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Hysteresis in Experimental I–V Curves of Electron Hop Funnels

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Electron hop funnels provide a method to integrate field emission arrays into microwave vacuum electron devices, to protect the arrays, and to provide a method to study the secondary electron characteristics of dielectrics. A hop funnel is a dielectric material with an electrode, known as the hop electrode, placed around the narrow end (exit) of the funnel to control the current transmitted through the device. Current is transmitted through the funnel via electron-hopping transport. This work investigates a hysteresis observed in the current-voltage characteristic of the device. The experimental results showing the observed hysteresis will be presented. This work will demonstrate that charging on the bottom of the hop funnel is not the fundamental cause of the hysteresis.

I. INTRODUCTION

Field emission arrays (FEAs) have many benefits over thermionic cathodes as an electron source[1,2]. A FEA has greater spatial controllability and can be modulated at a higher frequency[1] than a thermionic cathode. However, FEAs suffer from poor emission uniformity and lifetime[1]. By overcoming these disadvantages, FEAs have a variety of possible applications such as integration into microwave vacuum electron devices

(MVEDs). Using FEAs in MVEDs allows for a more spatially and temporally controllable electron source than capable with current electron sources. Electron hop funnels are a possible solution to overcome these disadvantages.

A hop funnel is a dielectric material that has been fabricated into a funnel shape. A cross-sectional diagram of a hop funnel is shown in Fig 1. The device operates by placing the funnel on top of an electron source such as a FEA. The source injects electrons into the wide end of the funnel and, through electron-hopping transport[3], the current is sustained along the funnel wall until it reaches the funnel exit.

An electrode is placed around the funnel exit, and this hop electrode provides the necessary electric field to pull electrons through the funnel and to sustain secondary electron emission[4-6] which is necessary for electron-hopping transport along the funnel wall. When the potential of the hop electrode is high enough, the amount of current leaving the funnel is the same as the current injected into the funnel; this operating point is known as unity-gain[3]. When the potential of the hop electrode is too low, the electric field in the funnel is not sufficient to sustain the current on the wall, and no current is transmitted. The relation between the transmitted current and the potential of the hop electrode is the I-V characteristic (curve) of the hop funnel.

Electron hop funnels utilize the electron-hopping mechanism to sustain current on the funnel wall. Primary electrons are injected from the FEA into the wide end of the funnel. Primary electrons either strike the funnel wall or exit the funnel through the narrow funnel opening. The primary electrons that strike the funnel wall may cause the dielectric to emit secondaries. The secondaries then may either strike the funnel wall in another location or exit the funnel. If the secondaries strike the funnel wall, the secondaries may create additional secondaries. The creation of new secondaries continues along the funnel wall appearing that electrons are ‘hopping’ along the dielectric surface.

A surface charge is created on the dielectric surface by primary electrons striking the wall and the secondaries emitted. The surface charge on the funnel wall affects the energy and trajectory of subsequent primary and secondary electrons. In steady state, the surface charge on the funnel wall regulates the current that exits the funnel to never be greater than the amount of current injected.

The use of hop funnels has been shown to increase emission uniformity, to increase current density of the electron beam, and to provide protection of FEAs[7-10]. Hop funnels are usually operated in the unity-gain regime and have not been well studied in a non-unity regime. The measurement of the I-V curve provides an indication of the potential needed on the hop electrode to operate the device in unity gain. This work will focus on the hysteresis in the I-V curve that is observed when ramping the hop electrode voltage. In prior experiments[7] and those presented here, the hop voltage was ramped from a low (0V) to a high voltage (550V); the transmitted current behaved differently then when the reverse ramp (550V to 0V) was performed. This hysteresis is an interesting behavior to investigate as it may help provide insight into the physics of electron hop funnel operation.

