Vacuum Microelectronics
for
Beam Power and Rectennas

Henry F. Gray
Naval Research Laboratory
Washington, DC 20375

SUMMARY

VACUUM MICROELECTRONICS FOR BEAM POWER AND RECTENNAS

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 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 reasonalbly 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.

Technical Promise

- High Current Density: > 1000 A/cm^2

- Very Radiation Hard: "Vacuum Tube" Hardness

- Temperature Insensitive: -100C to +1000C

- Long Operational Life: No known wearout mechanism

- Ultra-high Speed: $>$ 100 Ghz for medium power mm wave amplification

- $<$ 150 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.

HUMAN HAIR

METAL
OXIDE
SILICON

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

Sharp

Tungsten

Needle
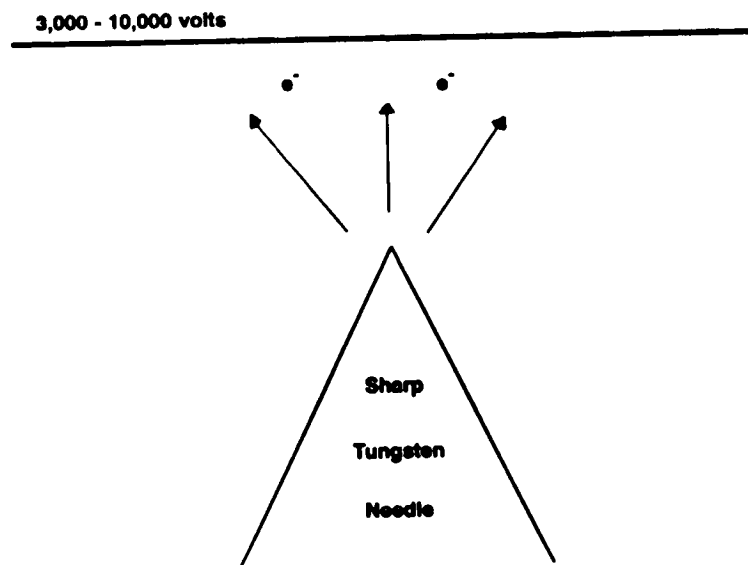
- FIRST REPORTED IN 1897 (R. W. WOOD)

- THEORY DEVELOPED IN 1928 (FOWLER, NORDHEIM)

VACUUM LEVEL

EV 4
    3
    2
    1

$V = \phi + E_F - \varepsilon F \cdot X$

$F = 3 \times 10^7$ V/CM

5   10   15   A

$X \longrightarrow$

E_F
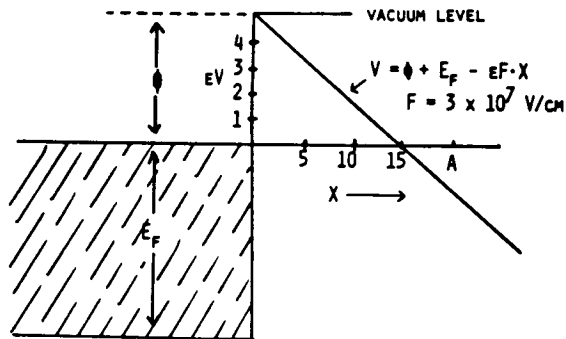
$V_B(E_X) = \phi + E_F - E_X - \varepsilon F \cdot X$

