# REPORT DOCUMENTATION PAGE

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R&D Status Report 10/01/93 - 12/31/93

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RF Vacuum Microelectronics

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13. ABSTRACT *(Maximum 200 words)*

We summarize our progress towards developing a thin film edge emitter vacuum transistor capable of 1 GHz modulation. The second fabrication run of vacuum transistors was carried out and is approximately 90% complete. Fabrication is anticipated to be completed in early January 1994.

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# R&D Status Report
# RF Vacuum Microelectronics
# Quarterly Progress Report #9
(10/1/93 - 12/31/93)

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| | |
|---|---|
| Effective Date of Contract: | September 30, 1991 |
| Contract Expiration Date: | May 31, 1993 (Baseline) |
| Option Expiration Date: | February 15, 1994 (Revised) |
| Contract Amount: Baseline | $1,315,650 |
| Option: | $ 465,000 |



| | |
|---|---|
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Title of Work: **RF Vacuum Microelectronics**

# I. Executive Summary

**Technical Approach**: Our technical approach is to utilize thin film technology and surface micromachining techniques to demonstrate an edge emitter based vacuum triode. An array of vacuum transistors are connected in parallel to achieve microwave performance. The edge emitter triode approach offers several potential advantages to achieving high frequency device operation (compared to cone emitters or wedge emitters):

- Thin film processes for the films used in the triode process are well controlled and reproducible. Control of film thicknesses to within 5% for the emitter film thickness is easily attainable resulting in a well-controlled edge emitter.
- Device capacitance for the edge emitter is less than that achievable for cones or wedges resulting in potentially higher frequency operation.
- The fabrication process is a planar process, compatible with most silicon IC manufacturing.

**Program Objective:** **Demonstrate an edge emitter based microwave vacuum transistor with gain at 1 GHz continuously for 1 hour.**

**Key Achievements:** (this reporting period)

- Fabrication of the second run of microwave transistors was carried out this quarter. Device fabrication is 90% complete with completion anticipated in early January.

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## II. Milestone Status

| | Completion Date | | Comments |
|---|---|---|---|
| | Planned | Actual | |
| **Task 1. Field Emitter Development** | | | |
| Test Structure Design Complete | 12/91 | 01/91 | complete |
| Determine Workable Emitter Structure | 03/92 | 12/92 | complete |
| Demonstrate Emission Current of 10 μA/μm | 11/92 | 11/92 | complete |
| Deliver 10 Field Emitting Diodes | 12/92 | 10/92 | delivered |
| **Task 2. Process Development** | | | |
| High Resistivity Thin Film Resistor | 04/92 | 09/92 | complete |
| Complete Dielectric Studies | 05/92 | 06/92 | complete |
| Mechanical and Electrical FEM Analysis | 05/92 | 08/92 | complete |
| **Task 3. Triode Development** | | | |
| Triode Design Complete | 04/92 | 05/92 | complete |
| Demonstrate Reliable/Uniform Current Emission | 07/92 | 10/92 | complete |
| Demonstrate Modulated/Edge Emitter Triode | 08/92 | 12/92 | complete |
| Demonstrate 1 GHz Modulation of Triode | 02/93 | 12/92 | behind plan |
| Deliver 2 Triodes | 03/93 | 08/93 | complete |
| **Task 4. Final Report (Baseline)** | 04/93 | 04/93 | complete |
| **Task 5. High Frequency Demo** | | | |
| Design Microwave Vacuum Transistor | 06/93 | 06/93 | complete |
| Complete Process Development | 06/93 | 06/93 | complete |
| Complete High Frequency Probe Assembly | 06/93 | 06/93 | complete |
| Demonstrate Vacuum Transistor with High Current | 10/93 | 02/94 | behind plan |
| Demonstrate 1 GHz Modulation with Gain | 10/93 | 02/94 | behind plan |

# III. Technical Progress

## Microwave Vacuum Transistor Fabrication

We completed two fabrication runs during this reporting period. The first of the two fabrication runs did not yield devices because of the formation of metal wings during the definition of the edge. The definition of the edge was done by a combination of plasma etches for the nitride layers and ion mill for the 300 Å TiW emitter layer.

