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***Abstract*—Electron hop funnels have been simulated using the new version of the particle trajectory simulation software, Lorentz-2E. Simulations were conducted to determine the validity of the version 9.2 results and the consistency of the results to a previous version of the software, version 8.0. In addition, a new method of injecting a uniform current with all rays of equal charge is discussed, and the results of the method are presented. Version 9.2 of the software was successfully implemented and a new emission model tested. The transition of the software version will allow for faster simulation times of the electron hop funnel simulations to increase the understanding of the device.**

***Index Terms*— Field emission arrays, secondary electron emission, surface charging, vacuum microelectronics.**

I. Introduction

ELECTRON hop funnels [1] are dielectric materials that have been milled into a funnel or slit shape. These funnels are used to improve the performance and to protect field emission arrays. The implementation of electron hop funnels could allow for the use of gated field emission arrays (FEAs) [2] in microwave vacuum electron devices (MVEDs). Implementing FEAs into MVEDs is of interest because FEAs can produce an electron beam with spatial and temporal capabilities not available with conventional electron sources [3].

The use of gated FEAs in MVEDs is limited by poor current uniformity and by the susceptibility of the FEAs to high electric fields (arcing) and ion back bombardment [2]. Hop funnels are useful in applications of FEAs because they increase the electron current density, increase uniformity of the emitted electron beam, and provide protection of the FEA. By covering the FEA, hop funnels provide protection from ion back bombardment and from high electric fields. The protection to the FEAs is achieved by reducing the amount of FEA surface exposed to the intense interaction space present in MVEDs. Certain configurations of hop funnels can have no FEA surface exposed and can be completely protected [4]. Simulation of the electron hop funnels makes it possible to obtain a better understanding of the device's behavior, to allow for optimization of the device design, and to study secondary electron emission.

A pictorial representation of a hop funnel is presented in Fig. 1, while Fig. 2 shows a simulation of electrons in the hop funnel. The funnel is placed directly above a FEA, and electrons are emitted into the wide end of the funnel. An electrode, known as the hop electrode, is placed around the narrow (exit) end of the funnel to create a vertical electric field in the funnel. The hop electrode does not cause the FEA to emit; it only provides a vertical electric field to pull the electrons emitted from the gated FEA into the funnel and to sustain current on the dielectric funnel wall using a mechanism known as the electron hopping transport (explained in detail below).

This work focuses on the simulation of I-V curves of electron hop funnels performed using the particle trajectory software Lorentz 2E [5]. An I-V curve is the comparison of the amount of current collected on an anode above the funnel exit (amount of current that is transmitted through the funnel) versus the potential on the hop electrode. This measurement provides an indication of the potential needed on the hop electrode to support electron hopping transport in the hop funnel [1].

I-V curves have been successfully measured and simulated [1, 4, 6-8] for various types of hop funnels. The I-V curve from previous simulation work [7], using version 8 of Lorentz 2E, is shown in Fig. 3. The I-V curve presented in Fig. 3 has been shown, in previous work [7], to resemble the experimental results of electron hop funnel performance.

The work presented here investigates the modification of the model used in previous work [6,7] and compares the new version (V9.2) of Lorentz 2E to the old version (V8.0). The curve presented in Fig. 3 will be used as the basis of all comparisons between the versions. The transition to the new V9.2 is desired because the new version implements parallel processing and improved algorithms for secondary electron emission from dielectrics. The parallel processing capability greatly reduces simulation time, which is a significant limitation for hop funnel simulations.

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II. Electron Hop Funnel Background

Electron hop funnels operate by sustaining current along the dielectric funnel wall through a mechanism known as electron hopping transport [1]. To initiate the electron hopping transport mechanism in the hop funnel, primary electrons are injected into the wide end of the funnel. The primary electrons are pulled toward the top of the funnel by the vertical electric field created by the hop electrode and either strike the funnel wall or exit the funnel through the narrow funnel hole. If a primary electron strikes the funnel wall, it has a probability of causing the dielectric to emit secondary electrons. The number of secondary electrons that are emitted from the funnel wall is based upon the secondary electron yield [9-11] of the dielectric. The secondary electrons that are emitted from the dielectric are pulled up by the electric field and may either exit the funnel or strike the funnel wall in another location. If the secondaries strike the funnel in another location, they may create additional secondary electrons. The motion of secondaries landing on the funnel wall and creating additional secondary electrons resembles 'hopping' of electrons.