X_0(THICKNESS AT FERMI LEVEL) $= \dfrac{\phi}{\varepsilon F}$

INTEGRAL GRIDDED SINGLE CRYSTAL SILICON FEA

+100 VOLTS

(111) PYRAMID

Au CONTACT

SiO_2

1 MICRON

SINGLE CRYSTAL
SILICON (100)
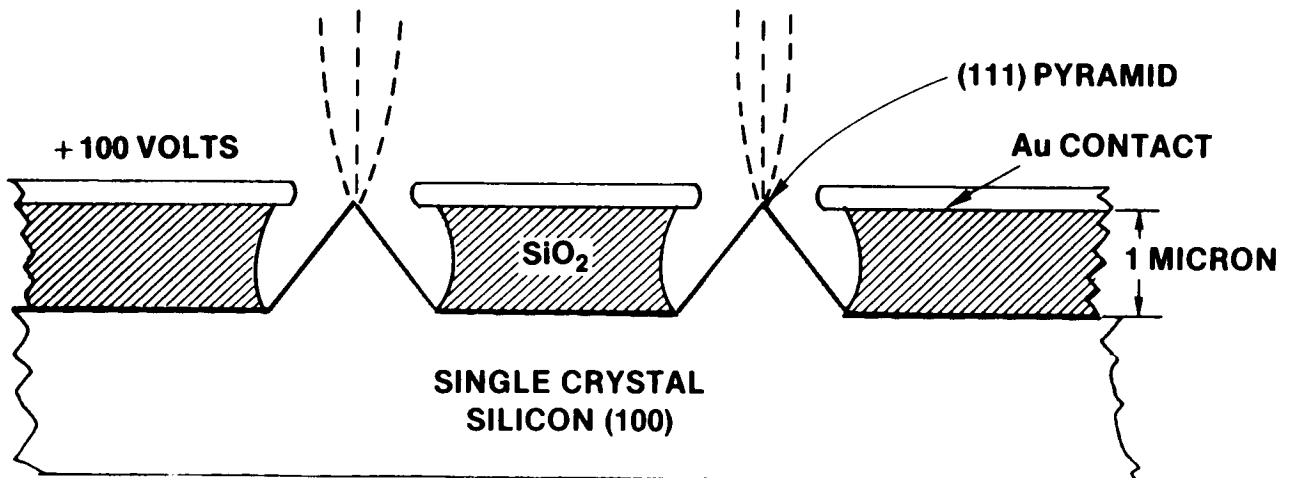
POTENTIAL DISTRIBUTION

$$GATE = 100 \quad Volts$$

$$COLLECTOR = 200 \quad Volts$$

$$APERTURE = 1.50 \quad \mu m$$
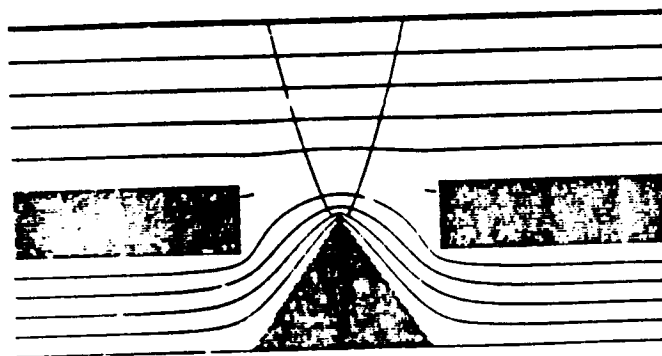
Ion Bombardment Effects

Conventional Electron Field Emission

Field Emitter Arrays

+ (3 -10) KV

+ 1 KV

Sharp
Tungsten
Needle

Metal or Semiconductor
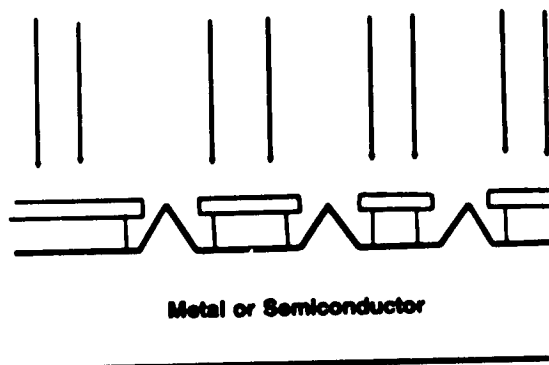
o   Saturation Velocity

      Solid State Devices

        $< 3 \times 10^7$ cm/s

    Due to. optical and acoustic

    phonon scattering

      Field Emitter Arrays

       $< 3 \times 10^{10}$ cm/s

    Practical value (at 100V):

        6×10^8 cm/s

o   Acceleration

Solid State Devices
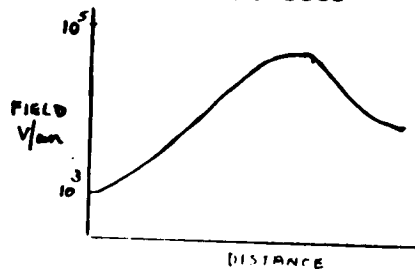
Field Emitter Arrays
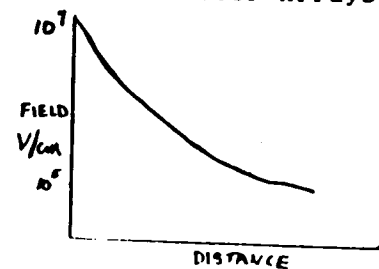
Field Emitter Array Electronics

Comparison of Electronics Technologies

- **Vacuum Tubes (1950 Vintage)**
  - **Current Density**   1 A/cm^2
  - **Large Device Structures**

- **Transistors**
  - **Current Density**   1000 A/cm^2
  - **Small Device Structures**

- **Field Emitter Arrays**
  - **Current Density** 10^7 - 10^8 A/cm^2
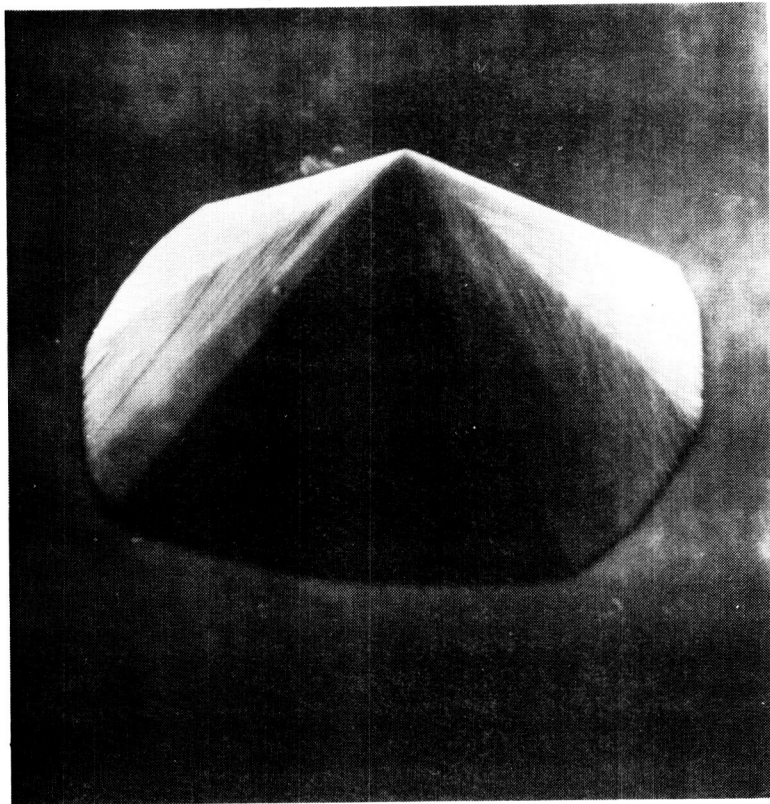 - **True Submicron and Nanostructure Devices**

