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Modeling and Quantifying Electrostatic Interactions for Kelvin-probe Measurements

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Summary:
In this paper we propose a quantitative model for the interaction between a sampling electrode and a sample surface in a Kelvin-probe surface potential measurement. We briefly describe the Kelvin method, then we introduce a capacitance based electrostatic model to quantify the interaction. We use this model to derive the Point Spread Function (PSF) of the measurement which can be used to enhance physical measurements using a deconvolution-based approach.

Keywords: Kelvin-probe, electrostatic, capacitive, deconvolution, modeling

Background, Motivation an Objective

In semiconductor metrology the ability to measure electrostatic surface potential can give valuable insights into the surface state of the sample and the physical processes going on inside the bulk material. To measure this potential several methods have been formulated such as the use of ChemFETs [1] and the Kelvin-probe method [2]. During the Kelvin-probe measurement a vibrating electrode is put in proximity to the sample's surface and the two surfaces interact through the electric field to produce a changing current that transport charges onto the sampling electrode. The amount of current is proportional to the potential difference between the sample's surface and the vibrating electrode. By changing the sampling electrode static potential, the transport current can be minimized by which we can determine the sample surface's electrostatic potential in a non-contact manner.

The goal of our paper is to derive a mathematical model which describes the interaction and to generate the Point Spread Function of the measurement setup, which then can be used in a post processing step to increase the measurement resolution after the scanning of the sample.

Physical and Mathematical Model

The vibrating sampling electrode is coupled to the sample's surface through the electromagnetic interaction between them. However, since the characteristic length scale and frequencies used during the measurement, the interaction can be simplified to only the electrostatic field. This field can be modeled with lumped capacitances and in the limit as a distribution of surface capacitance density.

Due to the vibration of the sampling electrode the coupling capacitance varies in time. This variation, along with the constant electric potential, implies a change in the amount of charge on the surface of the sampling electrode. In addition, due to the continuity equation of electromagnetic, the change in charge must come from a current density that transports carriers. This current takes the form as described by eq. (1)

$$i(t) = \frac{\partial z(t)}{\partial t} \iint \frac{\partial c(t,\vec{r})}{\partial z} \left(U - \phi(\vec{r})\right) ds \qquad (1)$$

By changing the amount of charge on the sampling electrode, a charge redistribution process will undergo on the surface of the sample. This process can be characterized by the charge relaxation time, assuming space and time invariant material properties. The charge relaxation time is the product of the sample's specific resistivity and its electric permittivity. So long as the charge relaxation time is orders of magnitude smaller than the sampling electrode's period this charge redistribution can be neglected. This is the case for most of the semiconductor materials with charge relaxation time in the ballpark of ps. Assuming the magnitude of the change in charge is negligible compared to the thermally generated ones, which govern the chemical potential and the thermodynamical processes in the bulk of the sample material, the coupling between the surface potential and the surface charges can be neglected too.

With these simplifications one can create an equivalent circuit diagram for the measurement setup using lumped elements (Fig. 1).

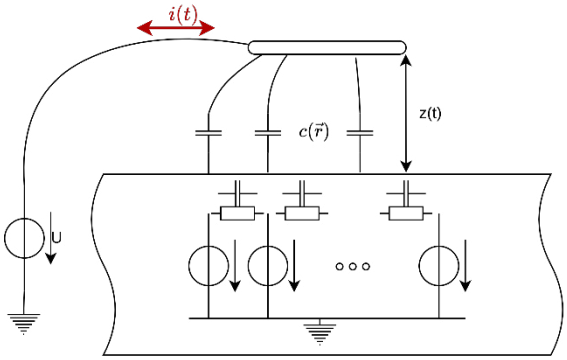

Fig. 1. Equivalent electrical model of the interaction between the sampling electrode and the sample's surface.

During the measurement the sampling electrode's potential is changed until the transport current is minimized. Assuming a homogenous surface potential distribution under the sampling electrode, the potential that minimizes the current is precisely the same as the sample's surface potential. In the case of a non-uniform potential distribution the optimal voltage on the sampling electrode will be the weighted average of the sample's potential distribution.

Since the relationship between the transport current and the surface potential distribution is linear it can be approximated with a matrix-vector equation. This equation can be used to predict the result of a measurement, given the underlying structures and potential distributions. In addition, the underlying potential distribution can also be estimated with it, given the measured sampling electrode's voltage and current waveform. Because many different potential distributions can result in a similar current waveform the estimated potential distribution won't be unique. Among these distributions, one can be chosen to minimize the residual error, by utilizing linear least squares method.

This method is analogous to the one utilized in optical systems where the image of a perfect point source is known well enough or at least estimated [3]. This image is called the Point Spread Function (or PSF for short), which is used to resolve smaller details that were captured by the optical system. In the image processing world this step is done by deconvolutions algorithms since the captured image is the convolution of the object and the PSF [3].

Results

By simulating the capacitive interaction between a square sampling electrode and the sample's surface one can acquire the necessary capacitance densities, which in turn enable the simulation of the measuring current in the case of different surface potential configurations, as seen in Fig. 2.

References

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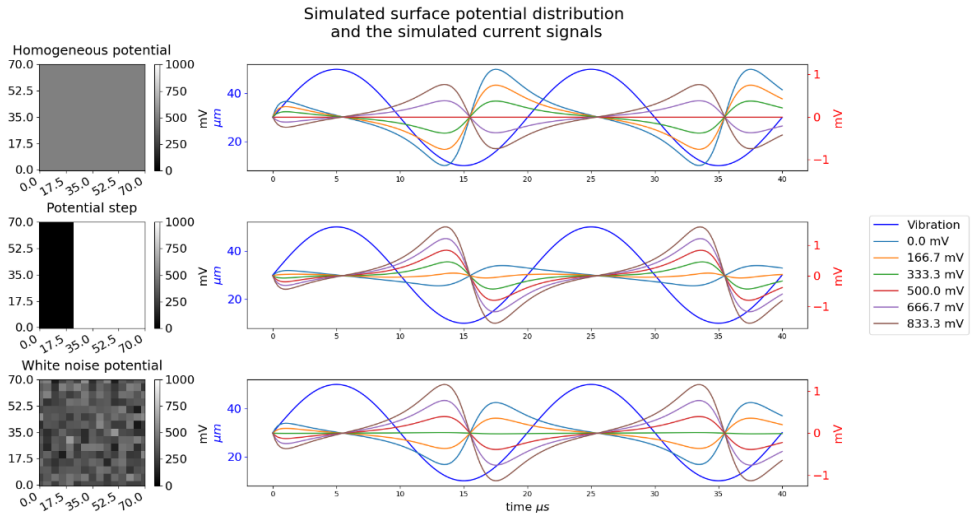

Fig. 2. Simulation of transport current due to different surface potential distributions and different sampling electrode potential.