Modeling and Controlling Electron Movement in a Ballistic Deflection Transistor

Logan Toops

Webster Thomas High School

Webster, New York

Advisors: Roman Sobolewski, Yunus Akbas

Laboratory for Laser Energetics

University of Rochester

Rochester, New York

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1. Abstract

In the ideal Ballistic Deflection Transistor (BDT), electrons bounce off the walls of the transistor in a ballistic fashion, like bullets, uninterrupted by a transport medium. The BDT, operating at terahertz frequencies, is expected to far surpass the conventional transistor in speed, while utilizing very little power and generating almost no heat. Unlike the conventional transistor, where computing is achieved by starting and stopping the flow of electrons, the BDT uses inertia and an applied voltage on its walls to control the output voltages by directing electrons to their proper pathways. The MATLAB program, MEME (Modeling and Etching the Movement of Electrons), was created to simulate the motion of electrons in the ideal BDT when different voltages are applied to the walls. After the user inputs values such as channel width, number of electrons, and voltage applied to the walls into a Graphical User Interface (GUI), the program calculates the electrons' trajectories and outputs the number of electrons that entered each drain (Left, Right, North, or South). MEME can also simulate the electrons bouncing in the BDT for visual purposes.

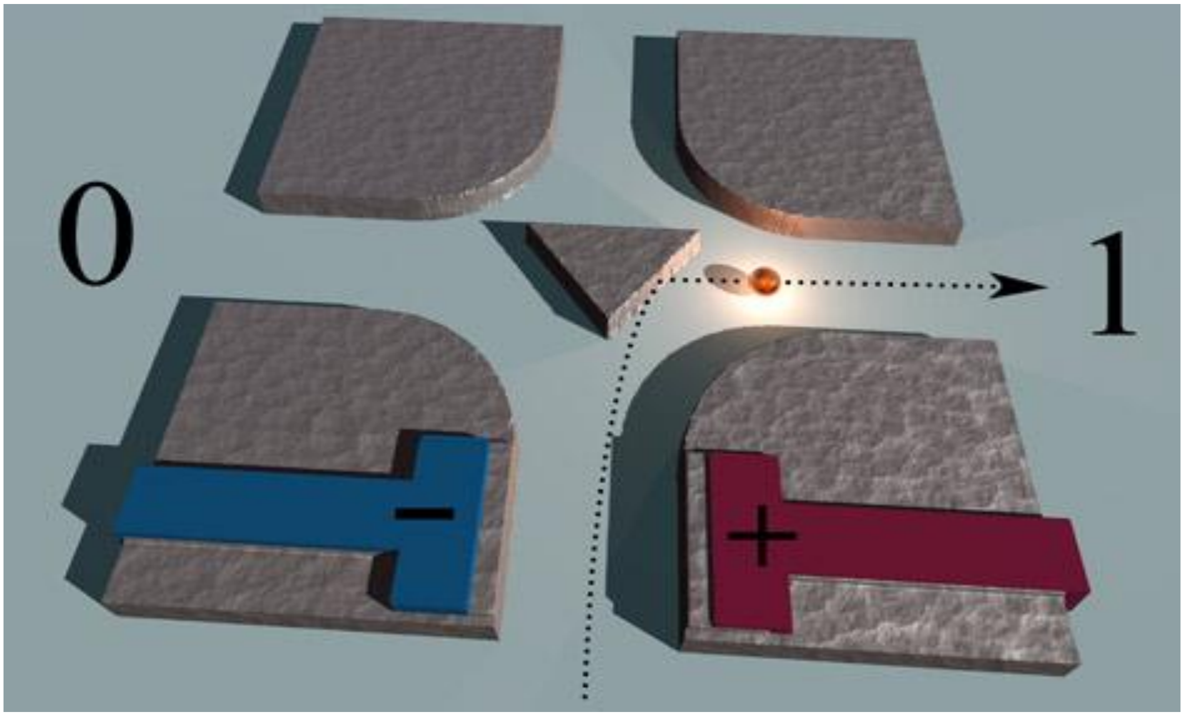


Figure 1: Simple depiction of a Ballistic Deflection Transistor

2. Introduction

Transistors are the basis of all modern day electronics. By starting and stopping the flow of electrons, transistors are able to output a 1 for the “on” state and a 0 for the “off” state. Transistors can be manufactured in the nano-scale, allowing billions of them to be placed on microchips. Computers operate by using the transistors on these microchips to complete many simple Boolean calculations with the 0 and 1 binary states. Because of the vast amount of transistors on these microchips, computers can complete very complex calculations by piecing together billions of simple calculations. Modern day transistors are made out of a semiconducting material (most often silicon) and operate at gigahertz frequencies. Despite their high reliability and small size, a fundamental flaw of modern day transistors is their inefficient use of energy, which is lost in the form of heat.

A ballistic deflection transistor (BDT, Figure 1) [1, 2] is a new type of transistor that not only uses less power and reduces the energy lost in the form of heat, but also operates at terahertz frequencies. This means that this transistor is more than 1000 times faster than conventional transistors. Also, the BDT is much more resistant to electrical noise. The BDT achieves high speeds and efficiency due to the way it uses the inertia of electrons to bounce them like billiards, as opposed to conventional transistors, which use energy to forcibly start and stop the flow of electrons. Electrons in the BDT are attracted by an upwards voltage pull as shown in Figure 1. Their trajectories are then altered by an electrical field, which is applied in the horizontal direction by the red and blue gates in Figure 1 and increases in strength as the electrons travel closer to the gates. A triangular reflector is also present in the middle of the BDT to help guide the electrons to their appropriate destination. In order for this transistor to output a 1 for the “on” state and a 0 for the “off” state, the electrons will have to enter the right drain and left drain, respectively. There are also very small chances that electrons might enter the north drain or even the south drain; however, those electrons are simply ignored (transistor loss).

In an ideal BDT, there are no scattering points in the transport medium that randomly change the electrons’ trajectories. In a realistic BDT, scattering points exist due to the atoms of the semiconductor material. However, due the extremely small size of the BDT, scattering has relatively little effect since the mean free path of the electrons is still greater than the size of the BDT. A program called MEME (Modeling and Etching the Movement of Electrons) was created in MATLAB to model the electron trajectories in an ideal BDT and record which drain each electron passes through, ultimately aiding future researchers to test new configurations on the BDT.

3. MEME

The program MEME consists of the MATLAB files named **draw**, **geometry**, **calculate**, **plot_e**, **many_electrons**, and **random_electron**. The **draw** file allows the user to enter the starting and ending coordinates for the lines representing the BDT to be drawn. The **geometry** file uses these coordinates to plot the outline of the BDT on a grid. Solid lines are used to mark the walls and triangular reflector; dotted lines are used to mark the electric field that alters the electrons' trajectories. After the **geometry** file draws the BDT model, the **calculate** file calculates the x and y coordinates that an electron will travel in the BDT. The **calculate** file accepts the initial angle of the electron, the starting x and y coordinates of the electron, the charges placed on the gates of Figure 1, and the initial channel wall width as parameters. The **plot_e** file plots one electron on the grid, **many_electrons** plots many electrons on the grid, and **random_electron** plots an electron with a random starting point near the south drain at a random launch angle between 45 and 135 degrees relative to the horizontal axis.

4. MEME Graphical User Interface (GUI)

A GUI was created to allow for easier interaction with MEME.