FIELD EMITTER ARRAY SWITCH

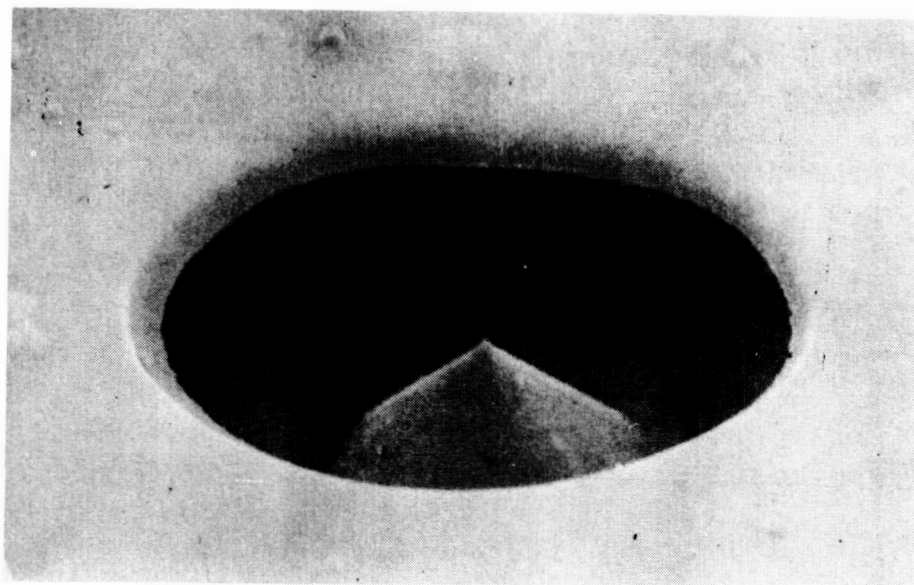• ULTRA FAST • NO LATCH-UP • PLANAR OR 3-D
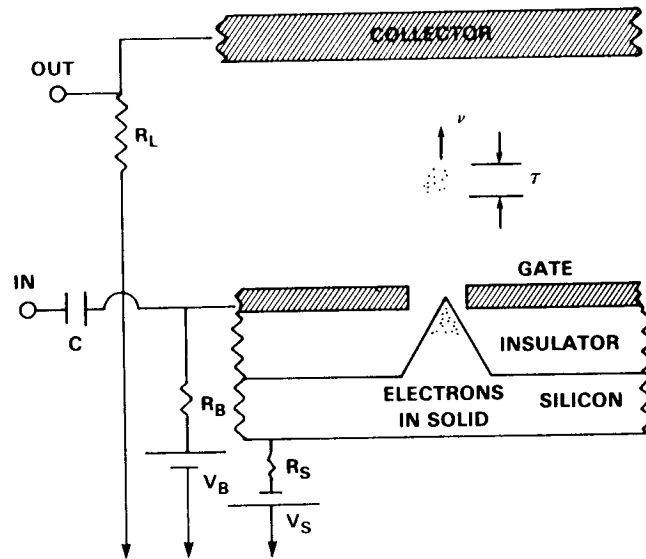
FEATRON
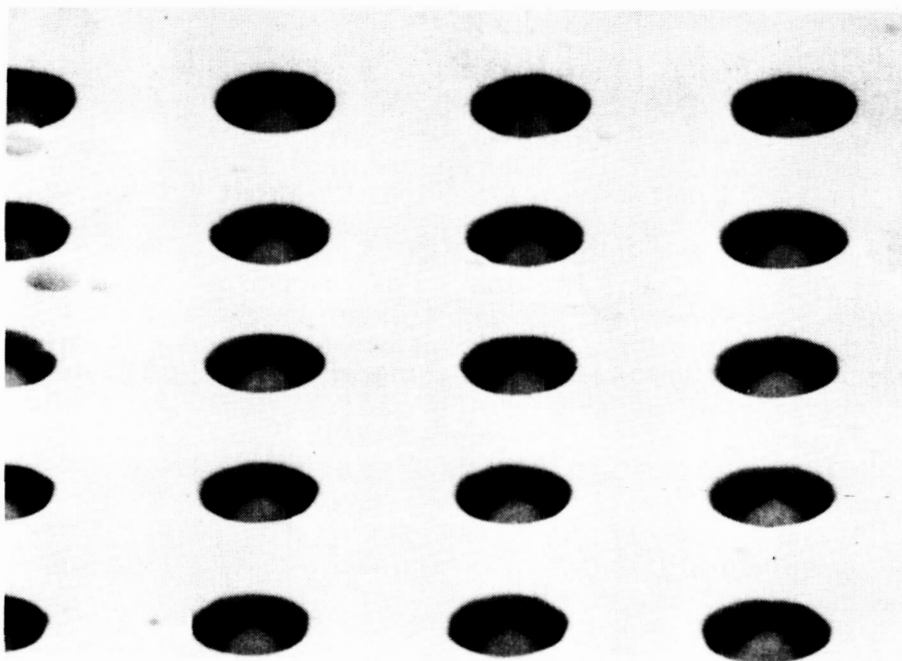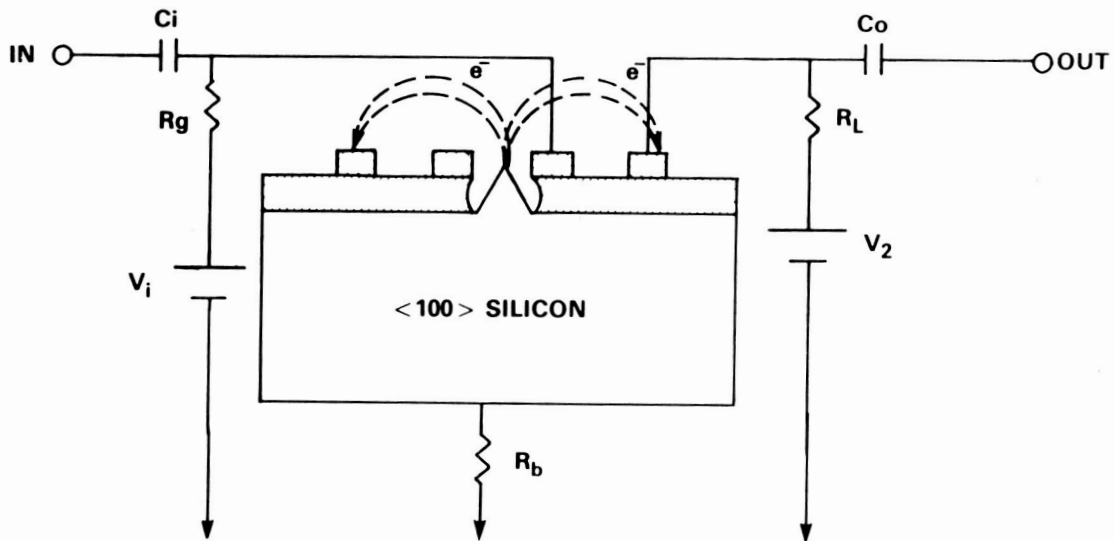# FABRICATION OF THE NRL FEA

