DESIGN AND FABRICATION OF A THz NANOKLYSTRON

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OVERALL OBJECTIVE

Develop a milliwatt level, fixed frequency, CW THz source for space borne Earth and planetary remote sensing instruments

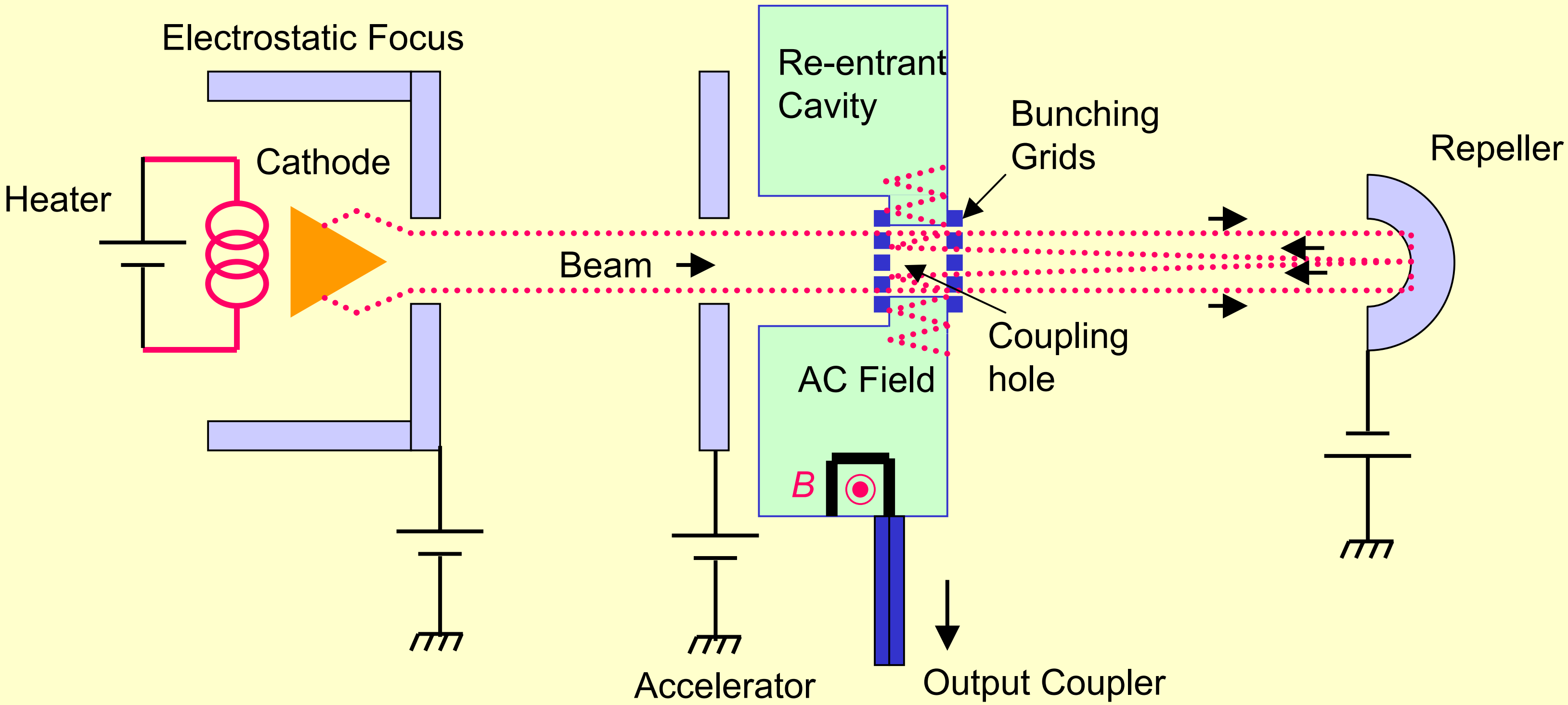
IMPLEMENTATION

Extend vacuum tube reflex klystron oscillator to THz frequencies.

TECHNICAL APPROACH

- Analyze millimeter-wave klystron performance limitations
- Design THz monolithic circuit based on silicon DRIE process
- Propose compatible cavity, bunching grid, repeller, output structure
- Realize ultra-high current density field-emission cathode
- Incorporate built-in low-voltage emitter/focusing grid with cathode
- Combine drop-in cathode/grid with cavity/output coupler
- Develop high vacuum sealing technique compatible with RF output
- Increase power output or frequency agility through array integration

SCHEMATIC OF A SIMPLE REFLEX KLYSTRON



MODIFICATIONS NEEDED TO REALIZE THZ MONOLITHIC DESIGN

- **Physical layout must be made compatible with standard MEMS processing**

  Including emitter, re-entrant cavity, focusing electrodes, repeller, output coupler, beam forming antenna

- **Split block construction required to allow sculpting of cavities and insertion of wires, focusing electrodes, emitter, repeller**

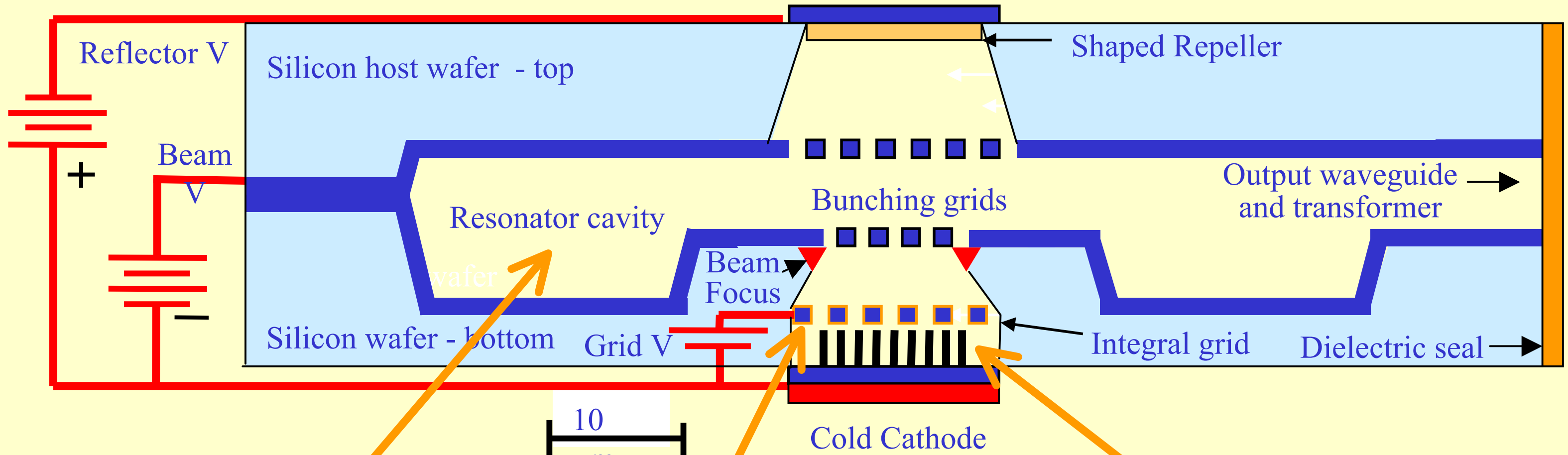
- **Tuning & output Q controllable via simply varied geometric parameters**