Three theories are proposed to explain the hysteresis in the I-V curve: (1) charging occurs on the FEA itself which affects the current emitted from the cathode, (2) charging occurs on the bottom dielectric surface of the hop funnel, or (3) the charging is an inherent characteristic of the hop funnel. To test hypothesis (1), a different cathode is required that contains a resistive layer which would bleed charge away and ensure that no charge can build up on the cathode dielectric surface. Such a cathode is not currently available to the authors, so this hypothesis cannot be tested. To test hypothesis (2), a metal layer, referred to here as the hop bottom electrode, was deposited on the bottom of a hop funnel to prevent charging on the hop bottom. To test hypothesis (3), simulations were performed to recreate the hysteresis observed and is explained in detail in other work[11,12].

This work focuses on investigating hypothesis (2) to determine if charging on the bottom surface of the hop funnel is causing the hysteresis. For this work, hop funnels have been constructed from Low Temperature Co-fired Ceramic (LTCC)[13]. Half of the funnels contain a metal electrode on the bottom surface of the hop funnel. The metal electrode allows experiments to test hypothesis (2) as the metal layer ensures that no charging is occurring on the bottom surface of the hop funnels. The I-V curves of these funnels have been measured and analyzed. The results of this work are presented here.

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II. EXPERIMENTAL SETUP

A. Field Emission Array

For all experimental work presented here, FEAs constructed by PixTech and Motorola[14] were used as the cathode. These cathodes contain Spindt type field emitters[15]. Originally, the PixTech cathodes were fabricated for use in field emission displays (FEDs) and were obtained in their original FED packaging; therefore these cathodes had to be de-packaged for these experiments. This process usually created unwanted resistive paths in the cathode resulting in a high leakage current between the gate and emitter electrodes. This leakage current prevented reverse biasing sections of the FEA meant to be off; therefore these sections were left floating, and these sections sometimes emitted current. In addition, this leakage current prevented the accurate measurement of emitted current. Neither ion nor electron back bombardment were a concern for the original design of the PixTech cathode; thus there is exposed dielectric on the surface that can charge up upon back bombardment.

The Motorola cathodes were fabricated as part of Motorola's FED program. These cathodes were obtained as bare cathodes, and de-packaging was not necessary. However, these cathodes still suffered from a leakage current. The Motorola cathodes were used for the initial work on hop funnels[7]; however specifics of the Motorola cathode (amount of exposed dielectric) are unknown. The PixTech cathodes were used in a majority of the results presented here. The leakage current of the cathodes limited the amount of possible emission current to less than 30 μA. In addition, the large leakage current prevented the measurement of true emission current (emitter current minus gate current) because the leakage current was two to three orders of magnitude larger than the emission current. Opto-isolators are used to measure the current, explained below, and each opto-isolator has a non-linear behavior to the 3rd significant digit; therefore, resolving emitted current from the leakage current was unreliable and unusable using the current measurement setup. When measuring leakage current it is also not possible to distinguish between emitted electrons that emit, turn around, and strike the gate, making it more difficult to measure true emission current.

B. Hop Funnel Construction

Two different funnel geometries were constructed for this work: 60° and 90° funnels as defined in Fig.1. For each of these geometries one funnel was constructed with a metal hop-bottom and one without for a total of four funnels. The funnels were constructed of LTCC, which is available in thin flexible sheets. The sheets are heat pressed together to the desired thickness and then milled to form holes or slits. After milling, the structures were fired to form the ceramic.

For the 90° funnels, the hop electrode and metal hop bottom were deposited using a silver paint that was hand applied to the LTCC. When constructing the 60° funnels, the process was improved by screen printing the thick film silver. It is not believed that this change in the method of silver deposition had any significant effect on the results. A picture showing the hop funnels and the electrodes is shown in Fig. 2.

C. Experiment Configuration

A diagram of the experimental setup is shown in Fig. 3. The FEA cathode is placed on a metal block biased at the cathode voltage of -1000V. The hop funnel is then placed on top of the cathode as closely as possible (<1mm). An anode biased at earth ground is placed over the funnel exit (anode to funnel gap ≈ 1cm) to measure the transmitted current. The hop funnel was aligned by hand to be directly above the emitters that were configured to emit. The gate, hop bottom electrode, and hop electrode were all biased relative to the cathode voltage of -1000V (floating ground). The gate voltage is held constant (≈ 80 V from the floating ground) to emit a constant current from the FEA. The electrode on the bottom of the hop funnel was connected to the floating ground. The sweep of the hop electrode voltage was performed slowly to ensure that the changing hop electrode potential did not affect the hysteresis observed in the I-V curve. It is not believed that the hop electrode potential affects the emitted current, but sweeping the hop electrode potential slowly ensures that any effect will be the same on both a ramp up and ramp down. The hop electrode voltage is swept from 0 to 550 V (relative to floating ground) and then back to 0 V over a period of 20 s.

