Transmission and Reflection Holography at Low Energies *

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We have designed a low voltage point source microscope operated with a nanotip field emitter and without any electron optical lenses such that it can be operated in the transmission mode as well as in a reflection mode. An electron gun needed in the reflection mode is the most important difference between the two modes of operation. The magnification of the object wave is achieved by placing the specimen in the divergent electron beam of a nanotip field emitter and observing the object wave using a micro channel plate (MCP) at a great distance from the sample. As no lenses are present a procedure for scaling the magnification has been developed. Since electrons from a point source are highly coherent the out of focus images of the sample are interferograms and contain true three dimensional information of the sample. The transmission mode gives us the following results: (1) Electrons diffracted at an edge of the specimen cause Fresnel fringes in the image plane. (2) An electrically charged holey carbon foil can act in the same way on the electrons as the Young's double slit experiment and results in an interference pattern consisting of parallel fringes. The reflection mode shows us: (1) The image depends on the angle of reflection. (2) An arrangement similar to a field ion microscope resolves single atoms of the specimen. [DOI: 10.1380/ejsnt.2004.81]

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I. INTRODUCTION

In 1939 Morton and Ramberg [1] introduced an new electron optical set-up which they called "point projector electron microscope" (PPM). They described the most important features of their invention as follows: "As this type of microscope involves no electron-optical lens elements, the images obtained are free from the ordinary aberrations. The limit of resolution depends solely on the distribution of initial velocities of the field electrons and on Fresnel diffraction by the object, making it possible to proceed beyond the resolution of the light microscope by some orders of magnitude." At that time, however, the brightness of the available electron sources was very limited. After the fabrication of a nanotip field-emitter by Fink [2] in 1986 the point projector microscope was newly applied to give answers to many questions in the scientific community [3-7]. The continuing reduction in feature size in the semiconductor industry has led to a search for electron-optical tools whose performance is not as limited as that of a conventional scanning electron microscope. One candidate for such applications is the PPM.

Based on the original PPM we discuss a microscope suitable for both the transmission and the reflection mode of operation. Since the interference pattern in the images and scaling the magnification are identical for both modes operation we begin with the easier to understand transmission mode before proceeding to the reflection mode. Comparing our experimental images with the ones modeled using the Simion software [8] is very helpful to exclude artifacts.

This software approximates the three dimensional parts of our microscope by arrangements of tiny cubes and the resulting electrostatic potential is calculated solving the

Laplace equation appropriate for the set-up. Electron trajectories are determined following the Lorentz force within the known fields. The electron trajectories which end in the micro channel plate form the modeled image. We do not observe any interference pattern in the simulated images as Simion does not include any wave optical aspects of the electrons in the ray tracing.

II. GENERAL SET-UP

The point projection microscope consists of the small UHV chamber shown in Fig. 1 and can be evacuated using a turbo pump backed by a rotary fore-pump. With the help of an additional 60 l/s ion pump a base pressure of better than 10^{-9} Torr can be reached after 12 hours of baking at 150°C . Although this pressure is relatively low compared with the 10^{-11} Torr for cold field emission guns of standard transmission electron microscopes, we found that the life time of our emitter as well as the stability of the emission current is improved at this higher pressure. Both the turbo and the ion pump can be separated from the chamber by gate valves. Under normal operation only the ion pump is working while the turbo and fore-pumps are turned off to reduce vibration. The pressure can be monitored by using a residual gas analyzer or reading the ion pump current. The electron signal is first amplified by a micro channel plate (MCP) mounted on the top flange and then converted to an image by a phosphor screen. A CCD camera transfers the image to a computer. Electrons inelastically scattered by the sample are filtered out by a weak negative voltage on the front plate of the MCP. The inside of the chamber is screened by two layers of mu-metal. To insulate the chamber against vibrations the whole setup is placed on a vibration insulating table top, which floats on an air cushion. Vibration of tip and sample can be additionally dampened by using a viton gasket assembly. The nanotip consists of a 230 micron diameter polycrystalline tungsten wire, which is electrochemically etched in a sodium hydroxide solution.