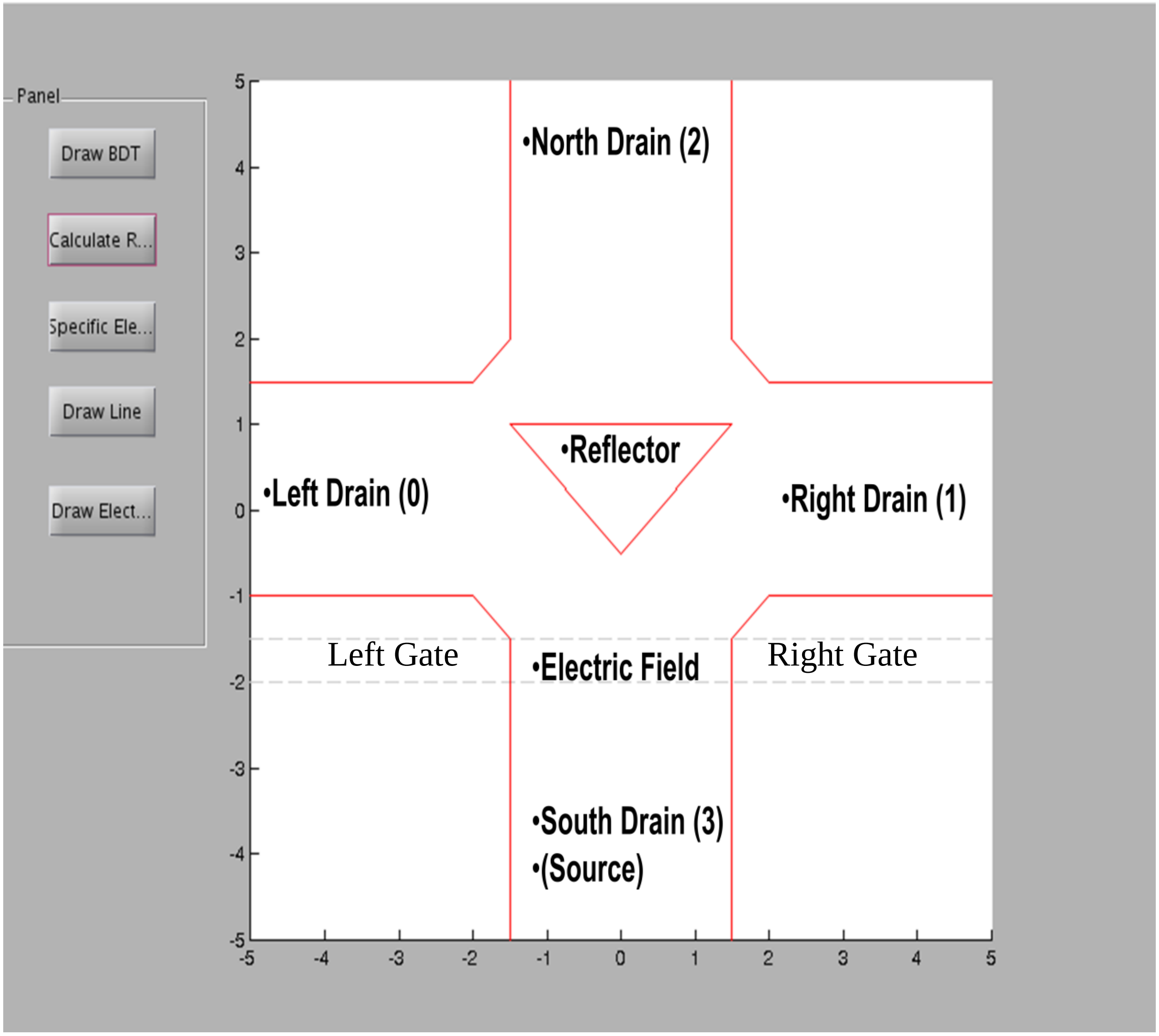
