Assignment 3 Part 1 - Andrew Paul

A constant voltage of 0.5 V was applied over the length of the semiconductor in the x direction (L) and the electric field (E) can be calculated by:

$$E = V/L$$

For a distance of 200 nm the electric field was calculated to be 0.5 mV/nm or 500000 V/m.

The force on each electron can be calculated by multiplying the charge of an electron (q) by the electric field in which the electron is present.

$$F = Eq$$

With an electron charge of 1.602 x 10^{-19} the force on the each electron was found to be 8.01 x 10^{-14} N.

The acceleration of the electrons is calcaulted by dividing the force on the electrons by the effective mass of the electrons which is 0.26 x 9.11 x 10^{-31} kg.

$$a = F/m$$

The acceleration is calcualted to be 3.3817 x 10^{17}.

The formula for electron drift current density is given be the following formula:

$$J_n = -enV_d$$

Where J_n is the drift current density, e is the charge of an electron, n is the electron concentration (per cm^2)and V_d is the average drift velocity.

```
%list of constants
m0 = 9.11e-31;
mn = 0.26*m0;
kB = 1.38e-23;
T = 300;
q = 1.602e-19;
n = 10^15;

%region limits
xlim = 200e-9;
ylim = 100e-9;

%assignment 3 calcualtions
voltage = 0.1;
E = voltage/xlim;
F = E*q;
acc = F/mn;

%thermal velocity
vth = sqrt(2*kB*T/mn);
```

