A New Field Nullification Method for Electrostatic Force Microscope (EFM) for Unknown High Voltage Measurement

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Abstract

We have invented a new sensor adjacent methodology for high spatial resolution and high voltage measurement apparatus with which we are able to accomplish arbitrary voltage measurement without causing any unexpected arcing. We have introduced two new techniques, i.e. 1) continuously providing a voltage feedback to the sensor to make sure that it nullifies electric field between sensor and surface under test through the course of sensor approaching to the surface under test, 2) adjusting AC bias voltage to control the motion of cantilever to be constant although the sensor is far apart from the surface under test. We were able to successfully let the sensor approach a 500 V of surface under test without causing any arcing with keeping both DC and AC feedback system for the distance from 1,000 µm to 5 µm through adjusting AC bias voltage to the sensor from 200 $V_{p\text{-}p}$ *to 12* $V_{p\text{-}p}$*.*

Introduction

The latent image of electrophotography system is highly susceptible to any contact with a sensor. We have introduced a high voltage with high spatial resolution measurement system without letting a sensor contact an organic photoreceptor [1].

We have already reported that we developed a high voltage measurement system which enables to measure up to +/-1 kV with a spatial resolution of 10 µm [2]. However, in our prior art, we could only accomplish a measurement of arbitrary voltage if we had a known voltage reference close to the sensor. An issue for this measurement apparatus is how we can conduct unknown voltage measurement with high spatial resolution. We need both DC and AC feedback voltage to the sensor for not only nullifying the electric field between the sensor and the surface under test but also keeping the motion of the cantilever vibration to be constant regardless the sensor is placed either far away or close to the surface under test. We realized that we would have to incorporate a new sensor adjacent methodology to solve aforementioned issue.

In our prior art, firstly we set the sensor at the distance of 5 µm from a surface under test of which surface voltage was zero. Secondly we applied AC resonant frequency voltage to the cantilever with fixed amplitude then slowly increased the DC voltage on the surface under test while applying DC feedback voltage to the sensor, which was proportionally increased in accordance with the voltage change on the surface under test. If we were able to let the cantilever vibrate with its resonant frequency, we were able to obtain the information of DC voltage on the surface then we were able to feedback DC voltage which is almost the same voltage as the voltage on the surface to the sensor. The issue is how we can obtain adequate resonance for the cantilever although the sensor is located anywhere within 1,000 µm from a surface under test. What we are reporting here is that we have invented a new sensor adjacent methodology for high spatial resolution and high voltage measurement.

Basic Principle of Electrostatic Force Microscope

A sensor is set on a cantilever of which motion is detected with an optical system as shown in Fig. 1. The sensor is set close to a surface under test. We apply both DC bias voltage (V_{DC}) and AC bias voltage (V_{AC}) to the sensor and cantilever. Whenever any voltage appears on the surface under test, we should be able to expect either attractive or repulsive electrostatic force induced on the sensor. The electrostatic force can be detected through measuring bending amount of the cantilever with an optical leverage method. If V_{AC} is sinusoidal (sin ωt), an electrostatic force induced on the sensor consists of two different forces, namely F_ω and $F_{2\omega}$ where F_ω has the same frequency component as the applied AC bias voltage, whereas $F_{2\omega}$ has twice higher frequency component as the applied AC bias voltage. Appling a parallel plane model on the apparatus, those two forces can be explained with the following equations [3].

$$F_\omega = \frac{V_{DC} - \rho d_0/\varepsilon_0}{\{d - (1-\varepsilon_0/\varepsilon)d_0\}^2}\varepsilon_0 S V_{AC} \sin\omega t \quad \cdots(1)$$

$$F_{2\omega} = -\frac{1}{4\{d - (1-\varepsilon_0/\varepsilon)d_0\}^2}\varepsilon_0 S V_{AC}^2 \cos 2\omega t \cdots(2)$$

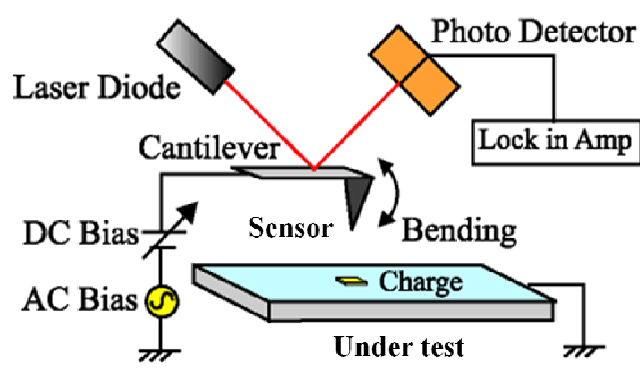

Figure 1. *The schematic diagram of the electrostatic force microscope.*

If the configuration of the parallel plane model is as shown in Fig. 2, we can measure $\boldsymbol{F_\omega}$ with applying a known, preset $\boldsymbol{V_{DC}}$ to the sensor so that we can simply calculate the voltage on surface under test ($\rho d_0/\varepsilon$) with aforementioned equation (1).

