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14. ABSTRACT
The objective of the LIVEC advanced study project was to develop a platform for large-scale integrated vacuum electronic circuits (LIVEC), which overcomes limitations inherent to vertical emission devices, achieves long-term reliability, and enables revolutionary scales of vacuum device circuit integration. Vacuum devices are preferred to solid-state for applications requiring radiation stability, a wide range in operating temperature, or high power at high frequency. However, difficulty integrating these devices on the microscale has limited their development. In

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MEMS Platform for Large-Scale Integrated Vacuum Electronic Circuits (LIVEC)

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Project Overview

The objective of the LIVEC advanced study project was to develop a platform for large-scale integrated vacuum electronic circuits (LIVEC), which overcomes limitations inherent to vertical emission devices, achieves long-term reliability, and enables revolutionary scales of vacuum device circuit integration. Vacuum devices are preferred to solid-state for applications requiring radiation stability, a wide range in operating temperature, or high power at high frequency. However, difficulties associated with integrating these devices on the microscale have limited their development. In this 12-month effort, we sought to demonstrate the potential of a monolithic MEMS-based integrated vacuum electronics platform.

Devices are made from freestanding vertical panels using the versatile and reliable **M**ulti-**U**ser **M**EMS **P**rocessing service (MUMPs®) and integrated carbon nanotube (CNT)–based cold-cathode field emitters as shown in Figure 1. This fabrication technology is highly versatile because the number of process steps does not increase with increasing numbers of devices, and there is no need to align external components or integrate multiple substrates. In competing technologies, in which devices are comprised of stacked layers, key parameters in the device geometry (e.g., cathode-grid spacing) are determined by layer thicknesses and are therefore difficult to vary within an integrated circuit. Freestanding panel structures also offer the advantage of low capacitance to ground and therefore high-speed capability. Finally, supporting elements such as resistors and inductors can be easily incorporated in this technology.

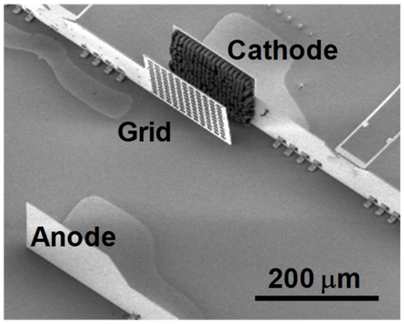

Figure 1. A scanning electron micrograph of RTI's triode made from freestanding MEMS panels.

In this advanced study project, we were able to demonstrate some key improvements in individual component performance and show that devices can be placed in close proximity without sacrificing performance when appropriate isolation measures are included. We also addressed some of the issues of CNT-based field emission cathodes for a circuit platform.

Summary of Activities

The project work was organized into three tasks designed to address the three greatest technology risks in large-scale integrated vacuum circuits. Task 1, Component Development and Integration, focused on the development of new device designs to reduce variations in device performance that may limit integration capability. Task 2, Cathode Performance Improvement, focused on developing cathodes with sufficient current density and lifetime for a practical circuit platform. Task 3, Panel Reliability Enhancement, focused on the evaluation of the reliability of microfabricated structures under continuous electron bombardment.

Funding was discontinued part way through the program, thus, several of the tasks originally proposed could not be completed. Details of accomplishments for each task are provided in the sections that follow.

Task 1. Component Development and Integration

The key active component for an integrated vacuum circuit platform is a high-performance triode. We had previously demonstrated functional vacuum triodes using this MEMS platform. In this program we successfully addressed three key limitations to help further the development of integrated vacuum electronic circuits.

The first limitation of the previously demonstrated devices was that poor transmission efficiency between cathode and anode reduced device performance. The poor transmission resulted from a lack of focusing of the electrons leaving the cathode. We demonstrated a different device structure with a screening electrode added between the cathode and the extraction grid. The SIMION simulations shown in Figure 2 show that this new geometry focuses the electrons emitted from the CNT bundles to reduce grid loss.