We corrected the problems in the next fabrication run by hard baking the resist layer before the etches. This solved the problem of formation of wings on the wafers after the edge definition step.

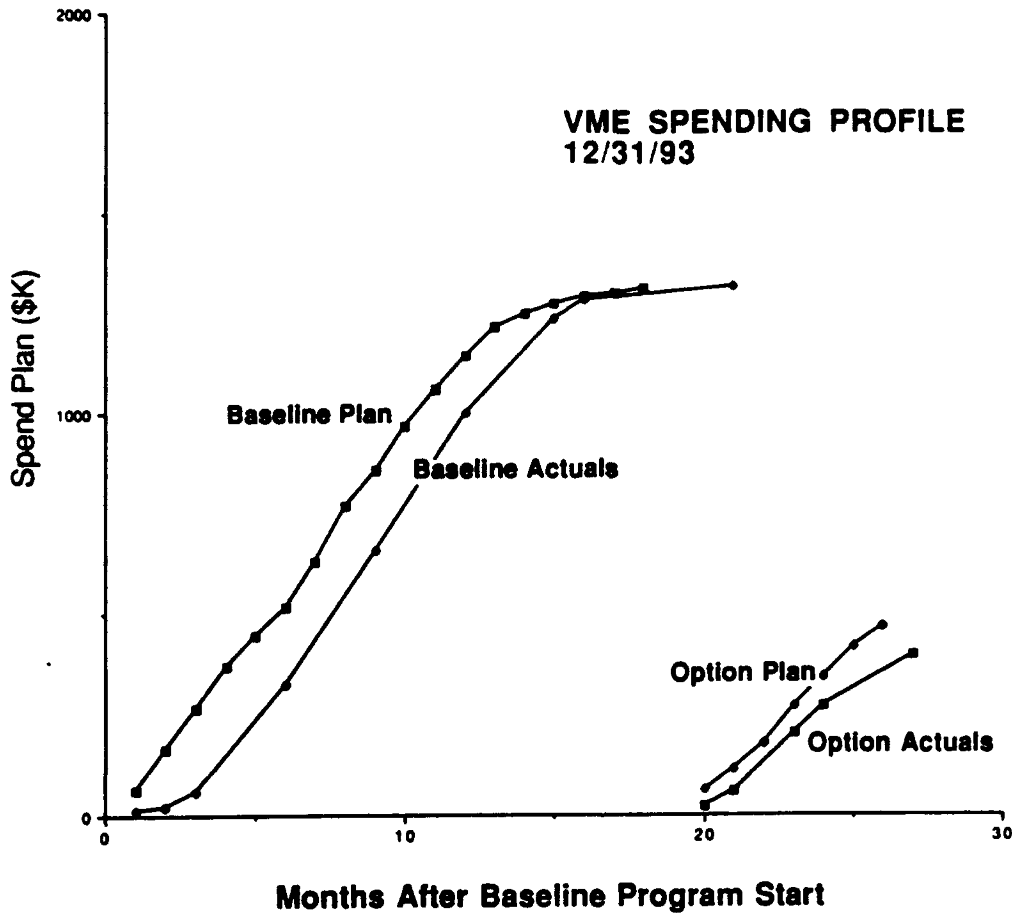
Figures 1 and 2 are photos of devices from the final fabrication run which are currently under testing. Figure 1 shows 12 fingers of emitter/gate (together) and 12 fingers of anode. The emitter segments are all connected in parallel. The same applies to the gate segments and the anode segments. The metal on the outer ring is the emitter/ground. The gate/input pad feeds into "green T", and it is connected to 12 gate segments each with a lower and upper gate electrode. The output/anode is the top inverted T (near the numbers), and it consists of 12 segments also. There are also 12 emitter segments. They are sandwiched between the upper and lower gates. The emitter "runners" run parallel to the gate electrodes. The output pad is opposite the input pad. The input and output pads are both surrounded by the ground/emitter pad. Each segment is 200 μm long leading to a total emitter width of 2400 μm. This device design is really sophisticated and has a lot of promise for low-cost assembly, test, and manufacturing. We have found in the course of this program simpler approaches that can be implemented in the future. One such technique is the use of high aspect ratio reactive ion etching. Such a tool will drastically reduce the complexity and cost of this particular device because the alignment of the two gates and emitter will no longer be critical.