- **Current densities of existing hot cathodes must be increased dramatically**

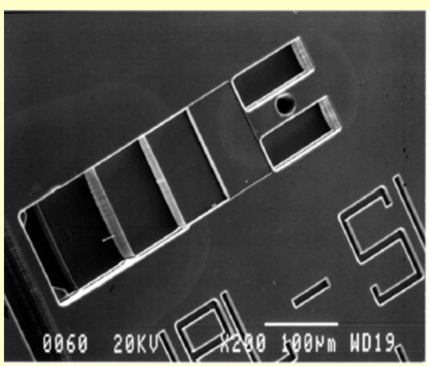
MODIFICATIONS NEEDED TO REALIZE THZ MONOLITHIC DESIGN

- **Cold cathode operation preferred for space operation and reduced thermal load**
- **Cold cathode operation implies integrated emitter grids and extra beam focus**
- **Vacuum sealing techniques/window compatible with low RF output loss**
- **Early design flexibility needed to allow some trial and error testing**
- **Detailed analysis of full circuit and RF beam interactions essential**

SCHEMATIC CONSTRUCTION WITH REALIZED STRUCTURES

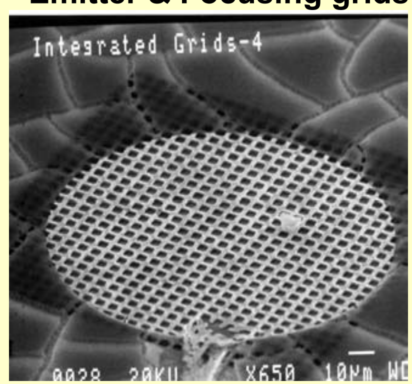


Vacuum sealed split block



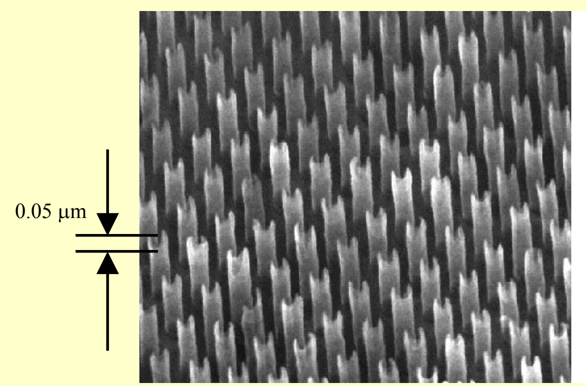
Silicon micromachined cavity (JPL)

Emitter & Focusing grids



Micromachined emitter grid (JPL)

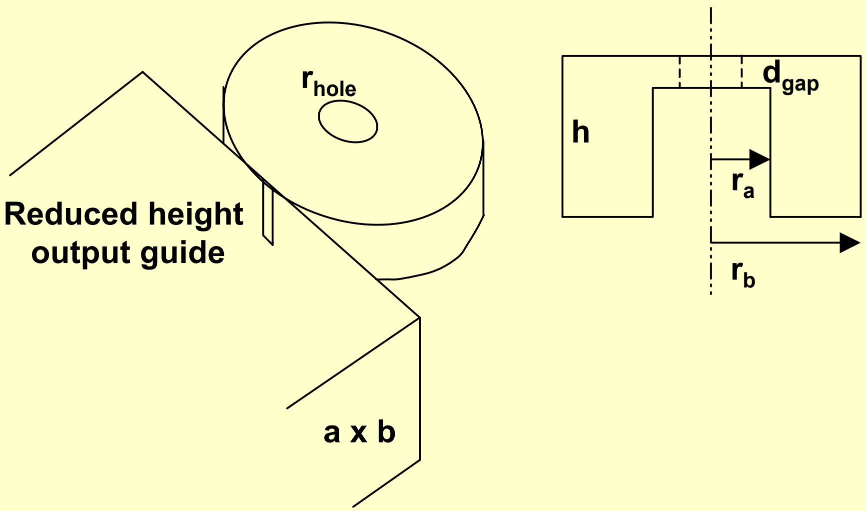
Nanotube or Spindt cathode

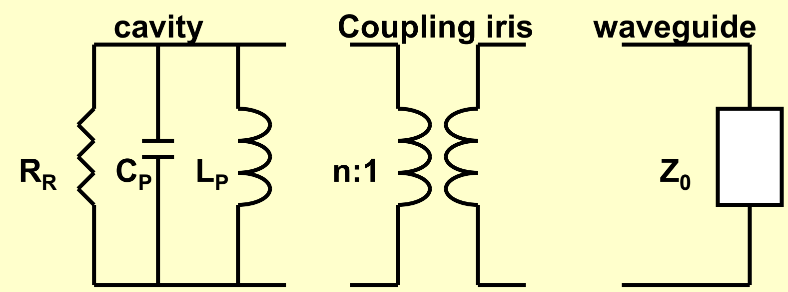


Brown Univ. highly ordered carbon nanotube array (cathode) Li. et.al. APL 75, no.3, Jul 19, 1999

SIMPLIFIED BEAM ANALYSIS FROM J.J. HAMILTON (1958)