Because the funnel wall is a dielectric, the surface will charge and regulate the number of secondaries that are emitted by affecting the kinetic energy of electrons in the funnel. In a state known as unity-gain [1], the wall charges such that the current transmitted through the funnel is equal to the current injected into the funnel. The unity gain state is achieved if the potential on the hop electrode is large enough to cause secondary electrons to gain enough energy during their lifetime to create additional secondaries when they strike the funnel wall. Figure 2 shows the operation of the hop funnel in the unity gain regime using the simulation Lorentz 2E. In Fig. 2, primary electrons are emitted into the wide end of the funnel, and the electric field created by the hop electrode supports the hopping of electrons along the funnel wall.

If the hop electrode voltage is not high enough to sustain electron hopping transport on the entire funnel wall, transport may be sustained on a smaller portion of the wall or none of the wall. This condition results in a funnel exit current of less than the injected current. When the device is less than unity gain, the electrons emitted from the FEA are turned around by surface charge on the portion of the funnel wall that does not sustain electron hopping transport and are collected on the FEA surface. This mechanism is described in great detail elsewhere [1].

III. Simulation Software

Lorentz 2E is a two-dimensional particle trajectory software. An explanation of the Lorentz 2E simulation of the electron hopping mechanism and of the I-V curve generation with Lorentz 2E is described here. More details of the Lorentz 2E simulation of hop funnels can be found in [6,7].

A. Simulation Overview

Lorentz 2E uses a four step method to simulate the electron hop funnels. First, a boundary element method (BEM) [5] is used to calculate the electric fields throughout the simulation model. Secondly, primary particles are emitted from the FEA in the model, and their trajectories are tracked using a 5th order Runge-Kutta (RK5) [12] method. Particles are simulated as rays which contain a fixed amount of charge. The amount of charge that each ray contains is an input parameter to the simulation and was selected to match previous work [6]. When primary electrons strike the funnel wall, the energy of the bombarding electron is evaluated, and the number of secondary electrons that are emitted is based upon the Vaughan secondary electron emission model [11]. The input parameters from the Vaughan model used in the Lorentz model are the maximum secondary emission coefficient (δ_{max}) and the energy at which that maximum emission occurs (E_{max}). All of the simulations presented here used a δ_{max} of 2 and an E_{max} of 300 eV, which are values that were selected to match experimental work [7, 13]. The average energy of the emitted secondaries is also an input parameter of the simulation (W_{avg}) and is set to 5 eV, which is a reasonable assumption for secondary electron emission [9].

In the third step of the method, the emitted secondary electrons are then tracked and may exit the funnel or strike the funnel wall. The energy of secondary electrons that strike the wall is then calculated, and additional secondaries may be emitted. The process of calculating the energy of bombarding secondary electrons at the wall and emitting new secondary electrons is repeated until no new secondary electrons are emitted.

Finally, the fourth step of the method is to evaluate the surface charge on the funnel wall for each of the 600 discrete elements (segments) of the funnel wall [6] by dividing the charge on each segment by the surface area of the segment. Because the electron hop funnel is a cone, each segment forms a frustum of a cone surface. The surface area of each conical frustum is used for the surface charge calculations. Charge is determined by subtracting the number of rays emitted from the element from the number of rays that landed on each element multiplied by the length of the surface charge time step. The surface charge time step is an input to the simulation and was configured to be 5 μs. This entire process is considered one surface charge time step and is repeated until the surface charge on the funnel wall reaches a relatively steady state value.

B. Simulation Procedure for I-V Curve

To obtain the I-V curve for the hop funnel, the simulations were conducted using a method developed by Pearlman [7]. Using this method to obtain the I-V curve produces results much more consistent with experimental results than if this method is not used [7]. Pearlman's method consists of the following procedure:

1. Start with an uncharged funnel wall and the hop electrode at 0V.
2. Simulate the electron hopping process until a steady state surface charge is observed.
3. Output the funnel wall's surface charge.
4. Increment the hop funnel voltage by V_{step} and import the saved funnel wall surface charge from the previous voltage simulation.