CREATION OF SILICON FIELD EMITTER ARRAYS
(FEA) BY ANISOTROPIC ETCHING (10,000×)

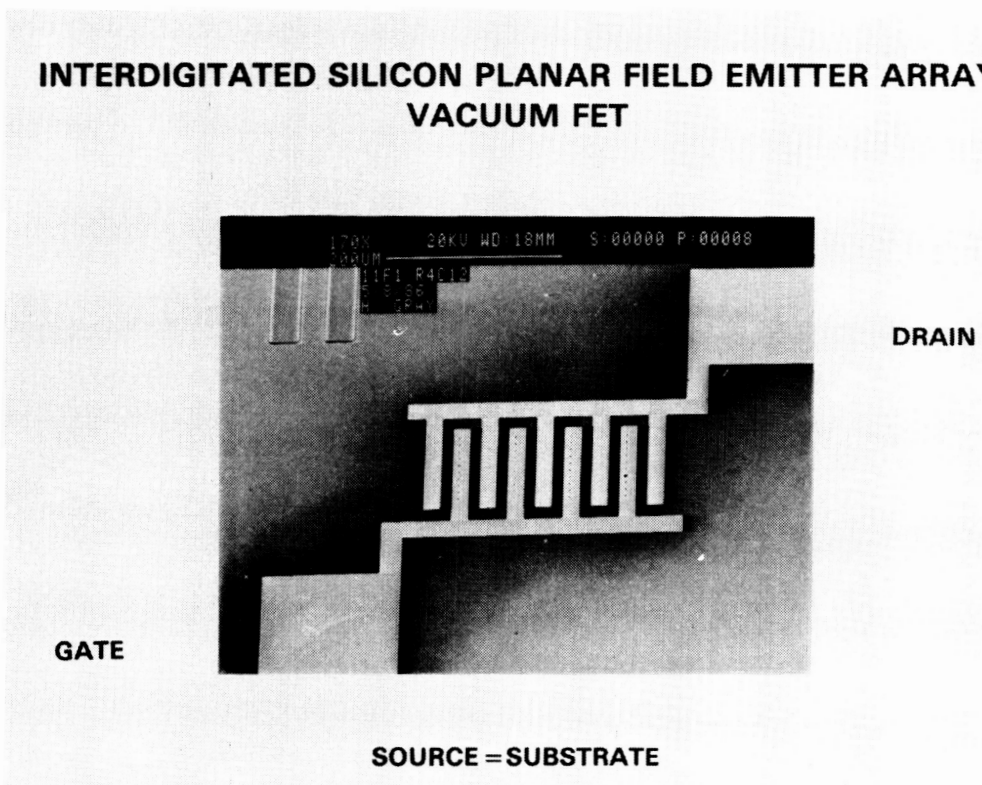30KV X100000 1II 014 NRI △MD

117
