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KELVIN PROBE'S STRAY CAPACITANCE AND NOISE SIMULATION

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Stray capacitance effects and their influence on Kelvin probe's performance are studied using mathematical and computer simulation. Presence of metal surface, even grounded, in vicinity of vibrating Kelvin probe produces the additional stray signal of complex harmonic character. Mean value and amplitude of this stray signal depends mostly on the ratio of stray and measurement vibrating capacitors gaps d_1/d_0. The developed model can be used for theoretical analysis of Kelvin probe configuration and probe electrometer's input circuit.

Keywords: contact potential difference, Kelvin probe, compensating technique, dynamic response, measurement uncertainty.

Introduction

The most common method of contact potential difference (CPD) measurements [1] is Kelvin–Zisman technique which implements vibrating capacitor probe (also called Kelvin probe) [2]. Due to non-destructive character and extreme sensitivity to any changes in surface properties CPD measurements can be used to characterize precision surfaces of semiconductor wafers, sensor structures, micromechanics etc. A method can be used to reveal stressed areas, chemical impurities, dislocation sites and other surface defects [3] including that of submicron scale. At the same time, high sensitivity to the factors mentioned means that Kelvin probe is sensitive to any surface adjacent to the probe, e.g. constructive parts of the measurement installation made of metal. Because of dissimilarity of probe's and constructive parts' materials there will exist a parasitic CPD between them that alters a Kelvin probe's output signal. Therefore an effect of stray capacitance between probe and other-than-sample metal surfaces must be taken into consideration and analyzed thoroughly.

An influence of stray capacitance on Kelvin probe's input was studied by D. Baikie [4] and A. Hadjadj [5] but obtained results were mostly of empirical character. A. Hadjadj [5] used both theoretical and experimental methods. The geometry of Kelvin probe's sensing plate was thought to be hemispherical allowing author to treat the electric charge of a plate as point charge. At the same time real Kelvin probe configuration in most cases is closer to parallel-plate capacitor [2] therefore obtained results are of limited applicability in most practical cases. Due to complexity of mathematical model developed in [5], A. Hadjadj then used mostly empirical approach for calculation of measurement errors based on introduction of experimentally determined coefficients. These coefficients could be determined only on real probe, so the proposed model cannot be used in theoretical development of Kelvin probe design.

Present paper is devoted to the analytical study of stray capacitance and parasitic CPD effects and their influence on Kelvin probe's performance and output signal. Main methods used are mathematical and computer modeling with respect to the vibrating Kelvin probe's output signal model developed in a previous study [6]. The study is focused on compensation scheme of CPD measurements as the most common case in measurement practice [1].

Experimental

Classic Kelvin probe can be described as a dynamic (vibrating) capacitor where one plate (sample surface) is immovable whereas other (probe's sensor) vibrates in the direction orthogonal to the sample surface. Due to vibration an electrical capacitance C between sensor and sample is modulated in a periodical manner. In a presence of CPD U_{CPD} between capacitor plates this modulation produces an electrical current i calculated as:

$$i = U_{CPD} \frac{\partial C}{\partial t}. \quad (1)$$

Other metal surfaces should also influence on a sensor via CPD effect. The most significant is presence of the probe's mount situated not far from the sensor (probe's tip). Schematic model of such a situation is shown on Figure. 1.

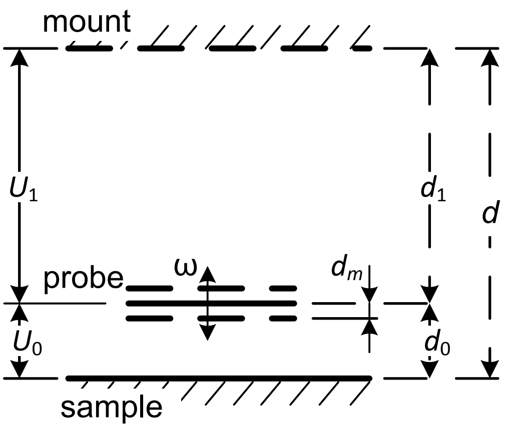

Figure 1 – Schematic representation of stray capacitor on Kelvin probe's input

Probe vibrates at frequency ω with amplitude d_m at a distance d_0 from a sample and at a distance d_1 from the mount. The mount is not vibrating, so the mount to sample distance d is constant and:

$$d_0 + d_1 = d. \quad (2)$$

Actual CPD between sample and probe's tip is U_0. U_1 is parasitic CPD between probe's tip and mount. This parasitic CPD exists because of difference in work function between probe and mount materials [1] and could not be eliminated.

