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Quantifying Field-Induced Contrast Effects in Photoelectron Emission Microscopy

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ABSTRACT

Samples consisting of electrically isolated titanium lines fabricated on a titanium surface were used to quantify voltage-induced contrast effects in photoelectron emission microscopy (PEEM). Induced contrast effects were observed to extend 6 μm for a -5 V bias applied to a 303 nm tall raised line. We therefore explored, via numerical calculation, the spatial extent of the perturbation to the PEEM accelerating field caused by the bias applied across the step height. The intensity full width at half minimum agreed well with the calculated width defined by the 10% level of lateral field strength. For a line 550 nm tall, a correspondence was found for a calculated width defined by a 5% lateral field strength. It was observed that neighboring structures a few μm away affected the image contrast, for sufficiently strong applied bias. This suggests that effects can easily be induced at distances of 0.5 μm for modest applied voltages, as has been previously observed for structures buried under oxide layers 0.5 μm thick [1].

INTRODUCTION

Photoelectron emission microscopy (PEEM) is sensitive to near-surface voltage gradients because of the extremely low initial energy of photoemitted electrons (< 1eV) that form the image [2,3]. The presence of voltage gradients at the surface can alter the imaging conditions enough that dramatic contrast can result. These lateral surface fields can arise simply from surface topography [4,5] or in combination with an externally applied bias, making it difficult to discern the source of the contrast. Thus, it is necessary to quantify this field-induced effect in a controlled manner to establish a basis for quantitative image interpretation.

To generate voltage gradients at the sample surface under controlled conditions, we have fabricated layered device structures where the top metal layer is electrically isolated from the bottom metal layer. The spatial extent and magnitude of the surface field effect can then be investigated systematically by controlling the applied bias voltage on structures of varying height, and at varying distance from a neighboring structure. In this paper, we report on a quantitative investigation of field-induce contrast generated on well-characterized Ti/SiO_2/Ti structures.

EXPERIMENTAL DETAILS

Electrically isolated titanium lines were fabricated by successive e-beam evaporation of Ti, SiO_2 and Ti on clean 3 inch Si wafers. The tri-layered wafers were then patterned via photolithography and etched back to the bottom Ti layer, leaving sets of isolated raised lines which could be addressed with a different bias voltage. The bottom Ti layer was at least 300 nm thick while thickness of the intervening oxide varied, and the top Ti layer was 100 nm thick. In

Fig. 1a, a diagram is shown beside an SEM micrograph of the layered, etched sample in Fig 1b, and a PEEM image showing a grounded and a biased line in Fig. 1c.

Imaging was performed on a horizontally configured Staib PEEM with samples illuminated at 70 degrees from the surface normal by a 100 W Hg arc lamp, which has a high energy cut-off of approximately 5 eV. The samples were transferred through a load lock to a 5-axis positioning stage in the imaging chamber. The average background pressure during imaging is $8x10^{-9}$ – 10^{-8} Torr. The image exposure time was varied to keep intensity within the dynamic range of the camera. Images were captured with 12-bit pixel depth. For the various data sets, the image intensity was scaled to a 3 sec exposure and intensity profiles across the line edges were averaged over approximately 200 line scans. A simple background, obtained by a polynomial fit to one image, was subtracted from all the intensity profiles taken in the same biasing series.

RESULTS

After positioning the grounded sample, a bias was applied to the top surface of a line. Changes in the real-time image due to changes in applied bias are immediate. Observed contrast effects induced by varying the applied bias voltage included variation of the width of the intensity minimum at the line edge, as well as variation of the depth of this intensity minimum. These contrast effects were measured by varying the bias on two steps of height 303 and 550 nm.

Numerical models, essentially similar to one described in previous work [6-8], were used to