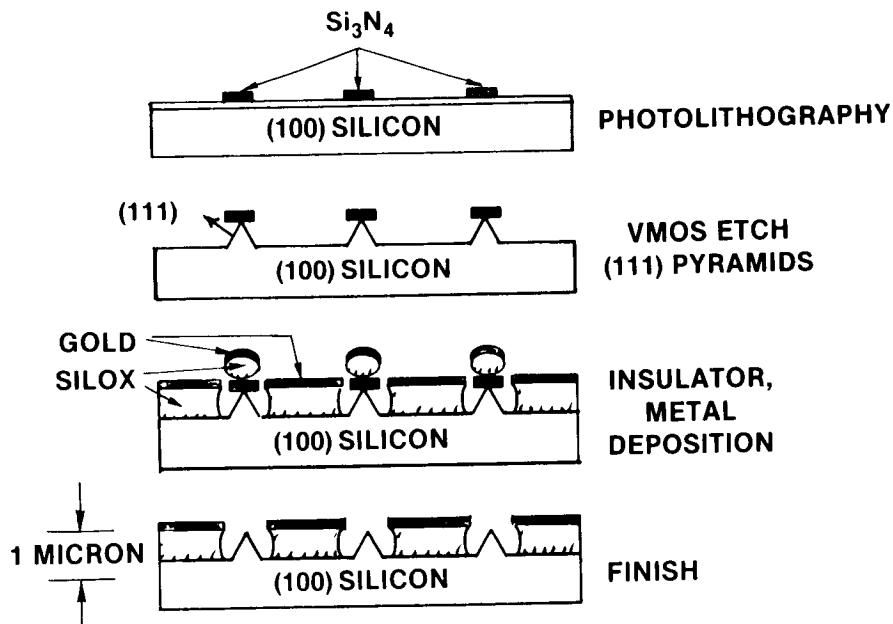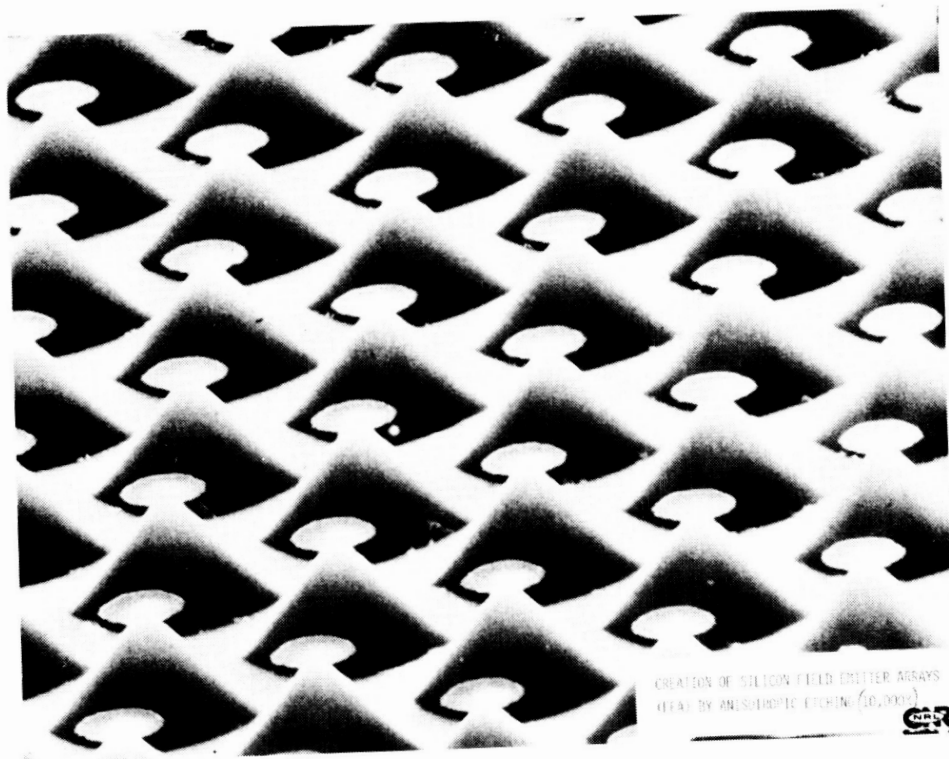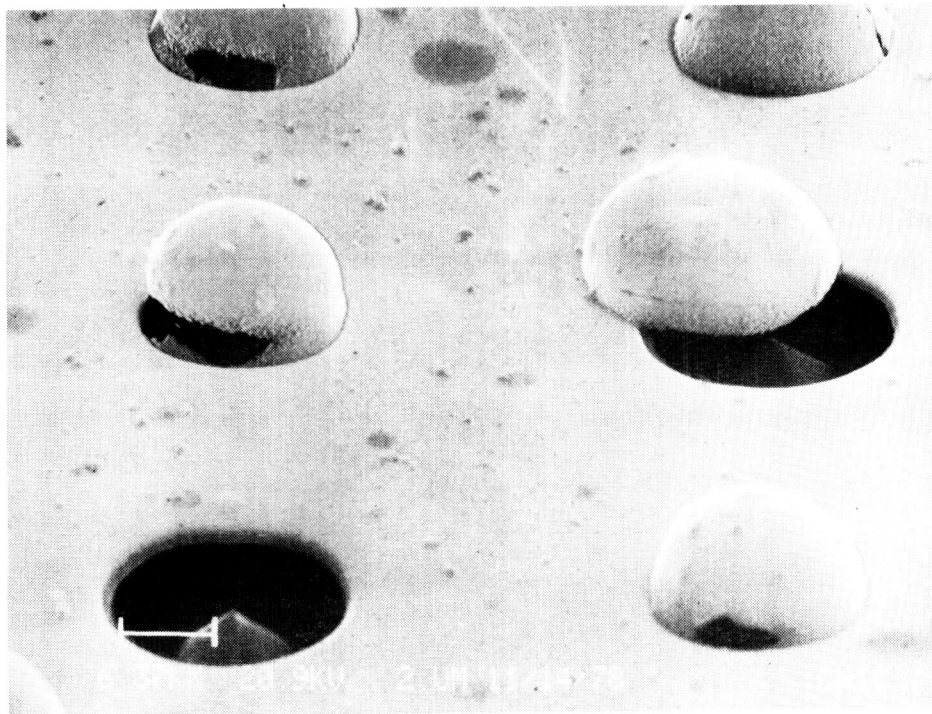
ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

