Drift-to-Ballistic Electron Transport for Operation of Ballistic Deflection Transistors

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December 2013

Abstract

The program *ETCHD (*Electron Trajectory & CHannel Deflection) was created in MATLAB to simulate electron motion, drift or ballistic, through a ballistic deflection transistor (BDT) or conducting nanochannel of any shape. Each electron's velocity is continuously monitored and changed in *ETCHD* simulations. By calculating the angle of incidence between the transistor's walls and the electron's velocity, new electron velocities are output for ballistic collisions. Electron drift is modeled by creating a nearly uniform field of scatter points. Electric fields are also applied to the motion of electrons. Simulations were run to measure electron velocities and directions with varied electric fields and scatter densities. It was found that the BDT efficiency increases dramatically as electron motion changes from drift to ballistic. A working BDT is unrealistic with a scatter density that is very high, such as 0.1 pts/nm^2. Increasing the gate width to strengthen the lateral electric field increases electron lateral displacement in the ideal BDT. However, it has a negligible effect with scatter densities that are too high. These *ETCHD* results provided valuable information about the feasibility of a real, working BDT.

Introduction

A key function of transistors in contemporary electronics is to act as a switch, producing outputs of "one" or "zero" by turning on or off, respectively. Conventional field-effect transistors work by amplifying electrical inputs and moving electrons on and off a capacitor. When electrons collect on the capacitor, the memory bit element of the transistor registers as "on" and produces a "one." When the electrons are removed, it registers as "off" and produces a "zero." The memory capacitor must be repeatedly filled and emptied, starting and stopping the flow of electrons, so the speed of the transistor is limited [1]. Emptying the capacitor also produces large quantities of heat, allowing electrical "leaks" to form in the transistor's ultra-thin walls. The drawbacks of conventional transistors are amplified as transistors are scaled down, and they will eventually prevent further progress. The ballistic deflection transistor (BDT) aims to alleviate these drawbacks by discarding the capacitor in favor of a ballistic design, bouncing individual electrons off deflectors to different directions [2].

A simplified BDT schematic is shown in Figure 1. Electrons move in uninterrupted pathways and, due to their inertia, bounce off the walls of the transistor. The BDT also produces "one"s and "zero"s, but does so by changing the direction of electrical current instead of starting and stopping it.

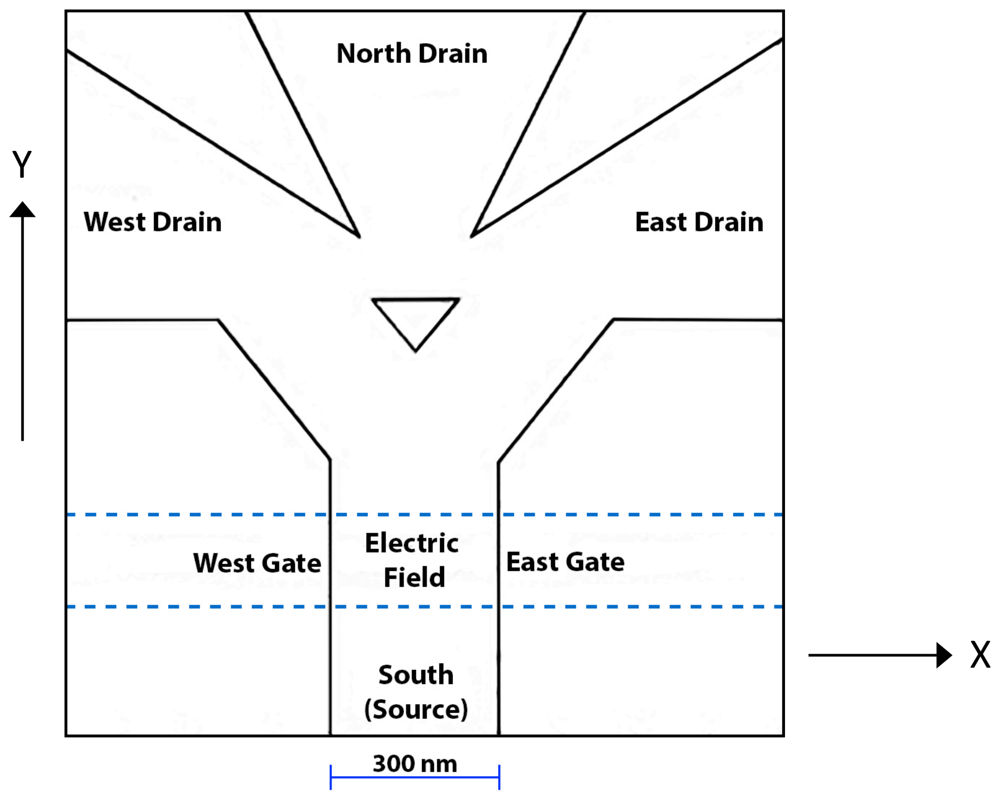

Figure 1*: Schematic of a ballistic deflection transistor generated by the program* ETCHD.

From the "South" end of the BDT called the source, electrons enter the transistor. As they move upwards under the action of an electric field applied in the vertical direction (not shown), they pass through an electrical field between the East and West gates that pushes them east or west depending on the charge applied. The electrons then bounce off a central triangular platform to the desired direction. If the electrons bounce "East" and exit in the east drain, the BDT will produce an output of "zero". If the electrons bounce "West" and exit through the west drain, the BDT will produce an output of "one".

If manufactured correctly, the BDT will have numerous advantages over conventional transistors. Because electrons move ballistically via inertia, the BDT uses less energy [3]. Their ballistic motion also reduces electrical noise generated by the random thermal movement of electrons, producing less heat [3]. Because less heat is produced, BDTs do not have problems with electrical "leakage" as do conventional transistors [2, 3]. The BDT runs at speeds measured as high as terahertz frequencies [1], a thousand times faster than conventional transistors, because it does not stop and start the flow of electrons.

BDTs can be manufactured using current nanoscale fabrication technologies and existing materials. The conducting medium of the transistor is typically a two-dimensional electron gas (2DEG), instead of the silicon present in conventional transistors. A 2DEG is a gas composed of electrons that is very thin in a third dimension and thus appears as nearly two-dimensional. When electrons move in 2DEGs, their paths are nearly uninterrupted and thus ballistic. However, the manufacturing process is not perfect, which can result in an imperfect conducting medium. When electrons hit imperfections in the BDT, they scatter randomly, leading to electron drift. Electron drift hinders the performance of BDTs.

