Behavior Analysis of Scanning Tunneling Microscope, Atomic Force Microscope and Biprism Interference

ELEC 4704 A

Lab 2

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TABLE OF CONTENTS

1.0 INTRODUCTION

This lab focuses on sensitivity of scanning tunneling microscope (STM) and an atomic force microscope (AFM) along with the behavior of a biprism. Section 2.0 goes in detail about the simulations, with section 2.1 focusing on the STM and AFM, section 2.1.1 focuses on the variation in the sensitivity of STM and FAM in lateral and horizontal direction. Further, section 2.1.2 analysis the acceptable thermal noise resistance for atomic level resolution. Moving forward section 2.1.3 calculates the mass of the AFM cantilever in situation of resonance and without resonance. Section 2.2 of the simulation deals with Biprism interference with section 2.2.1 focusing on physical setup of the Biprism such that it leads to the fringe width of 1mm. Section 2.2.2 analysis the biprism such that in place of light an electron beam is used and in section 2.2.3 the interference pattern is analyzed using Monte Carlo simulation such that one electron is interfering with the biprism at a given time. Finally, section 3.0 discusses on the learnings from this lab.

2.0 SIMULATIONS

This section focuses on the MATLAB lab code that was run to simulate the results of various situations and analyze the working of STM, AFM and biprism interference.

2.1 STM & AFM Simulations

This section analysis the difference between a tube STM and a tripod STM. The difference in their resolution in lateral and horizontal direction and the acceptable thermal noise which allows for atomic level resolution. From the AFM its cantilever's mass is calculated such that its vibrations are in resonance vs when their vibrations are not in resonance.

2.1.1 Sensitivity of a STM tube vs STM tripod

Figure 1 depicts two plots The curve in Blue depicts the variation of sensitivity of the STMs in lateral direction, i.e., x-y plane. The Red curve depicts the variation in sensitivity in the horizontal direction, z -axis. From the curves it can be observed that the tripod is more sensitive than the tube in either case but the sensitivity of the tube in the x-y plane is much higher than that in the vertical direction, along z-axis.

The MATLAB code associated with plotting the above figure in given below:

```
%Calculate and compare the relative sensitivities (lateral and vertical) of
the two

%reasonable voltage range
V = linspace(-250, 250, 1000);

%Dimentions of Tube
H_tube= 0.5e-3;
D_tube = 10e-3;
L_tube = 30e-3;

%Tripod Dimentions
H_tripod = 0.75e-3;
L_tripod = 30e-3;
```

```
%Calculating D value for tube
D_x_tube = ((pi*D_tube*H_tube)/ (power(2,1.5)*power(L_tube,2)))*0.04*(1e-6);
D_z = (H_tripod/L_tripod)*0.018*(1e-6);


delta_x_tube =
V.*((power(2,1.5)*D_x_tube*power(L_tube,2))/(pi*D_tube*H_tube));
delta_z_tube = V.*D_z*(L_tube/H_tube);
delta_x_tripod = V.*D_z*(L_tripod/H_tripod);
delta_z_tripod = V.*D_z*(L_tripod/H_tripod);

plot (delta_x_tube, delta_x_tripod)
hold on
plot (delta_z_tube, delta_z_tripod);
xlabel('Variation due to Tube')
ylabel('Variation due to Tripod')
title('Curves Comparing sensitivity of an STM Tube and STM tripod')
```