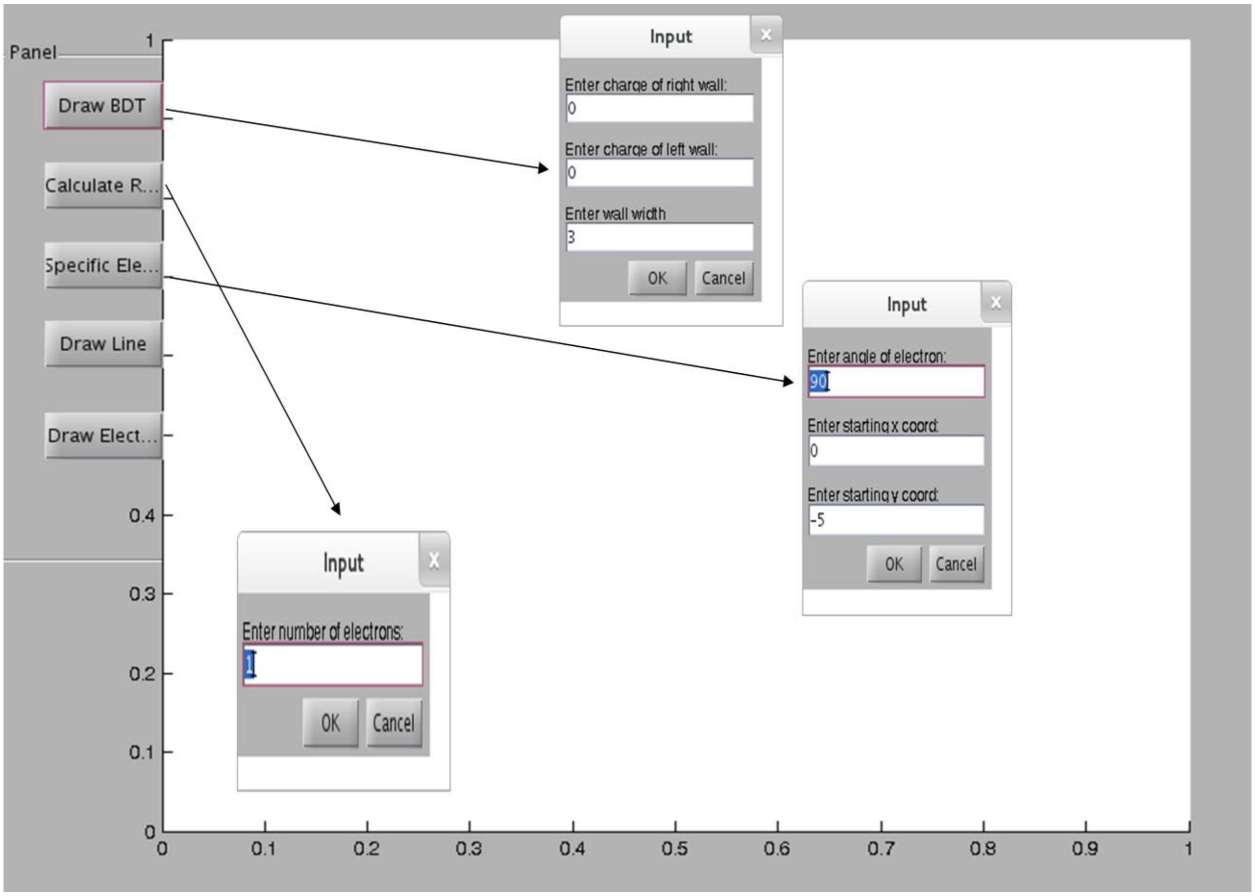