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SILICON PLANAR FIELD EMITTER ARRAY VACUUM FET

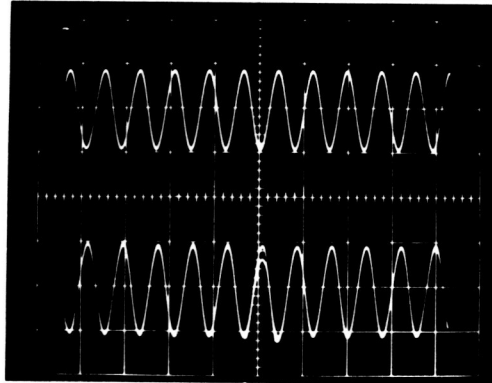## INTERDIGITATED SILICON PLANAR FIELD EMITTER ARRAY VACUUM FET

DRAIN

GATE

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
(10^{15}/cm^3 PHOSPHORUS)
INTERDIGITATED PLANAR COLLECTOR
40 TIP FIELD EMITTER ARRAY

10^{-6}AMPS

LOG (AMP/(VOLTS)^2)

1/(VOLTS)$^{-1}$ × 10^3

Current Saturation in n-Type Semiconductors

$$I = A_i n_i e v_i$$
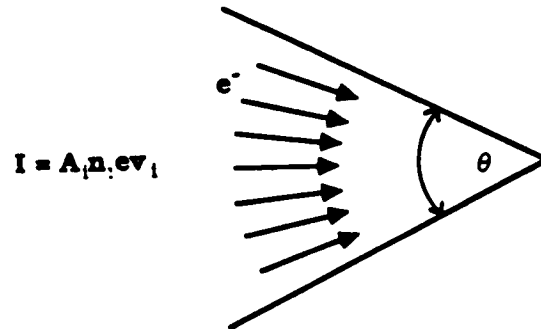
v_i = constant in saturated regime