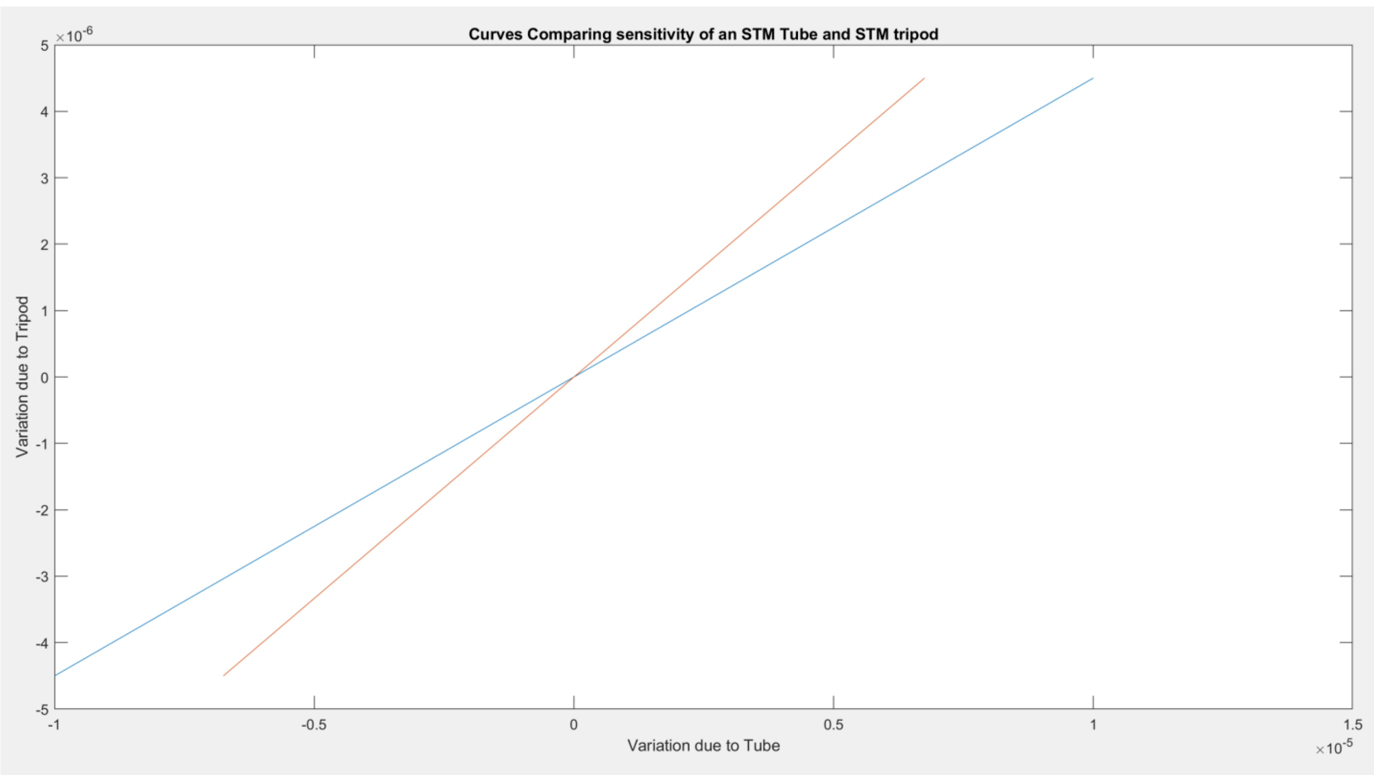

Figure 1: Variation in Sensitivity of STM tube and tripod in lateral direction and z-axis

2.1.2 Thermal Noise Resistance of STM tube and STM tripod

This section calculates the acceptable thermal noise resistance for which the resistance for which the atomic resolution remains about 0.1nm. Using the code given below the values were calculated to be 5.1500e+09 Ohms for the STM tube and 8.4532e+10 Ohms for the STM tripod.

The MATLAB code associated with plotting the above figure in given below:

```
%Assume you are to use a feedback loop (similar that shown in slide 2-28) with a loop bandwidth of B = 75kHz and the dominant thermal noise source is equivalent to a resistance of RN when referred to the output (i.e. at the piezo-actuator).Calculate the size of RN required to maintain sufficient accuracy to measure to atomic resolution (i.e. about 0.1 nm) at room temperature.

%Constants
boltzman = 1.380649e-23;
T = 293;
f = 75000;
delta_x = 0.1e-9;

%voltage calculation
    %Dimentions of Tube
    H_tube= 0.5e-3;
    D_tube = 10e-3;
    L_tube = 30e-3;

    %Tripod Dimentions
    H_tripod = 0.75e-3;
    L_tripod = 30e-3;

D_x_tube = ((pi*D_tube*H_tube)/ (power(2,1.5)*power(L_tube,2)))*0.04*(1e-6);
D_z = (H_tripod/L_tripod)*0.018*(1e-6);

V_tube = (delta_x*pi*D_tube*H_tube)/(power(2,1.5)*D_x_tube*power(L_tube,2));
V_tripod = (delta_x*H_tripod)/(D_x_tube*L_tripod);

R_tube = (V_tube*V_tube)/(4*boltzman*T*f)
R_tripod = (V_tripod*V_tripod)/(4*boltzman*T*f)
```

2.1.3 Mass and Resolution of an AFM

This section calculates the mass of an AFM cantilever that will result in 0.1nm resolution. The mass is calculated such that the cantilever will vibrating at its resonant frequency and when it will not. The mass value at resonance is 6.7898e-11 Kg and that without resonance is 1.6974e-07 Kg.