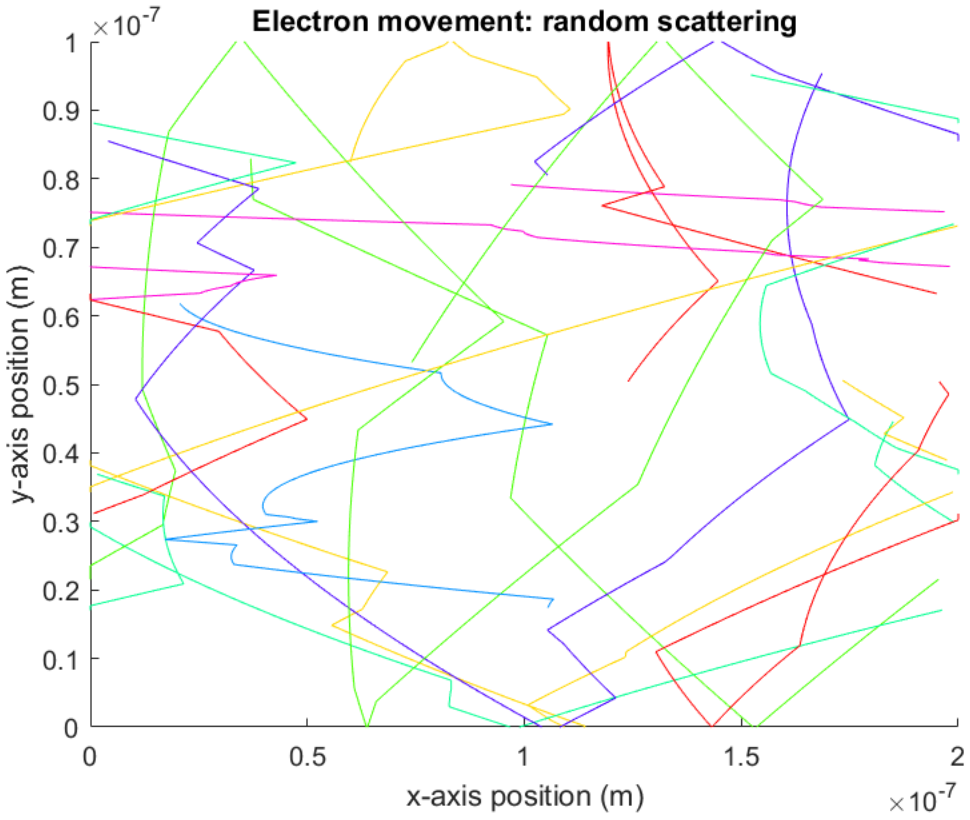
```
%initialize the number of electrons
num_electrons = 7;

%defining array for electrons (x postion, y position, angle, velocity)
electron = zeros(num_electrons, 6);

% the previous position of the electron (previous x position, previous
 y
% position)
electron_prev = zeros(num_electrons, 2);

%spacial step should be smaller than 1/100 of region size
time_step = xlim/vth/100;
time_total = time_step*250;
%num_step = time_total/time_step;

% used to make each electron a different colour
electron_colour = hsv(num_electrons);

% counter used to check temperature is constant
count = 0;

% scattering probability
Pscat = 1-exp(-time_step/0.2e-12);

%set an initial random postion and a fixed velocity for each electron
for i=1:num_electrons
    for j=1:6
        if(j==1)
            electron(i,j) = xlim*rand();
        elseif(j==2)
            electron(i,j) = ylim*rand();
        elseif(j==3)
            electron(i,j) = 2*pi*rand();
        elseif(j==4)
            electron(i,j) = randn()*vth;
        % set vx value
        elseif(j==5)
            electron(i,j) = electron(i,4)*cos(electron(i,3));
        % set vy value
        else
            electron(i,j) = electron(i,4)*sin(electron(i,3));
        end
    end
end

% figure(3)
% hist(electron(:,4))
% title('Velocity Distribution')

% define a temperature and time array for plotting
temperature= zeros(time_total/time_step,1);
time = zeros(time_total/time_step,1);
```

```
% counter for mean collision time
collision_count = 0;

running_time = 0;

% velocity array used to calculated mean free path
velocity = zeros(time_total/time_step,1);
avg_drift = zeros(time_total/time_step,1);
drift_current = zeros(time_total/time_step,1);
drift_vx = 0;

% update each electrons positon for each time step
for k=0:time_step:time_total
    avg_temp = 0;
    avg_velocity = 0;
    for m=1:num_electrons
        % allows electrons to pass through to the other side of the
 region
        %in the x-direction
        if (electron(m,1) >= xlim)
            electron(m,1) = 0;
            electron_prev(m,1) = 0;
        elseif (electron(m,1) <= 0)
            electron(m,1) = xlim;
            electron_prev(m,1) = xlim;
        end
        % electrons are reflected at the same angle if they strike the
 limits
        % of the region in the y-driection
        if ((electron(m,2) >= ylim) || (electron(m,2) <= 0))
            %electron(m,3) = pi - electron(m,3);
            %electron(m,4) = -electron(m,4);
            electron(m,6) = -electron(m,6);
        end

        % see if the particle scatters or not
        if(Pscat > rand())
            % scatters at a random angle
            electron(m,3) = 2*pi*rand();
            % new velocity for scattering - gaussian with some
            % MAXWELL-BOLTZMAN standard deviation
            vx_new = randn()*vth;
            vy_new = randn()*vth;
            v_new = sqrt(vx_new^2+vy_new^2);
            electron(m,4) = v_new;
            electron(m,5) = cos(electron(m,3))*v_new;
            electron(m,5) = sin(electron(m,3))*v_new;
            collision_count =+ 1;
        end

        avg_temp = avg_temp + (electron(m,4)^2)*mn/(2*kB);
        avg_velocity = avg_velocity + electron(m,4);
```

```
        %plot the movement of each electron
        if(k~=0)
            %UNCOMMENT TO SEE PLOT TRAJECTORY MOVIE
%             figure(1)
%             plot([electron_prev(m,1),electron(m,1)],
[electron_prev(m,2),electron(m,2)],'color',electron_colour(m,:))
%             axis([0 xlim 0 ylim]);
        end

        drift_vx = drift_vx + electron(m,5);

    end

    %UNCOMMENT TO SEE PLOT TRAJECTORY MOVIE

%     title('Electron movement: random scattering')
%     xlabel('x-axis position (m)')
%     ylabel('y-axis position (m)')
%     hold on
%     pause(0.001)

   % set the previous postion of the electron to the current electron
   %postion for the next itteration
   electron_prev(:,1) = electron(:,1);
   electron_prev(:,2) = electron(:,2);

   % set the electron postion to an updated position
   electron(:,1) = electron(:,1) + electron(:,5).*time_step;
   electron(:,2) = electron(:,2) + electron(:,6).*time_step;

   electron(:,5) = electron(:,5) + acc*time_step;

   count = count +1;
   temperature(count,1) = avg_temp/num_electrons;
   time(count,1) = k + time_step;
   velocity(count,1) = avg_velocity;

   avg_drift(count,1) = drift_vx/num_electrons;

   drift_current(count,1) = q*n*avg_drift(count,1);

end

   figure(6)
   plot(time,drift_current)
   title('Drift current density over time')
   xlabel('time (s)')
   ylabel('Drift current density (A/cm^2)')

   figure(7)
   hist(drift_current')
   title('Drift Current Density Distribution')
   xlabel('Drift current density (A/cm^2)')
   ylabel('Counts')
```

```
% mean_collision = time_total/collision_count;
% avg_vth = 0;
% for n=1:500
%     avg_vth =+ velocity(n,1);
% end
% avg_vth = avg_vth/size(velocity,1);
%
% MFP = avg_vth*mean_collision;
%
% figure(2)
% plot(time,temperature)
% axis([0 time_total, 0 1100])
% title('Temperature of electrons over time')
% xlabel('time (s)')
% ylabel('Temperature (K)')

electron_grid = zeros(100,100);
temperature_grid = zeros(100,100);

% create density regions with grid vectors of final temperature and
%electron position
for x_pos=1:100
    for y_pos=1:100
        for q = 1:num_electrons
            if((electron(q,1) <= (xlim*(x_pos/100))) && (electron(q,1)
 > (xlim*((x_pos-1)/100))) && (electron(q,2) <= (ylim*(y_pos/100))) &&
 (electron(q,2) > (ylim*((y_pos-1)/100))))
                electron_grid(x_pos,y_pos) =+ 1;
                temperature_grid(x_pos,y_pos) =+ (electron(q,4)^2)*mn/
(2*kB);
            end
        end
    end
end


figure(2)
plot(time,temperature)
axis([0 time_total, 0 1100])
title('Temperature of electrons over time')
xlabel('time (s)')
ylabel('Temperature (K)')


figure(4)
surf(electron_grid)
colorbar
title('Electron Density Map')
xlabel('x-axis position (m)')
ylabel('y-axis position (m)')
shading interp
view(0,90)
```

