High Spatial Resolution Measurements on Surface Voltage Distribution with Electrostatic Force Microscope

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***Abstract* -- We have been working on the development of an Electrostatic Force Microscope (a.k.a. EFM). The EFM enables to measure surface voltage distribution with a spatial resolution of 10 µm. Although the spatial resolution is incomparably higher than any other conventional electrostatic voltmeters, it can measure voltage up to +/-1kV with extremely wide scanning area, i.e. a few mm^2. We have successfully observed charge migration in charge transfer layer (CTL) of a few organic photoconductor materials in real time basis. We report a few test results of the EFM in this paper including a phenomenon of voltage generation on PZT materials due to laser exposure on the PZT surface.**

***Index Terms*--Electrostatic, surface voltage, Electrostatic Force Microscope, High resolution, High Voltage, High sensitivity, Wide area, CTL, toner Si wafer, Piezo**

I. INTRODUCTION

Measurement of surface voltage distribution on electrophotographic photoreceptor is commonly made with using an electrostatic voltmeter. Electrostatic voltmeter is conventionally used with a non contacting method with taking a fairly large spacing (around 3 mm) between detector probe and surface of photoreceptor, therefore the expected spatial resolution from measurements with an electrostatic voltmeter is extremely large so it is inadequate to accomplish a direct measurement of electrostatic latent image on a photoreceptor. Surface voltage measurement on photoreceptor with much higher spatial resolution than conventional electrostatic voltmeter has been a critical demand for electrophotography for a long time.

Trek Japan K.K. and Nihon University have been working jointly on a research for the development of electrostatic voltage measurement apparatus having relatively high spatial resolution. Surface voltage on electrophotographic photoreceptor is relatively high namely in the range between the absolute value of 200 V and 800V and area needs to be measured is fairly large. Requirements for a new surface voltage distribution measurement apparatus, i.e. an electrostatic force microscope (EFM) are (1) having a spatial resolution of 10 µm in diameter, (2) having a capability to measure wide area such as it should cover an area as large as a few mm^2, (3) surface voltage to be measured should be as high as 1kV, and (4) It can be easily operated in the atmospheric environment.

For the sake of understanding our goals clearly, we have done numerical simulations with the Finite Element Method (FEM) to start with. [1]

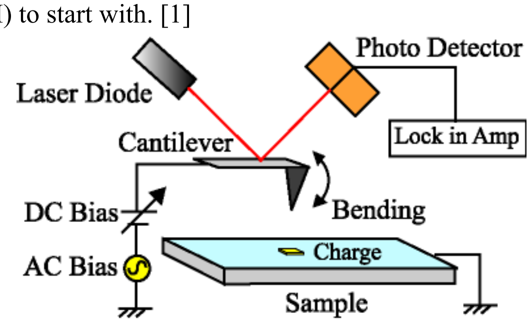

Fig. 1 Principle of EFM

Tip of detector on an optical cantilever is placed close to surface under test. DC bias voltage (V_{DC}) and AC bias voltage (V_{AC} sin ωt) are applied to cantilever including detector. If the surface under test is charged, we should be able to expect either attractive or repulsive electrostatic force appeared on the detector. Either attractive or repulsive force can be detected through measuring the bending amount of the cantilever with an optical leverage method. The electrostatic force appeared on the detector consists of two different force components F_{ω} as well as $F_{2\omega}$ 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. If we utilize a parallel plane model on the apparatus as shown in Fig. 2, those two forces are obtained with the following equations [2], [3],

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

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

If the distance between detector and surface under test ($d - d_0$) as well as the dielectric constant of a material under test (ε) are evident, we can measure F_{ω} with applying a pre-set V_{DC} to the detector so that we can simply calculate the voltage on surface under test ($\rho d_0/\varepsilon$) with aforementioned equation (1). However, since high voltage is in existence on the surface under test, an arcing between detector and surface under test may occur. To prevent from the occurrence of any contingent arcing between detector and surface under test, we discussed a voltage nullification method. We firstly obtained a V_{DC} with which F_{ω} became to be zero in advance.

