# Nanoklystron: A Monolithic Tube Approach to THz Power Generation

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## ABSTRACT

The authors propose a new approach to THz power generation: the "*nanoklystron.*" Utilizing silicon micromachining techniques, the design and fabrication concept of a monolithic THz vacuum-tube reflex-klystron source is described. The nanoklystron employs a separately fabricated cathode structure composed of densely packed carbon nanotube field emitters and an add-in repeller. The nanotube cathode is expected to increase the current density, extend the cathode life and decrease the required oscillation voltage to values below 100V. The excitation cavity is based on ridged-waveguide and differs from the conventional cylindrical re-entrant structures found in lower frequency klystrons. A quasi-static field analysis of the cavity and output coupling structure show excellent control of the quality factor and desired field distribution. Output power is expected to occur through an iris coupled matched rectangular waveguide and integrated pyramidal feed horn. The entire circuit is designed so as to be formed monolithically from two thermocompression bonded silicon wafers processed using deep reactive ion etching (DRIE) techniques. To expedite prototyping, a 600 GHz mechanically machined structure has been designed and is in fabrication. A complete numeric analysis of the nanoklystron circuit, including the electron beam dynamics has just gotten underway. Separate evaluation of the nanotube cathodes is also ongoing. The authors will describe the progress to date as well as plans for the immediate implementation and testing of nanoklystron prototypes at 640 and 1250 GHz.

## INTRODUCTION

The millimeter and submillimeter-wave frequency bands, from 100 GHz to 3 THz (3 to 0.1 mm wavelength), are some of the least explored and yet information rich regions of the electromagnetic spectrum. The development of technology specifically aimed at remote sensing and identification of chemical species that thermally emit in this wavelength range has been a major thrust area at JPL for more than 10 years. Over this time, enormous progress has been made in both heterodyne and direct detection sensor technology. Significant developments include the realization of near quantum limited superconducting mixers up to 900 GHz, less sensitive but ultra high frequency (2.5 THz) space qualified ambient temperature semiconductor receivers, and most recently helium cooled hot-electron bolometer mixers which will work all the way up to far infrared wavelengths (10 THz). The lower end of the submillimeter band (100-300 GHz) has atmospheric windows that have been long exploited for both civilian and defense applications such as passive remote sensing and imaging, radar, and perhaps very soon ultra wideband communications systems. Although detector technology has made major inroads towards the realization of these high frequency systems, solid-state source development (a major component in every case) has lagged behind significantly.

Over the years, there have been many attempts to produce CW power above 100 GHz. The most popular method is to use lower frequency oscillators and now power amplifiers (at or slightly above 100 GHz) followed by nonlinear-reactance-based frequency multiplier chains (Schottky diodes) to get to higher frequencies. This process becomes dismally inefficient for multiplication factors of 4 or greater. All attempts at making direct solid-state oscillators at these frequencies have so far failed from lack of efficient output coupling schemes, too low RF power levels, low Q, or internal device parasitics that limit the effective cutoff frequency. Optical downconversion, through laser heterodyning or photomixing, have also proven to be extremely inefficient as well as being difficult to stabilize and fairly bulky. The only methods of THz power production that have proven sufficient for submillimeter-wave heterodyne, communications or radar applications to date are direct laser-to-laser pumping, i.e. using a $CO_2$ laser to pump a methanol gas laser, or slow-wave tube structures, like backward wave oscillators and carcinotrons. Both of these sources are large and heavy, are extremely expensive (>$100,000), require high power, have limited operational lifetimes and are restricted in their frequency coverage. Backward wave tubes die off above 300 GHz (although a few tubes have been constructed with small amounts of output power up to 1.2 THz), and the number of available submillimeter-wave laser lines with reasonable output power are few and far between. So far as the author knows, no viable THz solid-state source exists with sufficient power to drive even a THz superconductor mixer at this time. Our concept addresses this situation with a new approach to the generation of radiation hard, frequency agile, phase lockable, high frequency power: a micromachined vacuum tube oscillator, the "*nanoklystron*."