Figures 3, 4, and 5 are SEM of the device structure taken after the final sacrificial layer etch. From the SEMs, it can be seen that the microstructure appears exactly as planned within the alignment tolerance of the photolithography system. The SEMs show some views taking at a tilt of 80°, and they show the emitter sandwiched between the upper and lower gate and the anode is 10 μm from the emitter/gate stack.

## Microwave Vacuum Device Evaluation

Our initial test results on two completed wafers show triode action with the gate voltage controlling the anode current. The anode current and the emitter currents are equal, while the gate current is usually below 5% of the anode current. However, the maximum current we have attained thus far is 35 μA. We believe the low current is an indication of dirty surfaces or an oxide on the emitter film and emission is only occurring where there is a break in the oxide. We believe the oxide is TiOx and we are exploring ways of removing it ex-situ and in-situ.

## IV. Fiscal Status




| | Baseline Program | Option Phase |
|---|---|---|
| Expenditures this quarter | | $127K |
| Total expenditures to date | $1,395K | 395K |
| Projected expenditures (baseline): | | |
| 10/93 - Program Completion | 0 | 70K |
| Total Projected Cost for Program | $1,315,650* | $465K |

*Total cost to ARPA. The remaining funding for the baseline program (~$80K) is being cost-shared by Honeywell through a limitation of its overhead rates. In addition, as a result of the February 1, 1993 program review with ARPA, Honeywell agreed to an additional investment (internal development funds) of approximately $71K to provide further testing, testing enhancements and process enhancements to the VME effort. Of this $71K committed all has been spent.

### Plans for Next Reporting Period

- Complete fabrication of run #2.
- Complete dc and ac characterization of VME devices from run #2.
- Demonstrate 1 GHz modulation on a thin film edge emitter triode device.

## V. Programmatics

- To ensure the greatest possibility of success of yielding high performance vacuum transistors, the fabrication process has been slowed down to allow for step-by-step inspection of the devices. This has necessarily resulted in an extension of the original schedule. A request to ARPA has been made to extend the technical period of performance to February 15, 1994.