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FIG. 1: Set-up of point projection microscope (PPM).

III. TRANSMISSION MODE OF OPERATION

Looking through the viewport in Fig. 1 shows the simplicity of the set-up that is displayed in Fig. 2. In the transmission mode of the microscope electrons are extracted from a negatively biased ultrasharp tungsten tip by an earthed sample. An electron gun is not needed as

FIG. 2: Look through viewport of PPM in Fig. 1.

FIG. 3: Schematic set-up of PPM and modeled electron rays.

the sample acts as anode. Standard values for extraction voltage and emission current are 300 Volts and several microamps, respectively. The sample stage can be shifted in x, y, and z direction. The tip can be shifted only in one direction, but, in addition to this, it can be tilted. Fig. 3 shows a schematic set-up and simulated electron rays. A standard copper grid for a transmission electron microscope (TEM) is used as sample for the simulation. As can be seen no lenses, apertures or any hardware is present between sample and electron detector. Thus the images are free of lens aberrations and unwanted diffraction effects. The point resolution is defined by the sharpness of the emitter and can be better than 1 nm. A magnified shadow image of the sample is obtained as the beam emitted from the source is divergent. The magnification can be changed by changing the distance between sample and emitter and/or the distance between sample and detector. Greatest magnifications are obtained when the distance between sample and emitter is small (several micrometers in our case) and when the distance between sample and emitter is great (100 mm in our case). A series of magnifications of a holey carbon foil on a TEM grid can be seen in Fig. 4. The tiny hole in Fig. 4(a) pointed at by an arrow is greatly magnified in Figs. 4(b), (c), and (d). Figs. 4(b) and (c) are used to calibrate the magnification (see next section), and the magnification in Fig. 4(d) is high enough to resolve interference fringes.

FIG. 4: Holey carbon foil on standard grid for transmission electron microscope. (a) Arrow points at hole which is greatly magnified in (b), (c) and (d). (b) and (c) are used to scale magnification. (d) Magnification is sufficiently high to resolve interference fringes.

FIG. 5: Schematic for scaling magnification.

IV. SCALING THE MAGNIFICATION

Since no lenses are present in a point projection microscope the magnification can not be scaled using the laws of lens optics. Instead, taking two images at different magnification enables us to evaluate the magnification very precisely. This can be seen by Fig. 5 and the following considerations. Let the indices a (figure on the left) and b (figure on the right) represent the data of the first and second image, respectively. Let the distance between source and electron detector be constant and identical when taking the two pictures, $z_{1a} + z_{2a} = z_{1b} + z_{2b} = \text{const}$. This means that the magnification is increased by moving the sample closer to the source. We acquire the first image at a given z_{1a} and z_{2a} and we measure the distance D_a between two selected points in this image. Then we change the magnification by moving the sample

closer to the source by $z = z_{1a} - z_{1b}$, and we measure the increased distance D_b between the two points selected in the first image. The magnification of the first and second picture is given by Eq. (1) and Eq. (2), respectively.

$$M_a = \frac{D_a}{d} = \frac{z_{2a} + z_{1a}}{z_{1a}} \quad (1)$$

$$M_b = \frac{D_b}{d} = \frac{z_{2a} + z_{1a}}{z_{1a} - z} \quad (2)$$

$$d = D_a \cdot \frac{z_{1a}}{z_{2a} + z_{1a}} \quad (3)$$

$$d = D_b \cdot \frac{z_{1a} - z}{z_{2a} + z_{1a}} \quad (4)$$

$$z_{1a} = z \cdot \frac{D_b}{D_b - D_a} \quad (5)$$

$$z_{1b} = z \cdot \frac{D_a}{D_b - D_a} \quad (6)$$

Eqs. (3) and (4) are obtained from Eqs. (1) and (2) by simple arithmetic. Combining Eq. (3) with Eq. (4) leads to Eqs. (5) and (6), the distance from source to sample. This distance, z_{1a} (or z_{1b} for the second image), can be found for both imaging conditions by D_a , D_b , and z , three parameters that can be precisely measured. Finally, the magnification is given by z_{1a} (or z_{1b}) and the distance from source to detector. As this procedure depends on the linearity of the rays it should be applied only for small changes in magnification.