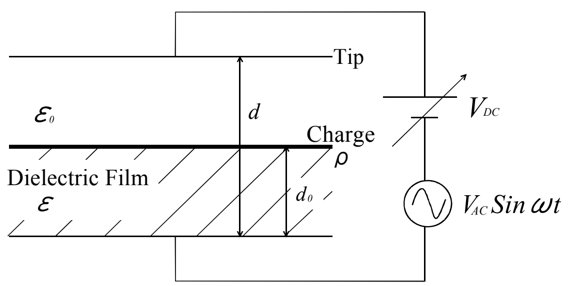

Fig. 2 Parallel Plane Model

II. VERIFICATIONS OF SPATIAL RESOLUTION CAPABILITY

We have attained measurements with an apparatus designed based on aforementioned principle. A cantilever with a detector was made out of nickel having a thickness of 5 µm. The tip of the detector was sharpened by a Focused Ion Beam (FIB) system. In parallel with conducting experiments, we also have carried out simulations for analysis of electric field distribution with the Finite Element Method (FEM) to verify the performance of the EFM. [1], [2], Two graphs are shown in Fig. 3 which is the comparison of actual data and simulation results in spatial frequency. The blue line shows the actual measurement obtained with the EFM, whereas the red line shows the results of the FEM simulation with using comb-shaped electrodes furnished on a glass substrate for both experiments and simulation. Each plot was normalized as spatial frequency to be "1" with signal strength from a detector when the detector was placed exactly over the center of each electrode. From this comparison, the overall differences between actual data and simulation results were within the range of 5% therefore if we define the spatial resolution capability of the EFM at a half value of each signal strength, we can conclude that we have accomplished one of our goals of voltage measurement with a spatial resolution of 10 µm (approximately 2,400 dpi).

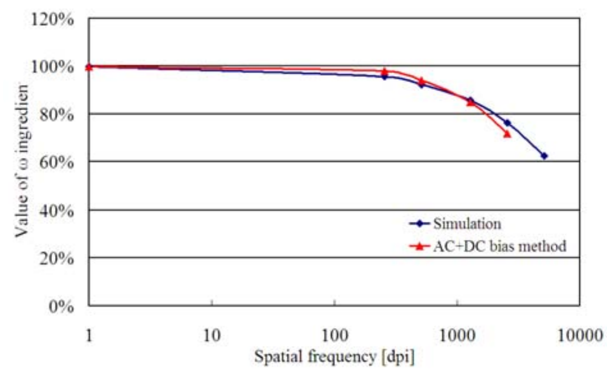

Fig. 3 Spatial frequency of EFM

III. OUTLOOK OF EFM, CANTILEVER AND DETECTOR

We are showing here the pictures of the outlook of the EFM, cantilever and detector.