To improve spatial resolution of the scanning Kelvin probe the probe-to-sample gap d_0 should be less then lateral dimensions of the probe [7] so combination of probe and sample can be treated as parallel plate capacitor with one vibrating plate. The system including sample, probe and mount can be described as differential capacitor with static peripheral plates and vibrating central plate. This differential capacitor is highly non-symmetric with stray capacitance much less than probe-to-sample capacitance. Kelvin and stray capacitor voltages are also different in general.

Gaps in differential capacitor are modulated with different modulation factors $m_0 = d_m/d_0$ and $m_1 = d_m/d_1$ and in counterphase to each other in accordance to (2). Sinus-like modulation of a gap leads to more complex periodic capacitance modulation that can be expressed as:

$$C_K(t) = \frac{\varepsilon\varepsilon_0 S}{d_0 + d_m \sin \omega t} \quad (3a)$$

and:

$$C_P(t) = \frac{\varepsilon\varepsilon_0 S}{d - d_0 - d_m \sin \omega t}, \quad (3b)$$

where $C_K(t)$ and $C_P(t)$ are vibrating Kelvin probe capacitance and stray capacitance; S is an effective area of vibrating plate; ε_0 is dielectric constant, ε is electrical permittivity of probe's environment.

Capacitance modulation with constant U_0 and U_1 voltages produces a current that is determined by both measured and stray CPDs:

$$i = \frac{\partial}{\partial t}\left(U_0 \frac{\varepsilon\varepsilon_0 S}{d_0 + d_m \sin \omega t} + U_1 \frac{\varepsilon\varepsilon_0 S}{d - d_0 - d_m \sin \omega t} \right), \quad (4)$$

Equation (4) can be analyzed using a computer simulation as it is discussed further.

Results and Discussion

Mathematical model (4) describes highly nonlinear system. Measurement and stray components of a signal are combined additively so they can be analyzed separately. Computer simulation was used to calculate output signal waveform with and without stray capacitor presence for different combinations of measurement and stray capacitor geometrical parameters, measured and stray CPDs. Typical waveform of vibrating Kelvin probe output current without considering the stray capacitance effect is shown on figure 2. Modulation factor for figure 2 was set at relatively low level m_0 = 0,2 and the CPD was conditionally set to 1 V.

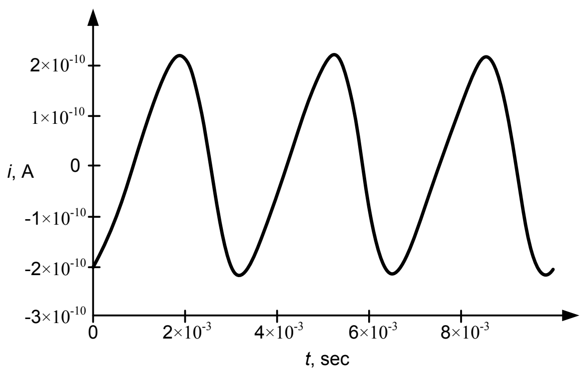

Figure 2 – Typical waveform of Kelvin probe output current signal in absence of stray capacitance effect

Modeling of full equation (4) with stray component produces slightly different in shape waveform. Stray signal component can be obtained by subtraction of «pure» measurement signal (Figure 2) from this waveform. A result of this subtraction for model situation d_0:d_1 = 1:20 is shown on Figure 3. It can be seen that the shape of calculated stray signal is almost sinusoidal that can be explained by small modulation factor of the stray capacitor. A frequency of the stray signal coincides with the frequency of measurement signal. Phases of measurement and stray signal are opposite so stray signal lowers the output current of the vibrating Kelvin probe (and therefore worsens the signal-to-noise ratio) and distorts its shape. Amplitude of the stray signal in the modeled configuration three decimal orders lower than full input signal amplitude indicating signal-to-noise ratio (SNR) due to stray capacitance effect about 60 dB.

Because of frequency equality this SNR cannot be improved by filtration of a signal. It must be noted, however, that the relation of the second harmonics of measurement and stray signal is much higher than the relation of their first harmonics due to difference in modulation factors [7]. It means that rejecting of the first harmonic with measurements on the second harmonic of a signal could provide higher SNR value while using the low-noise preamplifier of input signal. This approach would be developed in a separate study.

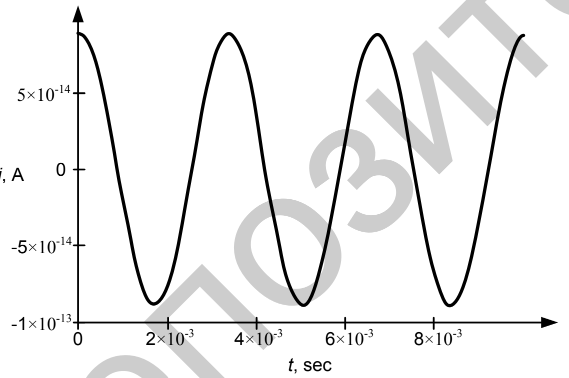

Figure 3 – Stray component of real Kelvin probe output signal

Guarding a Kelvin probe with grounded shield, that is traditional action in electrostatics measurements, would not be effective in a situation where work functions of probe and shield materials are different that is common point for any design. Alternative measures that will reduce the stray capacitance effect must be developed with respect to the electrical scheme of probe electrometer's input circuit.