## TECHNICAL CONCEPT AND RATIONALE:

In the 1930's and 40's a great deal of effort was put into the design and manufacture of thermal emission devices (vacuum tubes) that worked at millimeter wave frequencies (up to 30 GHz). Much of this work involved extensions of the simple vacuum triode which relies on an electron beam pulled from a hot cathode and accelerated through a grid. The grid serves the purpose of bunching the electrons with a resulting high frequency oscillation and amplification of the grid current as the beam is collected at the anode. Variations on the triode (tetrode, pentode etc.) were of course widely employed as oscillators and amplifiers well before the advent of the transistor.

In the push towards higher frequencies the triode was ultimately abandoned because it is limited by parasitics between the emitter and grid as well as the transconductance of reliable cathodes. Two differing techniques emerged in the high frequency vacuum emitter world – slow wave or magnetically confined beams (backward wave tubes, carcinotrons, extended interaction oscillators, gyrotrons) and focused cavity oscillators (klystrons). Slow wave structures require high magnetic fields for focusing or steering the electron beam and hence are currently large and enormously heavy. Klystrons rely on passing the electron beam through one or more weakly coupled resonant cavities for the bunching operation and from which the accumulated RF oscillations are removed. Since no magnetic field is required, klystrons are small and lightweight compared to slow wave devices. They can be configured as single or multiple cavity oscillators or, if an RF input is applied to one of the cavities, as amplifiers.

The reflex klystron, [1] and Fig. 1, is a compact form of klystron oscillator that uses only a single cavity and a repeller or reflector to focus the accelerated electron beam back onto itself through a small gap in the walls of the resonator. The gap plays a critical role in establishing and maintaining oscillation at a frequency determined by the surrounding cavity. It takes the form of a precisely spaced set of grids (or gridless gap) at the center of a cylindrical re-entrant cavity that produces an alternating field from random oscillations in the impinging electron beam. This in turn causes bunching of the electron stream and upon proper reflection in phase from the repeller results in significant energy coupling to the surrounding cavity. The reflex klystron is a particularly useful short wavelength oscillator, as far as tubes go, and has been made to work at frequencies as high as 212 GHz [2]. However, the last commercial millimeter-wave reflex klystron was made almost 20 years ago and interest in these devices, at least for high frequency applications, has almost wholly disappeared (although room sized klystrons are still used for mega-watt power generation at microwave frequencies in accelerators and plasma fusion reactors!).

In the meantime, revolutionary advances in microfabrication techniques have enabled researchers to fabricate traditional emitter cathodes on a micron scale, photolithographically, with unprecedented packing densities and uniformity [3,4]. These emitters have even been formed into miniature vacuum tubes and operating triodes with ultra small (<1 micron) grid and emitter-collector gap lengths [5-7]. Again, the triode arrangement makes the high frequency potential of these structures very limited and even the most optimistic projections show the response falling off below 100 GHz [4].

This paper describes an approach which capitalizes on the use of MEMS (micro-electro-mechanical machining) and deep reactive ion etching (DRIE) microfabrication techniques as well as recent advances in monolithically fabricated cold cathodes to realize a miniaturized reflex klystron – the "nanoklystron" [8]. By scaling the gap, cavity and repeller dimensions of a working 100 GHz klystron to dimensions consistent with microlithographic techniques (factors of 5-10) we expect to realize oscillations at frequencies at least as high as 1.2 THz and power levels/device in the milliwatt range. We also plan to overcome a major limitation of existing cold cathodes – breakdown due to non uniformity of the emitter tips – by utilizing newly developed carbon nanotube emitter arrays [9] which have unprecedented packing densities and uniformity, high thermal conductivity and a metallic support substrate. In addition, the required beam voltage (typically 2-3kV in a standard klystron) is expected to go down drastically with shrinkage of the cathode-repeller distance and the use of a packaged carbon nanotip array and emitter grid. Experimental emitters using carbon nanotubes have threshold voltages as low as a few volts/micron [10]. Finally, taking advantage of the monolithic design implementation, we will incorporate frequency agility, high levels of redundancy, multiple power or multiple beam capability into the nanoklystron [11].