Iris-coupled Cylindrical Re-entrant cavity





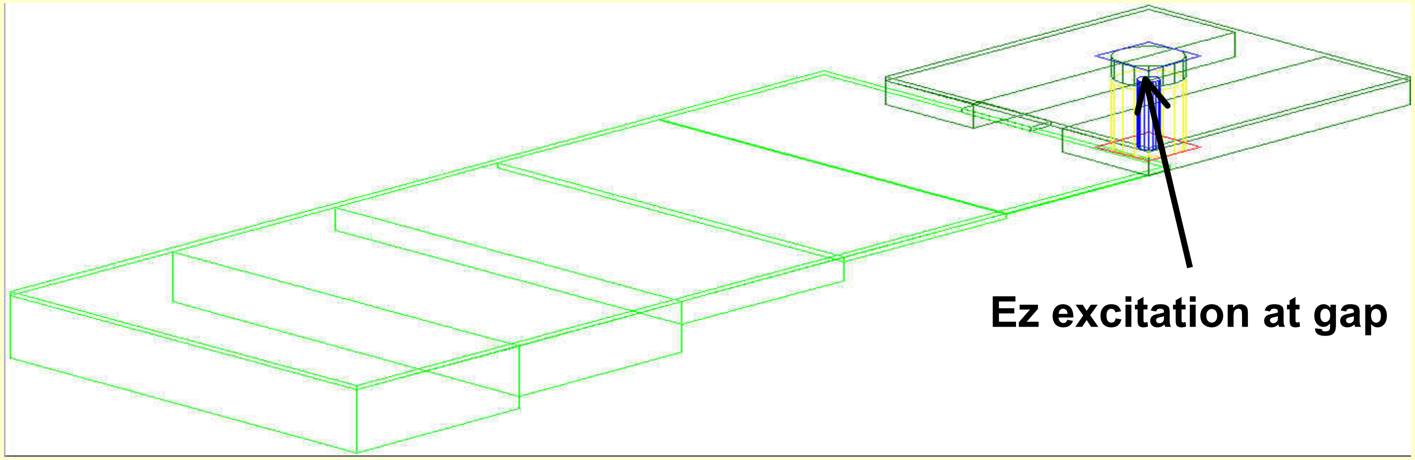
Resonator equiv. circuit

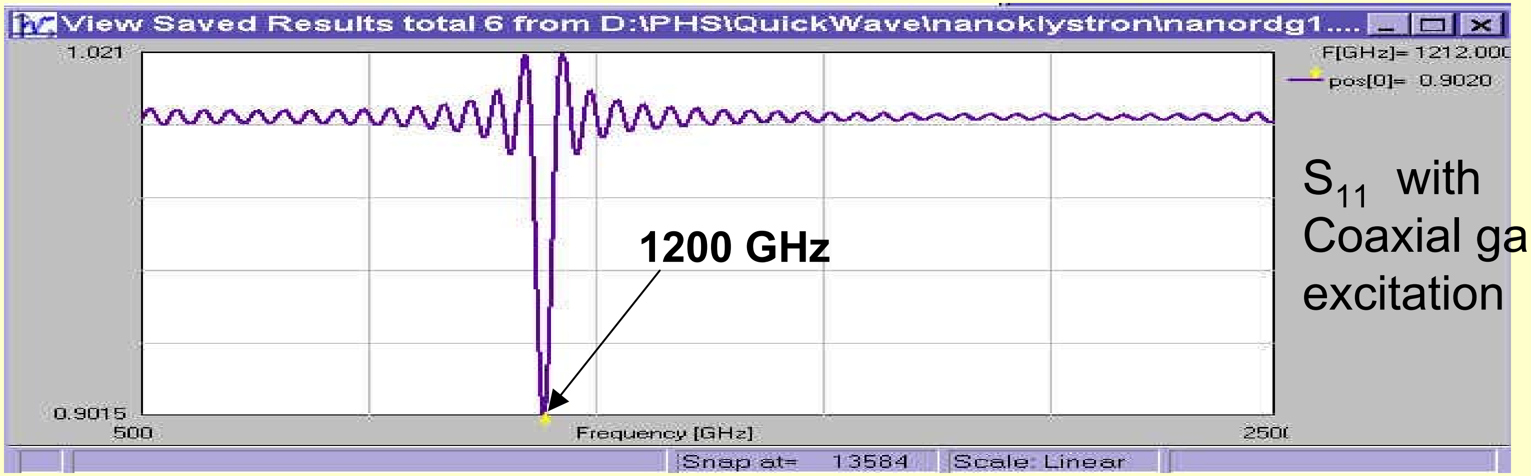
1200 GHz Example

With 500V beam, 3mA current:

52 mW produced by beam,
49 mW lost in cavity,
3 mW delivered to output load

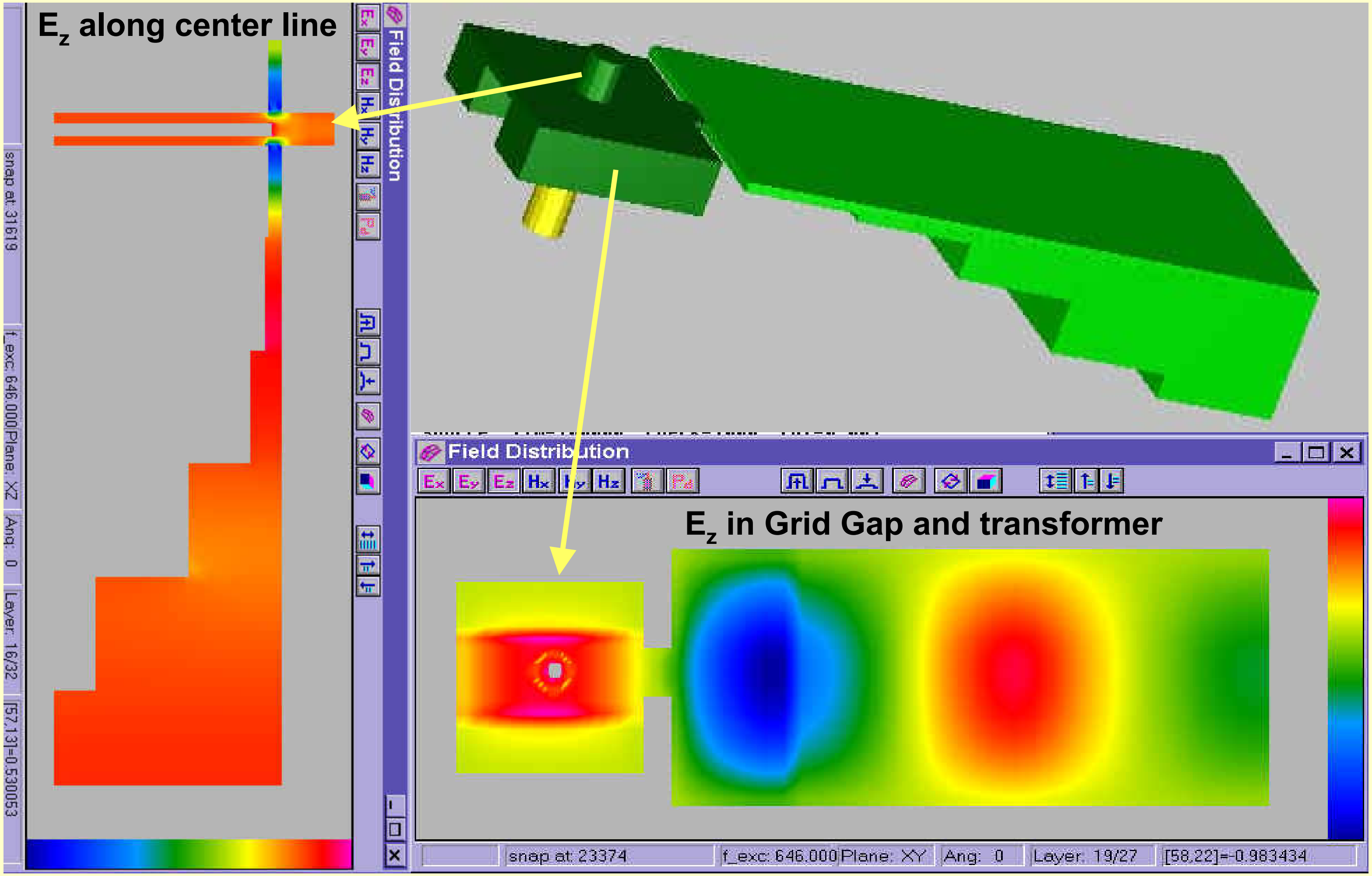
1200 GHZ RIDGED-WAVEGUIDE RE-ENTRANT CAVITY ANALYSIS FOR NANOKLYSTRON USING QUICKWAVE FDTD