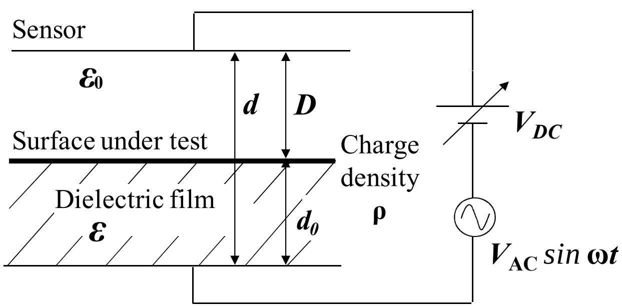

Figure 2. *Schematic diagram of the parallel plane model [3].*

New Sensor Adjacent Methodology with Electric Field Nullification

A sample of a surface voltage distribution measurement of a comb-shape electrode is shown in Fig. 3 [2]. A bias voltage of 700 V was applied to the center electrode. The other electrodes were connected to the ground. 700 V could be measured without any arcing although the sensor was set very close to the surface under test [2]. If the signal obtained ($\boldsymbol{V_\omega}$) was zero, the potential difference between sensor and surface under test should have been zero. However, we were not able to practically obtain the signal to be zero due to the noise component of the measurement system. What we had to do is to identify an absolute zero voltage. In order to seek out the absolutely zero voltage, we applied a few volts of offset shown as $\boldsymbol{V_{DC+}}$ and $\boldsymbol{V_{DC-}}$ in Fig. 4. From the measurement of $\boldsymbol{V_\omega}$ and positive and negative voltage offset, we were able to find the point of $V_\omega = 0$.

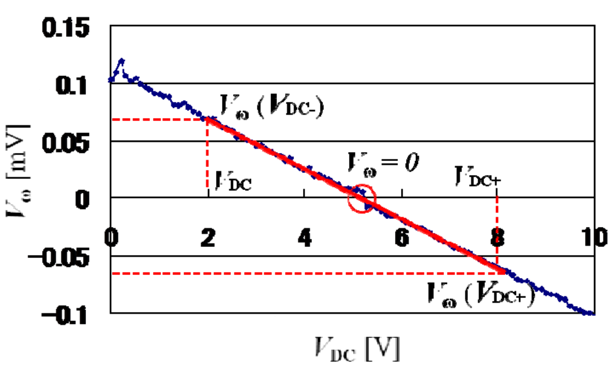

Figure 3. *An example of measured surface voltage of comb-shape electrodes biased with 700 V [2].*

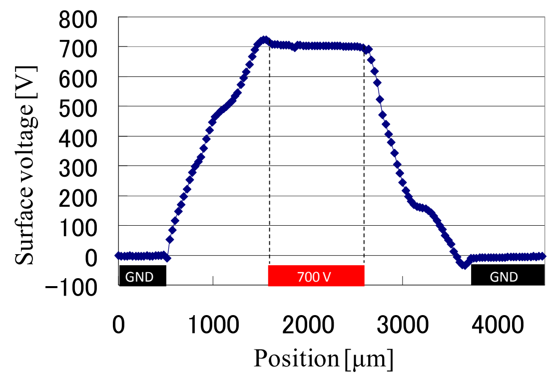

Figure 4. *The relationship between $\boldsymbol{V_\omega}$ and $\boldsymbol{V_{DC+}}$, $\boldsymbol{V_{DC-}}$ for the null-method [2].*

We could measure high voltage up to +/-1 kV on the comb-shaped electrodes without any arcing through utilizing this measurement method with a sensor located at a distance $\boldsymbol{D}$ = 5 μm from surface under test as reported formerly [2]. However, we realized that if the sensor was located far away from a surface under test, we were not able to obtain adequate vibration of the cantilever since the sensor was too far apart from the surface under test. Therefore, we found that the said method did not work properly if sensor was located far away. We are reporting here a new voltage measurement method through introducing a concept of voltage detecting sensitivity ($\boldsymbol{G}$) in conjunction with a dependency on distance D between the sensor and the surface under test. We have acknowledged that the minimum detecting sensitivity ($\boldsymbol{G_{min}}$) is required to obtain strong AC feedback signal to guarantee adequate and accurate measurement. The minimum detecting sensitivity $\boldsymbol{G_{min}}$ is attainable by increasing AC bias voltage $\boldsymbol{V_{AC}}$. Consequently this method works well though the sensor is located far away from surface under test.