Fig.4 Outlook of EFM

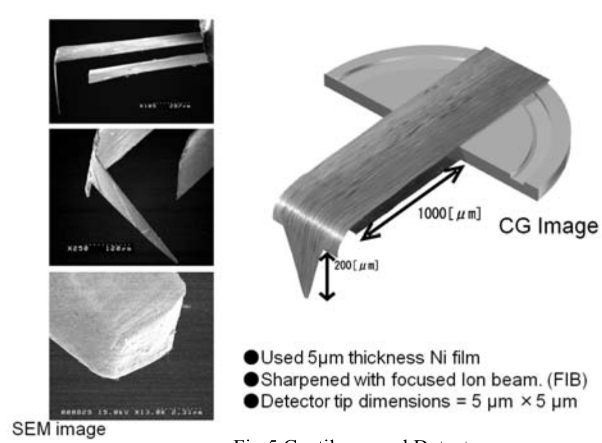

Fig.5 Cantilever and Detector

IV. Test Results with EFM

A. Voltage Distribution of Toner for Electrophotography

We tried to measure the voltage distribution on one particle of toner for electrophotography. The toner and carrier used were the ones that are commercially available from the Imaging Society of Japan. The carrier and toner are designed to provide reference amount of charge with known polarity on toner. The toner is sort of false toner. As a preparation for the voltage measurement of one particle toner, we mixed the carrier and toner with a certain weight ratio. Certain amount of agitation was given to the mixture to provide adequate amount of charge on toner. We then measure the polarity of the charge on the toner as well as the charge to mass ratio (*Q/m*). The charging characteristics as well as the *Q/m* data were shown in Tables 1 (a) and (b). Table 1 (a) shows the data of false toner (MX-500) with carrier (P02) which is suppose to provide positive charge onto toner, whereas Table 1 (b) shows the data of negatively charge toner (N01T) and the carrier (N01) which is suppose to provide negative charge on toner.

The toner voltage measurement by the EFM is shown in Figs. 6 and 7

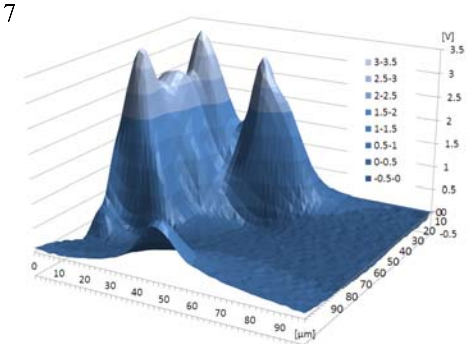

Fig. 6 MX-500 Toner/ P02 Carrier 5wt%

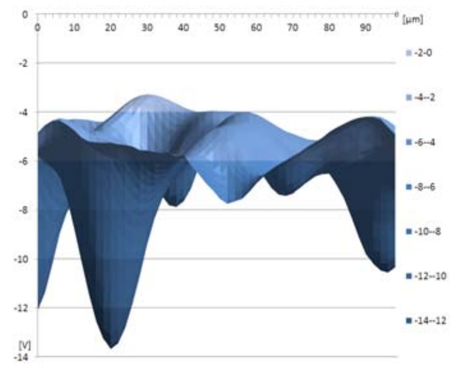

Fig. 7 N01T Toner/ N01 Carrier 5wt%

Table 1 Charge to mass ratio (Q/m) of toners with carrier

(a) MX-500 Toner/ P02 Carrier 5wt%

Toner	Carrier	Toner density[wt%	Number of measurement	Weight of developer [mg] Before	After	Charge [nC]	Q/m [nC/mg]	Average (Q/m) [nC/mg]
MX-500	P02	4	1	184.4	178.2	810	130.6	137.839
			2	190.8	184.3	842	129.5	
			3	192.4	187.3	782	153.3	
		5	1	197.1	185.2	1153	96.9	112.095
			2	205.4	195.7	1152	118.8	
			3	187.8	178.3	1146	120.6	
		6	1	213.0	200.1	1322	102.5	105.685
			2	197.8	187.8	1072	107.2	
			3	197.6	187.7	1063	107.4	

(b) N01T Toner/ N01 Carrier 5wt%

Toner	Carrier	Toner density[wt%	Number of measurement	Weight of developer [mg] Before	After	Charge [nC]	Q/m [nC/mg]	Average (Q/m) [nC/mg]
N01T	P01	5	1	190.1	179.4	54	5.0	5.507
			2	199.3	189.6	56	5.8	
			3	231.2	219.8	65	5.7	
	P02	5	1	216.5	206.1	243	23.4	21.480
			2	198.0	188.7	198	21.3	
			3	186.2	176.9	184	19.8	
	N01	5	1	188.5	181.9	-220	-33.3	-30.535
			2	286.5	278.7	-261	-33.5	
			3	195.5	187.6	-196	-24.8	
	N02	5	1	200.3	193.1	-139	-19.3	-19.925
			2	190.8	184.3	-134	-20.6	
			3	187.7	180.9	-135	-19.9	

We were able to see very good correlations between the data that we took prior to the EFM measurement and the data obtained by the EFM. Since we scanned the EFM detector over the toner with each 2um incremental step, we were roughly able to obtain the size of toner to be measured through this measurement. We believe it is quite likely that we can define electrostatic charge characteristics of one toner particle if we further analyze the data obtained by the EFM.