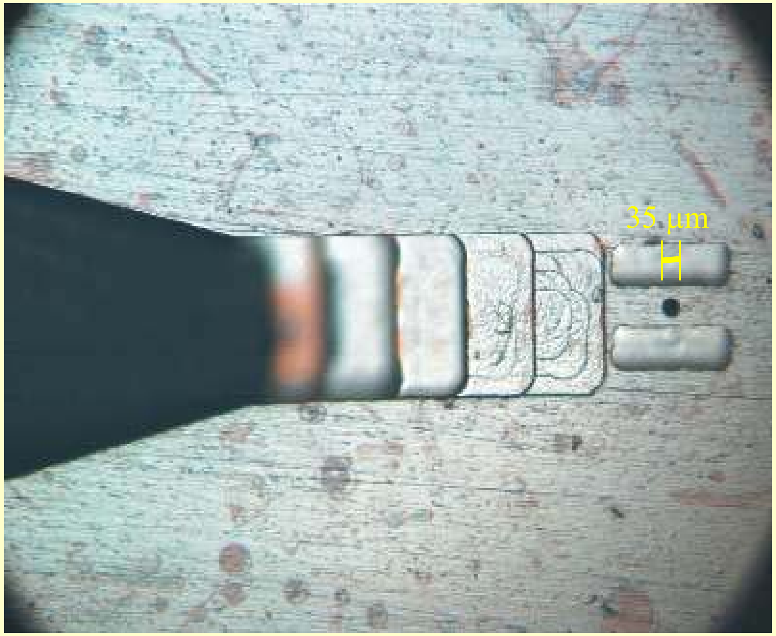


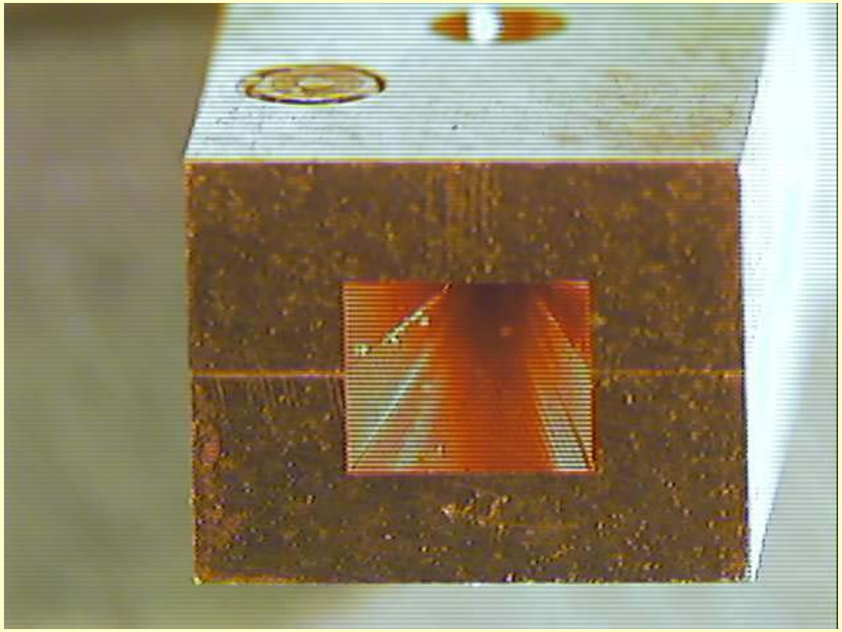
S_{11} with Coaxial gap excitation

FIELD DISTRIBUTIONS



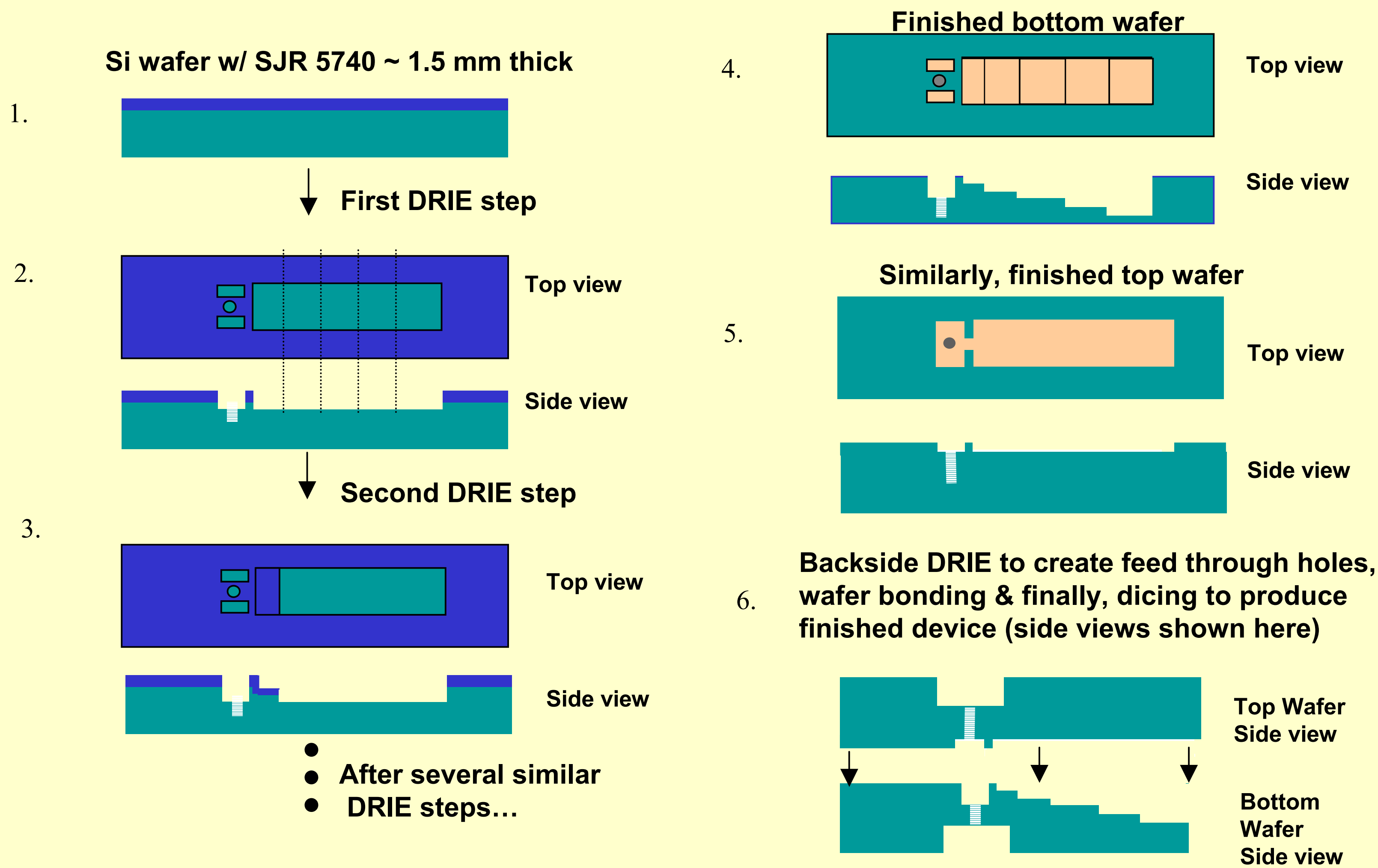
FABRICATION OF 640 GHZ CIRCUIT USING PRECISION METAL MACHINING



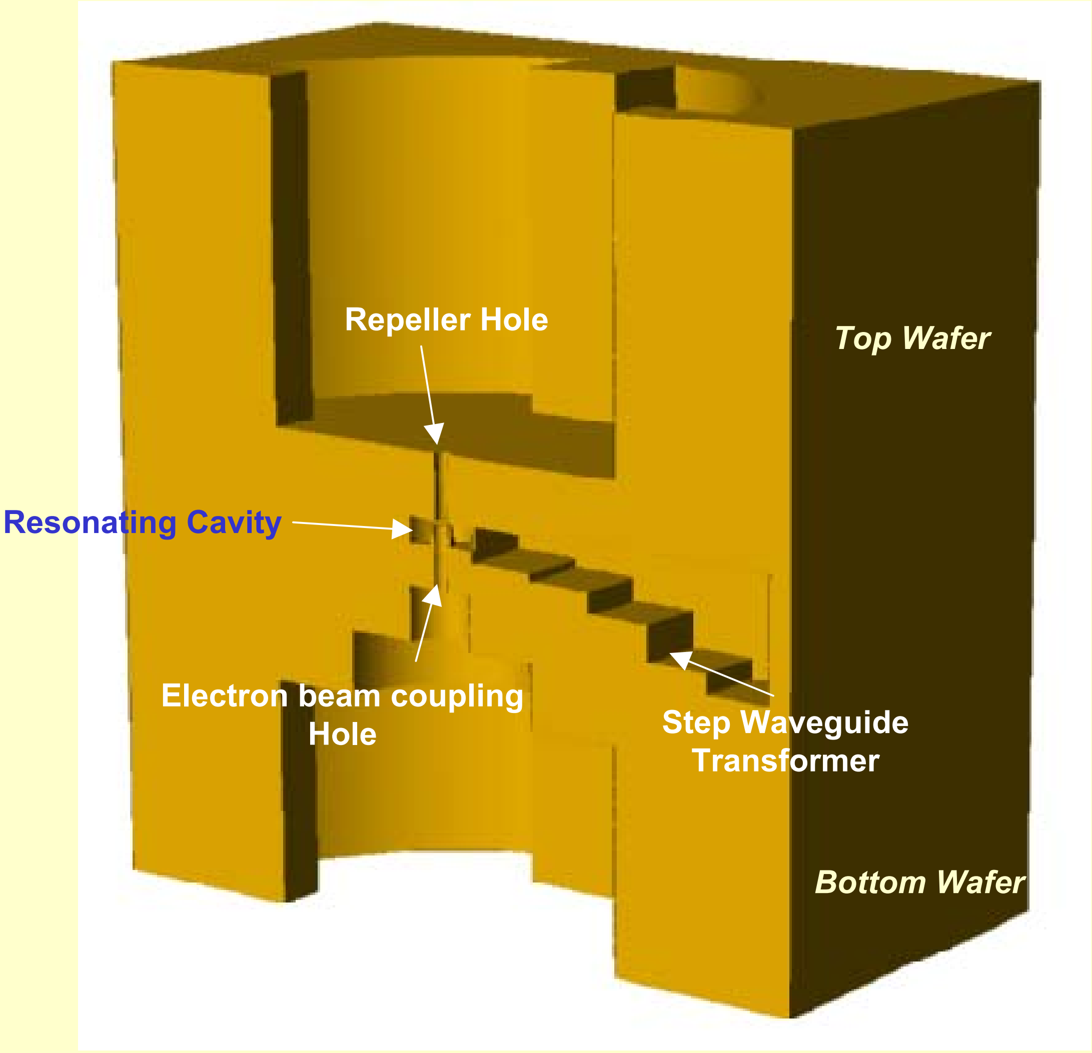


640 GHz Nanoklystron fabricated using precision machining in metal split block. The smallest feature