BDTs are highly adjustable, from their basic shape to the size and location of the applied electric field. These varying aspects have not yet been tested, so the optimal configuration has not yet been recognized. In this project, a program titled Electron Transport and CHannel Deflection (*ETCHD*) was created to realistically simulate electrons traveling through a BDT. The program can simulate electron movement whether the motion is drift or ballistic, and the user is able to define the amount that electrons drift. *ETCHD* has been used to determine the degree to which electrons must be ballistic, as opposed to drift, for a BDT to function effectively. *ETCHD* results also provide valuable information about the feasibility of the BDT in varying sizes and strengths depending on the prevalence of electron drift. As electron motion is changed from drift to ballistic, electrons behave differently inside the BDT and require different transistor configurations for optimization.

Electron motion

When traveling through conducting media, electrons hit impurities that interrupt their pathways. The average path length that an electron moves through a material between collisions is called its mean-free path (ℓ). ℓ is dependent on a variety of factors. First and foremost is the medium in which the electrons are moving [4]. Depending on the atomic packing and density of the medium, electrons can have longer or shorter ℓs. The next important factor that affects ℓ is the temperature of the medium [4]: when the medium is hot, atoms vibrate with more energy and thus electrons more frequently hit imperfections, shortening ℓ. In some cases, ℓ is dependent on the physical size of the conducting medium: if the conductor is relatively large, there is a high chance that the electron will scatter before traveling the full length of the conductor [3].

If the conductor is at nanoscale, it is possible that the electron will hit the edges of the medium before travelling the complete length of ℓ. In such an ideal BDT, electrons are “ballistic”. These ballistic electrons move rapidly in relatively long, uninterrupted pathways, much like bullets. When electrons move ballistically through the BDT, the only time their trajectories change is when they collide with the transistors’ walls or are influenced by an electric field; they do not bounce in unpredictable manners, because they do not complete their ℓ before hitting a transistor wall [3]. Thus, in order for electrons to move ballistically, the BDT must be manufactured at nanoscale. If the BDT is too large, electrons will be able to travel their full ℓ before hitting the walls of the channel, and they will randomly scatter. Scattering in a conducting channel is illustrated in Figure 2. On a scale larger than nanoscale, electron motion is determined predominantly by scattering in a Brownian manner.

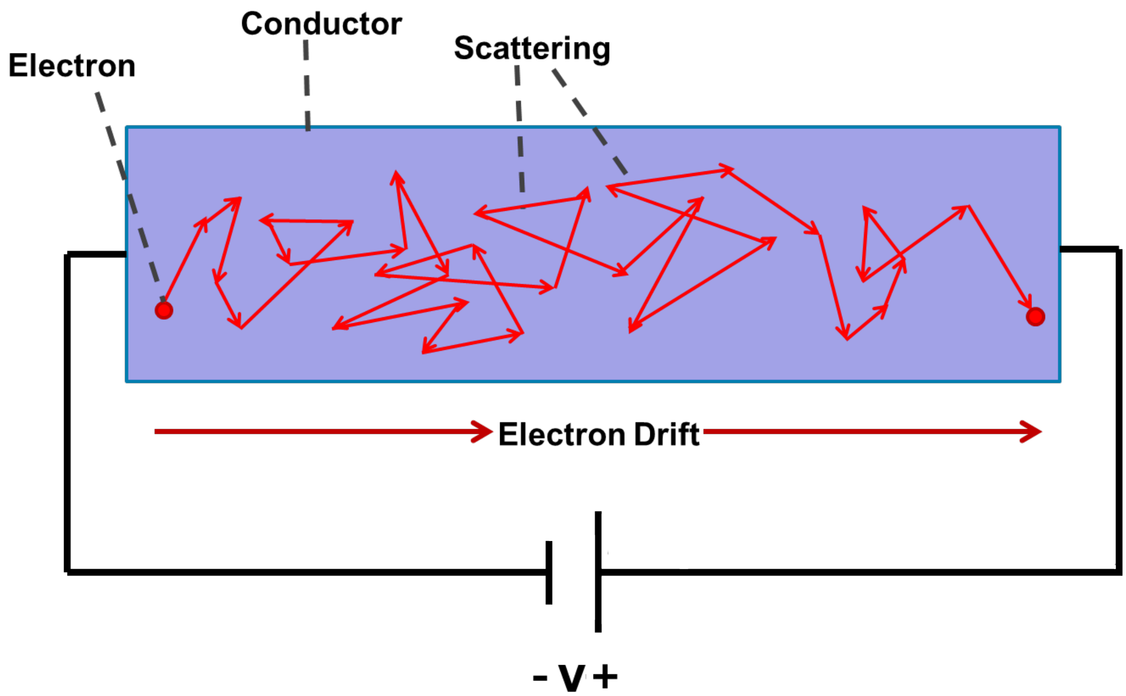

Figure 2: *Path of an electron in a conducting channel. The electron is pulled in a net direction because of an applied voltage but scatters through collisions in the conducting medium.*

Even though electrons bounce randomly, they are still impacted by electric and magnetic fields. When a voltage is applied to a conducting medium in which electrons are scattering, the electrons are affected by the field in between scatters as they travel ℓ. Because of this, even though the electrons bounce randomly, as a whole they move more in the direction that the field is pulling them. This motion is known as electron drift.

Both electron drift and ballistic electron motion can be used to move electrons in one direction. When electrons are drifting, many electrons all drift in one direction as a cloud at low velocities. This happens at a large scale. When electrons are ballistic, they move in one direction individually, bouncing at high velocities. This happens at a very small scale.

Program *ETCHD*

The program *ETCHD* was coded in MATLAB. It is consists of three main components which work in sequence to produce a visual display of electrons moving through a BDT as well as a collection of the results for each electron. These three components are entitled *Geometry*, *Calculate*, and *Plot_e*.

Geometry allows the user to define the precise, coordinate-based geometry of the BDT. The function takes in parameters that allow the user to define the shape of the BDT, the scatter point field, and electric field. Vectors are provided that contain the start points and endpoints of each transistor wall in the BDT's shape. *Geometry* uses these coordinates to output a list of equations that define the walls of the transistor (the shape). This data is carried onto the next file, *Calculate*. *Geometry* also draws out each line on-screen to create a visual setup of the BDT, as shown in Figure 1. Other parameters draw scatter points and dotted lines to visually represent nonuniformities and the applied electric field.