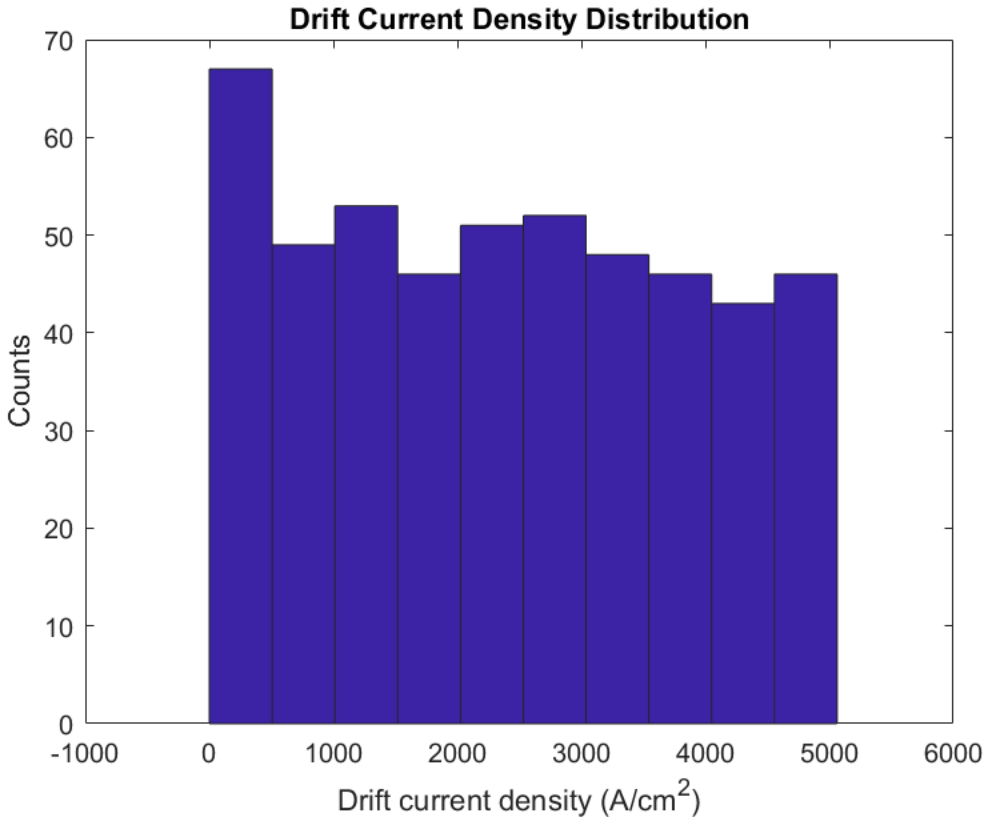
```
% figure(5)
% surf(temperature_grid)
% colorbar
% title('Temperature Map')
% xlabel('x-axis position (m)')
% ylabel('y-axis position (m)')
% shading interp
```