is the 0.0015” diameter bunching grid hole. The assembled unit with an output waveguide horn is shown on the right.

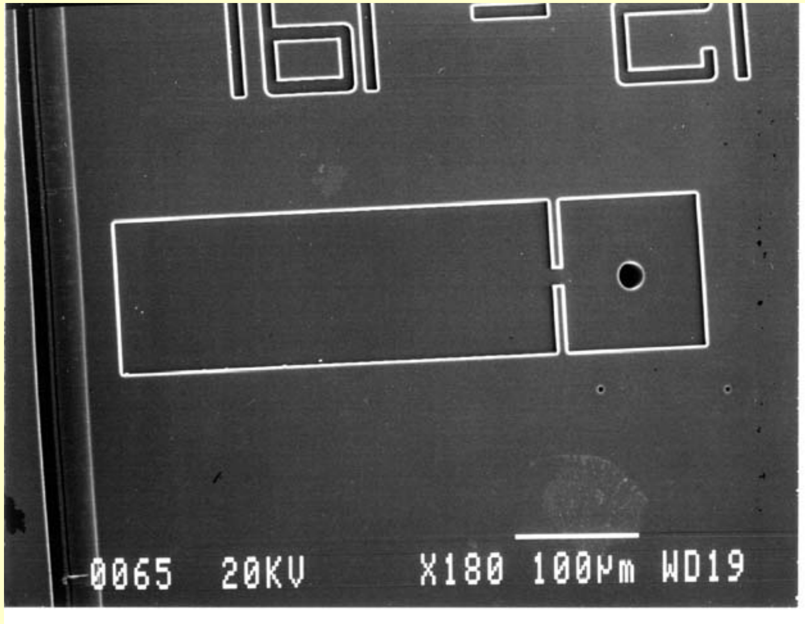
SILICON DEEP REACTIVE ION ETCH WAFER PROCESSING STEPS



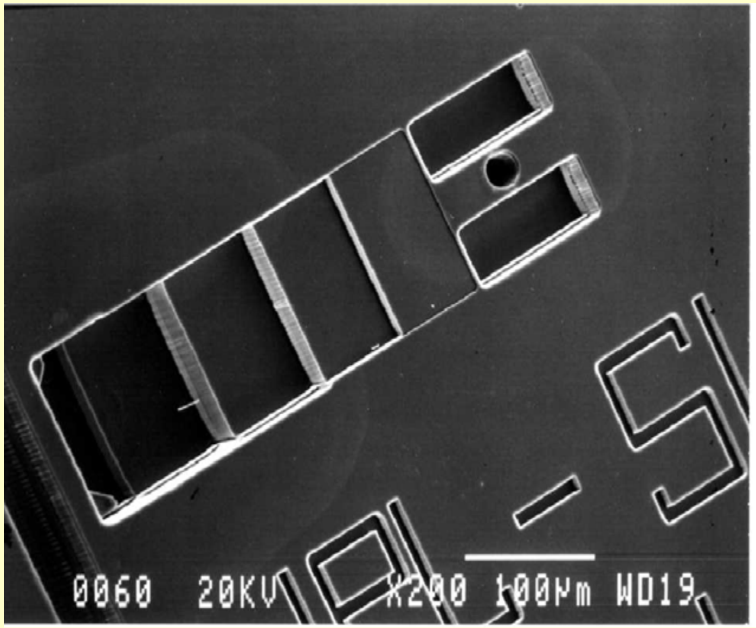
CUT-VIEW OF A WAFER BONDED NANOKLYSTRON (A MODEL)



1st ITERATION MONOLITHIC NANOKLYSTRON CAVITY
[1200 GHz cavity split into two halves]