5. Repeat steps 2 through 4 to complete an entire ramp up from 0 V up to V_{max}, then down to 0V, and then back up to V_{max}.

For the work presented here, V_{max} is set to 750V and V_{step} is set to 50V. V_{max} is selected such that the funnel reaches unity gain for several consecutive voltage steps. V_{step} is selected to be small enough to not create drastic changes in the electric field between simulations, which introduces errors, yet large enough to allow for reasonable simulation times (less than one month per I-V curve). V_{step} was selected to be 50V based upon the results of previous work [6,7].

The steady state current is somewhat noisy; to get the most accurate anode current, the anode current from the last 25% of the surface charge iterations of each voltage step are averaged. The noise of the steady state current could also be reduced by increasing the number of rays simulated. The number of rays used in the simulations of this work, 192, is selected to match previous work [6], which determined the optimal number of rays for this specific electron hop funnel geometry to balance between simulation time and error.

In all I-V plots shown for this work the curves have been normalized by the amount of current injected into the funnel. A funnel in unity gain will show a normalized current of one.

IV. Transition from Version 8 to Version 9

It would be most appropriate to compare the different versions of Lorentz using identical parameters. However, the Runge-Kutta time steps, the emission angle of secondary electrons, and the emission energy of secondary electrons had to be modified due to reasons explained in the following sections. All other parameters of the model such as the number of rays, dimensions of the funnel, material of the funnel, surface charge time step, initial electron energy, etc. were kept consistent between the different versions. Table 1 summarizes the three changes between V8.0 and V9.2 that are discussed below.

A. Decrease of Maximum Runge-Kutta Time Step

A software issue was discovered in V9.2 where secondary electrons would not be properly emitted if the RK5 time step values used in V8.0 were used. This software issue was remedied if the RK5 maximum time step was decreased. While Lorentz does allow for the usage of different integration routines, such as constant step Runge-Kutta 4, adaptive step Bulirsch-Stoer, and adaptive step Runge-Kutta 8, it was desired to use RK5 in V9.2 to keep the simulations as consistent as possible with previous work.

Because of the parallel processing capabilities of V9.2, the decrease of the RK5 time steps only produced a small increase in simulation time; therefore shorter RK5 time steps were used in the V9.2 simulations. Using smaller times steps was an easy fix for this application, but the software still cannot model large time steps correctly in this configuration. Future work will be necessary to correct the software to model large time steps correctly.

B. Secondary Electron Emission Angle Change

In V8.0 of Lorentz, the angle at which secondaries are emitted is fixed at 45°, 90°, or 135° from the secondary electron surface. Version 9.2 of Lorentz emits secondaries with a random emission angle. The random emission angle is taken from a distribution of angles, which has a peak at an emission angle normal to the surface. While this random angle is an improvement in the modeling of the actual physics of secondary electron emission [9], it requires that the simulation have many more rays (it is anticipated that an order of magnitude in the number of rays would be necessary) to correctly model the funnels because many rays are needed to obtain a significant distribution of angles. The Lorentz model was modified so that all secondary electrons were emitted normal to the surface. The normal emission was the only alternative option provided by the software.

C. Secondary Electron Emission Energy Change

In V8.0, the initial kinetic energy of emitted secondary electrons was either 1.43 eV or 6.93 eV, when the average energy was set at 5 eV. In V9.2, the energy of each secondary electron is determined from a distribution of energies. The electron energies range from 0 eV to 20 eV when the average energy, W_{avg}, (peak of the distribution) is set to 5 eV. Similar to the secondary electron emission angle, this change in the energy of the secondary electrons is a better model of the actual physics [9]; however it also requires that the number of rays in the simulation be dramatically increased by at least one order of magnitude. Similarly to the solution for the secondary emission angle, the secondary electron initial energy was modified in V9.2 such that it was closer to the V8.0 simulations. In this modified V9.2, when the average energy of the secondaries is set to 5 eV, the secondary electrons emit with five distinct energies: 2.14 eV, 2.68 eV, 4.16 eV, 5.88 eV, and 6.69 eV with a Gaussian distribution.