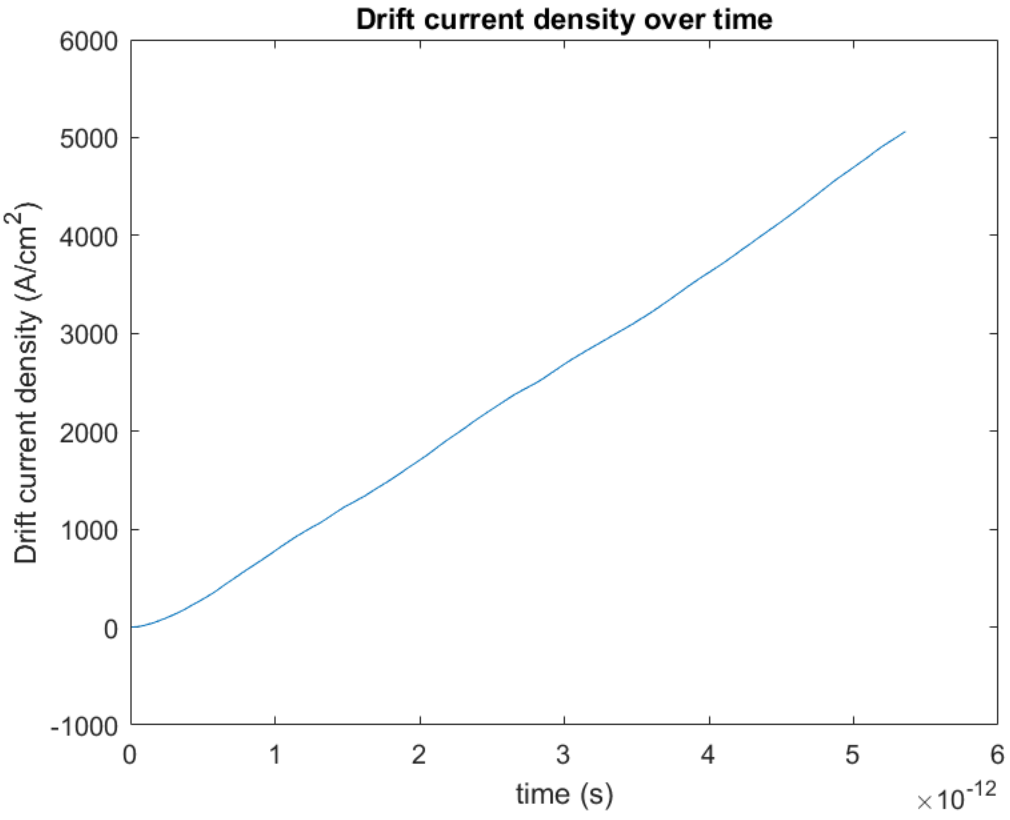


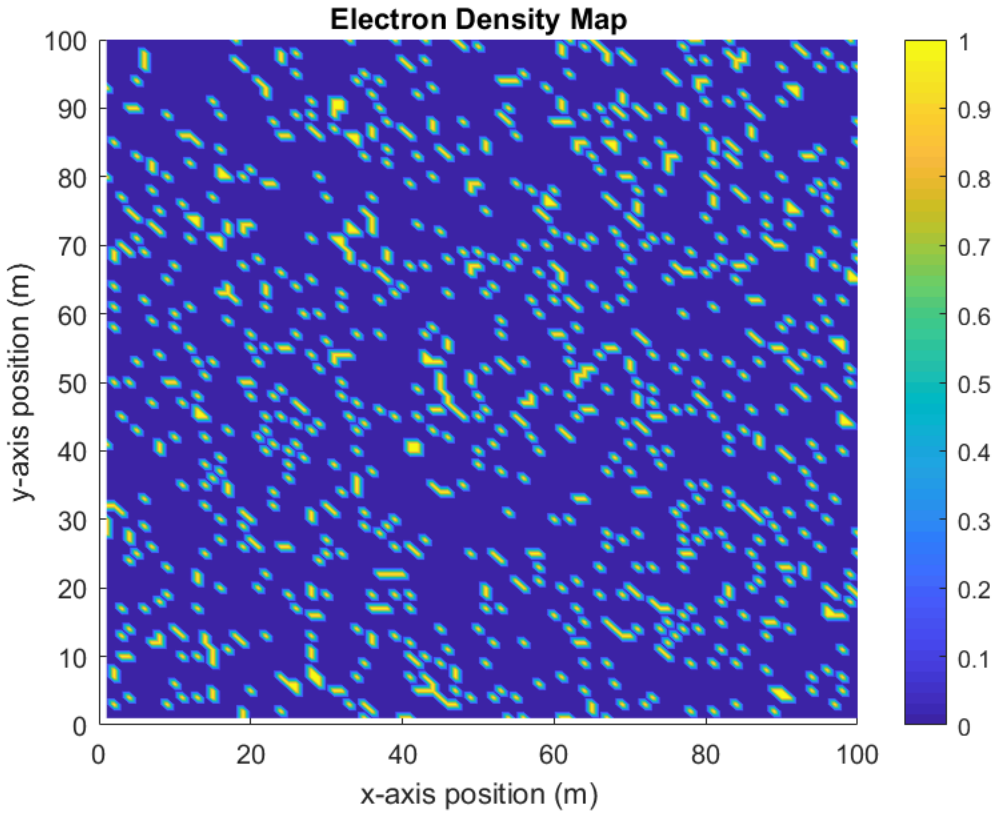
The plot above shows the plot trajectory of 7 electrons. It is clear that there is a curve on the path of the electrons caused by an electric field applied across the region.