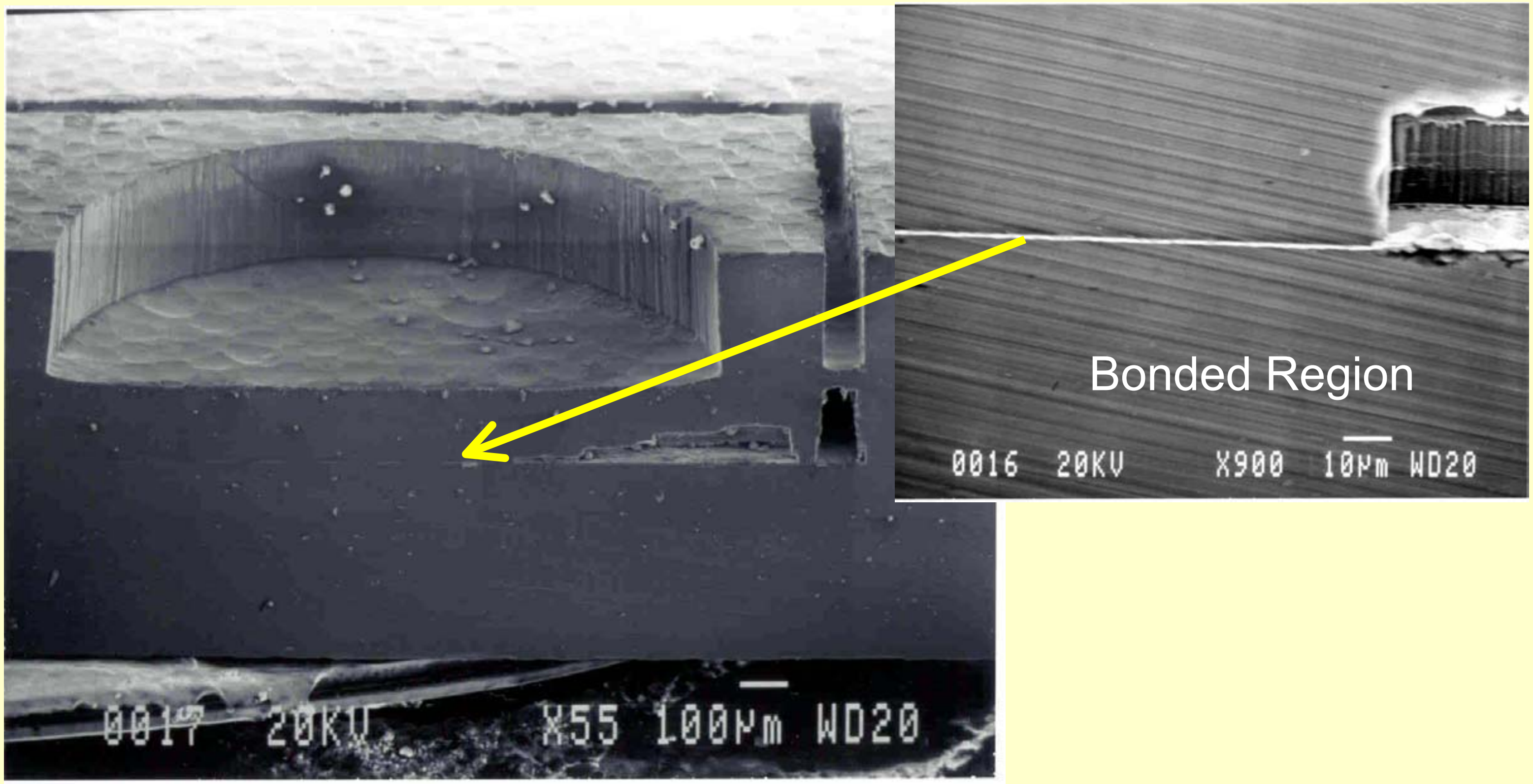


Top half micromachined in silicon showing a repeller hole



Bottom half of in silicon showing an emitter hole and a 5-step waveguide transformer terminating in a silicon window

BONDED WAFER HALVES WITH CAVITY CUTAWAY



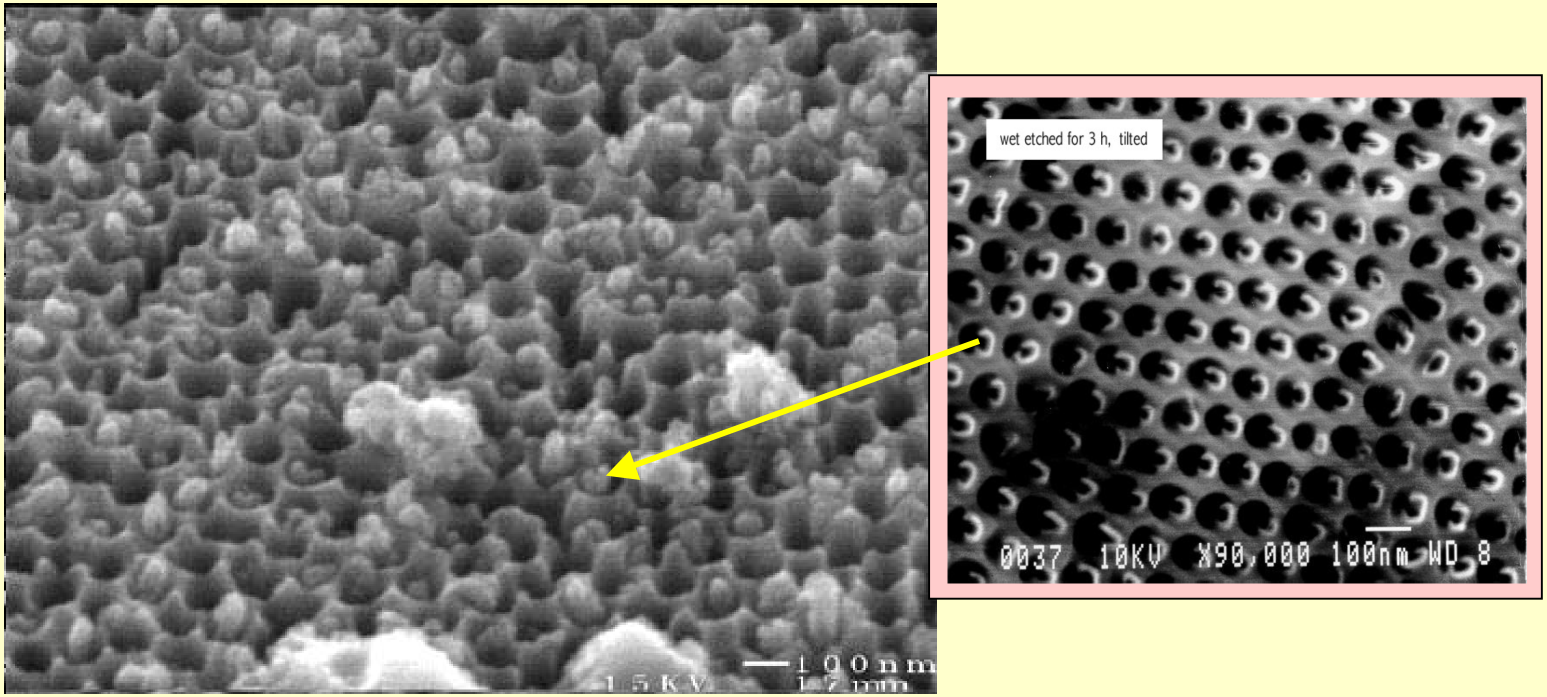
Wafer bonded cavity and a magnified view of the bonded interface showing fused gold layers of the top and the bottom halves

DEVELOPMENT OF COLD EMITTER CATHODES

- **Electron source for nanoklystrons must be capable of generating current densities of at least 1000 A/cm^2 at low operating voltages.**
- **Such current densities can be generated by employing cold cathodes, especially carbon nanotube-based field emitters.**
- **The small diameter of carbon nanotubes (diameter of a single single-walled-nanotube can be <1 nm) enables efficient emission at low fields, despite their relatively high work function (>4.5eV).**
- **At 1-3 V/μm of threshold voltage, carbon nanotubes are the best suited for low-power, high-current density applications.**