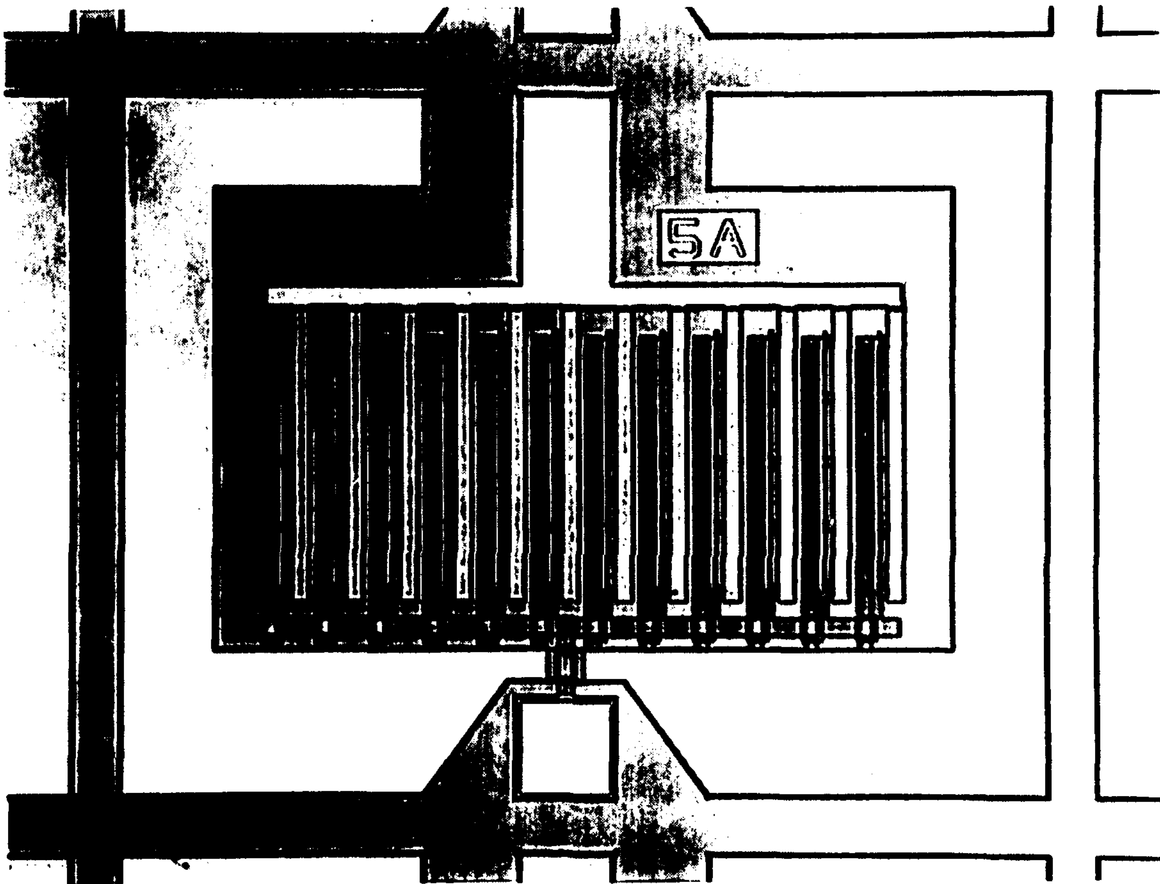



**Figure 1 :** Photo of Microwave Vacuum Transistor showing the three electrodes—anode, gate, and emitter. It shows the device consists of 12 segments each 200 μm long.