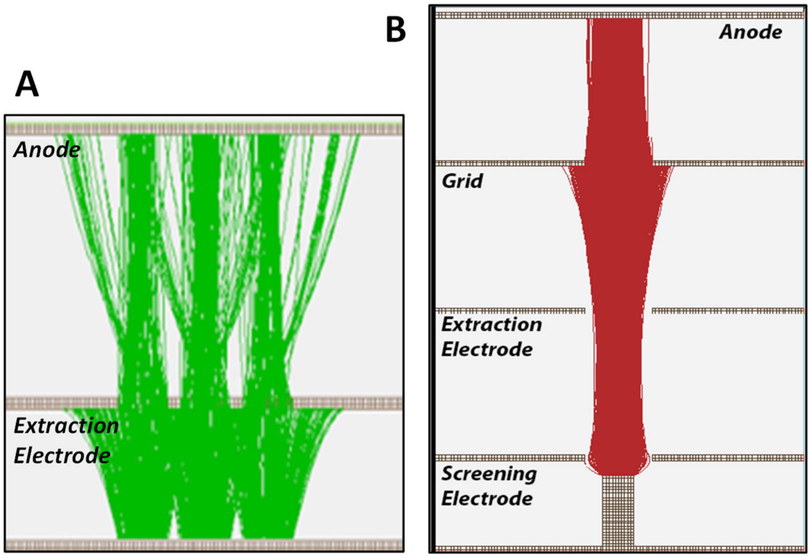

Figure 2: SIMION simulations showing electron trajectories in (A) the original 3-panel device structure and (B) the new geometry with a screening electron added. Electron focusing in (B) results in greatly reduced current loss at the grid.

A second limitation of the three-panel device is that the grid voltage is coupled to the cathode field emission, resulting in poor transconductance as shown in Figure 3A. In the four-panel structure in Figure 3B, the first two panels form a functional cathode and a separate "control grid" panel

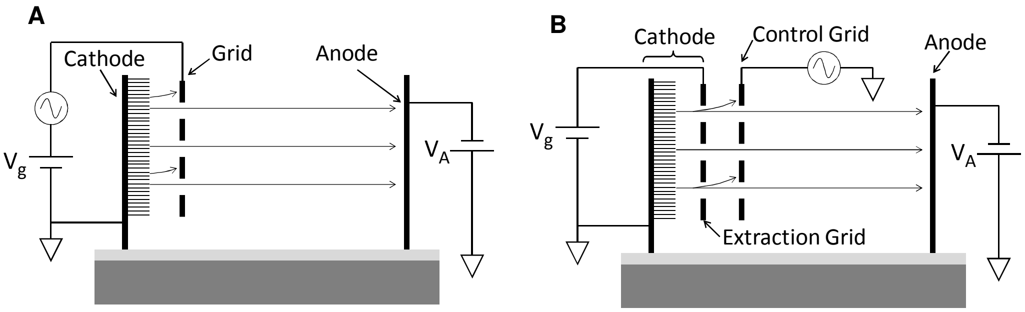

Figure 3. (A) The three-panel microtriode structure with a single grid for extraction and control. (B) Four-panel triode with a control grid decoupled from field emission.

modulates the electron current at the anode. A third panel can be added to the cathode to enable implementation of the improved focus of electrons demonstrated in Figure 1.

We developed models of this 4-panel triode operation in SimIon to provide visualization of electron trajectories and quantify measures of performance. Figure 4 shows an example of a modeled 4 panel device structure and corresponding triode performance curves.