Calculate is an extensive iterative and algorithm-based file that uses the linear, piecewise equations outputted from *Geometry* to determine an electron's trajectory through the BDT. Every physical property of the transistor and the electron is programmed in *Calculate*. The coordinates of the electron's path are generated entirely by this file. Four numbers determine each electron's existence: its x-coordinate, y-coordinate, x-velocity component, and y-velocity component. The coordinates represent the electron's location in the BDT, and the velocity components represent the direction that the electron is travelling. In all *ETCHD* simulations in the BDT, the electrons enter the source channel with a random x-coordinate, a fixed positive velocity magnitude, and a random direction between 0 and 180°. In all nanochannel simulations, the electrons enter the source channel centered and travelling due north. Unaltered, each electron would continue in a straight line forever with constant velocity. However, a number of factors within the channel can alter the electron's velocity and, consequently, its trajectory. If an electron hits a channel wall, encounters an electric field, or scatters due to nonuniformities its velocity must change. *Calculate* functions by checking continuously whether the electron is encountering any of these events and by changing its position and velocity appropriately.

The first factor that frequently modifies an electron's trajectory is a collision with a channel wall (Figure 4). *ETCHD* assumes that collisions are elastic, which means that the angle of incidence between an electron and a wall is the same as the angle of reflection and that the electron loses no energy in the collision; thus, the magnitude of its velocity remains the same. Because the electron's final direction is dependent entirely on angular geometry, *ETCHD* considers every possible orientation.

β: Angle of the wall relative to the +x axis

θ_A: Angle of electron before collision relative to +x axis

θ_C: Angle of the electron relative to the wall

θ_D: Angle of the electron after collision relative to +x axis

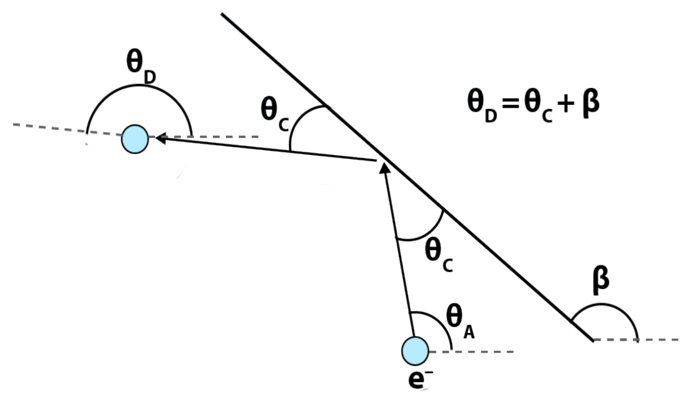

Figure 4*: The geometry and important angles in an electron-wall collision. The wall is represented by the thick black line positioned* β *away from the horizontal. The light blue circle represents the electron.*

For each case, θ_D is calculated from the other three angles according to the geometry. *Calculate* continuously monitors whether an electron is hitting a wall and determines which case it is by identifying the angle of the wall and the incoming electron. In order to determine which wall the electron will hit, *Calculate* references the equations matrix generated in *Geometry* to identify the nearest wall's β angle and start and end coordinates.

The next factor that modifies the position and velocity of electrons is the presence of electric fields in the BDT. Because the transistor works on the basis of a central voltage pull upwards, the electron is always being affected by an electric field in the y-direction of Figure 1.

Additionally, as the electron enters the region between the East and West gates, the applied electric field of the transistor pulls the electron towards one side by changing the x-velocity.

Lastly, the electron's trajectory can be changed by colliding with a scatter point. *ETCHD* continuously detects whether the electron is colliding with any of the thousands of scatter points that may be simulated at any moment. A collision is defined as a distance of less than or equal to 1 nm between the electron and scatter point. When the electron does scatter, it is randomly assigned a new velocity of the same magnitude but with a new direction between 0 and 180° (this is an approximation to the true unpredictable behavior).

ETCHD's *Calculate* file must monitor each of these factors every time it moves the electron. Upon completion, it outputs a list of 1000 coordinate points in sequence that track the electron's trajectory through the transistor. The program takes different amounts of time depending on the simulation. For example, running three tests of 100 electrons through the nanochannel at 10 different scatter point densities (3000 electrons total) took about 30 seconds. Animating more than 100 electrons at once caused MATLAB to lag or freeze, so the algorithm should be optimized for any future testing to improve performance.

The third and last major component of *ETCHD* is *Plot_e*, which serves the purpose of visually displaying the results of *Calculate* for quick, qualitative results. It is able to draw a line tracing the electron's trajectory or animate a (much enlarged) image of an electron moving through the transistor. *Plot_e* also serves as a log-file creator. It tracks the number of electrons that are outputted in each drain of the BDT as well as each electron's average velocity. It can combine data from thousands of electrons into a cumulative data set. The end result of these three comprehensive files is an easy-to-use system to track any electron moving through any BDT. The user may enter a BDT's shape, calculate the trajectories of any number of electrons moving through it, then plot the calculated coordinates and observe the results.

ETCHD Simulations

ETCHD has been used to carry out a variety of simulations. *Geometry* has been used to set up both a nanochannel (two walls) and the entire BDT (the thirteen walls of Fig. 1). Four main types of simulations were run in a nanochannel whose width was 1300 nm and length 2200 nm. An electric field was applied to the nanochannel near the source to deflect electrons towards the East or West drains. The first simulation (Fig. 5) allowed electrons to flow through the nanochannel without interruption, moving ballistically. In a nanochannel, the lateral displacement seen in Figure 5 can serve as an indicator of how easy it is to physically move an electron in the BDT.