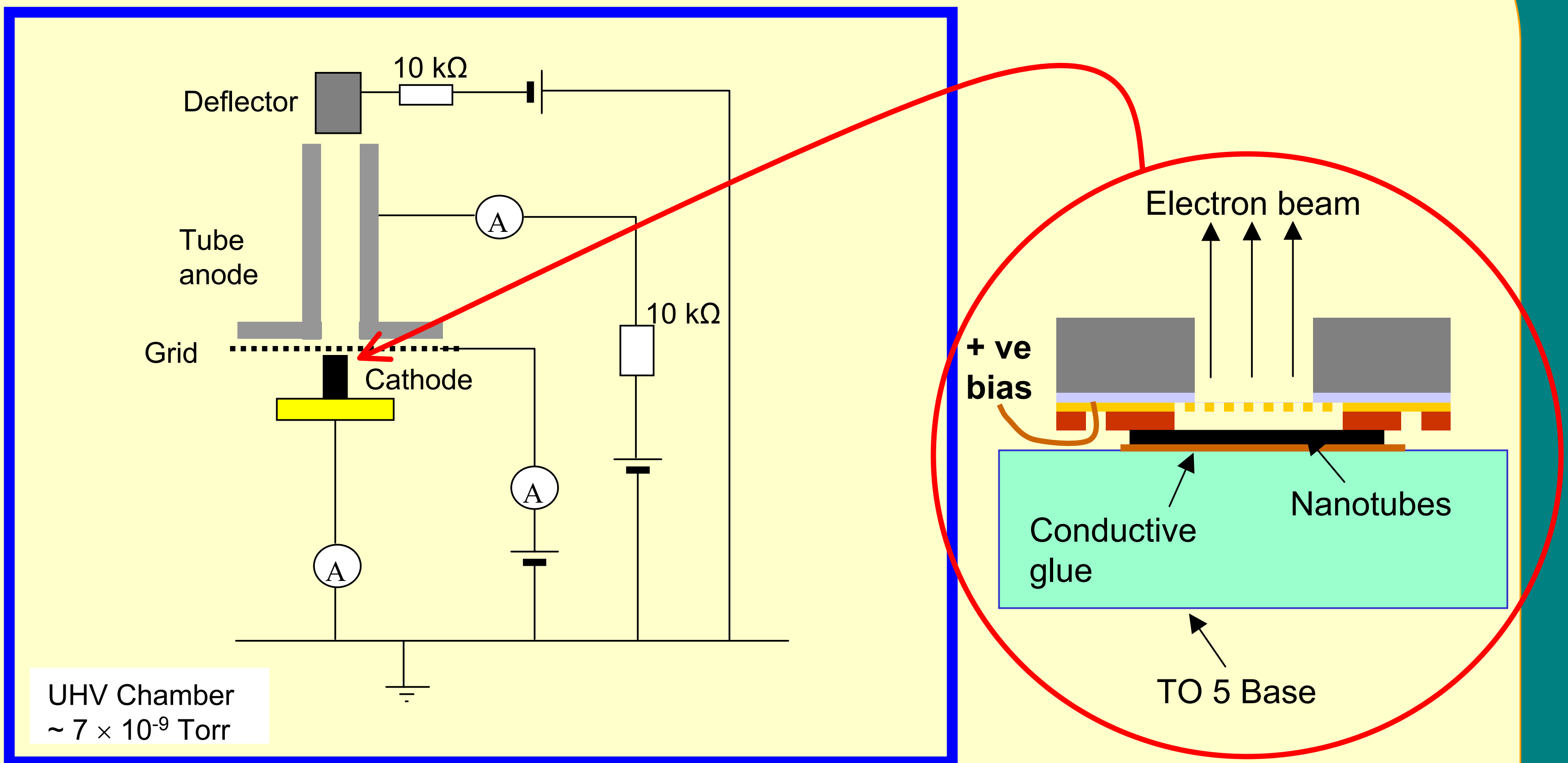
Efforts are underway to develop flat bed of grid-integrated ordered arrays of carbon nanotubes and tailor their field emission to suit nanoklystron applications.

ORDERED ARRAYS OF CARBON NANOTUBES FOR THE FIRST TIME GROWN ON Al-DEPOSITED Si-WAFER



- Nanotubes exposed after ion-milling the anodized pores of alumina
- Tube diameter is typically 40 nm with a density of ~100 tips/μm^2

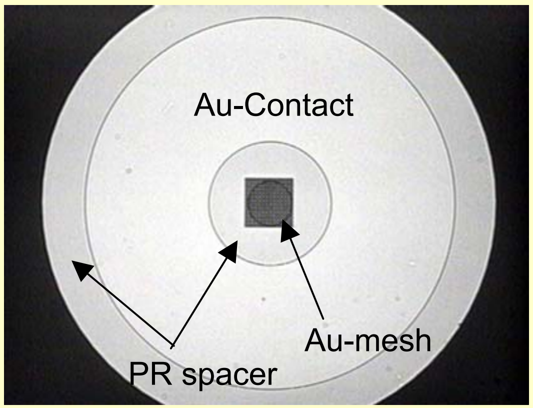
FIELD EMISSION MEASUREMENTS

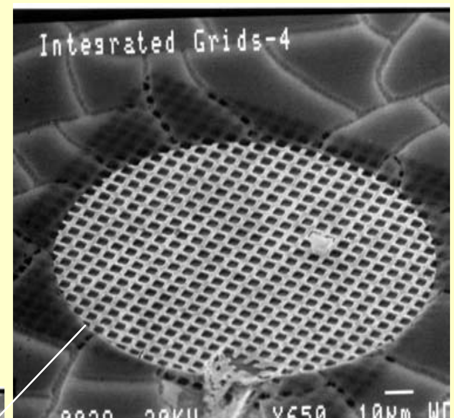


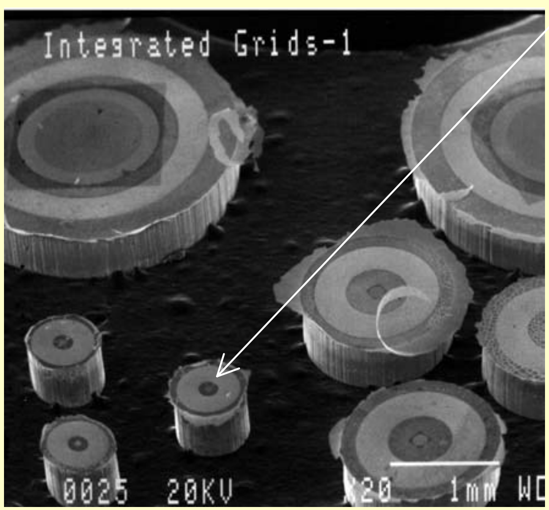
Distance from top of the sample to anode is 2 mm vertically and 5 mm horizontally.

Micromachined grid with nanotubes for field emission measurement

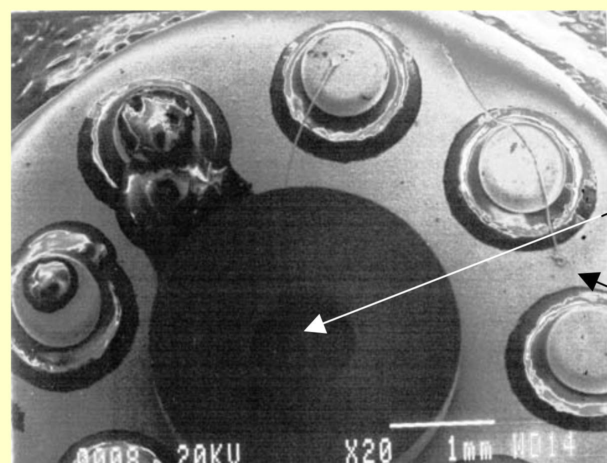
SILICON MICROMACHINED GRID STRUCTURES WITH INSULATING PHOTORESIST SPACER FOR MICRON SEPARATION