Figure 2: MEME GUI with BDT labeled (each interval represents 150 nm for the x and y axes)

The MEME GUI (Figure 3) draws a model of the BDT when the user hits the Draw BDT button. The solid red lines represent the walls of the BDT. The light gray dotted lines represent the electric field that alters the trajectory of the electrons only when they are between the two dotted lines. Electrons are launched from the bottom, known as the source. They are then pulled upwards by a voltage as they travel through the BDT. The number representing the drain that each electron travels through is recorded and then outputted after the electron trajectories are calculated.



Enter charge of right wall: 0
Enter charge of left wall: 0
Enter wall width 3

Enter angle of electron: 90
Enter starting x coord: 0
Enter starting y coord: -5

Enter number of electrons: 1

Figure 3: Popup Dialogue Boxes of the GUI

The *Draw BDT*, *Calculate R*, and *Specific Ele* buttons generate popup dialogue boxes (Figure 3) when clicked. These boxes accept the necessary parameters that the files require in order to function. The *Draw BDT* button requires the charge of the right and left walls of the electric field and the source channel wall width to be entered. The *Calculate R* button requires the user to enter the number of randomly launched electrons to be calculated. The *Specific Ele* button requires the starting x and y coordinates as well as the launch angle of the electron. Large tests of random electrons can be run over night with the *Calculate R* button, while specific tests can be launched individually with the *Specific Ele* button.