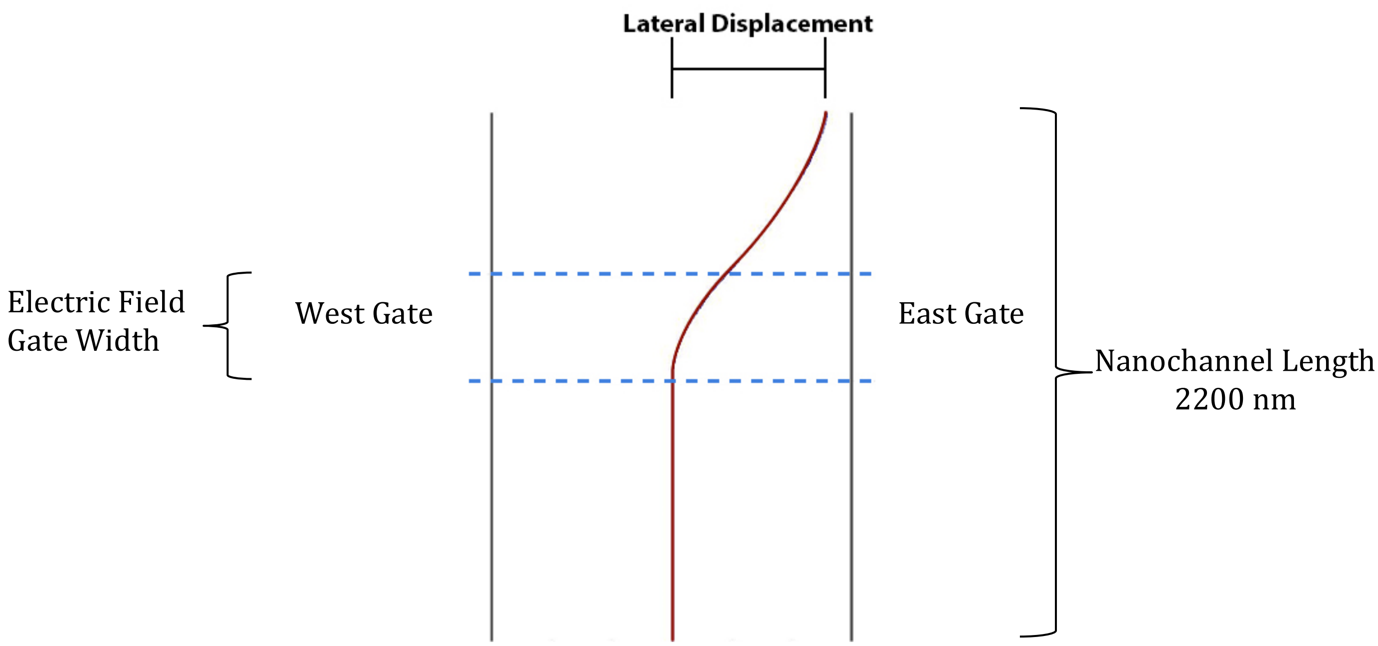

***Figure 5**: An electron's path through a nanochannel traced with a solid line. It enters from the South, moves upward through the channel, and is laterally displaced some amount East by an electric field within the East and West gates. There is also a uniform electric field in the vertical direction.*

The goal was to determine the relationship between the physical extent of the electric field and the lateral electron displacement. Theoretically, the larger the width of the electric field, the farther each electron should be displaced as it moves through the source channel. Since there were no scatter points in the conducting medium for the first simulation, the electrons' lateral displacements were undisturbed by scattering. The width of the electric field in the simulation was increased from 0 nm to 800 nm to 1540 nm while the MATLAB file *Plot_e* recorded the lateral displacement, in nanometers, of each electron that was sent through the nanochannel. This simulation was repeated for five different applied voltages (1-5 V). The corresponding applied electric field was 3.3×10^6 to 1.7×10^7 V/m. As seen in Figure 6, as the electric field's gate width increased, the lateral displacement of an electron moving through the nanochannel increased. The stronger the applied voltage, the larger the displacement of the electron for a given gate width.

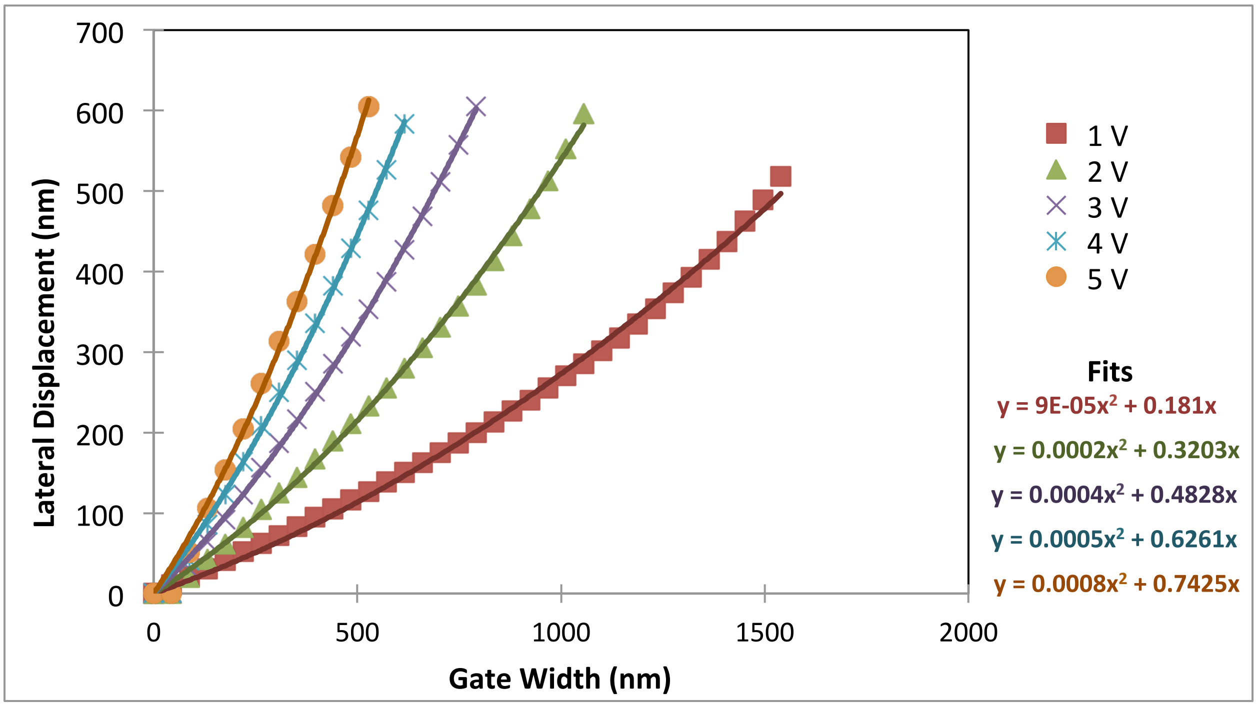

Figure 6: *Electron displacement as a function of gate width for several applied lateral voltages. Lateral voltages push West to East, and a central voltage of 1 V pushes North.*

A second simulation conducted in a nanochannel measured lateral displacement as in the first simulation but included the possibility of electron scattering. In this second simulation, electrons were sent through the nanochannel with varying electric field gate widths from 0 to 1540 nm, with varying voltages from 1 to 10 V, *and* with an applied scatter point density of 0.05

pts/nm^2. The magnitude of the electric field remained in the range between 3.3×10^6 and 1.7×10^7 V/m. Figure 7 displays these results.