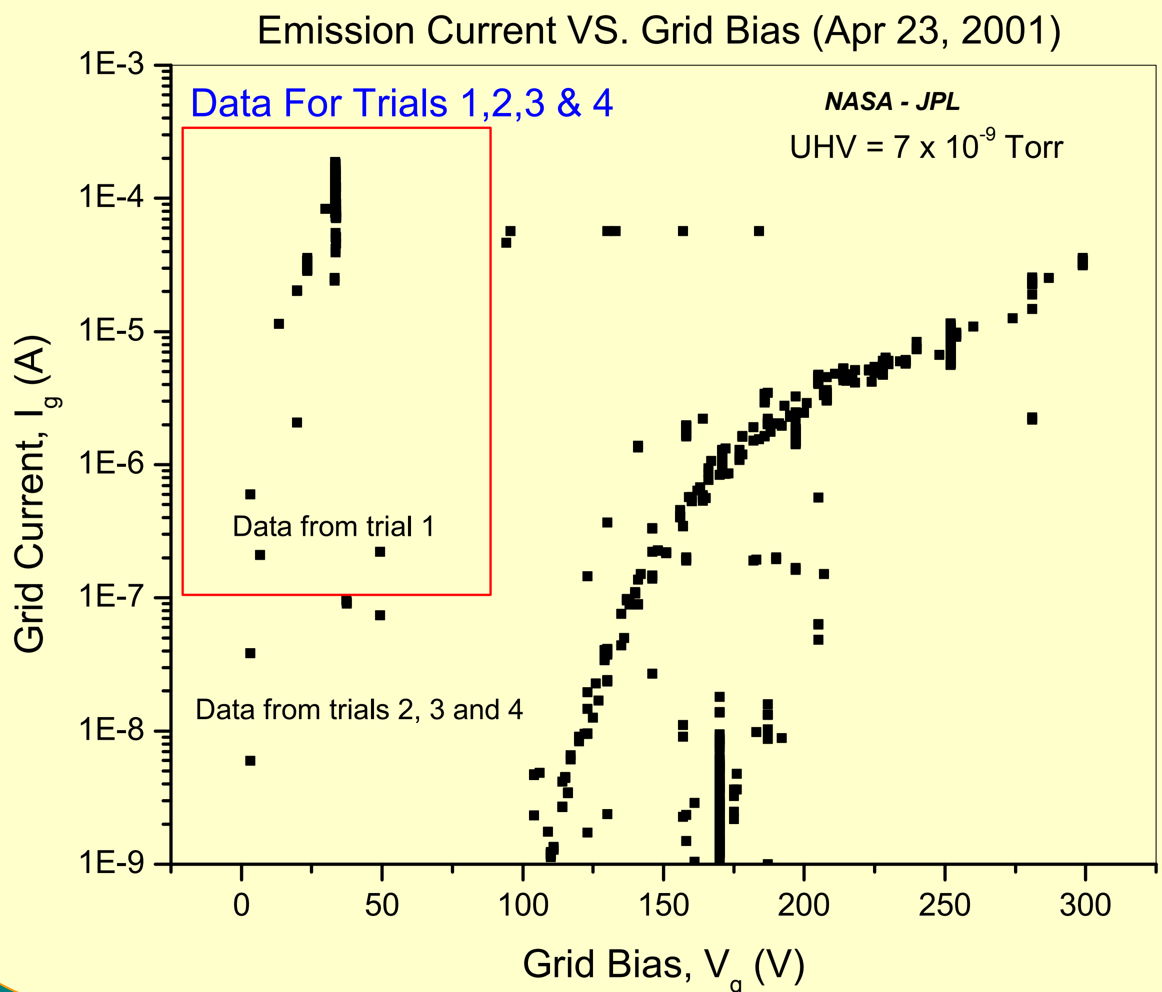
Assembly for field emission measurements



Emission hole made using DRIE

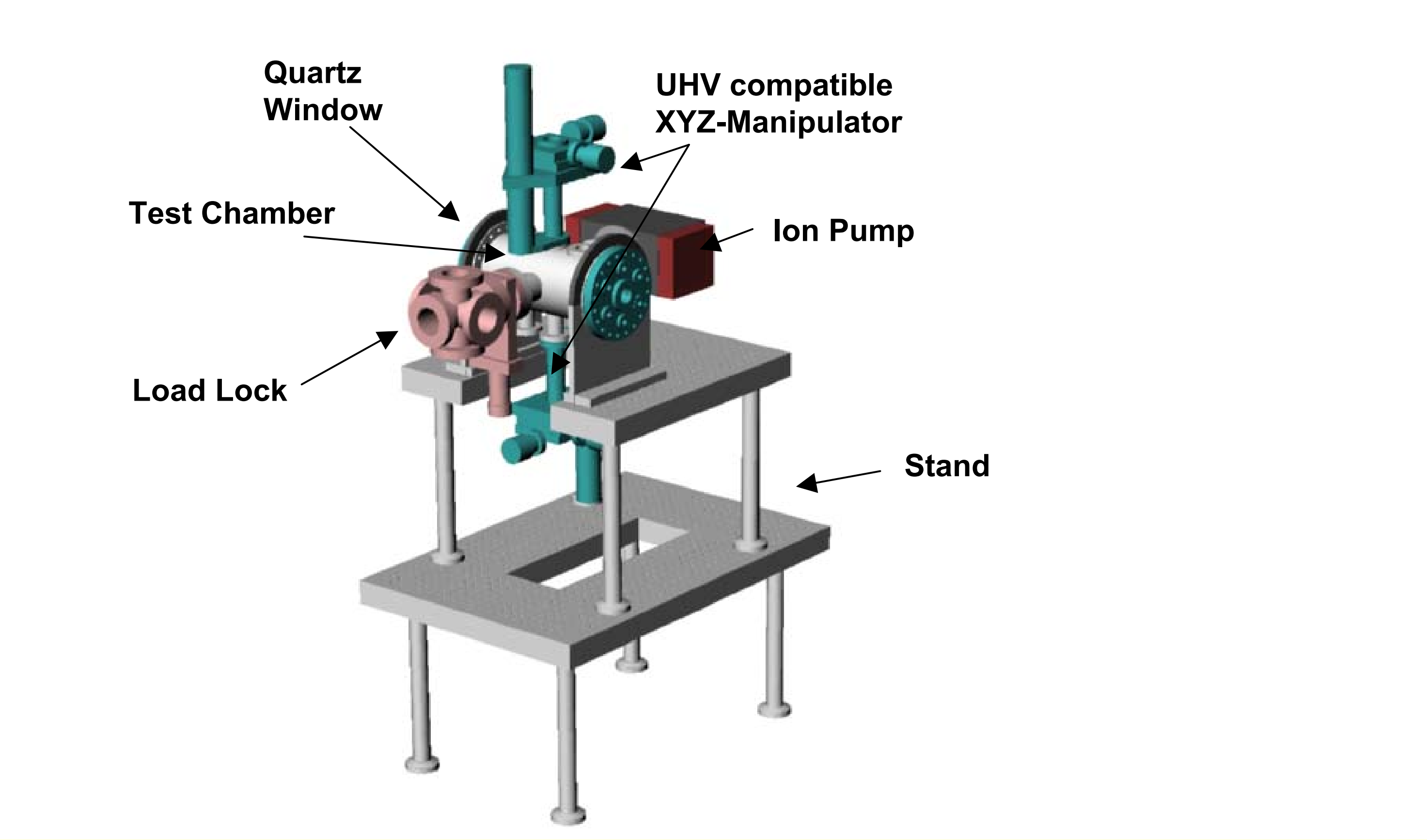
TO 5 Base

ORDERED CNT ARRAY EMISSION MEASUREMENT



Grid area=0.0078 cm^2
#tips=100/μm^2=10^{10}/cm^2
Equiv. Current density=.01A/cm^2
Typical current/tip=300nA
Estimated number emitters=300 for 100μA
Number of tips total=7.8*10^8

NEW NANOKLYSTRON AND EMISSION TEST CHAMBER



SUMMARY

- Design concept, circuit layout & simple analysis of a 1200 GHz nanoklystron presented
- New style ridged waveguide re-entrant cavity designed and analyzed
- Simple cathode/grid field emission tests performed in existing chambers.
- New assembly/measurement chamber being built.
- Close-in cold cathode emitter grid developed for carbon nanotube arrays
- Copper 640 GHz nanoklystron cavity completed.
- First iteration silicon monolithic 300/600/1200 GHz nanoklystron cavities completed. Wafer bonding tests successful.