Results and Discussions

1) Detecting Sensitivity

We typically deal with distance $\boldsymbol{D}$ at 5 μm and we are able to enjoy sufficient signal to noise ratio (S/N Ratio) for the system. If we let the distance $\boldsymbol{D}$ set far away from surface under test, the said S/N Ratio decreases accordingly. If we let the sensor get closer to the voltage of unknown, we have to understand the detecting sensitivity $\boldsymbol{G}$ at each distance $\boldsymbol{D}$. We define the detecting sensitivity $\boldsymbol{G}$ with the following equation,

$$G = \frac{V_\omega(V_{DC+}) - V_\omega(V_{DC-})}{V_{DC+} - V_{DC-}} \dots (3)$$

where $\boldsymbol{V_{DC}}$ is the DC bias voltage applied to the sensor and $\boldsymbol{V_\omega(V_{DC})}$ is the signal obtained with applying $\boldsymbol{V_{DC}}$. Under the typical measurement condition ($\boldsymbol{D}$ = 5 μm), $\boldsymbol{G}$ is in the range of $2\text{x}10^{-4}$ to $4\text{x}10^{-4}$, which depends on the characteristics of each cantilever and sensor, which had under the conditions of $\boldsymbol{G}$ = $2.3\text{x}10^{-4}$ at $\boldsymbol{D}$ = 5 μm prior to plotting the data.

2) Dependency of Detecting Sensitivity on Distance

The dependency of $\boldsymbol{G}$ on $\boldsymbol{D}$ while $\boldsymbol{D}$ changes from 1 to 30 µm was plotted and shown in Fig. 5. This dependency was measured under the condition $\boldsymbol{V_{AC}}$ = 12 $V_{p\text{-}p}$ over a flat copper plate as the surface under test. We found that the relationship between $\boldsymbol{G}$ and $\boldsymbol{D}$ is exponential and it is likely ideal relation. Therefore, we acknowledged that using this relationship is very useful for us to calculate appropriate DC bias voltage $\boldsymbol{V_{DC}}$ to the sensor when the sensor is located at the distance $\boldsymbol{D}$. Prior to this measurement we obtained $\boldsymbol{G} = 2.3\text{x}10^{-4}$ at $\boldsymbol{D}$ = 5 µm. When distance $\boldsymbol{D}$ is at 30 µm, we confirmed that the $\boldsymbol{G}$ was approximately $1\text{x}10^{-4}$. We also tested other sensor which may have higher sensitivity than the other sensor, we could also confirm that $\boldsymbol{G}$ was approximately $1\text{x}10^{-4}$ at distance $\boldsymbol{D}$ = 70 µm. Whenever $\boldsymbol{G}$ is greater than $1\text{x}10^{-4}$, we are able to calculate appropriate $\boldsymbol{V_{\omega}} = 0$ wherever the sensor is located.

3) Method to Increase Detecting Sensitivity

The issue that we have to solve is to design a high spatial resolution and high voltage measurement apparatus without having any arcing between sensor and surface under test although the voltage appeared on the surface under test is unknown. We have been discussing the detecting sensitivity $\boldsymbol{G}$ here in this report. However, the detecting sensitivity $\boldsymbol{G}$ is extremely small if the distance $\boldsymbol{D}$ is very far, i.e. the distance $\boldsymbol{D}$ = 1,000 µm.

For the sake of increasing $\boldsymbol{G}$ if the $\boldsymbol{D}$ is extremely far away from the conventional usage such as $\boldsymbol{D}$ = 1,000 µm, we increased the amplitude of AC bias voltage $\boldsymbol{V_{AC}}$ to the sensor. We obtained $\boldsymbol{G_{min}}$ of $1\text{x}10^{-4}$ with applying $\boldsymbol{V_{AC}}$ = 200 $V_{p\text{-}p}$ at the distance $\boldsymbol{D}$ = 1,000 µm. The data dispersion of this measurement with a 500 V of surface under test out of 50 times of the same measurement was less than 0.2 %.

4) A New Method for Sensor to Approach Surface under Test

We are discussing a new method for letting a sensor approach to an object with voltage unknown through introducing a new methodology, i.e. introducing a detecting sensitivity $\boldsymbol{G}$ as well as applying higher AC bias voltage $\boldsymbol{V_{AC}}$ to the sensor.

We modified the system software to let the apparatus adapt the new methodology. The details of the software modifications are as follows. The block diagram of this software is shown in Fig. 6.