The MATLAB code associated with plotting the above figure in given below:

```
% If instead of STM we chose to use atomic force microscopy (AFM) using the same measurement bandwidth in (b) with a cantilever quality factor of Q = 50, and force constant k = 1.0 N/m. What cantilever mass would be required to achieve atomic resolution at room temperature both at resonance and off resonance?

B = 75000;
Q = 50;
k = 1.0;
Rsq = power(0.1e-9,2);
T = 293;
boltzman = 1.380649e-23

% At resonance
Omega_Resonance = (4*boltzman*T*B)/(k*Rsq);
m_resonance = k/(Omega_Resonance*Omega_Resonance)
```

```
% No resonance
Omega = (4*boltzman*T*B)/(Q*k*Rsq);
m = k/(Omega*Omega)
```

2.2 Bi-Prism Interference

This section analyses the behavior of a biprism in an optical system with an incident plane wave, an electron beam and with individual electrons.

2.2.1 Setup for Appropriate Resolution

In this section the MATLAB analysis the given parameters, to calculate the value of 'L' distance between screen and prism, and 'ϴ' Maximum angle at which interference fringes can be found, such that the fringe width in 1.0mm. Figure 2 depicts the interference pattern as simulated by the MATLAB code. The value found by implementing the code below were:

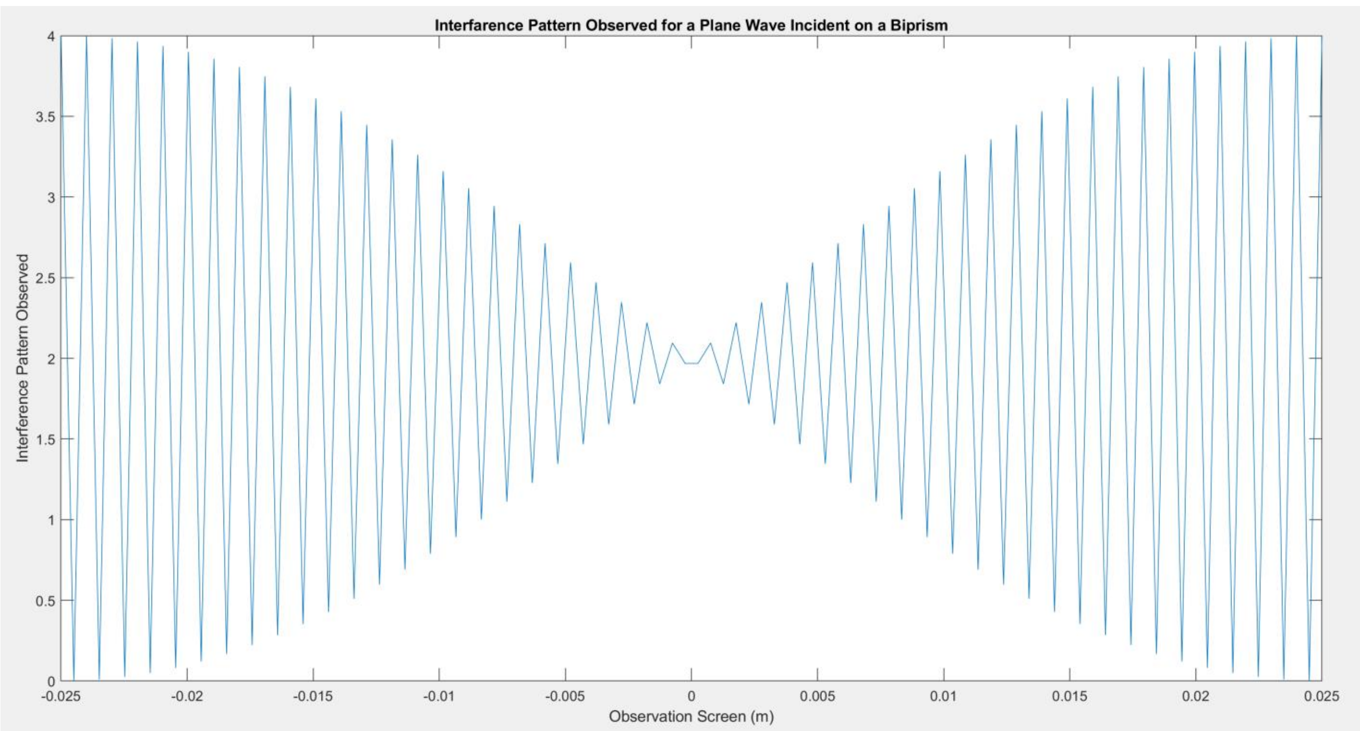

Figure 2: Interference observed due to a plan wave incident on a Bi-Prism

L = 39.3701 m

ϴ = 3.1750e-04 radians

The MATLAB code associated with plotting the above figure in given below:

```
% A HL6312G AlGaInP laser diode with a multi-quantum well (MQW) structure (data sheet