The substitution scheme of a probe electrometer input with vibrating stray capacitor is shown on fig. 4. C_K represents the Kelvin probe capacitance and C_P represents the stray capacitance. Corresponding measured and stray CPDs are designated U_K and U_P. Input parallel capacitance of preamplifier and input wirings is represented by capacitor C and the preamplifier's active input resistance – by resistor R_{in}. Figure 4 represents a full compensation measurement scheme (Kelvin-Zisman scheme) so there is a variable compensation voltage source U connected in series with preamplifier's input. A negative feedback loop (not shown on the scheme) monitors the input current i automatically adjusting voltage U in such a way that $i = 0$. U acts as output measurement signal stated to be equal to measured CPD in the absence of stray signals.

Input current i of the Kelvin probe is formed by two parallel capacitive sources C_K and C_P generating currents i_P and i_K:

$$i = i_P + i_K. \tag{5}$$

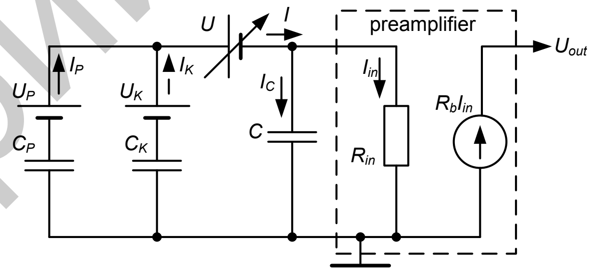

Figure 4 – Substitution scheme of probe electrometer input in the presence of stray capacitance

At the input of probe electrometer this current divides onto two components: capacitive (reactive) and active:

$$i = i_C + i_{in}. \tag{6}$$

Implementation of the Kirchhoff's law to the contours of substitution scheme (Figure 4) gives:

$$\int_0^t \frac{i_P}{C_p} dt - \int_0^t \frac{i_K}{C_K} dt = U_P - U_K; \tag{7a}$$

$$\int_0^t \frac{i_K}{C_K} dt + \int_0^t \frac{i_C}{C} dt = U_K - U; \tag{7b}$$

$$\int_0^t \frac{i_C}{C} dt - i_{in} R_{in} = 0. \tag{7c}$$

Differentiation of (7) produces:

$$\frac{i_P}{C_p} - \frac{i_K}{C_K} = \frac{\partial U_P}{\partial t} - \frac{\partial U_K}{\partial t}; \quad (8a)$$

$$\frac{i_K}{C_K} + \frac{i_C}{C} = \frac{\partial U_K}{\partial t} - \frac{\partial U}{\partial t}; \quad (8b)$$

$$i_C = R_{in} C \frac{\partial i_{in}}{\partial t}. \quad (8c)$$

Solving (6)–(8) for U and i_{in} simultaneously one would obtain the equation

$$\frac{\partial U}{\partial t}\left(C_K + C_p\right) = -i_{in} - R_{in}\left(C + C_p + C_K\right)\frac{\partial i_{in}}{\partial t} + C_K \frac{\partial U_K}{\partial t} + C_p \frac{\partial U_P}{\partial t}. \quad (9)$$

Probe electrometer's output signal can be calculated by integration of equation (9):

$$U\left(C_K + C_p\right) = -\frac{1}{C_K + C_p}\int_0^t i_{in}\,dt - R_{in} \times \times \left(C + C_p + C_K\right) i_{in} + C_K U_K + C_p U_P. \quad (10)$$

Taking into account that compensation criteria is $i_{in} = 0$ and assuming compensation errors to be negligible, equation (10) can be rewritten as

$$U = \frac{C_K U_K + C_p U_P}{C_K + C_p}. \quad (11)$$

C_K and C_P capacitances are modulated under law (3). Due to difference in distances d_0 and d_1 mean value of C_P is much less then mean value of C_K and modulation factor $m_P = d_m/d_1$ of the former is much less then modulation factor $m_K = d_m/d_0$ of the latter. Taking into account also the fact that static input capacitance C of the preamplifier is much greater than C_K approximated solution of (11) can be found as

$$U = U_K + \frac{m_P C_p U_P}{\varepsilon_0 S \Delta d} d_0^2. \quad (12)$$

Obviously the second term in equation (12) represents the systematic measurement error due to stray capacitance effect:

$$\Delta U = \frac{m_P C_p U_P}{\varepsilon_0 S \Delta d} d_0^2. \quad (13)$$

Non-linearity of function describing the vibrating capacitance time dependence makes the analytical solution of (10) with substitution of C_K and C_P from (3) too cumbersome. Numerical solution could be found on a basis of computer simulation while substituting real (or model) parameters of probe's geometry, measured and stray CPD.