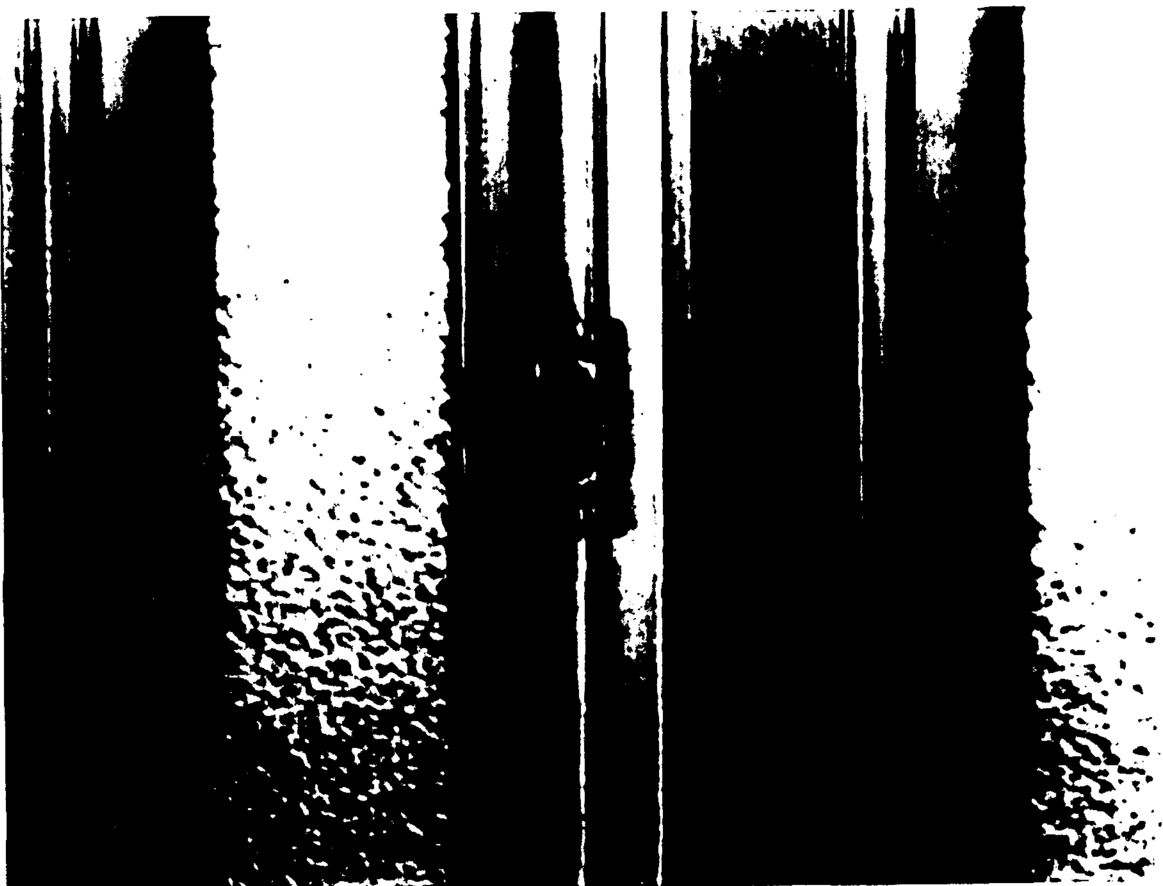


Figure 2 : Close-up photo of the Microwave Vacuum Transistor showing the anode gate and emitter of a segment.

Figure 3 : SEM of the Vacuum transistor showing the anode gate and emitter of a segment.

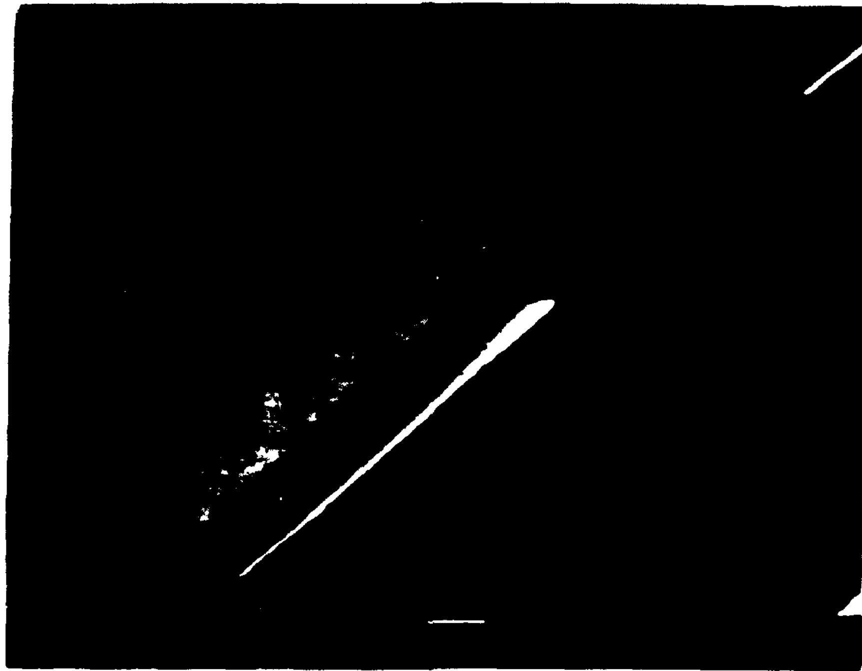


**Figure 4 : SEM of a Microwave Vacuum Transistor.**

Figure 5 : SEM of a Microwave Vacuum Transistor.