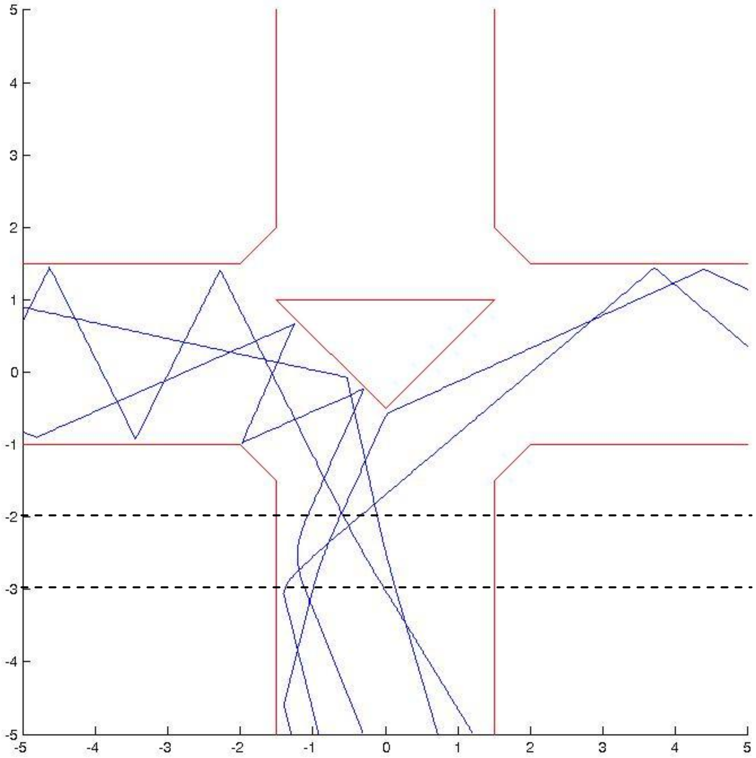


Figure 4: 5 random electrons launched with the Draw Line button (each interval represents 150 nm for the x and y axes)

Figure 4 shows a BDT that was drawn with a channel width of 3 (450 nm), a -2 charge on the left wall, and a +2 charge on the right wall using the *Draw BDT* button. The default upwards voltage was defaulted at 5. Then, 5 electrons were launched at a constant velocity of 350 nm/s and at random angles between 45 and 135 degrees using the *Calculate R* button. The *Draw Line* button was then clicked to draw blue lines representing the path that each electron would take. The *Draw Elect* button can be clicked to animate small blue circles representing electrons bouncing in the BDT. Some of the blue electron trajectories do not exactly make contact with the walls because the electron trajectories were calculated in finite steps. Bounces were calculated when an electron was detected within a certain distance of a wall. This was done to ensure that the electrons did not skip over a wall during an iteration and tunnel through the BDT. Thus, some electrons might bounce a little before the wall, but none actually go through.