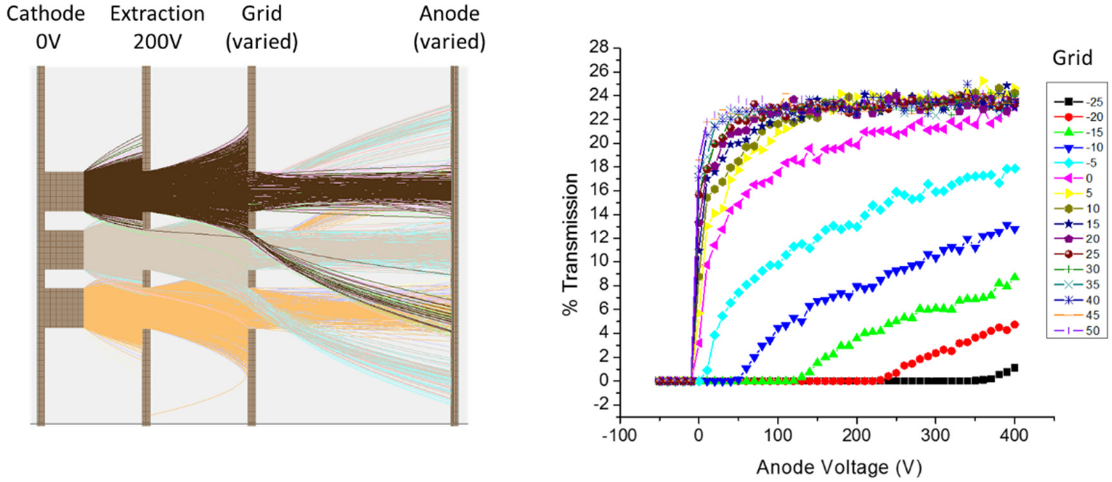

Figure 4: SimIon model of a 4 panel triode showing electron trajectories and triode performance.