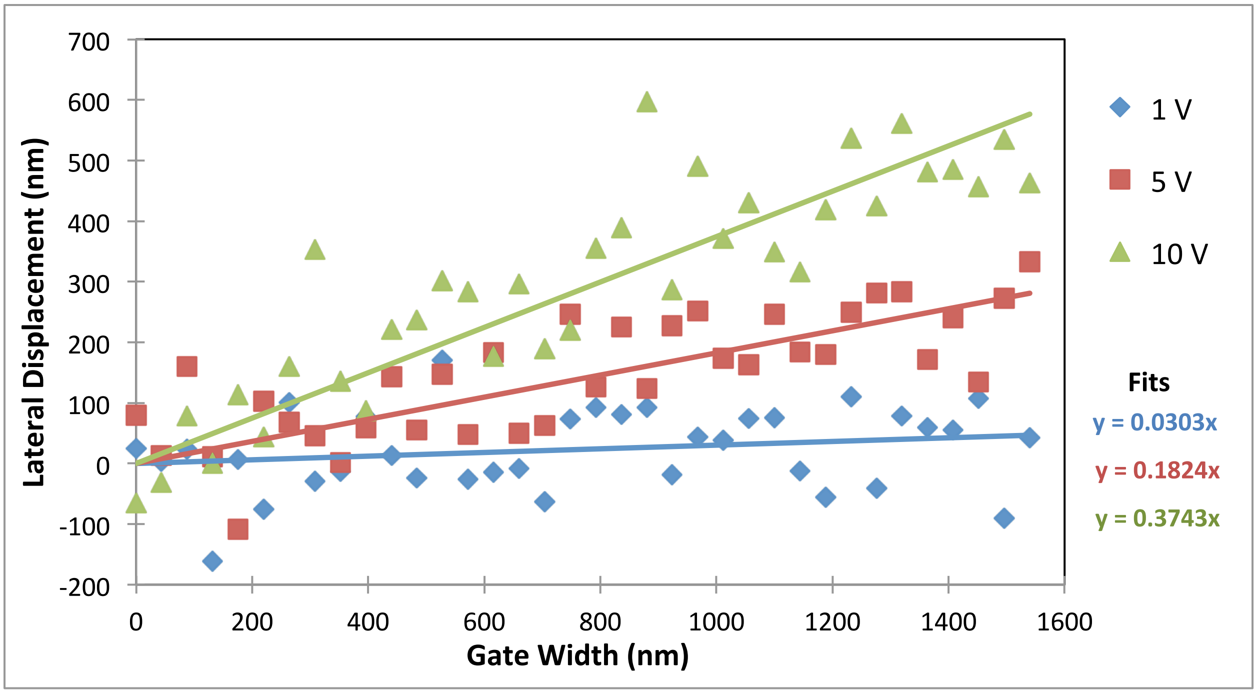

Figure 7: *Lateral displacement as a function of gate width for varying lateral voltages with a scatter density of .05 pts/nm^2. Lateral voltages push West to East, and a central voltage of 1V pushes North. Straight line fits for each voltage are shown in corresponding colors.*

As in the previous simulation, as gate width increases, so does lateral displacement. However, in this case a constantly increasing gate width leads to a constantly increasing lateral displacement. Because scatter points hinder an electron's displacement, it can also be seen that larger voltages are required to move an electron by the same amount as it moved while travelling ballistically. For instance, it takes a field width of approximately 1500 nm and a voltage of 10 V to move an electron just 500 nm laterally. In the previous experiment, it took a field width of 1500 nm and a voltage of only 1V to move an electron the same amount.

A third simulation examined the density of scatter points in the nanochannel's conducting medium. In this simulation, electrons were run through the nanochannel of width 1300 nm and *Plot_e* plotted each electron's lateral displacement (just as in the previous two experiments).

However, the electric gate width was fixed at 800 nm, while the scatter point density was raised from 0 pts/nm^2 to 0.1 pts/nm^2. Each scatter density was tested with voltages of 0 V through 10 V applied. The data for this simulation are recorded in Figure 8. This graph must be interpreted differently because there now exist negative lateral displacements, indicating that the electron was pushed West of normal. This is illustrated in Figure 9.

When the density is low, the electron is pushed so far East that it bounces against the wall of the nanochannel and is sent travelling West. When the density is high, the electron travels mostly in the vertical direction. The slight motion West in the case of no voltage between the gates is just the random result of scattering and is insignificant. That being said, Figure 8 clearly illustrates that higher scatter point densities approaching 0.1 pts/nm^2 stop the electron from being displaced laterally in either direction. At scatter densities higher than 0.1 pts/nm^2, the BDT would be ineffective, and the transistor would never register as "on" or "off." With a density this high, it is nearly impossible to control the direction of electrons moving through the transistor.

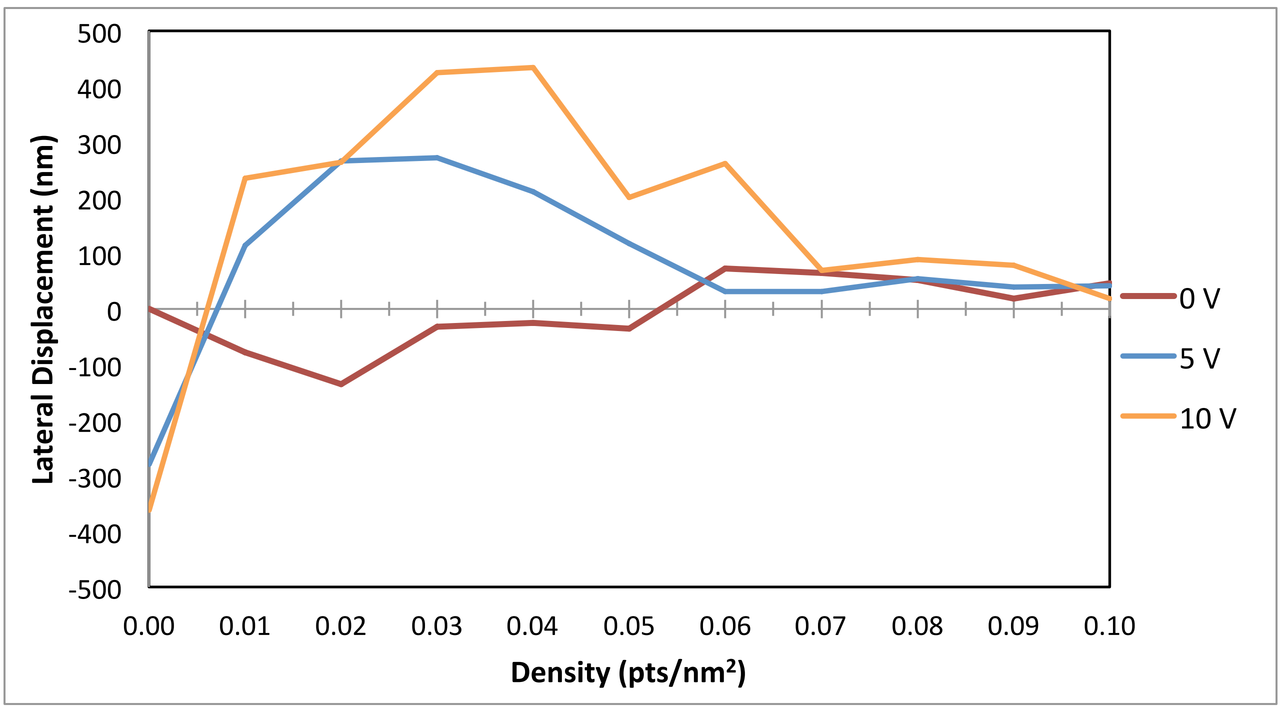

Figure 8*: Lateral displacement as a function of scatter point density for varied voltages and a fixed gate width of 800 nm. When density increases, electrons cannot be laterally displaced by an applied electric field.*