V. Current Density Emission Model

In the Lorentz simulations of previous work [6,7], the electron hop funnel model contained a fixed number of emission surfaces representing the field emitter array. All of these emission surfaces were equal size in the axisymmetric model, and at each of these emission surfaces an equal number of rays were emitted with identical current. However, this modeling technique is not the most accurate method to model the actual experiment. Because the model is axisymmetric, these equal size emission surfaces have a surface area that linearly increases with the radius; therefore using a constant number of rays at each emission location results in a current density that falls off as a function of 1/r instead of remaining constant.

In the physical device, a FEA injects a relatively constant current density into the hop funnel. Therefore, the model constructed for this work to compare V8.0 to V9.2 was modified such that the current injected maintained a constant current density. A constant current density was achieved by linearly increasing the number of rays emitted from each emission surface as the radius increased. By linearly increasing

the number of rays with the radius, a constant current density was achieved; in addition, the current per ray is kept constant throughout the model.

To determine the number of rays that should be emitted from each emitter, the surface area of each emitting section was calculated, and then the number of rays was specified such that the charge density being emitted from each section was roughly constant. This causes an increase in the number of rays from 192 to greater than 350 rays. This increase in the number of rays increases the simulation time and was the main reason this setup was not used in the previous work [6,7,13].

VI. Results and Discussion

The results from the new V9.2 models with and without the constant current density emission model are presented and discussed.

A. Version 9.2 Simulation Time

Lorentz 2E is a workstation software and does not have the capability of multi-machine parallel processing. All simulations presented in this work were conducted on a Windows based machine using a single, 4-core, Intel Xeon 2.8 GHz processor in conjunction with 16 GB of 1066 MHz double data rate, type three, synchronous dynamic random access memory (DDR3 SDRAM). Typical simulations conducted using V8.0 of the software, with 500 surface charge time steps and 192 rays, have a simulation time of approximately 20 hours. Note that this simulation time is for a single point on the I-V curve. To generate a complete IV curve, the hop voltage must be ramped up, back down, and back up to show the I-V hysteresis. Such a ramp sequence can require 60 to 200 (depending on the hop funnel geometry) [7] simulation runs of 20 hrs. When V9.2 of the software was used with 500 surface charge time steps and 192 rays, the simulation time for a single point was reduced to approximately 8 hours. The number of surface charge time steps necessary for convergence did not vary between V8.0 and V9.2 of the software. The decrease in simulation time is due to the improved parallel algorithm using all 4 cores.

As mentioned, to use the "random" secondary electron emission angle and energy models available in Lorentz V9.2, the number of rays would have to be increased. To test how an increase in the number of rays would affect simulation time a single point of the I-V curve was simulated with 400 rays (approximately two times the current number of rays). Using 400 rays the simulation time in V9.2 increased to greater than 20 hours per simulation point and required greater than the 12 GB of memory. A large amount of RAM is necessary for the Lorentz simulations because particle trajectories are all stored in memory until all surface charge iterations are completed. Because of time and hardware constraints, these longer simulations were not feasible for this work, and this issue was the primary reason that the modifications to the secondary electron emission angle and energy models were made.

B. Version 9.2 Models

Figure 4 shows the results of the I-V curve simulations when the electron hop funnels are simulated in V9.2 using the current injection model of previous work. The I-V curve presented in Fig. 4 shows a less than unity current at the anode, which is different behavior than the results from the previous version of Lorentz, shown in Fig. 3.

It was found that when the I-V curve was simulated in V9.2, a current on the hop electrode was observed. This current was not observed in V8.0 simulations of previous work. If current transmitted through the funnel is defined as the total of the current collected on both the anode and the hop electrode, the I-V curve shown in Fig. 5 is observed. The I-V curve shown in Fig. 5 is quite similar to the results of previous work shown in Fig. 3. Comparison of Fig. 4 and 5 indicates that as the potential on the hop electrode increases, the amount of current collected on the hop electrode increases as well. The high hop electrode current behavior shown in Fig. 4 was not observed in previous simulation or experimental work.