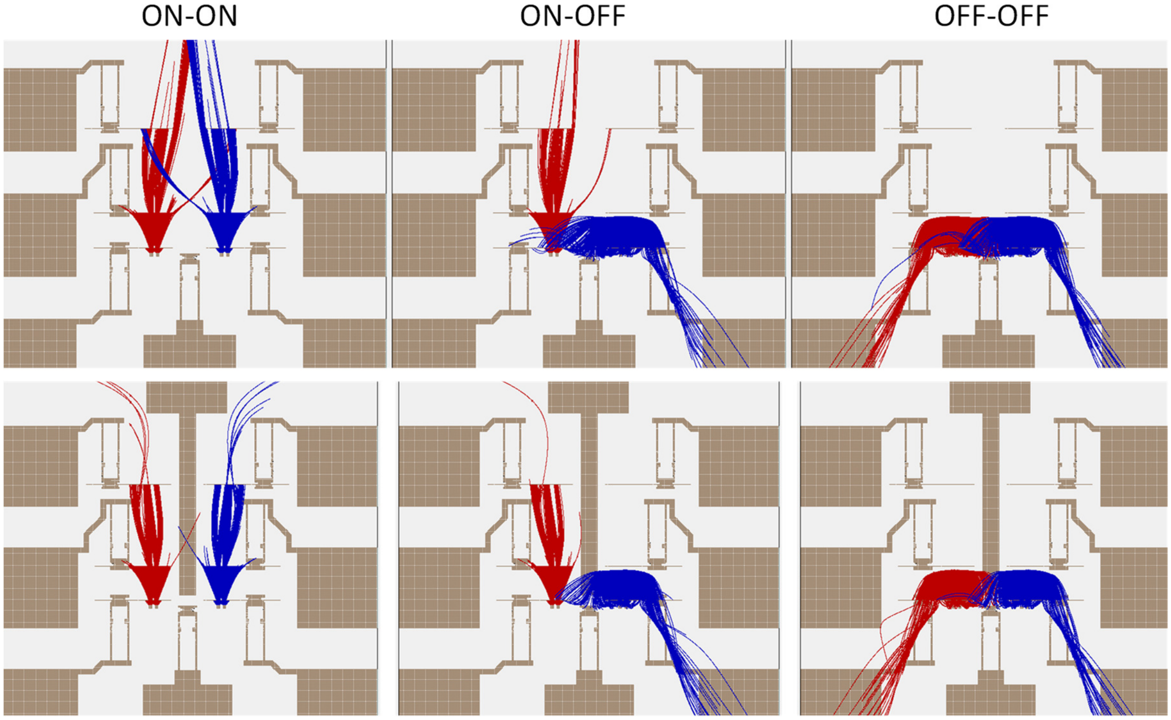

Figure 5: SimIon model of crosstalk between adjacent devices. The cathode, extraction, and anode panels are fixed at 0V, 200V, and 200V respectively. In the off state the grid is at -30V and in the on state the grid is at +30 V. The ground strip is included in the lower sequence of images and prevents electrons from hitting the output of the neighboring device.

A third limitation is that when integrating multiple triodes, significant crosstalk results from electrons travelling to panels of adjacent devices. We were able to eliminate this crosstalk by placing a narrow shielding strip on the floor between adjacent devices. This floor electrode does not require any additional processing steps, takes up minimal real estate, and enables closely spaced devices to operate independently. Figure 5 provides a SIMION comparison of two closely spaced triodes with and without a grounding strip.

A device was fabricated and tested incorporating both the shielding strip and the 4-panel structure for improved transmission as shown in Figure 6. On average, the percentage of cathode current reaching the anode improved from 25% to 65%. Additionally, the ground strip effectively eliminated crosstalk current from 10-15% of emitted current reaching a neighboring device to nearly zero. These two solutions are key enablers for further development of integrated vacuum.

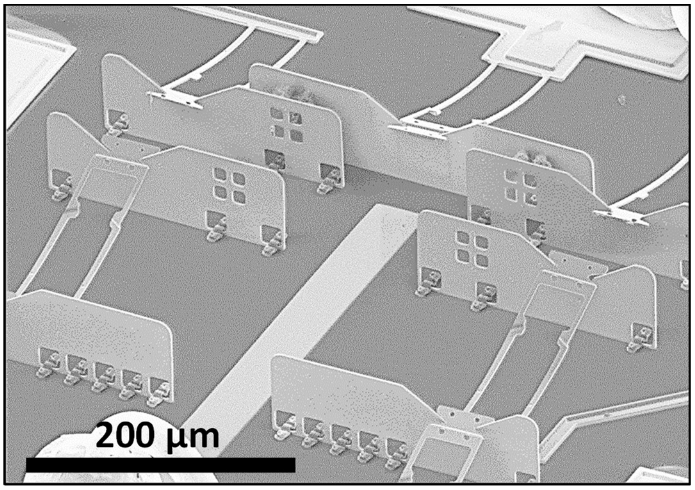

Figure 6: SEM image of two integrated triodes with a floor isolation strip that enables operation of both devices without measurable crosstalk. The four panel geometry enables improved device efficiency.

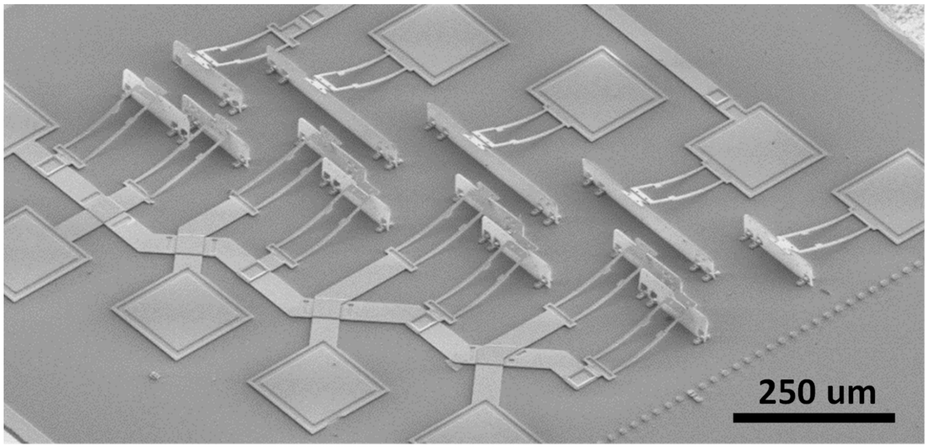

Figure 7: SEM image of integrated vacuum oscillator.