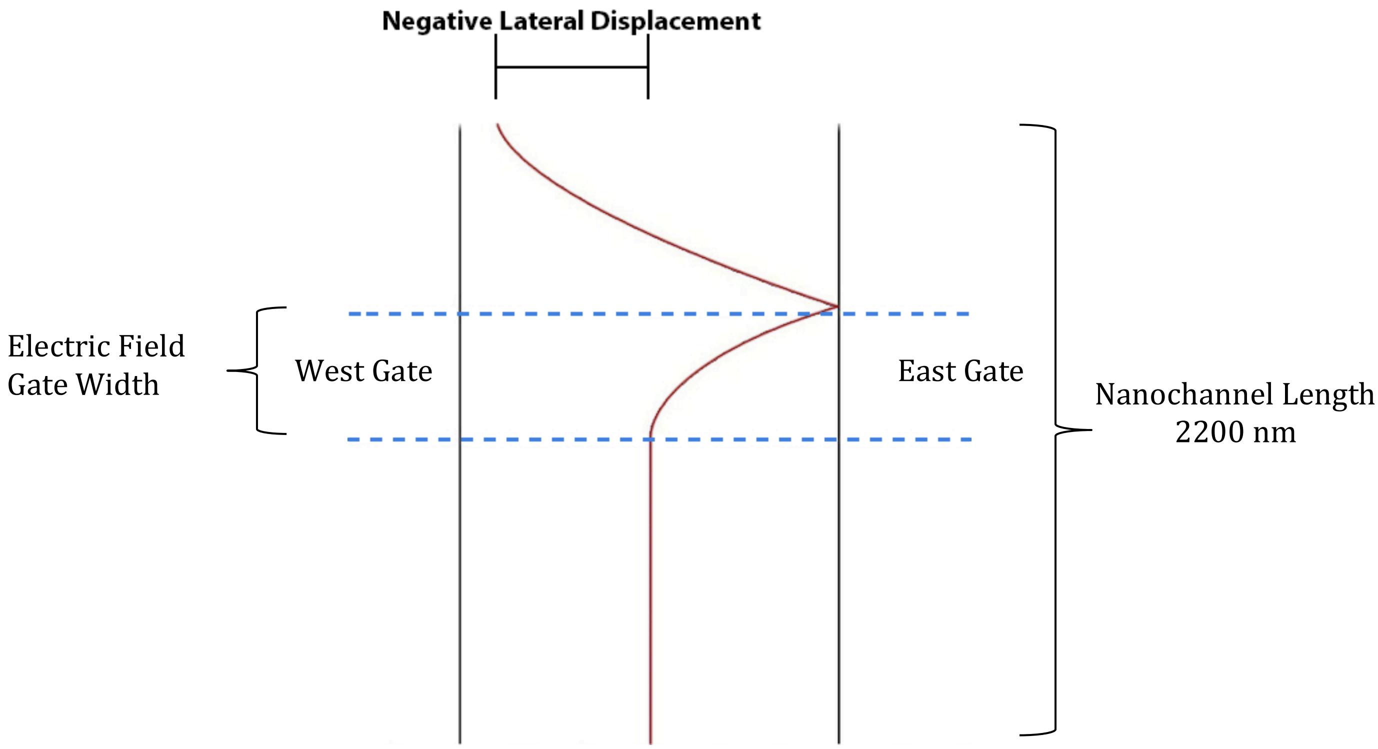

Figure 9*: An electron's path through a nanochannel traced with a solid line. It enters from the South, moves upward through the channel, and is laterally displaced by an electric field between the East and West gates. It is pulled enough that it collides with the channel wall and is displaced West of vertical (negative displacement).*

The last major simulation run in the nanochannel digresses from the study of electron lateral displacements and focuses on the velocity of the electron. When the scatter density becomes close to zero, the electron becomes more and more ballistic. Ballistic electrons move much faster than electrons that drift, due to fewer interruptions in velocity. *ETCHD* simulated the velocity of electrons in a nanochannel with the approximate true length of a BDT (2200 nm). In this simulation, electrons are sent through the nanochannel at densities from 0.1 to 0 pts/nm^2, simulating drift-to-ballistic transport. Results are shown in Figure 10.