The I-V curve is obtained by measuring the current to the anode versus the potential on the hop electrode. All currents were monitored by measuring the voltage across a resistor and using an opto-isolator circuit to pass the analog values to an analog to digital converter to record the data. All experiments were performed in vacuum of less than 5e-7 Torr.

III. RESULTS AND DISCUSSION

The I-V measurement results were found to be very consistent within one experimental setup but very different from setup to setup. In addition, if the experiment is preformed repetitively with or without a time delay between measurements of the I-V curve, very consistent results are measured including the presence of the hysteresis. Each time the structure was removed from the chamber to recreate the same experiment on a different location of the cathode or to use a different funnel of the same type, the I-V curves would show different behavior. The "new" behavior, however, would be consistent within that setup. In some cases small bumps or plateaus were seen in the I-V curves, and these features were very repeatable. These features may be related to mechanical variations (grooves or edges) in the hop funnel. Many different setups were tested with and without the metal hop bottom. Figures 4 and 5 show the results that were most commonly observed for the 60° and 90° hop funnels, respectively, both with (c, d) and without (a, b) the metal electrode on the hop bottom.

It is immediately apparent that hysteresis is present with and without a metal hop bottom. This hysteresis is observable in all I-V curves that were measured, not just those shown here. In Figs. 4c, 4d, 5c, and 5d it can be seen that the metal hop bottom has little effect on the hysteresis on both the 60° and 90° funnels. The I-V curves with and without the metal had very similar results.

Figures 4 and 5 show a difference in the hysteresis behavior with different funnel angles. For the 60° funnels (Fig. 4) the ramp down transition occurs at a lower voltage than the ramp up; whereas with the 90° funnels (Fig. 5) the opposite behavior was most common. While this was the most common behavior, it was not always the case. Figure 6 shows two I-V curves demonstrating other shapes of I-V curves that were observed. Figure 6b shows a case where a 90° funnel exhibited behaviors commonly seen in the 60° funnels such as the ramp down transition occurring at a lower potential than the ramp up transition and having much more of a knee like behavior. This is the only example of this behavior in this paper, but this phenomenon occurred often and is not an outlier.

By comparing Fig. 4 and Fig. 5 it can be noticed that the 60° funnels appear to have a more drastic ‘knee’ behavior; however this was also seen with the 90° funnels (Fig. 6b) but not so commonly. There are also I-V curves that showed only a small hysteresis. While none of these curves are discussed in this paper, it should be noted that the slight differences in these curves were repeatable and was, in fact, evidence of hysteresis. The reason that different funnel angles produce different IV results is still under investigation and will be discussed in future work.

One difference in the experiment conducted for the I-V curve in Fig. 6b was the FEA. For the I-V curve in Fig. 6b the Motorola[13] cathode was used; whereas all other I-V curves presented were conducted with PixTech cathodes. Differences in how the cathodes are charging may contribute to the location of the ramp-up and ramp down transitions. This difference in cathode charging was not investigated in this work and is left for future study.

Some I-V curves, Figs. 6a and 6b, also show discrete levels of transmission where the transmission current will increase, remain constant, and then increase again throughout the ramping of the hop electrode. This behavior was common, and it is believed that these levels are caused by ridges or bumps on the surface of the funnel wall. To confirm this, a cross section of the funnels will be studied in future work and then simulated.

The wide range of results is not uncommon when dealing with secondary electron emission[16]. Hopping transport is very susceptible to external forces[3], and slight changes in the setup can drastically change the results. Monolayers of gas or contaminants formed on the funnel wall can change the SEY characteristic of the material which will affect the

I-V curves. Removing the structure from vacuum to modify the structure will result in an inconsistent surface. Spontaneous current near the interaction region, caused by leaving the unused pixel lines floating, may also modify the results. All these factors may contribute to the differences observed in the results.