The collection of current on the hop electrode is due to one of the following three differences between the V8.0 and V9.2 models: (1) in V9.2 all secondaries are emitted normal to the surface which may affect the trajectory of the secondaries, (2) the different energies of the secondaries are affecting the trajectories of the secondaries, or (3) a decrease in the maximum RK5 time step is somehow causing electrons to collect on the hop electrode. To determine if difference (1) was the cause of the additional hop current, a simulation was created in V8.0 where all secondaries were emitted normal to the surface. This V8.0 simulation had a few rays strike the hop electrode. The number of rays that struck the hop electrode was slightly greater than from the previous V8.0 models with a angular distribution, but not nearly so many as observed in V9.2; therefore difference (1) is not the primary cause of the hop electrode current. At the current time it is not possible to test difference (2) or (3) because (2) would require a modification of the code by the developers, and (3) would require months of simulation time in V8.0. Investigation of this collected hop current issue is left for future work. Because this behavior was not observed in previous simulations or experiments, it is assumed that current collected on the hop electrode is current that would be collected on the anode. All subsequent I-V curves presented in this article define transmitted current as the sum of both anode current and hop electrode current.

While the I-V curve from V8.0, shown in Fig. 3, is not identical to the curve from V9.2, shown in Fig. 5, the two curves have very similar behavior, and the funnels demonstrate the same mechanisms which create the curves [7, 13]. The I-V curves both include a hysteresis, and the general shape of the curve is preserved across the versions. The first ramp up exhibits linear behavior while the ramp down contains a sharp knee transition from near unity gain to zero transmission. The ramp back up follows the ramp down knee and then becomes linear. The explanation for why this behavior occurs is thoroughly explained in [7]. Some differences in the amount of current transmitted at each voltage step between the versions

should be expected because of the change in the secondary electron emission energies and angles explained above.

The difference in the knee location and the slope can be explained by one additional difference between the V8.0 and V9.2 runs. The V9.2 simulations used voltage steps of 50 V, while the V8.0 results used 25 V steps. 50 V steps were used in V9.2 to reduce the simulation time by half. For the specific geometry and secondary electron parameters selected in this work, the increase in voltage steps still preserves the general shape of the curve, and the hysteresis still exists with a 25 V or 50 V step [13]. However, an increase in voltage steps does introduce some error in the location of the knee and the slope of the curves.

C. Constant Current Density Models

Figure 6 shows the I-V curve of the electron hop funnel when the constant current density model is implemented in V9.2 of Lorentz 2E. In Fig. 6 anode current is defined as the summation of the current collected on the anode and the current collected on the hop electrode as explained previously. By comparing Fig. 6 with Fig. 5 it is possible to see that the I-V curves are very similar regardless of which emission model is used. The only difference between the two I-V curves is that the constant current density model has a slightly shallower slope on the initial ramp up and ramp back up.

As explained previously, the electron hopping transport mechanism is regulated by surface charge on the dielectric funnel wall. The surface charge on the funnel wall regulates the secondaries that are emitted thereby regulating the current along the funnel wall. The similarity of Figs. 5 and 6 is due to the self regulating nature of the electron hop funnels. The self regulating nature causes the results to be consistent so long as enough rays exist in the model to strike enough of the hop funnel wall to cause a steady state surface charge.

VII. Conclusion

Simulating the hop funnel hysteresis in V9.2 has been moderately successful. Some differences between the two versions of the software exist, and these differences generate small effects on the hop funnel I-V curves. The most significant different between the V8.0 and V9.2 results is the presence of current being collected on the hop electrode in V9.2 simulations. However, the general shape of the I-V curve is consistent across versions. Consistency of the results across the different versions also shows that the V9.2 simulations exhibit the same behavior as the experimental results except for the hop electrode current. Investigation of which specific difference between the codes that is affecting the results is left for future work. Future simulation work of electron hop funnels will now be able to use the parallel processing of Lorentz 2E to conduct many more simulations than previously possible. In addition, with a few modifications to the software, the current hardware limitations could be remedied. Solving the hardware limitations would allow for the possibility to use the new random secondary electron emission algorithms available in V9.2 of Lorentz 2E, which are a closer model to the actual physics of the device and may further improve the simulation accuracy.