on website) has a wavelength of λ = 635nm is used to generate a collimated beam that
is incident on a biphase optical prism of width W = 5.0cm. This beam is modelled as an
ideal plane wave. Using appropriate calculation and plotting code in Matlab solve the
EM wave equation and generate a plot of the optical intensity distribution in the
observation plane, which is at distance L from the prism, as shown below. (Choose
```

```
values for L and θ such that the interference pattern has peak-valley structure on the
order of 1mm.)

Lamda = 635e-9; % wavelength
W = 0.05; %
r = 1e-3;  % Width of fringes
k = 2*pi/Lamda; % Wavenumber
x = linspace(-W/2, W/2, 100);
% Caluculating L, distnace from prism to screen
%phi = (k*x*W)/(2*sqrt((L*L)+(W*W/16)));
% at x = 1mm, phi is equal to 2pi hence rearranging the above equaltion to
% calculate L
A =  (k*r*W)/(4*pi);
L = sqrt((A*A)+(W*W/16))
% USing the calculated value of L, calculate Theta;
Theta = tan(W/(L*4))
phi =  (x.*k*W)./(2*sqrt((L*L)+(W*W/16)));
I = 2*( 1 + cos(phi));
plot (x,I);
xlabel('Observation Screen (m)')
ylabel ('Interference Pattern Observed')
title ('Interfarence Pattern Observed for a Plane Wave Incident on a Biprism')
```

2.2.2 Probability Distribution of an Electron Bean Incident on a Bi-Prism

This section simulates the behavior of a collimated electron beam incident on a biprism. Using he Schrodinger's wave equation, the probability amplitude of finding the electrons at various positions on the screen was calculated. The results obtained by the simulation can be seen in figure 3.