IV. CONCLUSIONS

Overall, the experiments show a wide range of results; however two very clear conclusions can be drawn: (1) hysteresis is present and (2) the metal hop bottom has little effect on the hysteresis. Even with the variety of results that were observed, it was very clear that the addition of a metal electrode on the bottom of the hop funnel had little effect on the presence of hysteresis. This result disproves hypothesis (2) that charging on the hop bottom is the fundamental source of hysteresis. Therefore, the fundamental source of hysteresis must be charging of the cathode, hypothesis (1), or an inherent characteristic of the hop funnel, hypothesis (3). Based upon the conclusions presented in this paper, hypothesis (3) is being investigated in other work[11,12].

Acknowledgments

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Figure Captions

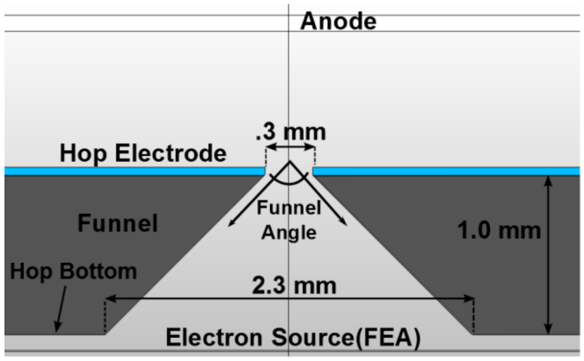

Figure 1. (Color online) A cross sectional diagram of a 90° hop funnel.

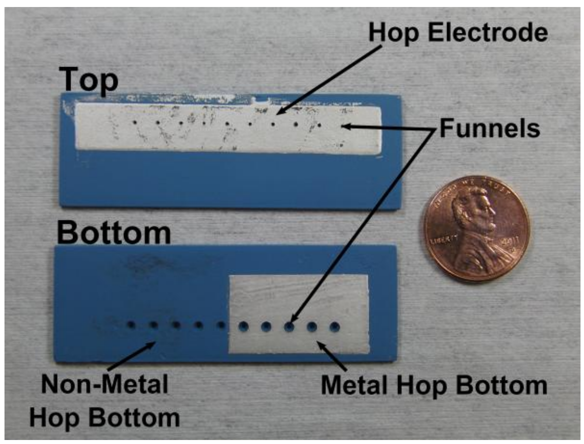

Figure 2. (Color online) Photograph of 60° hop funnels that were constructed out of LTCC for this work. Half of the funnels have a metal layer on the hop bottom and half have no metal bottom.

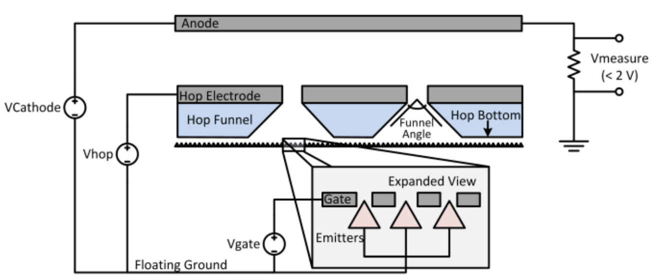

Figure 3. (Color online) Experimental setup showing the anode, field emission array, hop funnel, and configuration of bias voltages. The inset shows an exploded view providing the pictorial representation of the field emitters.