Additionally, we demonstrated that complex circuit geometries can be integrated in a compact form on a single substrate. Figure 7 depicts a ring oscillator using four integrated microtriodes. Due to reduced funding part way through the program, we were not able to test this device.

Task 2. Cathode Performance Improvement

Improved cathode lifetime and current density are key elements to a reliable, high-performance vacuum microelectronics platform. Although there have been numerous demonstrations of CNT-based field emission devices, achieving long-term emission stability and device consistency are challenges. We addressed the emission stability issue by improving the catalyst deposition process which reduced the number of stringers (long CNTs that preferentially emit but easily “burn out”). The improvement can be seen in Figure 8.

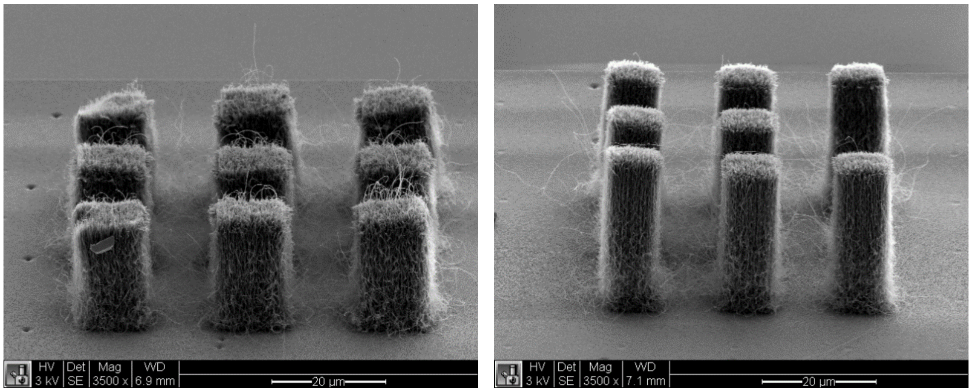

Figure 8. CNTs grown on catalyst before (left) and after (right) catalyst deposition process development.

To improve cathode lifetime, we investigated depositing a metal layer between the iron catalyst and polysilicon to eliminate CNT pull-out because poor adhesion between the CNT emitter and its substrate is the primary limiting factor for overall device lifetime. A loss of adhesion between the emitter and the substrate renders the emitter electrically inactive and could lead to catastrophic device failure if the emitter bridges electrically isolated components such as the cathode and the extraction grid. The intermediate metal layer reduces the formation of iron silicide and promotes adhesion between the polysilicon and the CNTs. We investigated molybdenum and titanium metal layers. Titanium and molybdenum adhesion layers, or interlayers, were specifically chosen based on the best literature results on crystalline silicon. They were compared to a reference sample without an adhesion layer. The titanium interlayer produced the best adhesion compared to the reference and the molybdenum interlayer samples (Fig 9). The reflectance for the as-prepared films and the average reflectance after each subsequent tape pull were directly compared to the other interlayer samples by measuring against a control sample of a metal interlayer without a CNT forest. The titanium interlayer samples required 2.5 times more adhesion tests to reach saturation when compared to the reference sample, whereas the molybdenum showed only a small improvement of 1.3 times more than the reference sample.