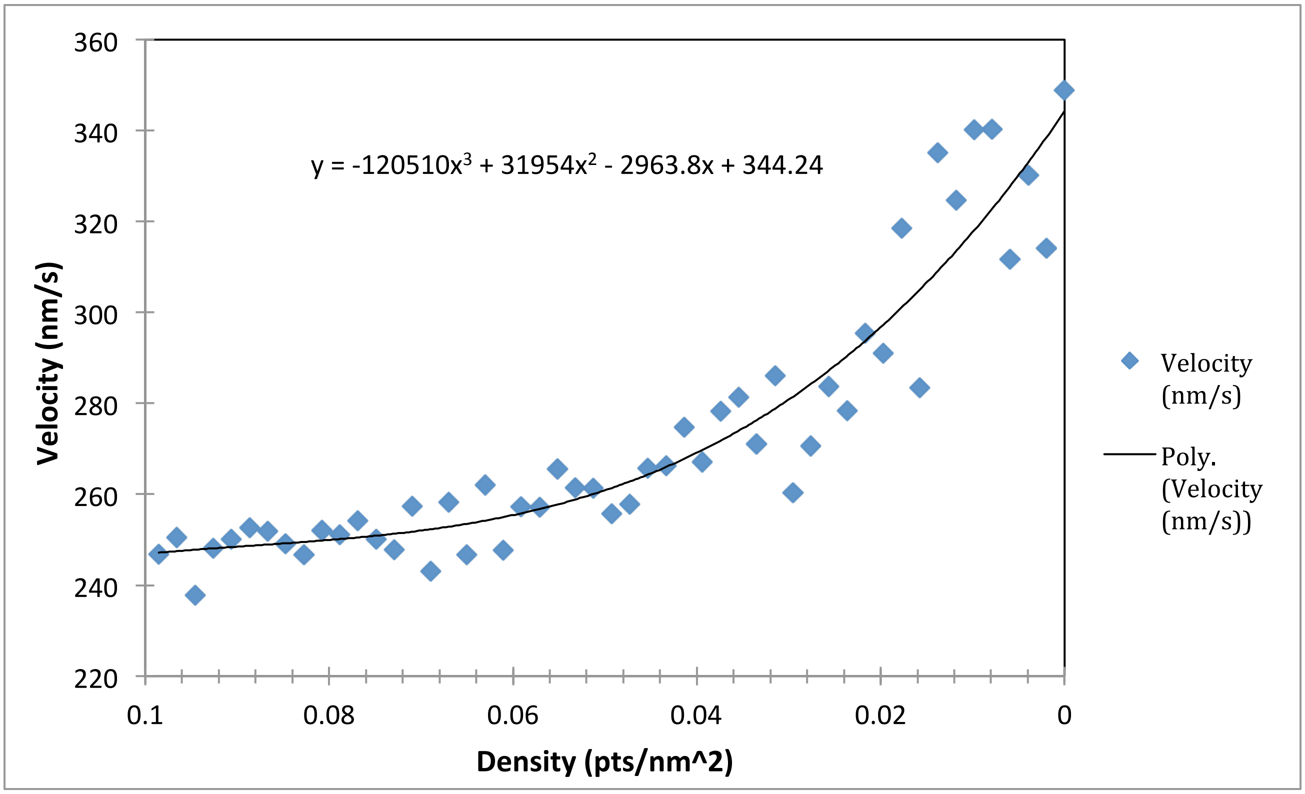

Figure 10*: Electron velocity at the end of the nanochannel as a function of scatter point density. Density is shown from high to low to illustrate the trend of a drifting electron becoming ballistic. A polynomial fit is shown with a black line to model the observed pattern; it does not extrapolate past the domain shown.*

From Figure 10 it can be seen that the fastest velocity for an electron at the end of the nanochannel is about 350 nm/s. Once the scatter density approaches 0.1 pts/nm^2, the electrons jitter and slowly move north. The velocity of the electrons in *ETCHD* plateaus with a high scatter point density. This is a phenomenon caused by the way *ETCHD* was coded. Because each scatter point actually affects a 1 nm radius surrounding it, the electrons are always scattering when the scatter point density is high. In a real BDT, the velocity of the electrons would be inversely proportional to the number of scatter points per unit area, thus the velocity graph would not plateau. Figure 10 serves as a proof of concept but not an accurate predictor of the velocity of electrons in a manufactured BDT. It illustrates that a BDT becomes unrealistic with scatter point densities that are too high. Electrons scatter and slow down, so they are unable to travel ballistically.

When considering the entire BDT of Fig. 1, the program *ETCHD* shows that an ideal BDT with no scatter points in the conducting medium is extremely efficient. This is seen in Figure 11, which shows the directional data of electrons that were pushed with varying voltages. A negative voltage indicates that there was a positive charge applied to the left wall of the BDT source channel and a negative charge applied to the right wall of the channel, causing the electron to be pushed West. A positive voltage indicates that there was a negative charge applied to the left wall and a positive charge applied to the right wall, pushing the electron to the East.

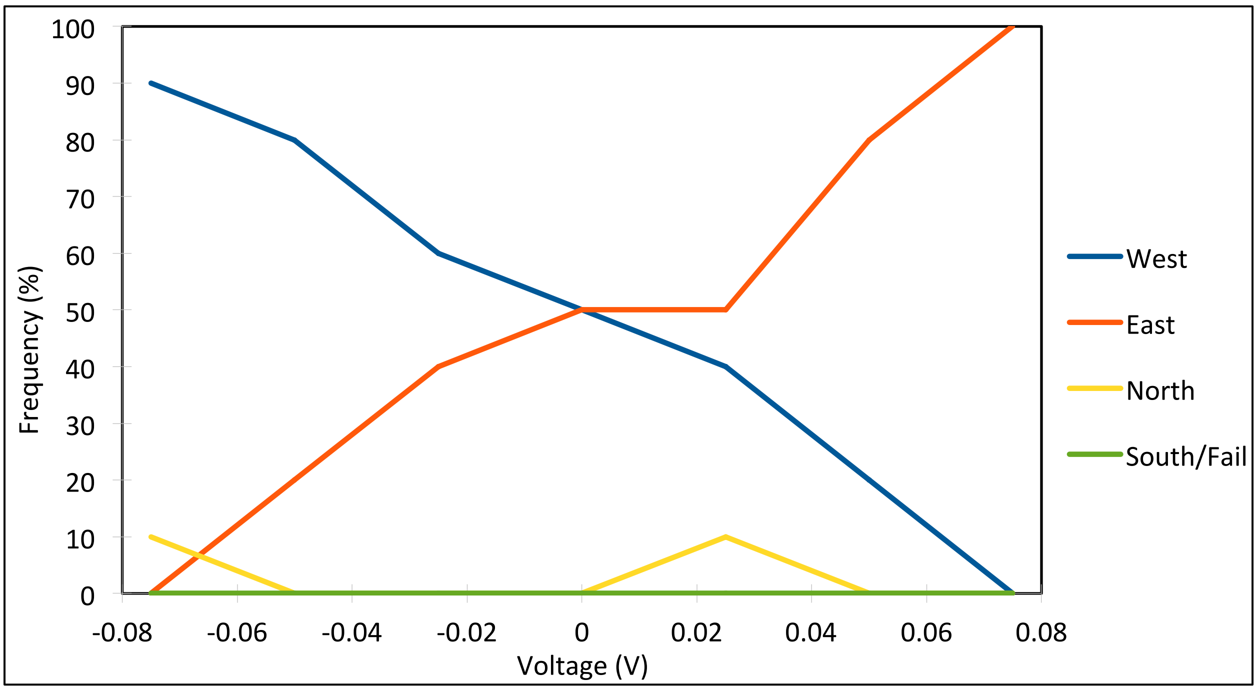

Figure 11: *Percentages of electrons exiting the four gates of the BDT with different applied lateral voltages, for the case of no scatter points. The gate width was 300 nm.*

It can be seen that, with positive voltages, electrons drain mostly in the East drain, which is the desired outcome as the electrons have been pushed east in the BDT source channel due to the applied electric field. Likewise, with negative voltages, a majority of electrons drain in the West drain after being pushed West. Furthermore, the larger the magnitude of the applied voltage, the greater percentage of electrons drain in the desired direction. Thus, an ideal BDT with completely ballistic electrons can be very efficient. The frequencies recorded in Fig. 11 are recorded from individual sample simulations; they are examples but they are not absolute.