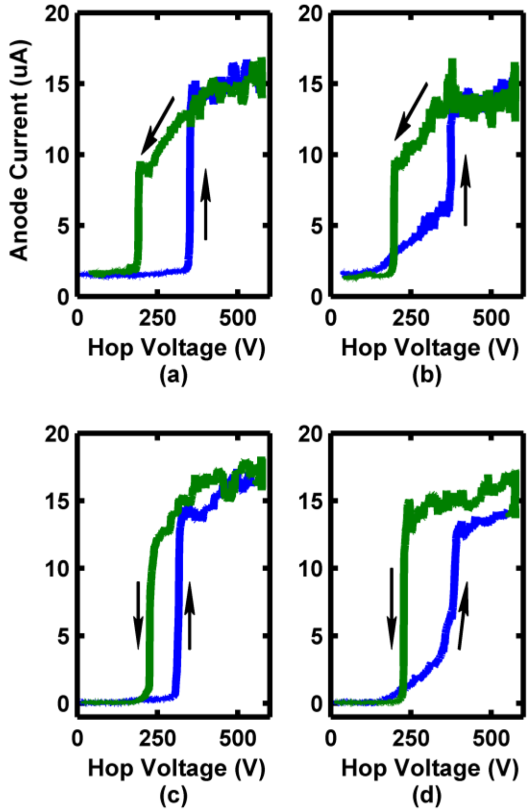

Figure 4. (Color online) I-V curve behavior that was most commonly seen with the 60° funnels where (a,b) are funnels without a metal bottom and (c,d) have a metal hop bottom. The curves show a relatively consistent form with sharp transitions on the ramp up and ramp down; however the voltage at which this transition occurs is not consistent. Note that ramp up has a higher transition voltage than the ramp down.

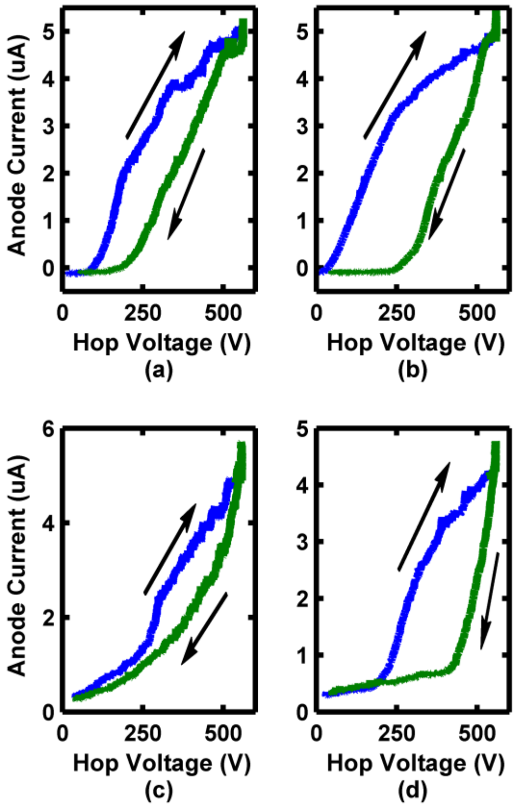

Figure 5. (Color online) I-V curve behavior that was most commonly seen with the 90° funnels where (a,b) are two curves obtained from funnels without a metal bottom and (c,d) are two curves obtained from funnels with a metal hop bottom. A more linear behavior was seen with these funnels, but was not always the case. Note that ramp down has a higher transition voltage than the ramp down, which is opposite from the results observed with the 60° funnels.

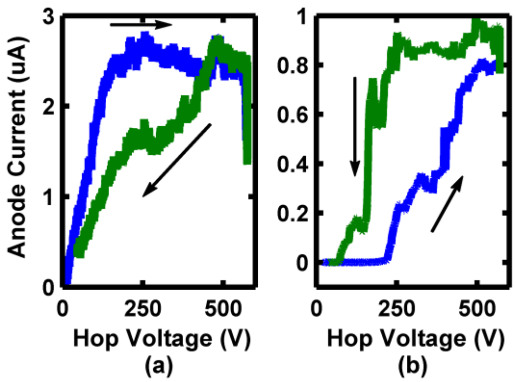

Figure. 6. (Color online) I-V curves showing additional results that were observed. (a) is a 90° funnel with a metal bottom; notice that the funnel reaches unity gain at a much lower voltage than common results shown in Fig. 4; (b) shows a 90° funnel without a metal bottom; this specific case showed more of a ‘knee’ type behavior that was more common in the 60° funnels. Also, the ramp down has a lower transition voltage than the ramp up. The I-V curve shown in (a) was conducted using a PixTech cathode; whereas (b) was conducted using a Motorola cathode.