Vacuum Microelectronics
for
Beam Power and Rectennas

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Both solid-state and vacuum electronics have serious limitations and weaknesses with respect to applications in space, particularly for beaming and receiving microwave and millimeter wave power. For example, solid-state devices are limited in speed due to velocity saturation of charge carriers in the transport channel of FETs. This saturation is due to the generation of optical and acoustic mode phonons which occurs in all materials. In order to increase the speed of solid-state devices, the transport channel length is decreased. However, as the length is decreased, the voltage across the channel must also decrease to prevent voltage breakdown of the device. The consequence is that significant power cannot be obtained in a single device, and power combining is difficult, if not technically or economically impractical. Vacuum electronics also have significant problems, the greatest of which is the size and weight of vacuum tubes. There is also the extremely high cost which is determined to a great extent by the machine shop manufacturing methods used. In addition, they cannot be integrated into high density circuits. Vacuum microelectronics, which is presently based on field emitter arrays, promises to eliminate many of the problems experienced in both solid-state and vacuum electronics. It takes advantage of the fabrication and processing methods of solid-state and the ballistic electron advantage of vacuum electronics. Vacuum Microelectronic devices can be described as vacuum transistors or micro-miniature vacuum tubes, as one chooses. The fundamental reason behind this new technology is the very large current densities available from field emitters, namely as high as $10^8 \text{ A/cm}^2$. Array current densities as high as 1000 A/cm$^2$ have been measured. Total electron transit times from source to drain for 1 micron feature size devices have been predicted to be about 150fs. This very short transit time implies the possibility of submillimeter wave transmitters and rectennas in devices which can operate with reasonably high voltages and which are small in size and are lightweight. In addition, they are expected to be extremely radiation hard and very temperature insensitive. That is, they are expected to have radiation hardness characteristics similar to vacuum tubes, and both the high temperature and low temperature limits should be determined by the package. That is, there should be no practical intrinsic temperature or carrier freezeout problems for devices based on metals or composites. But the technology is difficult to implement at the present time because it is based on 300-500 angstrom radius field emitters which must be relatively uniform. There is also the need to understand the non-equilibrium transport physics in the near-surface regions of the field emitters (both in the solid and in the vacuum). It appears, nevertheless, that this technology would be very attractive for future space beam power and rectenna applications.
Field Emitter Array Electronics

Technical Promise

- High Current Density: $> 1000 \text{ A/cm}^2$

- Very Radiation Hard: "Vacuum Tube" Hardness

- Temperature Insensitive: $-100\text{C} \text{ to } +1000\text{C}$

- Long Operational Life: No known wearout mechanism

- Ultra-high Speed: $> 100 \text{ Ghz for medium power mm wave amplification}$

  $< 150 \text{ fs for signal processing}$

Vacuum Microelectronics

Outline

- Can't Solid State Hack It?

- Classical Field Emission

- Field Emitter Arrays

- Beam Power

- Rectennas
What is "Vacuum Microelectronics"?

Vacuum Microelectronics is a new electronics technology that combines solid state microelectronics fabrication and processing with vacuum electron ballistic transport. It promises to extend the present limits of both solid state and vacuum electronics. The basis for vacuum microelectronics at the present time is the Field Emitter Array, where the active charge transport structure is a miniature electron field emitter of 500 angstrom radius, and the fundamental cell dimension is one micrometer or smaller; that is, as small as, or smaller than, VLSI active cells.
Vacuum Microelectronics Based on Field Emitter Arrays

Weaknesses of Solid State Electronics

- Temperature Sensitive
  - High Temperature Limit - Intrinsic Temperature
  - Low Temperature Limit - Carrier Freeze-out

- Radiation Sensitive
  - Bulk and Surface Charges
  - Lattice Damage
  - Electron-Hole Pair Generation

- Voltage Breakdown
  - High Electric Fields in One-Dimension
  - Thin Dielectric Layers

- Finite Carrier Velocity
  - < $5 \times 10^7$ cm/s in all solids
  - Acoustic and Optical Phonon Generation

Classical Field Emission

3,000 - 10,000 volts

e^-
e^-

Sharp
Tungsten
Needle
FIELD EMISSION

- FIRST REPORTED IN 1897 (R. W. WOOD)
- THEORY DEVELOPED IN 1928 (FOWLER, NORDHEIM)

\[ V = \phi + E_F - eF \cdot X \]
\[ F = 3 \times 10^7 \text{ V/cm} \]

\[ V_b(E_x) = \phi + E_F - E_X - eF \cdot X \]
\[ x_0 (\text{THICKNESS AT FERMI LEVEL}) = \frac{1}{eF} \]