current is not sufficient to support an arc

Non-equilibrium: velocity saturation

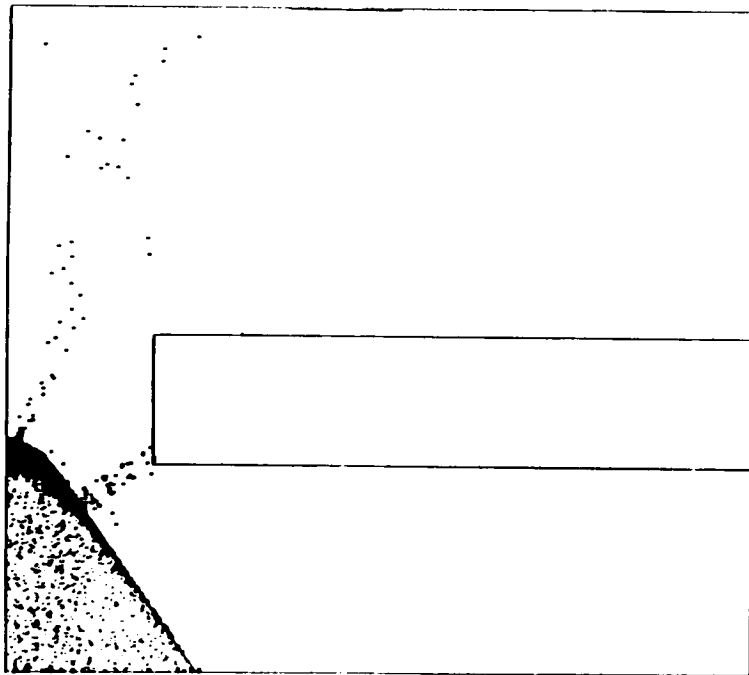### Electron Density

η_E

n

η_s

n_B

$\longleftarrow z$

Modified Energy-Band Diagram

F
W

c

$e^- \rightarrow$

ϵ_F

non-equil

equil

v

$\longleftarrow h$
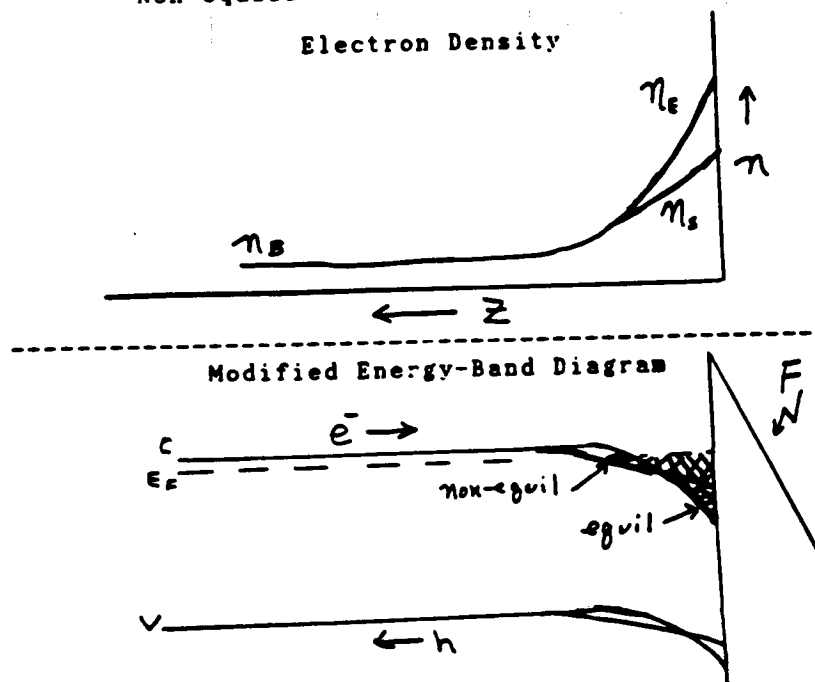
Surface charge depletion and increased field penetration

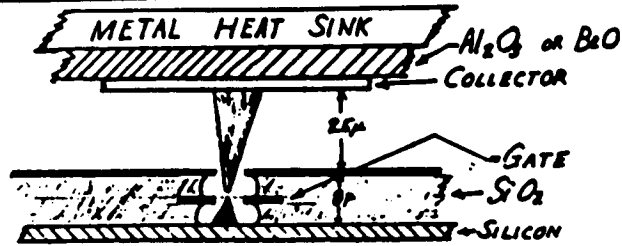## Field Emitter Array Embedded Stripline Triode
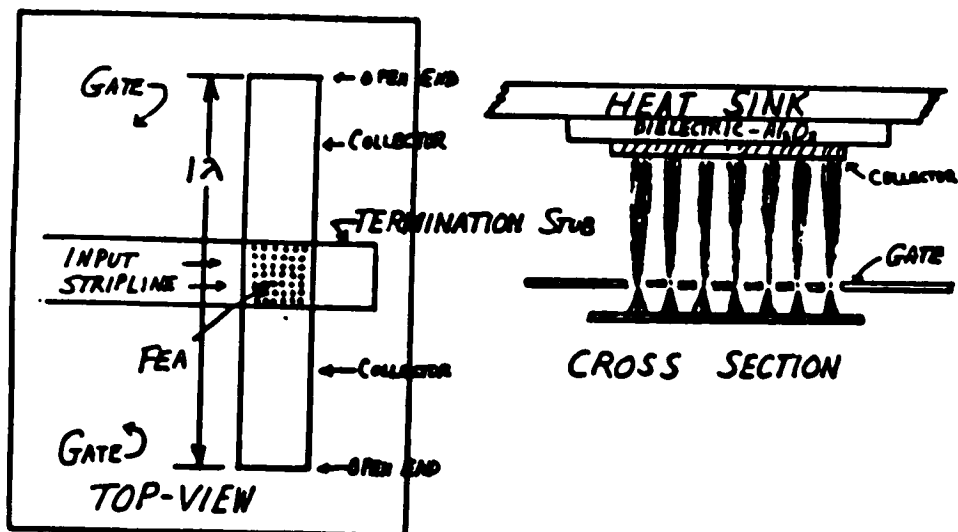
Not to Scale

Field Emitter Array Triode Space-Charge Limit

MINIMUM COLLECTOR VOLTAGE (Volts)	MAXIMUM "SCREEN"-COLLECTOR SPACING (micrometers)
16.0	25.0
50.0	44.3
75.0	54.5
100.0	63.0
200.0	88.7
300.0	109.0
400.0	125.6

$$ J_m = \frac{2.3 \times 10^{-6} \times (V_i^{\frac{1}{2}} + V_c^{\frac{1}{2}})^3}{D^2} \quad \frac{Amps}{cm^2} $$