An Example: Let the distance from the source to the MCP be $z_{1a} + z_{2a} = z_{1b} + z_{2b} = \text{const} = 100$ mm and let the distance between two points in the first image be $D_a = 62$ mm (see Fig. 4(b)). Since this distance is magnified to $D_b = 70$ mm (see Fig. 4(c)) when we move the sample closer to the tip by $z = 2$ micrometer we find by applying Eqs. (5) and (6) z_{1a} and z_{1b} as 15 micrometer and 13 micrometer, respectively. Applying these numbers to Eqs. (1) and (2) results in $M_a = 6700$ and $M_b = 7700$.

V. COMPARISON BETWEEN TRANSMISSION MODE AND REFLECTION MODE

In order to show the great similarity between the transmission mode and the reflection mode we consider a transmission sample tilted with respect to the optical axis as seen in Fig. 6, top. In comparison, let us consider an arrangement for the reflection mode displayed in Fig. 6, bottom. Electrons are extracted by the electric field between emitter (here a nanotip with only one atom at the tip apex) and the sample. The surface of the sample acts as a mirror and the reflection angle is assumed to follow the laws of geometrical optics. When we extend the beams backwards through the sample they ideally meet in one point defining a virtual point source. However, the beams do not exactly meet at one point forming a source with an effective size. As a result the resolution of the image acquired in the reflection mode is limited by the effective source size. Fig. 6, bottom, also shows equi-potential lines of the electric field between emitter and sample.

FIG. 6: Transmission mode with tilted sample (top) and reflection mode (bottom). Both set-ups show great similarity.

VI. REFLECTION MODE OF OPERATION

The principle of our point reflection microscope (PRM) is shown in Fig. 7. A point source is placed such that the emitted beams hit a sample at an angle with respect to the surface that reflects the beams. In many cases the reflectivity of the sample can be too low to obtain a reasonable electron current at the electron detector. In order to increase the reflectivity we bias the sample negatively. This, however, decreases the extraction voltage if the sample is used as an extraction anode (as in the transmission mode). Our simulations show that the negative bias on the sample surface must be approximately the same as the extraction voltage which results in no electron emission. A possible way out is to replace the nanotip by an electron gun. This decreases, to some degree, the simplicity of the set-up compared with the set-up of the transmission mode, yet the results obtained with a preliminary gun (see Figs. 8, 9, 10 and 12) are promising. The highest resolution limit for this set-up can be estimated from the resolution limit of a mirror electron microscope (MEM) as the two instruments are very similar. Rempfer [9] evaluated the resolution limit of an MEM as about 1 nm.

VII. EXPERIMENTAL RESULTS

(1) The geometry, (virtual) point source - tilted sample - electron detector, is identical for both, the transmission

FIG. 7: Comparison between experimental set-up (top) and modeled set-up for ray tracing (bottom).

mode and for the reflection mode. Thus, the considerations on scaling the magnification (see Section 4) and on the interference pattern (see next section) are the same. First images of a copper grid at different magnification are shown in Fig. 8.

(2) As the electron beam is not normally incident on the surface of the sample the image shows severe distortions. This is demonstrated by both, the experimental and the simulated images in fig. 10 where the squares of the original sample are imaged as lines.

VIII. ELECTRON INTERFEROMETRY

Compared with conventional electron microscopy that delivers only the intensity of an electron wave electron interferometry gives us both the amplitude and the phase of the wave. The phase of the wave represents its wave front and is lost in conventional microscopy. However, the phase of an electron wave contains a lot of informa-

FIG. 8: First reflection images obtained with PPM. Images show copper grid with increasing magnification from left to right.

FIG. 9: Central beam of incident electrons and central beam of reflected electrons lie in plane at 45° to grid.