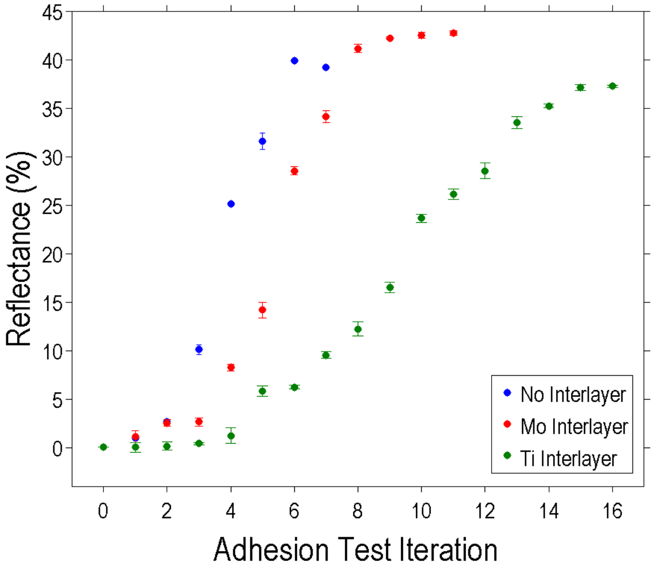

Figure 9. Average reflectance from the underlying substrate as measured by spectrophotometer for CNTs grown using various metallic interlayers. The error bars represent standard deviation. An adhesion improvement of approximately 1.3x was observed for Mo interlayers, and approximately 2.5x for Ti interlayers compared with the control sample of CNTs grown on Fe-coated poly-Si.

Another area of investigation was the use of conformal atomic layer deposition (ALD) coatings to to reduce the turn-on field and improve lifetime. ALD-deposited HfO_2 was chosen as the first candidate CNT coating. We developed and characterized a recipe for deposition of HfO_2 (Figure 10) in preparation for coating of CNT's.

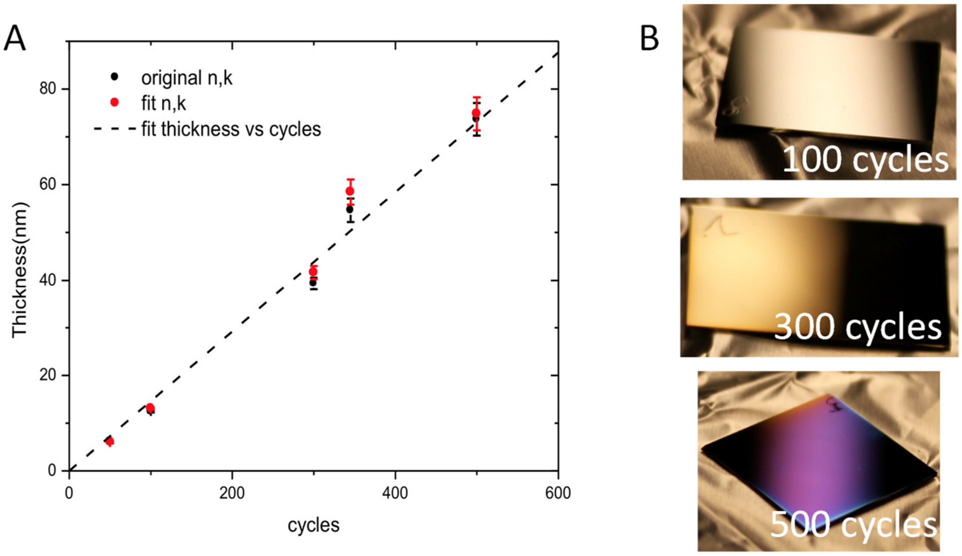

Figure 10: (A) Number of ALD cycles of HfO2 vs films thickness on silicon, as determined by spectroscopic ellipsometry. (B) Images of films of varying thickness.

Task 3. Panel Reliability Enhancement

The long-term reliability of microscale vacuum devices is a potential concern because the grids and anodes must be able to withstand an impinging electron beam for the lifetime of the device. Investigation into reliability characterization and enhancement was scheduled for the later stage of the program and was therefore not completed due to the discontinued funding. We were able to fabricate some test structures in the PolyMUMPS process to enable failure characterization in the future.