FIELD EMITTER ARRAY DISTRIBUTED AMPLIFIER
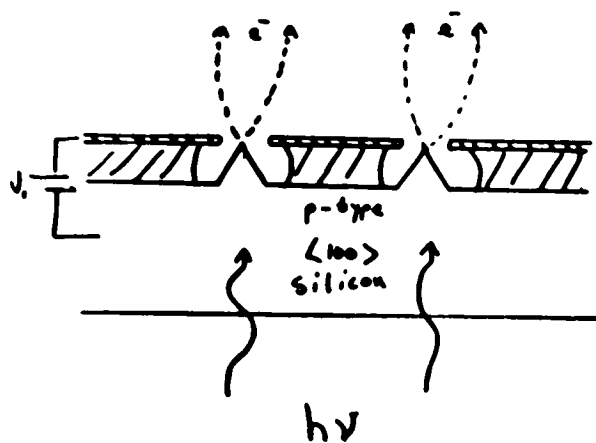### for
MICROWAVE AND MILLIMETER WAVE FREQUENCIES

Output Wave Direction ⟶

Input Wave Direction ⟶

123
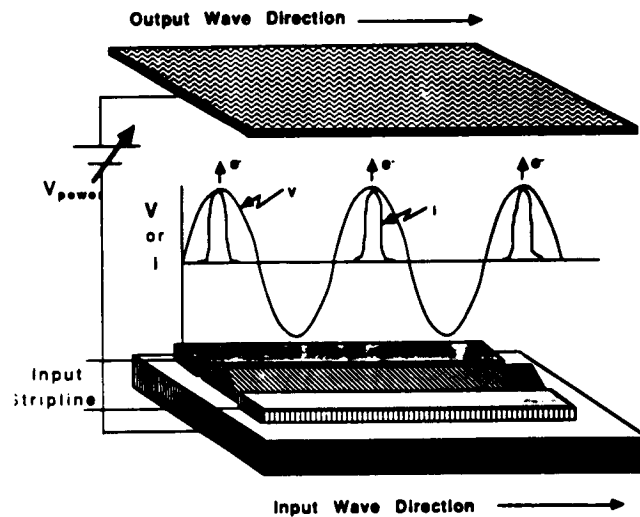
INTEGRAL GRIDDED SINGLE CRYSTAL
SILICON FEA
WITH SECOND FOCUS GRID

FOCUS GRID
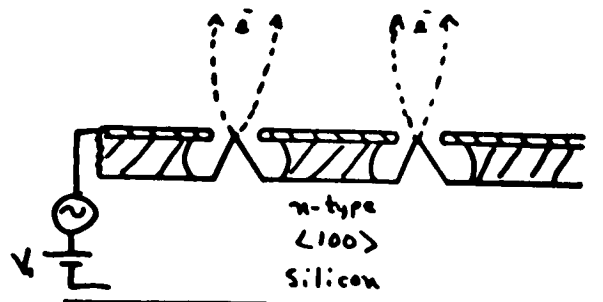
SiO₂

SiO₂

EXTRACTION
GRID

SINGLE CRYSTAL
SILICON (100)
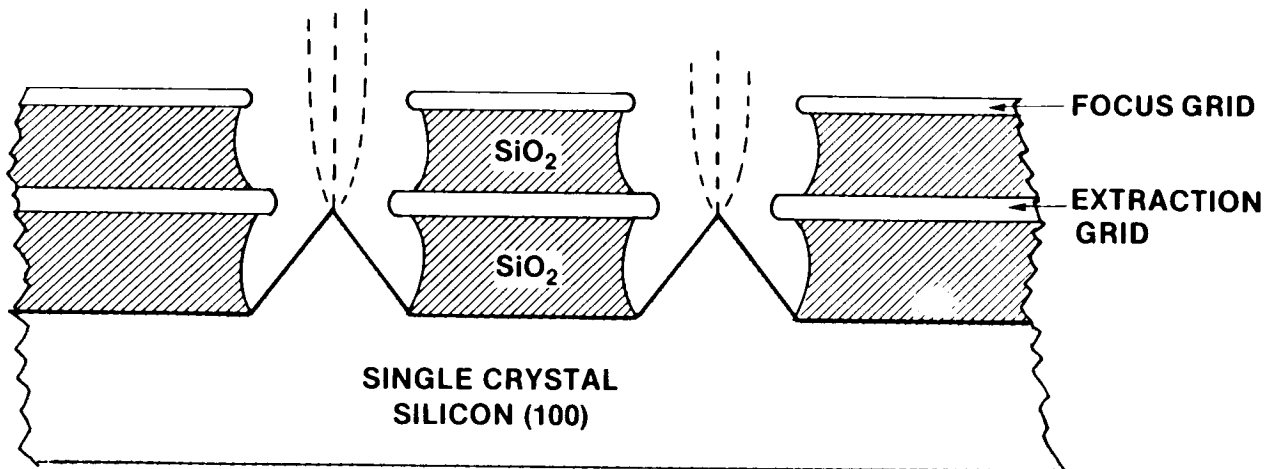
Vacuum Microelectronics

Photo-Excited Field Emitter Arrays

Photo-Excited Field Emitter Array   Voltage Modulated Field Emitter Array

p-type

⟨100⟩

silicon

n-type

⟨100⟩

silicon

hν

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