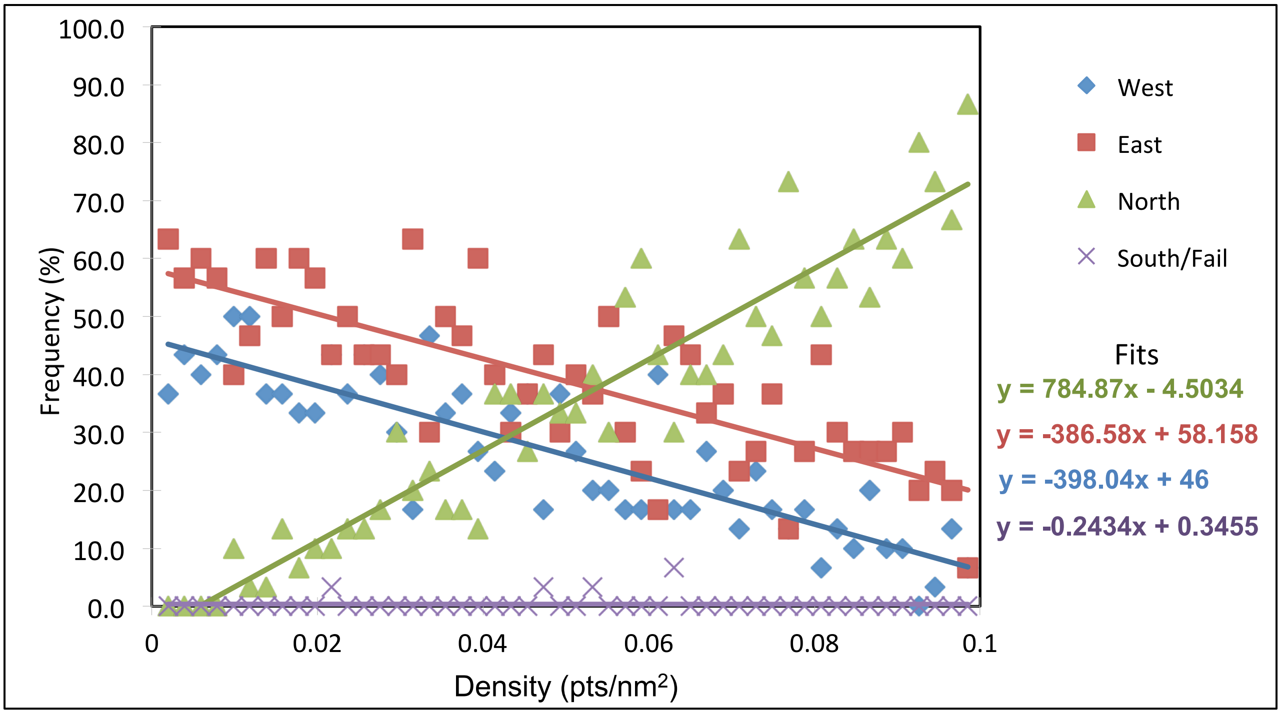

***Figure 12**: The proportion of electrons that exit through each gate for scatter densities between 0 and 0.1 pts/nm^2. Electrons were pushed East. When electrons drift, a higher proportion exit through the North drain and a lower proportion exit through the East drain. The lateral voltage was 0.1 V. The gate width was 500 nm.*

Another simulation was run in *ETCHD* that recorded electron directional data across the spectrum of possible scatter densities. Figure 12 shows how the frequency of exit directions changes as the scatter density increases and electrons drift more. In this simulation, two electric fields were applied. The main electric field pulled electrons North and had a magnitude of 1 V, which applied throughout the source channel and North drain. The lateral electric field had a magnitude of 3.3×10^5 V/m. An applied voltage of 0.1 V pushed electrons to the East, as a result of positive charge applied to the right gate wall and negative charge to the left wall. Figure 12 shows different frequency results than Figure 11 due to a larger gate width and due to random chance. The East-to-West difference is smaller for low scatter point densities because the larger gate width and lateral voltage caused electrons to bounce against the source channel walls (as in Fig. 9) and exit west.

As the density of scatter points increases (and electron motion transitions from ballistic to drift), a number of important trends can be seen. First, as the density increases, the number of electrons that exit in the East drain (the forced direction) decreases. Second, the number of electrons that exit in the West drain (the non-desired direction) also decreases. Third, the number of electrons that drain north increases at a faster rate than the other two trends. As the scatter density increases, the electrons only drift in the direction of the net voltage, which is North, and are not displaced laterally. Most electrons reach the central triangle of the BDT (see Fig. 1) but they flow around it continuing northwards instead of catching the walls of the East and West drains. Very few electrons ever drain South or fail to reach a drain.

Conclusion

In conclusion, a program entitled *ETCHD* was created to realistically simulate a BDT for the purpose of determining optimum conditions for future manufacturing processes. Results indicate that a BDT would be most effective when electrons are ballistic or near ballistic. In this scenario, the required voltage and the required electric gate width are minimal, which is the most energy efficient. A BDT is also feasible with small levels of electron drift. In this scenario, the required voltage is much higher that would be required when electrons are ballistic. This is less energy efficient, but still consistent and effective. In an ideal BDT, over three-quarters of the electrons can consistently be forced in the desired direction, which is a clear enough difference to indicate “on” or “off”. However, when electrons drift to a large degree, the BDT will not work. The electrons are only able to move in their net direction, which is upwards (North) due to the central voltage of the BDT. As a result the BDT cannot be turned “on” or “off”.

Acknowledgements

I will be forever grateful for the opportunity to work at the Laboratory for Laser Energetics. I would like to thank Dr. R. Stephen Craxton for running the high-school intern program and greatly helping me with this paper. Thank you to my advisors, Dr. Roman Sobolewski and Yunus Akbas, for providing me with an interesting project in the field of electrical engineering. My gratitude goes to Logan Toops, my partner, who worked together with me on a similar project. Without our teamwork, we would not have been able to complete this program. In addition, the other interns in Room 2650 deserve mention for helping me debug when I became frustrated; thanks especially to Ian Gabalski, who was kindly invested in this project just due to personal interest. Last but certainly not least, I would like to thank my family for inspiring and always supporting me.

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