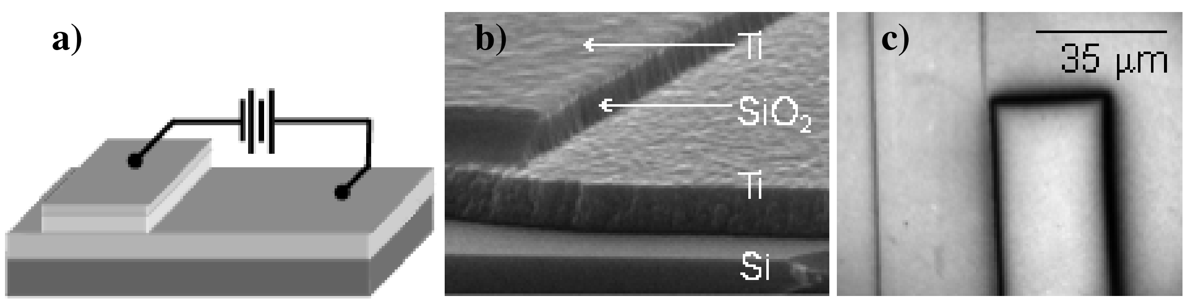

Fig. 1a) Schematic of the sample, Ti - SiO_2 -Ti on Si. 1b) SEM micrograph (horizontal FOV 2.3 µm) of a sample. 1c) PEEM image of two such lines 550 nm tall (FOV 94 µm × 75 µm). The left line is at ground while the right is biased at 5V.

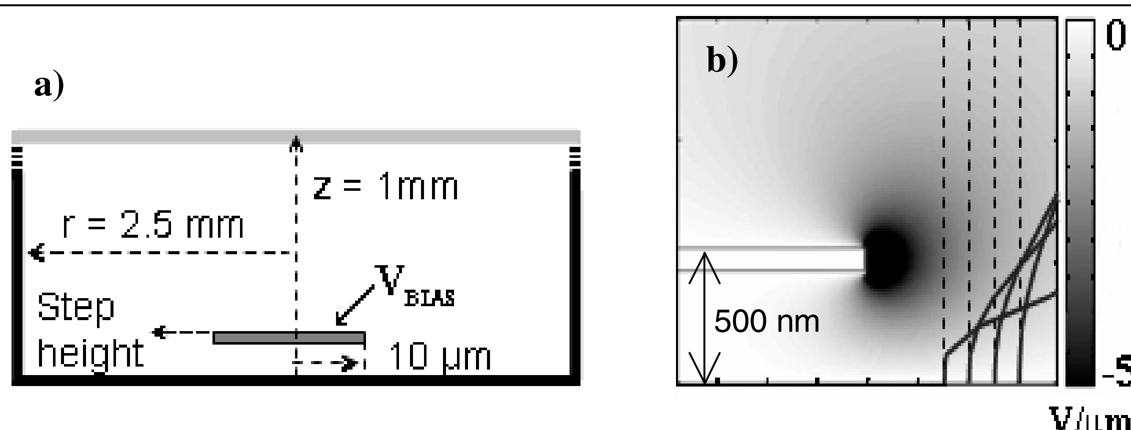

Fig. 2a) Schematic of the model which consisted of the grounded cathode with an electrically isolated step and the 3kV anode 1 mm away. 2b) Calculated lateral fields and resulting electron trajectories near a 550 nm tall step. FOV 1.5 µm ×1.5 µm.

explore the surface field configurations generated by the biased steps. A schematic appears in Fig. 2a, showing the simplified step model which consisted of the isolated 100 nm thick electrode above the grounded cathode. The chamber walls in the model are distant compared to the step dimensions. The 3 kV anode 1 mm opposite the cathode provided the longitudinal accelerating field in this model of the PEEM cathode lens. In Fig. 2b, the lateral field is calculated at 10 nm spaced points and is accurate to within ~20 nm of the step surface. Calculated electron trajectories are superimposed on the plot, showing the large deflections caused by the edge fields.

The sample patterned with 303 nm tall lines was imaged at 28 nm/pixel resolution and a field of view (FOV) of 36 x 29 μm^2. A spatially isolated 16 µm line was biased in 1 V steps in positive and negative directions. On the sample with 550 nm tall lines, a 32 µm wide line was imaged at 73 nm/pixel resolution and a FOV of 94 x 75 μm^2. A series of images, averaged 8 times, was again taken with the bias incremented in 1 V steps. The average full width at half minimum (FWHM) of edge intensity was measured from the intensity profiles across these spatially isolated biased lines.

In Fig. 3a, the measured intensity profile of the 550 nm tall step biased at -4V is shown. The half minimum intensity level shown on the profile indicates the edge field effects extend as much as 10 µm away. We explored the spatial extent of the perturbation to the accelerating field caused by the bias applied across the step height via numerical calculation using the model. Calculations were extended to plot the fields up to 20 µm from the step edges, at points spaced every 50 nm, for varying potentials on the step electrode. In Fig 3a and 3b, the intensity profile is compared to the calculated relative lateral field magnitude, $|E_{LATERAL}/E_{TOTAL}|$, for a 550 nm tall step biased at -4V. The 0.05 cutoff imposed on the plots of $|E_{LATERAL}/E_{TOTAL}|$ delineates the 5% level of relative lateral field strength, $|E_{LATERAL}/E_{TOTAL}|$.