A method to model a constant current density emission of electrons into the hop funnel model has been developed and tested. The simulation results show that the different electron injection models have little effect on the I-V curves of the funnels. The similarity between the results is a further demonstration of results of other work [1] which states that the electron hopping transport is self regulating. Because the mechanism is self regulating, the secondaries on the wall regulate themselves to create the appropriate current density causing very similar results. The verification of the new model emphasizes that future simulations can continue to use the non-constant current density emission model.

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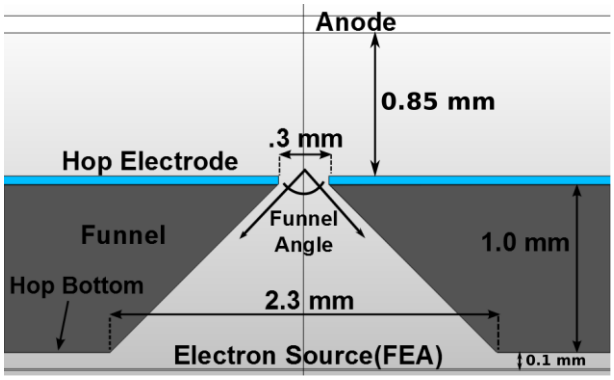

Fig. 1. Pictorial representation of an electron hop funnel. The dielectric hop funnel is much larger than individual field emitters and is placed above the FEA.

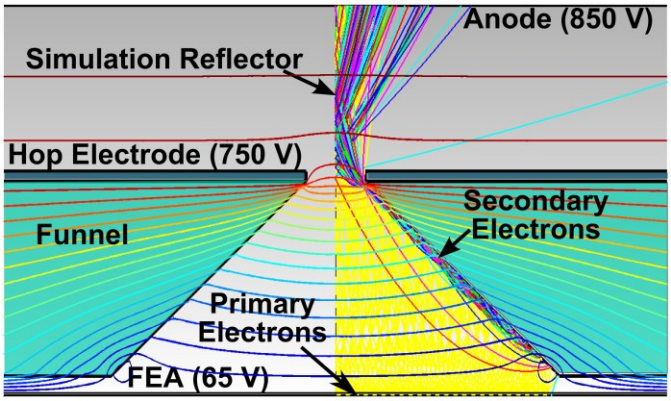

Fig. 2. The axisymmetric electron hop funnel model simulating the funnel in the unity-gain regime with equipotential lines shown. Primary electrons are emitted into the wide end of the funnel from the FEA. These primary electrons either exit the funnel through the narrow hole or strike the funnel wall. The primaries that strike the funnel wall may create secondary electrons. The hop electrode potential is large enough to cause electron hopping and support the current on the funnel wall.

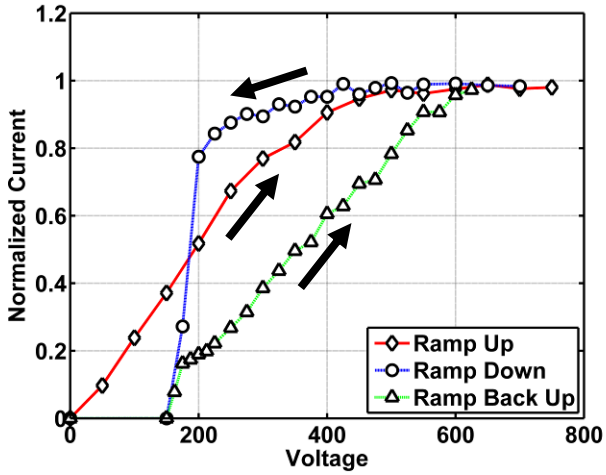

Fig. 3. I-V curve results of the electron hop funnel simulation when simulated using V8.0 of Lorentz 2E [7]. Secondary emission parameters used for all models in this work: $\delta_{max} = 2$ and $E_{max} = 300$. The current presented in this curve only includes rays that strike the anode.