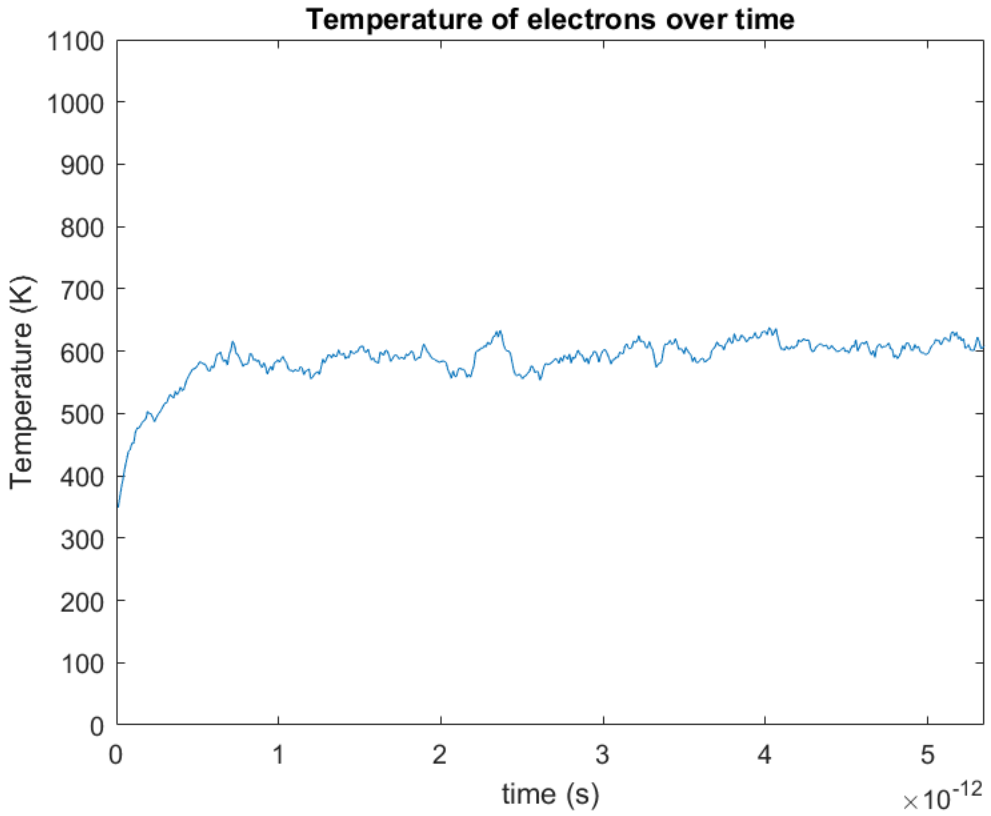
The plot trajectory shows that there is a curve on the path of the electrons due to the electric field applied across the region as expected.

Due to memory and timing concerns, the program was ran without the plotting of the trajectories in order to proprly display the temperature and dirft current density plots. 1000 electrons were used in the simulation and their results are shown below.


Drift Current Density Distribution
Counts
Drift current density (A/cm^2)
70
60
50
40
30
20
10
0
-1000
0
1000
2000
3000
4000
5000
6000


Drift current density over time
6000
5000
4000
3000
2000
1000
0
-1000
Drift current density (A/cm2)
0
1
2
3
4
5
6
time (s)
×10-12


Electron Density Map
y-axis position (m)
x-axis position (m)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



The plots for drift current density show that the initial current density is low which is expected because the initial velocity of the electrons is small and increases as the electic field accelerates the electrons. The histogram shows a relativly even distribution of the electrons which is due to the scattering which gives the electrons a new velocity, likely lower than the velocity they have been acceleratred to.

The electron density map shows an relativly even distribution of electrons thoughout the area which is expected as there are no restricing spacial factors within the region.

The temperature plot displays that the intial temperature of the electrons is lower and as they are accelerated and reach larger velocities, their temperature increases and somewhat saturates.

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