5. Sample Experiment

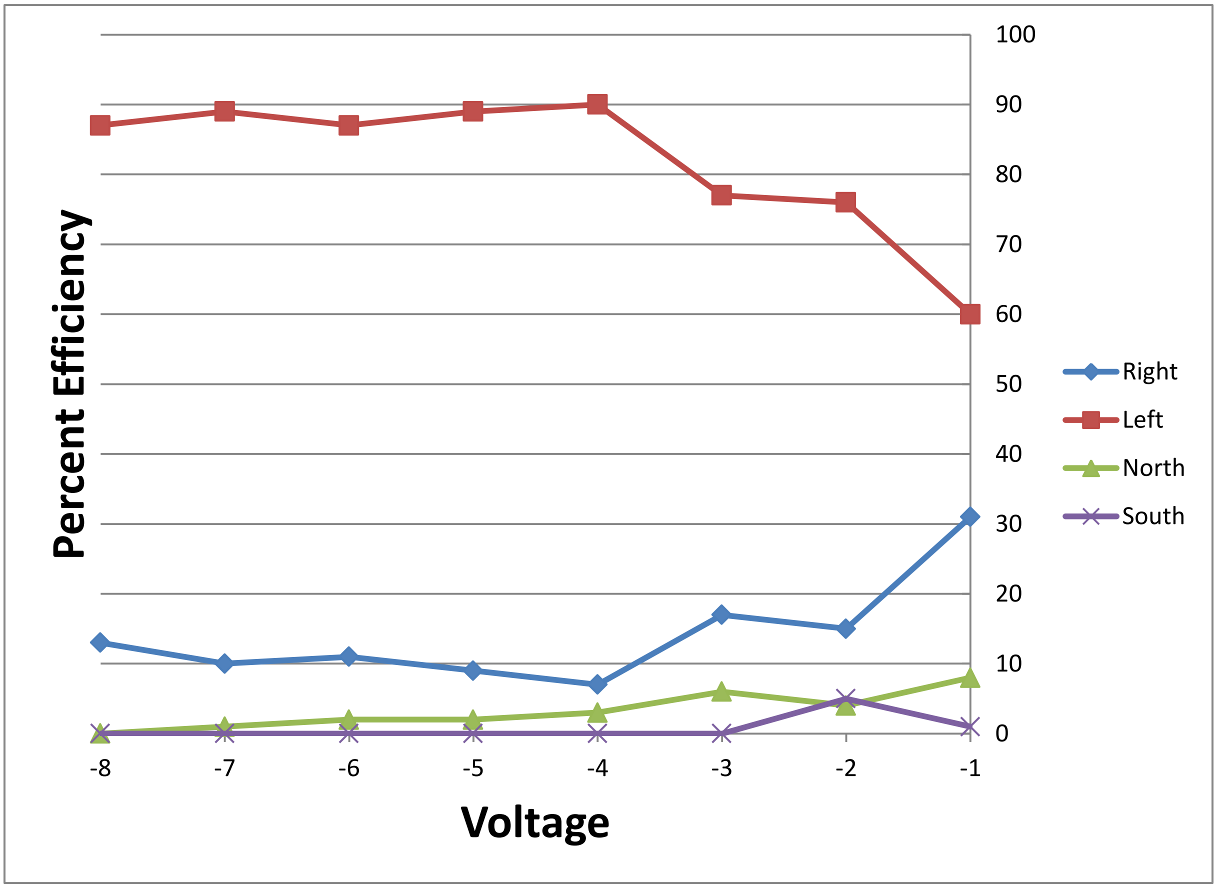


Figure 5: Percentages of electrons leaving through the right, left, north and south drains as a function of the voltage difference between the right and left gates. Samples of 100 electrons were launched in the same manner as Figure 4 with a negative voltage applied on the right gate and a positive voltage on the left gate (a voltage of -8 means that -4 volts

were applied to the right gate and +4 volts were applied on the left gate to shift the electrons to the left)

Figure 5 shows results from a sample experiment that was done to find the voltage that would produce the greatest efficiency, defined as the percentage of the electrons launched that entered the drain in the direction of the applied voltage. In Figure 5, negative voltages are applied to shift the electrons' trajectories to the left, so the efficiency is the percentage of electrons that enter the left drain (0). According to Figure 5, starting from the left, the efficiency remains relatively high until the voltage reaches -4. The efficiency then decreases because the voltage is not strong enough to shift enough of the electrons' trajectories to the designated drain.

6. Conclusion

The BDT holds many advantages over the conventional transistor. By using the electrons' inertia to bounce them through the BDT, the BDT is able to operate at terahertz frequencies and generate much less heat than the conventional transistor. The MATLAB program MEME was written to model electrons bouncing in the BDT and allow a user to change the shape of the BDT, gate size, and electric field strength as necessary. MEME will help future researchers working on the BDT to run experiments to determine what effects new configurations will have on the BDT's performance.

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8. References

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