B. Charge Distribution on Circuitry in a Wafer

We provided tribo-charge on a part of circuitry in a wafer and we measured the voltage distribution on the area with the EFM. The 3-D picture of the test result is shown in Fig. 8.

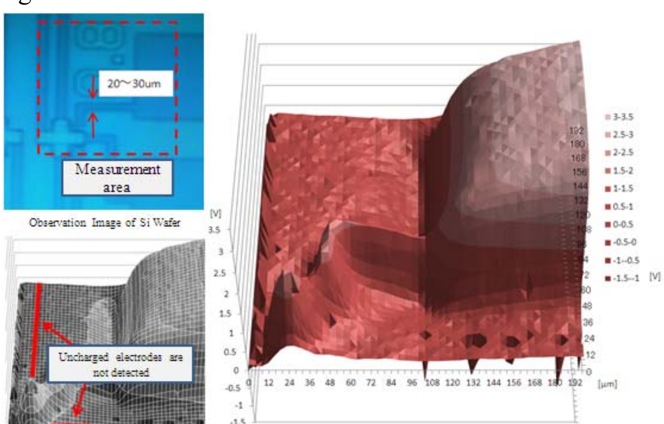

Fig.8 Voltage Distribution on a Part of Circuitry in a Wafer

C. Voltage Measurement on a Piezo Chip

We measured the surface voltage on a piezo chip having the dimensions of *3mm x 5mm x 0.1- 0.2mm thickness.* We were able to obtain the following test results; (1) We have observed that there was a large voltage generation on the piezo surface when we exposed the piezo surface with a laser having the wavelength of 670nm with 6mW of maximum power and the laser spot diameter is approximately 20 to 30μm. If we turned the laser off, the voltage generated disappeared instantaneously. We have confirmed that this was a repeatable phenomenon. (2) The surface voltage was subject to change due to power of the laser for exposure, the polarity and strength of the voltage used when the piezo poling was conducted. (3) We were not able to see this phenomenon from other materials such as electrostatic dissipative plastic, metal, etc. however we were able to observe the same phenomenon from electrostatic dissipative ceramic material although the voltage generated was very small. (40 – 100mV)

V. Summary

We have introduced the principle as well as a few test results of a new electrostatic measurement apparatus, EFM. The EFM enables the measurement of electrostatic voltage distribution which neither electrostatic voltmeter nor AFM/SPM could have accomplished thus far.

(1) High Spatial Resolution. The spatial resolution anticipated by conventional electrostatic voltmeter was *100μm* the highest whereas we have accomplished the spatial resolution of *10μm* with EFM.

(2) Electrostatic voltage distribution measurement option for Atomic Force Microscope (AFM)/ Scanning Probe Microscope (SPM) is commercially available. The problem of those apparatuses is that the area to be scanned is extremely small and the measurement voltage range is very low. Although the spatial resolution of EFM is lower than that of AFM/SPM, the area to be measured is almost *5mm x 5mm* which is incomparably wider as compared to the scanning area of AFM/SPM. Additionally the measurement voltage range is *0 to +/-1kV* which is almost as wide as the input voltage range of conventional electrostatic voltmeters. On top of that, the EFM can accomplish the measurement voltage resolution of less than *100mV*.

(3) We have acknowledged that EFM has the DC accuracy of better than *0.5%* at full scale.

We are expecting that EFM will be used for many different applications for electrostatic voltage measurement.
Through further enhancement of the EFM technologies, we believe that our newly invented measurement apparatus should be very useful not only for the development of entirely new applications that we have never realized but also for finding new electrostatic phenomena which we could not handle due to the restrictions of the spatial resolution of conventional systems in the past.

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