation (7):

$$\Delta_d = \left| \frac{\partial (d_0 / d_m)}{\partial (A_{2m} / A_{1m})} \right| \Delta_{A12}, \tag{8}$$

where Δ_{A12} is uncertainty of second-to-first harmonic amplitude ratio measurements. It can be seen that error calculated by (8) depends on probe-to-sample gap value and rises with the raise of the latter.

The method described here was accepted for realization in experimental scanning probe electrometer design. The vibrating probe was driven by a piezoelectric vibrator working at 800 Hz frequency. Diameter of the probe was 0,5 mm, amplitude of the vibration was stated to be d_m = 0.2 mm. Measurement signals were processed with high-speed STM32F4xx Cortex core microcontroller. There also was installed an optical proximity sensor to control a distance between the probe and sample surface. It was found that for small distances a sensitivity of optical sensor differs for surfaces of different nature: it “sensed” the metal surface at a distance twice more than the semiconductor one. In contrary, the method based on harmonic analysis of a signal gave the same results for metal and semiconductor surfaces. Experiments demonstrated that uncertainty of second-to-first harmonic amplitude ratio in real measurements was about 1 %. Corresponding errors of probe-to-sample gap determination calculated with the equation (8) for Δ_{A12} = 1 % are plotted as a graph on fig. 5.

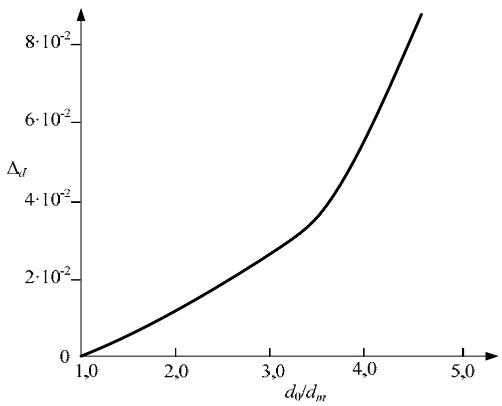

Fig.5. Error of probe-to sample gap determination for 1 % uncertainty of second-to-first harmonic amplitude ratio measurements

From fig.5 it can be seen that gap determination errors are about proportional to the second-to-first harmonic amplitude ratio measurements uncertainty up to the normalized gap value $d_0/d_m \approx 3.5$ and than are raising quickly due to weak dependence of harmonic ratio from the gap value for greater gaps.

The resulting error of Kelvin probe signal due to gap uncertainty can be found as a combination of probe-to-sample gap uncertainty (7) and the first harmonic error sensitivity on probe-to-sample gap uncertainty (8). Substitution of (8) into (7) yields a dependence of the Kelvin probe error on normalized gap value that is shown on fig. 6 in a graphical form. The resulting Kelvin probe error dependence has a minimum at a normalized gap value d_0/d_m = 2.0. For the values below this an output signal becomes too “sensitive” to the gap value due to high non-linearity of a vibrating capacitor with a high modulation factor, and big variations of a signal due to small variations of the gap cannot be compensated by high accuracy of gap value measurements. In contrary, raising the normalized gap value above d_0/d_m = 2.0 makes the vibrating capacitor less sensitive to gap variations but errors of gap value measurements become too high in this mode.

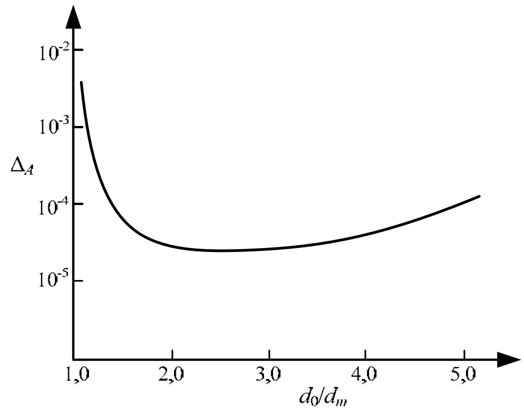

Fig.6. Kelvin probe error due to uncertainty of probe-to sample gap determination

We can make a conclusion that traditional Kelvin probe measurements without gap control must be held with a probe-to-sample gap far above two values of vibration amplitude $d_0 >> 2d_m$. In this case a Kelvin probe output signal will be relatively stable with gap variations but a spatial resolution of a probe will be poor. Improving the spatial resolution by reducing the probe-to sample gap [6] demands real-time gap control that can be made on a basis of harmonic analysis of output signal itself. An optimal value of a normalized gap with real-time gap control is d_0/d_m = 2.0 that corresponds to the minimum of a resulting error.

In a practical measurements there can persist additional sources of errors e.g. stray capacitance, electromagnetic interference, microphonic effect, mechanical system uncertainties etc. In an experiment that was held using the experimental scanning probe electrometer it was found that resulting errors are about 1.5 times more than predicted by graph on fig. 6. Presumably the main source of additional error was the feedback loop that controlled the probe-to-sample gap. Despite this the accuracy of CPD measurements with gap control based on harmonic analysis of output signal was found to be about twice better than without gap control. Also, the less influence of stray capacitance at small gap values lead to significant improvement of the signal-to-noise ratio.

Resume

Output signal of small-sized scanning Kelvin probe is characterized by additional measurement error due to instability of probe-to-sample gap. This gap-dependent error rises dramatically when gap value lowers below two values of vibration amplitude that corresponds to highly non-linear regime of vibrating capacitive probe. To reduce this error a probe-to-sample gap value must be monitored and controlled in real-time mode. It can be achieved by harmonic analysis of the output signal of probe itself, in particular, by calculation of the second-to-first harmonic amplitudes ratio. A signal proportional to the second-to-first harmonic amplitudes ratio is used in a feedback loop to maintain a constant value of the gap. In that case gap-dependent additional error reaches its minimum at a gap value $d_0 = 2d_m$. Less gap values are characterized by very sharp dependence of output signal on gap variations making a system highly non-linear. Raising the probe-to-sample gap value above $d_0 = 2d_m$ leads to high errors of gap value measurements and also to the growth of stray capacitance influence. Probe-to-sample gap control based on harmonic analysis of Kelvin probe's output signal allows to reduce gap-dependent errors about twice comparing to classic measurements with no gap control and also to reduce noise and to rise Kelvin probe spatial resolution due to reducing the gap value.

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Authors: *Ph.D. Andrey K. Tyavlovsky, Prof., D.Sc. Anatoly L. Zharin, Prof., D.Sc. Oleg K. Gusev, Belarusian State University, 65 Nezavisimosti Ave., 220013 Minsk, Belarus, E-mail: nilpt@tut.by;*
M.Sc. Konrad Kierczyński, Lublin University of Technology, Department of Electrical Devices and H.V. Technology, 38a Nadbystrzycka Str., 20-618 Lublin, Poland, E-mail: k.kierczynski@pollub.pl.