1) Start the system without the feedback mode (Feedback off).
2) Set sensor at approximately 1,000 µm above the surface under test. $\boldsymbol{V_{AC}}$ is set to be 12 $V_{p\text{-}p}$.
3) Measure detecting sensitivity $\boldsymbol{G}$.
4) Judging the following steps based on the figure of $\boldsymbol{G}$.
4-1) If the $\boldsymbol{G}$ is smaller than $\boldsymbol{G_{min}}$, increase $\boldsymbol{V_{AC}}$. Go to 3).
4-2) If the $\boldsymbol{G}$ is between $\boldsymbol{G_{min}}$ and $\boldsymbol{G_{max}}$, turn DC voltage feedback on and keeps the DC feedback on and let the sensor get close to the surface under test, and go to 3). (Where $\boldsymbol{G_{max}}$ is the value obtained at $\boldsymbol{D}$ = 5 µm.)
4-3) If the $\boldsymbol{G}$ is close to $\boldsymbol{G_{max}}$, go to 5).
5) Judging the following steps based on the figure of $\boldsymbol{V_{AC}}$.
5-1) If $\boldsymbol{V_{AC}}$ is smaller than 12 $V_{p\text{-}p}$, go to 3).
5-2) If $\boldsymbol{V_{AC}}$ is 12 $V_{p\text{-}p}$, start a normal measurement operation.

Through this method, we can use the figure of $\boldsymbol{G}$ to define the most appropriate distance $\boldsymbol{D}$.

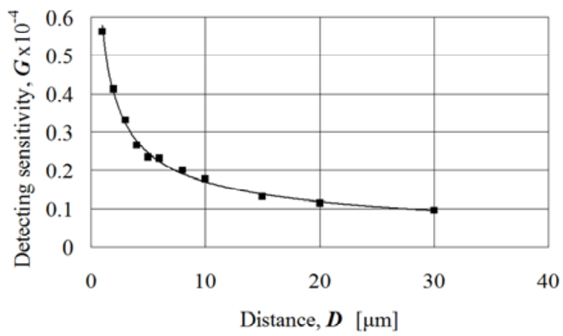

Figure 5. *The dependence of the detecting sensitivity **G** on the distance **D** between the sensor and the surface under test.*

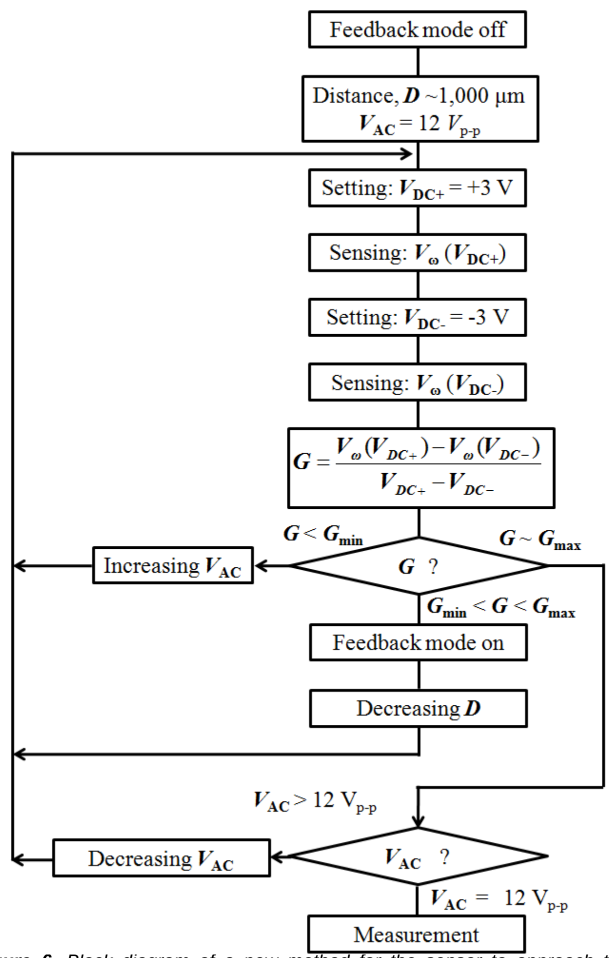

Figure 6. *Block diagram of a new method for the sensor to approach the surface under test.*

Conclusion

We proposed a new sensor adjacent methodology to high spatial resolution and high voltage measurement apparatus to measure specimen of unknown voltages on the surface without causing any arcing. Applying appropriate DC bias voltage as well as AC bias voltage to the sensor is critical to accomplish this objective.

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Author Biography

Toshio Uehara is CEO of Trek, Inc. and President of Trek Japan KK. He graduated from Nihon University, College of Science & Technology. He has been involved in the measurements on electrophotography for more than 25 years and is currently doing joint research on electrostatic microscope with Nihon University. He received President's Award of the Electrostatic Institute of Japan in 2002 and President's Special Award of Imaging Society of Japan in 2005.

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