In Fig. 4a, the measured FWHM is plotted as a function of applied bias voltage for the 303 nm tall step. Also plotted is the “field width”, i.e. the width of the 10% level of lateral field within which $|E_{LAT}/E_{TOT}| \geq 0.1$, versus step bias for the 300 nm tall model step. In Fig. 4b, a similar comparison is made for the 550 nm tall step. In this case the plot of measured FWHM versus step bias appears with a calculated “field width” for the 5% level of relative lateral field strength, $|E_{LAT}/E_{TOT}| \geq 0.05$, versus step bias.

Since the smallest edge effect did not occur for the line at 0 V but for a positive bias near 1 V, closer investigation was made by incrementing bias in smaller bias steps near 1 V at a resolution of

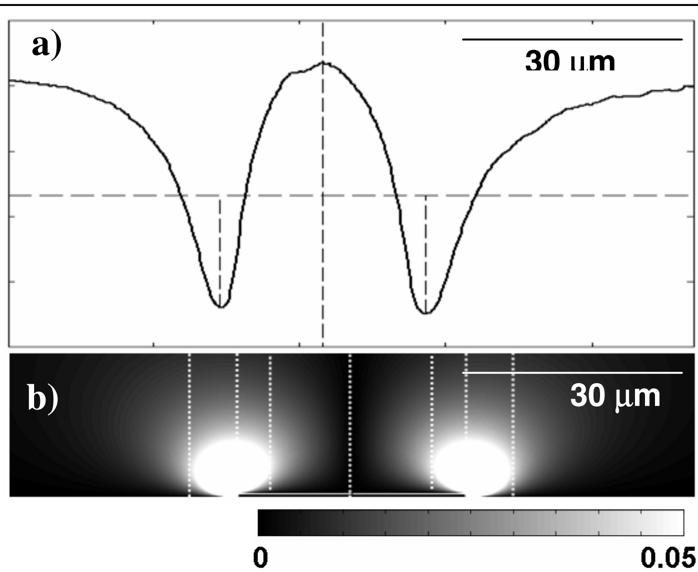

Fig. 3a) Intensity profile (arbitrary units) across a 32 um wide 550 nm tall line, biased at -4 (FOV 94 µm). 3b) The lateral field calculated for a 32 um wide 550 nm tall model line biased at -4V. A cutoff of 0.05 is imposed on the plot of $|E_{LATERAL}/E_{TOTAL}|$, demarking the point where lateral field is 5% of the total field (FOV 94 µm × 25 µm). The intensity profile appears to reflect the asymmetry about the step edge of the relative lateral field.

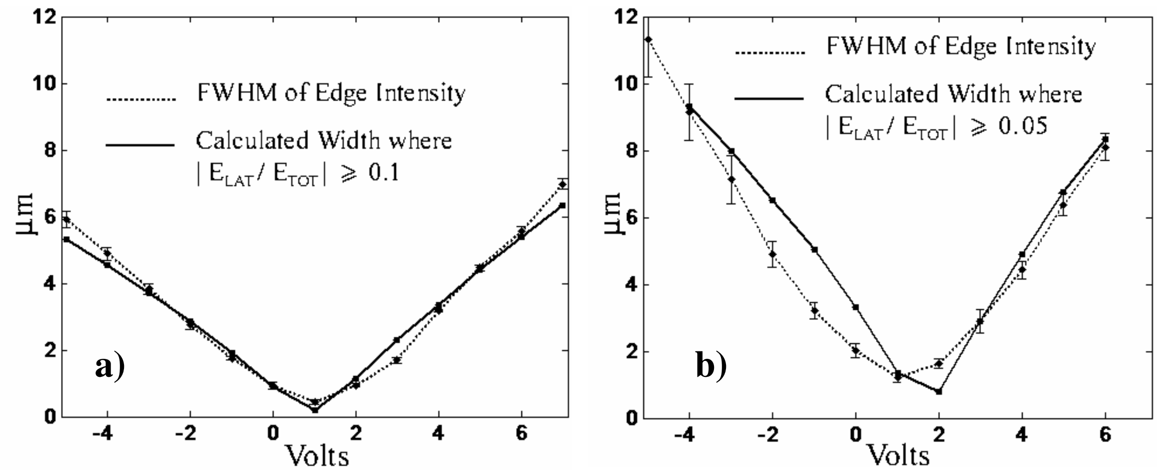

Fig. 4 (a,b) Plots of the measured edge intensity FWHM versus bias voltage, compared to the calculated "field width" versus bias. This width is defined as the distance between the edges of the strong lateral field. For the 303 nm tall step on the left, the limiting strength is $|E_{LATERAL}/E_{TOTAL}| \geq 0.1$. For the 550 nm tall step on the right, the plot is for $|E_{LATERAL}/E_{TOTAL}| \geq 0.05$.