## TECHNICAL APPROACH

Our proposed "nanoklystron" (Fig. 2.) consists of a cathodic array of highly uniform carbon nanotubes with a built in emitter grid sealed in a micromachined vacuum cavity with a photolithographically produced microresonator, a deposited microgrid, and a weakly coupled micromachined RF waveguide and beam forming horn for removal of the output signal. We plan to fabricate the entire structure monolithically from two silicon wafers that are thermocompression bonded and vacuum sealed in the final steps. The dimensions obtainable with existing micromachining and photolithography processes are consistent with klystron operation at frequencies from 300 GHz to at least 2 THz. Simple scaling of an existing millimeter wave klystron tube [2] at N band (120 GHz) can potentially yield THz oscillator designs without inventing any new lithographic processes. Decreasing the repeller-to-cathode distance will also reduce the required beam voltage to levels approaching those of traditional solid-state devices (10-100V). The use of high aspect ratio carbon nanotubes for the cathode rather than tapered silicon tip arrays [3,4] will greatly increase packing density, thermal conductivity and lifetime, which translates into higher current density and hence higher frequency operation. Finally, the klystron designers of the 1970's were at a great disadvantage. There were no electromagnetic modelling tools that allowed those early pioneers to verify grid, repeller and cavity designs, let alone optimize the performance of the tubes. All high frequency designs were established by trial and error and limited by mechanical machining techniques to gap dimensions greater than 50 microns [12]. The authors have access to several excellent electromagnetic simulator codes that they plan to apply to the design and optimization of a nanoklystron circuit. A recent calculation from a group at University of Leeds [13] supports the advantages of this approach.

We believe the three most significant hurdles for realizing a THz nanoklystron are: (1) basic cavity and output circuit realization compatible with monolithic processing, (2) implementation of a low voltage, high current density, miniature field emission cathode, (3) demonstration of a micro-scale high-vacuum-sealing technology compatible with low loss THz output. We are addressing each of these areas in turn.

***RF Cavity and Output Circuit:*** In order to realize an appropriate resonant structure and compatible THz output coupling circuit in a wafer level process we have abandoned the traditional cylindrical re-entrant cavity and magnetic coupling probe design often used in millimeter wave reflex klystrons [1] in preference to a simple aperture coupled vertical E field layout. The resonant cavity is designed around single ridged waveguide, which has both an attractive mechanical layout as well as a field distribution and mode behavior that makes vertical E field aperture coupling straight forward. The layout is shown in Figs. 3-5, where the output Q and load impedance are easily varied by the iris width and the height of the rectangular waveguide step immediately outside the cavity. For optimal coupling to the outside world, the waveguide height is sequentially increased (using quarter wave impedance transformers [14]) from the very reduced height ridge guide (5 microns at 1200 GHz) until the width to height is 2:1. In the first design iteration the vacuum seal occurs at this waveguide output plane and a separately attached and aligned feed horn is added on the outside of the RF transparent window. Eventually we plan to incorporate the horn into the substrate itself and make the vacuum seal at the horn aperture, where its impact on the impinging field will be reduced. The result of a simple EM field analysis (no electron beam present) showing $S_{11}$ from a z-directed gap excitation of the cavity and output waveguide transition is shown on the right in Fig. 3. A commercial finite difference time domain simulator (Quickwave [15]) was used for this analysis. Field cuts at two different planes are given in Fig. 4. Finally, Fig. 5 shows the assembled unit as it would look at 640 GHz.

The wafer processing steps for realizing the nanoklystron cavity structure are given in Fig. 6. The bunching grids are formed during the RIE process. The cathode and repeller are added afterwards by dropping them into via holes that have been appropriately sized and placed in the top and bottom wafers. The critical dimensions are the gap spacing and electron beam hole which are 5 microns and 20 microns respectively at 1200 GHz. This is no problem for the lithographic process but poses a significant hurdle to traditional metal machining techniques.