Results of the simulation demonstrate that the full solution of equation (9) is complex harmonic function with mean value close to U_K but never equals to it for any practical configuration of a probe except when $U_P = 0$. The error $\Delta U(t) = U(t) - U_K$ (see (13)) oscillates periodically at a probe vibration frequency. An amplitude of $\Delta U(t)$ oscillations depends on geometrical parameters of Kelvin probe and is of same order as the ΔU mean value. A result of stray signal modeling for $U_K = 300$ mV, $U_P = -200$ mV, $d_1 = 20d_0$ is given on Figure 5. Under such conditions a mean value of stray signal is calculated to be about 1,5 mV or 0,8 % of stray CPD voltage with amplitude of oscillation about 0,6 mV. This result is in a good agreement with D. Baikie [4] and A. Hadjadj [5] empirical conclusions stating that stray CPD reduction factor approximately equals to the relation of stray and measurement vibrating capacitors gaps d_1/d_0. Modeling also demonstrated that grows of the reduction factor with rising the ratio d_1/d_0 is not linear: whereas d_1/d_0 is growing twice, the reduction factor grows for almost 20 dB.

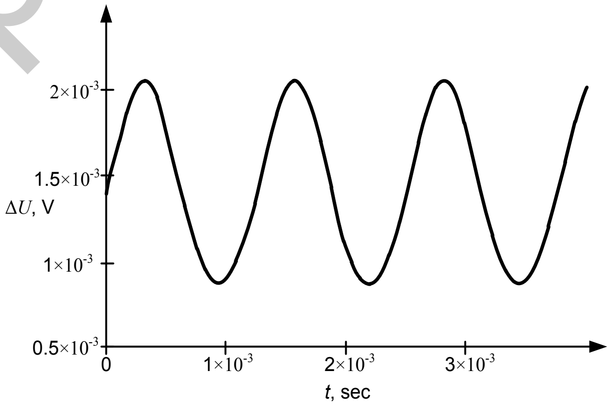

Figure 5 – Results of stray signal modeling for Kelvin probe with $d_1 = 20d_0$

The developed model can be used for theoretical analysis of Kelvin probe configuration and probe electrometer's input circuit as well as other devices containing a vibrating (dynamic) capacitor such as accelerometers, humidity sensors etc. At the same time obtained results should be treated as a first stage approximation because the model counts off fringing field effects and non-homogeneity of CPD distribution that are the second level influence factors.

Resume

Analysis of obtained results leads to the following conclusions:

1. The main factor determining the stray signal value in CPD measurements with a vibrating Kelvin probe is the ratio of measurement and stray capacitor gaps d_0/d_1. The dependence is not linear: for $d_0/d_1 = 1{:}20$ stray CPD reduction factor is about 40 dB whereas for $d_0/d_1 = 1{:}50$ it reaches 60 dB. Similar results were obtained in experiments made by A. Hadjadj [5].

2. Amplitude of AC component of a stray signal is one order of its mean value. Amplitude parameters of stray signal does not depend on vibration frequency of Kelvin probe. A numerical solution of stray signal mathematical model produces complex harmonic function with components in degrees 0, 1, 2 and –1 indicating the existence of lower and higher harmonics in a stray signal.

3. Further development of mathematical model should be aimed at counting fringing field effects and non-ideality of vibrating capacitor geometry and CPD distribution.

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МОДЕЛИРОВАНИЕ ПАРАЗИТНОЙ ЕМКОСТИ И НАВОДОК НА ЧУВСТВИТЕЛЬНОМ ЭЛЕМЕНТЕ ЗОНДА КЕЛЬВИНА

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Влияние паразитных емкостей на характеристики чувствительного элемента вибрирующего зонда Кельвина исследовалось с помощью методов математического и компьютерного моделирования. Показано, что присутствие в непосредственной близости от вибрирующего зонда Кельвина металлических поверхностей, в том числе заземленных, приводит к формированию на его входе паразитного сигнала наводки сложного гармонического состава. Среднее значение и амплитуда данного паразитного сигнала зависят главным образом от отношения зазоров в паразитном и измерительном конденсаторах Кельвина d_1/d_0. Разработанная модель может использоваться для теоретического анализа конструктивных параметров проектируемого зонда Кельвина и входных цепей зондового электрометра.

Ключевые слова: контактная разность потенциалов, зонд Кельвина, компенсационная методика измерений, динамическая характеристика, погрешность измерений.

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