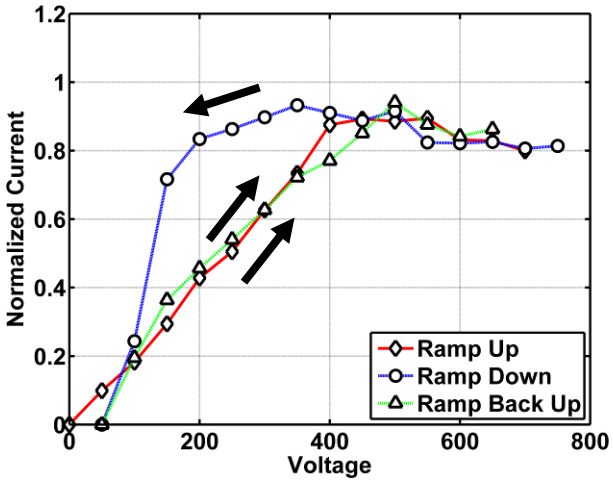

Fig. 4. I-V curve results of the electron hop funnel simulation when simulated using V9.2 of Lorentz 2E. The current presented in this curve only includes rays that strike the anode.

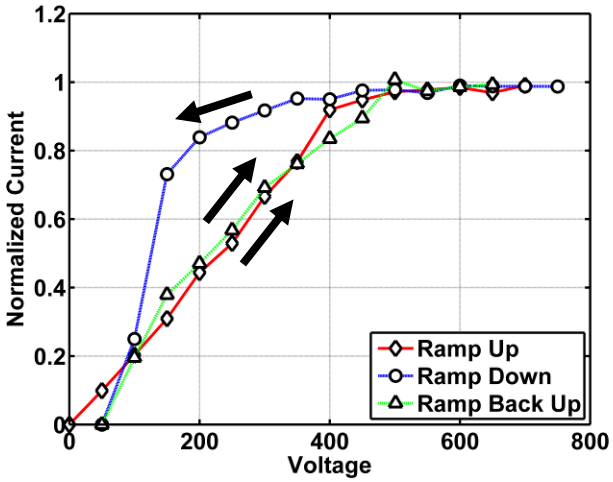

Fig. 5. I-V curve results of the electron hop funnel simulation when simulated using V9.2 of Lorentz 2E. The current presented in this curve includes rays that strike both the anode and the hop electrode.

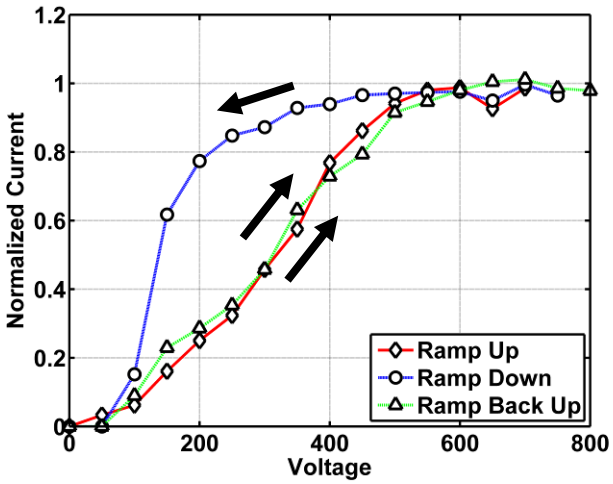

Fig. 6. I-V curve results of the electron hop funnel simulation with the constant current density electron emission V9.2 of Lorentz 2E. The current presented in this curve includes rays that strike both the anode and the hop electrode.

Table 1: Differences between V8.0 and V9.2 of Lorentz 2E

Parameter	**V8.0 Models**	**V9.2 Default**	**V9.2 Models Used In This Work**
RK Max Time Step	1×10^{-6} s	NA	1×10^{-9} s
RK Min Time Step	1×10^{-11} s	NA	1×10^{-12} s
Secondary Electron Emission Angle	45°, 90°, 135°	Distribution of Values	90°
Secondary Electron Emission Energy (W_{avg}=5eV)	1.43eV and 6.93eV	Distribution of Values	2.14 eV, 2.68eV, 4.16eV, 5.88eV, and 6.69eV