FIG. 10: Central beam of incident electrons and central beam of reflected electrons lie in plane parallel to grid.

tion. Firstly, it contains information on lens aberrations and enables us to numerically correct for it after the acquisition of the interferogram. In our case, a microscope without any lenses, this feature is of no importance. Secondly, the phase contains 3D information on the sample. This feature will be discussed in more detail below. It also contains information on magnetic potentials and electric potentials, on the mean inner potential which corresponds to the refractive index in light optics and on the thickness of the sample. The visibility of the interference pattern is modulated by the mean free path of electrons for inelastic scattering. An interferogram is called a hologram if it features many fringes. Then the reconstruction of the

image wave can be done by Fourier optics. Many detailed discussions on electron interferometry and electron holography can be found, for example, in the books edited by Tonomura [10] and Voelkl [11].

The simplest case of forming an interferogram can be seen in Fig. 11, top. A plane wave is coherently scattered by the sample which consists of only one point. The spherical wave emitted from that point interferes with the part of the plane wave not influenced by the sample (reference wave) and forms a system of concentric circles. Since no lens is used to image the sample the interferogram represents an out of focus image. If we used an ideal lens to image the sample in focus, the spherical wave from the

FIG. 11: Simple point projection interference patterns. Top: Plane wave is coherently scattered by sample, which consists of only one point. Spherical wave emitted from that point interferes with part of plane wave not influenced by sample (reference wave) and forms series of concentric circles. Since no lens is used, interferogram represents out of focus image. Bottom: If we add second point object such that distance to image plane is different from first one, plane wave interferes with both wave scattered by first point and with wave scattered by second point creating second system of concentric circles. Interference of waves scattered from two points has to be also taken into account. Different distance from two points to image plane results in different spacing of circles and in different centers, which reveals 3d structure of sample.

sample would be focused to one point in the image plane and no interference would take place. Thus, this kind of interferometry is always an out of focus interferometry. In order to approach an interferogram of a real sample we add a second point to Fig. 11, top, such that the distance to the image plane is different as seen in Fig. 11, bottom. As a consequence, the plane wave interferes with both the wave scattered by the first point and with the wave scattered by the second point creating a second system of concentric circles. The interference of the waves scattered from the two points also has to be taken into account for the simulation in this figure. The different distance from the two points to the image plane results in a different spacing of the circles and in different centers which reveals the three dimensional structure of the sample.

The interference pattern of a real sample is usually very complex. Fig. 12, top, shows an interferogram of a holey carbon foil. Since the foil is not transparent for 300 Volt electrons we observe mainly two different kinds of fringes, the Fresnel fringes and the Young's fringes. Fresnel fringes are formed when a coherent wave is scattered by an edge, in our case the edge of the foil at a hole, and then superimposed to a reference wave (wave through the hole). Spacing and contrast of the fringes decreases

FIG. 12: Interference fringes contain information on electric potential as well as on topography of sample. Top: Interferogram of holey carbon foil acquired in transmission mode shows Fresnel fringes as well as Young's fringes. Bottom: Interferogram of scratches on stainless steel surface acquired in reflection mode shows only few fringes.

rapidly with increasing distance from the edge. The magnification of the image can be checked by the fringes as the spacing of the fringes depends on the distance of the electron source to the foil. The original set-up to create Young's fringes consists of a double slit illuminated by a coherent wave. From the slits two spherical waves are emitted which can be considered, at a great distance from the slits, as plane waves $\Psi_1 = \exp[i\varphi_1]$ and $\Psi_2 = \exp[i\varphi_2]$. The interference pattern of this arrangement is given by $|\Psi_1 + \Psi_2|^2 = 1 + \cos[\Delta\phi]$, which correspond to equidistant parallel fringes. The spacing of the fringes is given by the distance of the slits from each other and from an observer screen, and the contrast of the fringes by the width of the slits. The arrangement in fig. 12 is slightly different from the original Young's set-up. We illuminate two holes in a carbon foil. The holes are separated by a thin carbon bridge positively charged by the electron beam. The voltage on the carbon bridge deflects the electron beam on each side of the bridge towards each other. As the observer screen is at a great distance from the foil we obtain the same fringe pattern as in case of a double slit. In case of the carbon foil the fringe spacing depends on the voltage on the bridge. The greater the voltage, the greater the angle of superposition and the smaller the