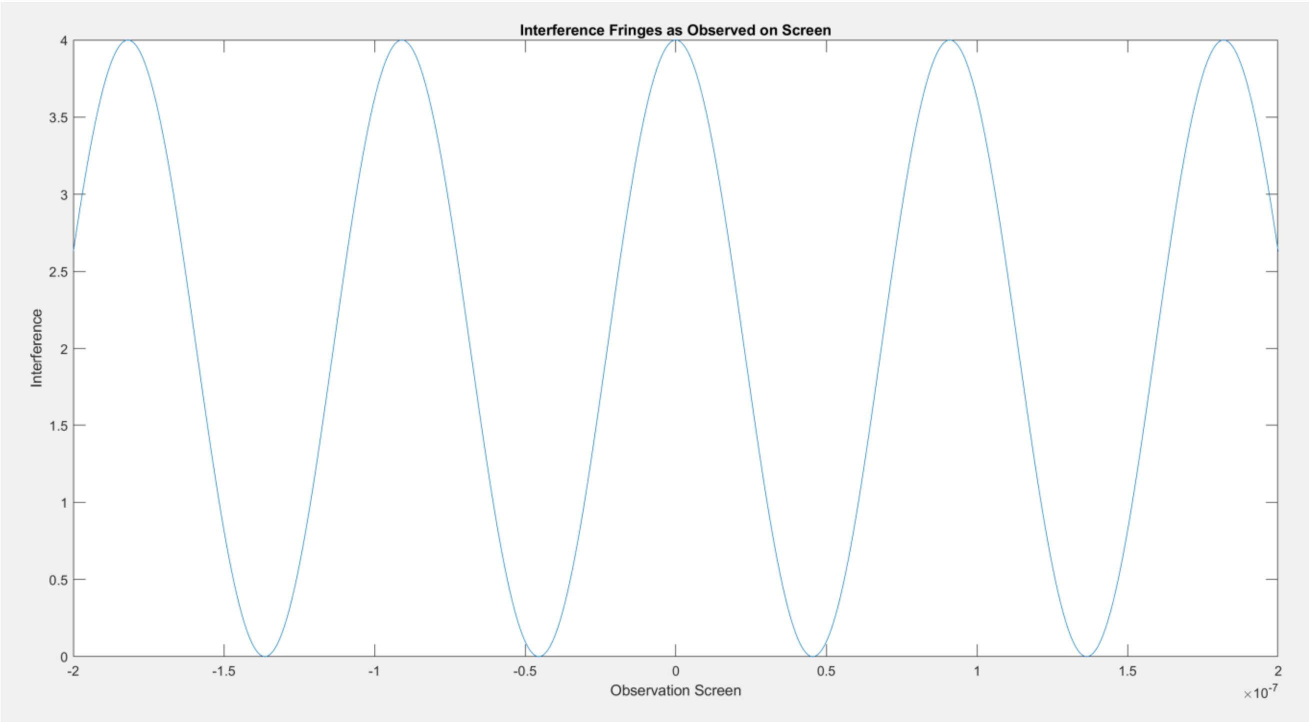

Figure 3: Probability Amplitude of an electron Bean caused by Interference with Biprism

The MATLAB code associated with plotting the above figure in given below:

```
% A collimated electron beam with particle velocities v is incident upon a biphase electron prism as illustrated in Section II of the Tonomara paper (see Activities above). Using appropriate calculation and plotting software use the solution to the Schrodinger wave equation as outlined in Section II of the Tonomara paper using the parameters given and generate a plot of the probability distribution for electrons in the observation plane.

Va = 10; %V, given in apper
vz = 1.5e8; % c/2, given in paper
b = 5e-3; %m, given in paper
a = 0.5e-6; %m, given in paper
hbar = 1.05457182e-34;
q = 1.602e-19;

x = linspace(-2e-7,2e-7,1000);

kx = ((pi*q*Va)/(hbar*vz))/(log(b/a))
Probamp = 4.*cos(x.*kx).*cos(x.*kx);

plot (x,Probamp)
xlabel('Observation Screen')
ylabel('Interference')
title('Interference Fringes as Observed on Screen')
```

2.2.3 Mont Carlo Solution for individual electrons

This section uses Monte Carlo simulation such that assuming a single electron interacts with the biprism at a given time and calculates the probability of finding the electrons at the stretch of the screen. Figure 4 depicts the histogram depicting the probability of finding individual electrons.