28 nm/pixel on both steps. The bias producing a minimum edge effect for the 303 nm step was measured to be 1.05 V with bias incremented in 0.1 V steps, and for the 550 nm step the minimum edge effect was found at 1.44 V bias, with bias incremented in steps of approximately 0.15 V. Calculations of the lateral field strength showed that the lateral field was almost extinguished near 1 V bias on a 300 nm tall model step. Further calculations were done to find the minimum lateral field generated at a step for model steps of height 200, 300, 400, 500 and 600 nm with the same applied 3 kV/mm accelerating field. The results gave a linear dependence on step height of the bias which generated minimum edge field. The slope was equal to the applied field, 3 kV/mm. For the two sample step heights which were imaged with a 10 kV PEEM anode, this implies a sample distance of 6.3 mm from the PEEM anode, which is reasonable for our configuration.

Finally, investigation of the 4 μm wide line with a 4 μm distant neighbor showed distortion of the intensity profile compared to the profile for an isolated line. A model similar to that used for the single line, with a duplicate line located 4 μm from the first, as on the sample, was used to calculate the field configuration of the line pair.

DISCUSSION

The field produced by the biased step is similar in magnitude but opposite in direction to the lateral field present on an unbiased 300 nm tall step in a 3 kV/mm accelerating field[6]. The observed minimum in the edge effect may therefore be explained as a reduction of the topographically generated edge field by the opposing applied field.

The calculated lateral "field width" agrees quite well with the measured FWHM for 300 nm sample and gives the correct trend for the 550 nm sample. This comparison of the calculated "field width" and the measured intensity FWHM indicates that the impact of the lateral field on electron trajectories is significant enough to cause large changes in image intensity when $E_{LATERAL}$ is 10% of the total field, for the 303 nm tall step. For the taller 550 nm step, a lateral field that is 5% of the total field appears to have similar impact on intensity. In Fig. 5, the calculated lateral fields for two step heights, 300 nm and 550 nm, are shown. The unperturbed parabolic electron trajectory is superimposed, and shows that the lateral edge field of the taller step will deflect electrons of more distant origin, which can result in the wider edge field effects for the taller step, and may explain why similar effects are generated by the weaker field further away from the taller step.

In Fig. 6 (bottom panel) plots of the numerically calculated fields for various applied voltages for a 300 nm tall pair of lines separated by 4 µm are shown. The relative lateral field of the step $|E_{lateral}/E_{total}|$ is clearly affected by the presence of the neighboring step in these plots, as is shown by the distortion of the saturated region. This suggests the interaction between line pairs is strong enough to affect the intensity of a neighboring line 4 µm away when the bias is sufficiently large. The corresponding PEEM images clearly evidence contrast induced by the presence of the neighboring grounded step. Where opposing fields cause compression of the region of strong field, ($|E_{lateral}/E_{total}| \geq 0.1$), a similar compression of the field-induced FWHM can be observed as in Fig. 6a and 6d. In Fig. 6b and 6e, the lateral fields are nearly suppressed in the calculation for 1 V bias, and the corresponding PEEM image shows an edge effect near minimum at this bias. In Fig. 6c and 6f, where regions of aligned field overlap from the two lines, a similar overlap is seen of the image intensity minima of the neighbor lines.

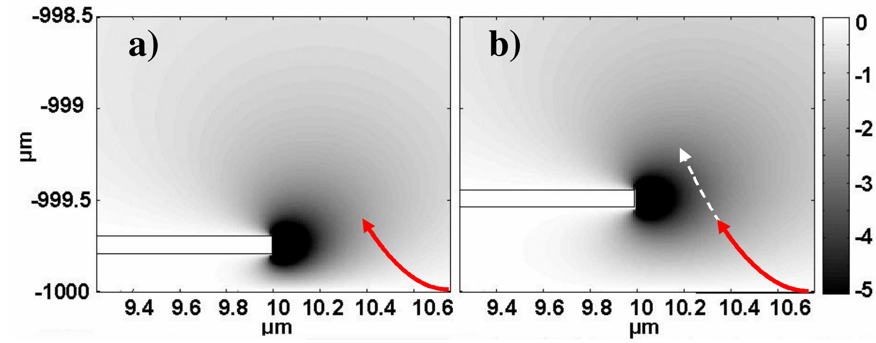

Fig. 5 (a,b) Lateral fields of the 550 nm step (right) and the 300 nm tall step (left), and the unperturbed parabolic electron trajectories. FOV 1.5 µm × 1.5 µm.