FIG. 13: Left: Schematic of field ion microscope (FIM). Polarized gas atom attracted by positively biased tip. Gas atom loses electron while at tip and is then repelled towards detector. Right: Trimer (top) and monomer (bottom) imaged by FIM. Tip was fabricated using single-crystalline $\langle 111 \rangle$ -oriented tungsten wire. FIM images: Courtesy Dr. A. Orchowski.

fringe spacing. The contrast of the fringes depends on many factors. (1) Coherence of wave: The greater the interference band, the greater the needed emission area of the electron emitter and the smaller the lateral coherence, (2) mechanical vibrations of the set-up, (3) stability of extraction voltage and electron current, (4) electromagnetic noise, (5) Modulation Transfer Function (MTF) of recording medium, (6) inelastically scattered electrons, and (7) electron statistics. If the contribution of (2) - (7) to the fringe contrast is negligible then the contrast depends only on the coherence of the wave and from that the effective source size can be evaluated. Assuming a fringe contrast of 20 % and 150 Volt electrons results in a 3 nm effective source size when the interferogram in fig. 12 top was taken. Fig. 12, bottom, shows some scratches in a flat stainless steel surface with only a few fringes. The fact that the fringe contrast is much weaker compared to the transmission image could be a consequence of the distortions due to a beam incident on the surface at an angle and due to the aberrations of our preliminary electron gun.

IX. ULTRASHARP ELECTRON EMITTERS

Ultrasharp electron emitters with low emission voltages are used for both the transmission mode and the reflection mode of our PPM. The emission can be confined to only one atom of the tip apex resulting in a nanotip (monomer) [2] and the angular half width of the diver-

gent electron beams amounts to only a few degrees. The fabrication process of the monomer is usually performed by electrochemically etching a single-crystalline $\langle 111 \rangle$ -oriented tungsten wire which yields a sharp tip curvature of about 10-100 nm. The subsequent sputtering with Ne ions in a UHV chamber further sharpens the tip and a tip apex consisting of only three atoms (trimer) can be obtained. The monomer is then produced by heating up the tip which moves one atom on the top of the trimer. Imaging single atoms of a nanotip can be done by field ion microscopy (FIM) the principle of which is sketched in Fig. 13, left. In order to apply this technique to our nanotip we fill our vacuum chamber with helium gas at a partial pressure of about 7.5×10^{-5} Torr and positively bias the tip under investigation by about 10 kV. In the strong and inhomogeneous field between tip end electron detector the helium atoms become polarized and are then attracted by the tip. In order to increase the time of the gas atoms at the tip and therefore to increase the probability of ionizing we cool the tip down to liquid nitrogen temperature. After the atom is positively ionized it is repelled by the tip towards the detector and finally contributes to the image. Field ion images of a trimer as well as of a monomer can be seen in Fig. 13, right.

Fig. 14, left, shows a schematic of a "field electron microscope" (FEM) in analogy to the FIM. Instead of using atoms polarized by a strong electric field and biasing the tip (which is the sample) positively we use electrons and a negatively biased tip as sample. The parallel electron beams emitted from another nanotip are repelled by the

FIG. 14: Left: Schematic of "field electron microscope". Tip is biased negatively and is imaged by electrons from field emitter. Right: First "field electron image". Tip was etched using polycrystalline tungsten wire.

negatively biased sample and form an image of the tip surface on the screen (see Fig. 14, right). Compared with the FIM images the FEM has a lower contrast as the tip was fabricated from a polycrystalline tungsten wire and the tip apex was several tens of nanometers. Our first field electron image shows that, for special cases, it is possible to achieve atomic resolution with the simple set-up of our point projection microscope.

X. CONCLUSIONS

We set out to demonstrate the PPM could produce useful imaging and holography in both transmission and reflection modes. The data shown here demonstrates that the concept of this approach is successful and applicable to the tasks for which it was designed.

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