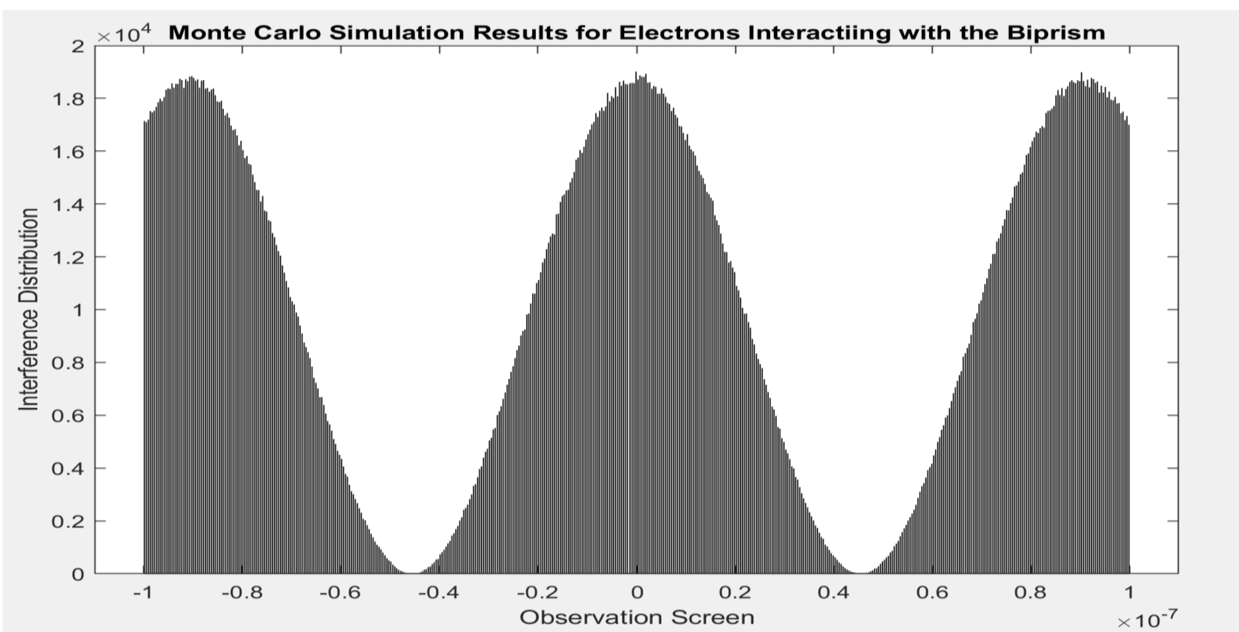

Figure 4: Individual Electron Interference Pattern Obtained by Monte Carlo Simulation

The MATLAB code associated with plotting the above figure in given below:

```
% Repeat the calculation in (b) by using a Monte Carlo calculation method rather than
using the continuous solution to the wave equation. (i.e. randomly transmit individual
electrons as particles having the same velocity and direction deflected through the
biprism and then count the linear density (number/length) hitting various positions in
the observation plane.)
i) under what assumptions about the electrons do you get no interference?
ii) what assumptions are required to get results that match part (b)?
iii) how do the results change if the electrons have a distribution of velocities Δv?
iv) how would you incorporate the effects of (iii) into part (b) above?

Va = 10; %V, given in apper
vz = 1.5e8; % c/2, given in paper
b = 5e-3; %m, given in paper
a = 0.5e-6; %m, given in paper
hbar = 1.05457182e-34;
q = 1.602e-19;
x = linspace(-2e-7,2e-7,1000);
kx = ((pi*q*Va)/(hbar*vz))/(log(b/a));
Probamp = 4.*cos(x.*kx).*cos(x.*kx);

y = randsample(x,10000000,true,Probamp);
x_vector = linspace(-1e-7,1e-7,length(y));
histogram(y,x_vector)
xlabel('Observation Screen')
ylabel('Interference Distribution')
title('Monte Carlo Simulation Results for Electrons Interactiing with the Biprism')
```

3.0 CONCLUSION

The analysis of the simulation sin this lab came to the following results. It was observed that the tripod is more sensitive than the tube in either case but the sensitivity of the tube in the x-y plane is much higher than that in the vertical direction, along z-axis. The acceptable thermal noise for an STM tube and am STM tripod were calculated such that they resulted in atomic level resolution. The acceptable thermal noise resistance for the STM tube is 5.1500e+09 Ohms and that for an STM tripod is 8.4532e+10 Ohms. For the AFM the mass of the cantilever is calculated such that it gives an atomic level resolution in case of resonance and without resonance. The mass of the cantilever in case of resonance is 6.7898e-11 Kg and that without resonance is 1.6974e-07 Kg.

For the biprism part of the distance between the biprism and the screen is calculated such that it gives the fringe width of about 1mm and based on that and the given wavelength of light used the value of theta that represents the angle of resolution from the prism to the screen. The calculated value of distance and theta are, 39.3701m and 3.1750e-0 radians. Similar analysis was done with an electron beam that gave a similar pattern output on the screen. When the simulation was repeated such that, an individual atom interacts with the prism at a given time by using the Monte Carlo simulation method, which resulted in the same pattern.

On an overall this lab acted as an excellent opportunity to understand the concepts of STM, AFM and the biprism better.