INTEGRAL GRIDDED SINGLE CRYSTAL SILICON FEA

\[ +100 \text{ VOLTS} \]

(111) PYRAMID

Au CONTACT

1 MICRON

SINGLE CRYSTAL SILICON (100)
POTENTIAL DISTRIBUTION

GATE = 100 Volts
COLLECTOR = 200 Volts
APERTURE = 1.50 \mu m

Ion Bombardment Effects

Conventional Electron Field Emission

Field Emitter Arrays

+ (3-10) KV

+ 1 KV

Sharp Tungsten Needle

Metal or Semiconductor
PHYSICS OF SPEED LIMITATIONS IN ELECTRONIC DEVICES

- **Saturation Velocity**
  - **Solid State Devices**
    - $< 3 \times 10^7 \text{ cm/s}$
  - Due to optical and acoustic phonon scattering

- **Field Emitter Arrays**
  - $< 3 \times 10^{10} \text{ cm/s}$
  - Practical value (at 100V):
    - $6 \times 10^8 \text{ cm/s}$

- **Acceleration**
  - **Solid State Devices**
    - 
  - **Field Emitter Arrays**
    - 

Field Emitter Array Electronics

Comparison of Electronics Technologies

- **Vacuum Tubes (1950 Vintage)**
  - Current Density $1 \text{ A/cm}^2$
  - Large Device Structures

- **Transistors**
  - Current Density $1000 \text{ A/cm}^2$
  - Small Device Structures

- **Field Emitter Arrays**
  - Current Density $10^7 - 10^8 \text{ A/cm}^2$
  - True Submicron and Nanostructure Devices
FIELD EMITTER ARRAY SWITCH

- ULTRA FAST • NO LATCH-UP • PLANAR OR 3-D

FEATRON
FABRICATION OF THE NRL FEA

Si$_3$N$_4$

(100) SILICON

PHOTOLITHOGRAPHY

(111)

(100) SILICON

VMOS ETCH
(111) PYRAMIDS

GOLD
SILOX

(100) SILICON

INSULATOR,
METAL
DEPOSITION

1 MICRON

(100) SILICON

FINISH
SILICON PLANAR FIELD EMITTER ARRAY VACUUM FET

INTERDIGITATED SILICON PLANAR FIELD EMITTER ARRAY VACUUM FET

SOURCE = SUBSTRATE
GATE MODULATION OF SILICON PLANAR VACUUM FIELD EMITTER ARRAY FET

Gate Voltage
(1V/cm)

Drain Voltage
(2V/cm)

Time
(5 ms/cm)

Fowler-Nordheim Plot

N-Type Silicon 5 Ω-cm
(10²⁰/cm² Phosphorus)
Interdigitated Planar Collector
40 Tip Field Emitter Array

\[
\text{LOG [AMP/VOLT²]} \quad -10 \\
\quad -11 \\
\quad -14 \\
\quad -13 \\
\]

\[
\frac{1}{(\text{VOLTS})^{-1}} \times 10^3 \\
5 \quad 6 \\
7 \\
8 \\
9 \\
10 \\
\]
Current saturation in n-type semiconductor

\[ I = A_0 n_s v_i \]

\( v_i \) = constant in saturated regime

Current is not sufficient to support an arc

Non-equilibrium: velocity saturation

Electron Density

Modified Energy-Band Diagram

Surface charge depletion and increased field penetration
Field Emitter Array Embedded Stripline Triode

Not to Scale
Field Emitter Array Triode Space-Charge Limit

![Diagram](image)

<table>
<thead>
<tr>
<th>MINIMUM COLLECTOR VOLTAGE (Volts)</th>
<th>MAXIMUM &quot;SCREEN&quot;-COLLECTOR SPACER (micrometers)</th>
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<tr>
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</table>

\[
J_a = \frac{2.3 \times 10^{-6} (V_{p}t + V_{l}t)}{h^4} \frac{\text{Amps}}{\text{cm}^2}
\]

FIELD EMITTER ARRAY DISTRIBUTED AMPLIFIER
for MICROWAVE AND MILLIMETER WAVE FREQUENCIES
INTEGRAL GRIDDED SINGLE CRYSTAL SILICON FEA WITH SECOND FOCUS GRID

Vacuum Microelectronics

Photo-Excited Field Emitter Arrays
Vacuum Microelectronics Based on Field Emitter Arrays

Research and Development

- 3-D Fabrication and Processing in the 300-500 Angstrom Regime
- 3-D Microstrip Transmission Line Theory and Calculations
- Field Emitter Array Physics - Theory and Experiment
- Device and Circuit Design