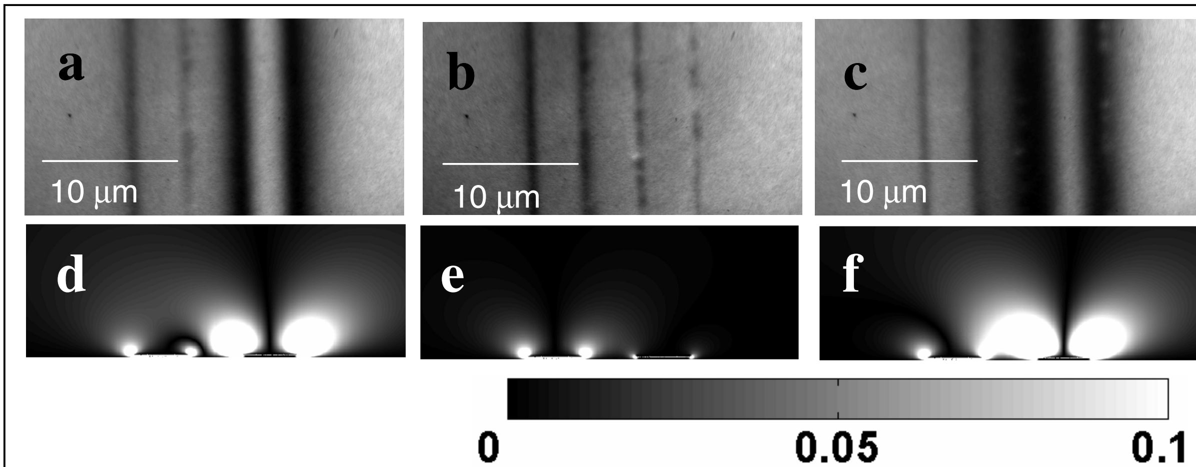

Fig. 6 (a-c) PEEM images for a pair of 4 µm wide lines, 303 nm tall, separated by 4 µm. The left line is at ground potential, the right line is biased at -4, 1, 6 V respectively. FOV 28 µm × 14.5 µm. Fig 6 (d-f) Plots of the calculated relative lateral field strength, $|E_{LATERAL}/E_{TOTAL}|$, for the corresponding model of paired lines, at the same potentials. A cutoff of 0.1 is imposed to show more clearly the width for which $|E_{LATERAL}/E_{TOTAL}| \geq 0.1$. FOV 28 µm × 12.5 µm.

CONCLUSIONS

In this work we have quantified field-induced effects on image intensity generated by externally controlling the bias applied to simple, easily modeled titanium structures. The width of the intensity minimum generated at the edge of the biased titanium steps was observed to increase about the step height-dependent bias which produced a minimum edge effect. Calculations indicate the bias for minimum edge effect is linearly dependent on step height, with slope equal to the accelerating field. For a known accelerating field, therefore, the height of a biased step can be determined from the bias which produces the minimum edge effect. For steps of less than 20 or 30 nm height, however, the topographically generated edge effect, which is minimized by appropriate biasing, is not discernable [4,6]. Clearly, an edge effect can be induced by external biasing to detect such small features, but conversely, the extent of a large biasing effect may obscure neighboring small features. For a 303 nm tall line, the half minimum of intensity appeared to follow the point where lateral field strength induced by the biased step was calculated to be 10% of total field strength. For a taller step of 550 nm, the intensity half minimum was produced near the point where lateral field strength was calculated to be 5% of total field strength. It is evident in the calculated plots of $|E_{lateral}/E_{total}|$ (see Fig 3b, for example) that the lateral field extends vertically nearly as far as it extends laterally, at the same strength which corresponds to halved intensity. We have previously demonstrated these contrast effects are generated by structures buried under 0.5 µm of oxide [1]. These results suggest that PEEM image contrast can be generated by structures buried under oxide layers at depths of 5 µm or more.

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