In order to speed up the development of a prototype, a scaled 640 GHz design (the highest frequency at which we felt we could reasonably machine the cavity and beam guides), was drawn up and, at time of writing, is being machined in the JPL Space Instruments shop. Representative drawings of this design, which includes a 20dB directivity standard gain horn, are given in Fig. 6.

***Field Emission Cathode:*** The cold cathode for the nanoklystron must be capable of generating beams with current densities of at least 100A/cm$^2$. Traditional Spindt type microcathodes [3,4] have been able to achieve 20X this current density [16]. Carbon nanotube emitters offer potential advantages over more traditional micro-emitter structures, including less susceptibility to tip breakdown and lower emission voltages as well as very high thermal conductivity (same order as diamond). In the case of the highly ordered nanotube arrays recently introduced by the research team now at Brown University [9] and shown in Fig. 7, the tip spacing and height is extremely uniform and the density of emitters can easily be as high as $10^{10}$/cm$^2$. In nonuniform nanotube emitters, threshold voltages of 5V/micron or less are typical and 2.5 V/micron has been realized commercially [17]. For use in the nanoklystron, 30,000 emitter tips of the type shown in Fig. 7 will fit within the electron beam hole at 1200 GHz. With even a modest emitter current of 100nA/tip [18], this means current densities (without focusing) of several kA/cm$^2$ are feasible. In order to measure the nanotube emitter properties we have developed a simple test jig that allows a small (3x3mm) emitter sample to be tested with a commercially installed grid (Fig. 8). Although this arrangement has yielded data on the commercial disordered nanotube arrays [17] it does not take advantage of the array uniformity in the same manner as the Spindt integrated grid cathodes [4]. For this reason a procedure for fabricating and inserting a close spaced (<1 micron) grid onto the carbon nanotube arrays has been developed (Fig. 9). This arrangement has not yet been tested, but is scheduled to be completed very soon.

***Vacuum Sealing:*** Vacuum sealing of the cavity, cathode, repeller and output structure requires both high vacuum ($10^{-8}$ Torr or better) and compatibility with low loss RF transmission through the output coupling window. This can be accomplished either with evaporated dielectrics or with a separately attached dielectric window. As a first attempt to accomplish the sealing, a simple microlithographic technique, using an etched -in-place ultrathin (5-10 micron) silicon window, will be tested. For the machined 640 GHz nanoklystron, a separately processed quartz window will be sealed in place with a commercial hermetic process.

Since we have not as yet completed the fabrication of either the machined 640 GHz nanoklystron or the micromachined 1200 GHz nanoklystron we cannot predict all the hurdles that will have to be overcome to produce oscillation and significant output power. Both detailed numeric analysis and sophisticated fabrication process steps are still to be worked out.

## SUMMARY

The authors have presented a conceptual design as well as some early progress on the layout and fabrication of a THz nanotube power source. This is clearly a "work in progress" and we apologize for the conceptual nature of the paper. Several important first steps have been made, however, including the design of a new form of re-entrant cavity and coupling structure amenable to lithographic processing, the testing and incorporation into the design of advanced carbon nanotube cold-cathode emitters which should significantly improve the potential current density, the design and incorporation of an integrated microgrid directly on the nanotube cathode, and the wafer processing steps needed to realize the full nanoklystron structure. If all the milestones in the program can be realized, then the concept of a nanoklystron beam switching array, such as that shown in Fig. 10, will be close at hand.

## ACKNOWLEDGEMENTS

The authors would like to thank Dick Fink of FEPET for supplying commercial nanotube emitter structures and making measurements on the TO-5 packages, Dr. Colleen Marrese and Dr. Brian Hunt of JPL and Dr. Jeff Hone of Caltech for useful discussions, Maurice Viant and the klystron team at CPI Canada for detailed discussions and an allowed site visit, and Dr. Tracy Lee, now at Copely Networks, for his work at the start of this program. We would also like to acknowledge the financial and programmatic support of

Tim Krabach and Carol Lewis in their roles as managers in the NASA BSICT program. This work was supported by the California Institute of Technology Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration. The work at Brown University was also sponsored by AFOSR.

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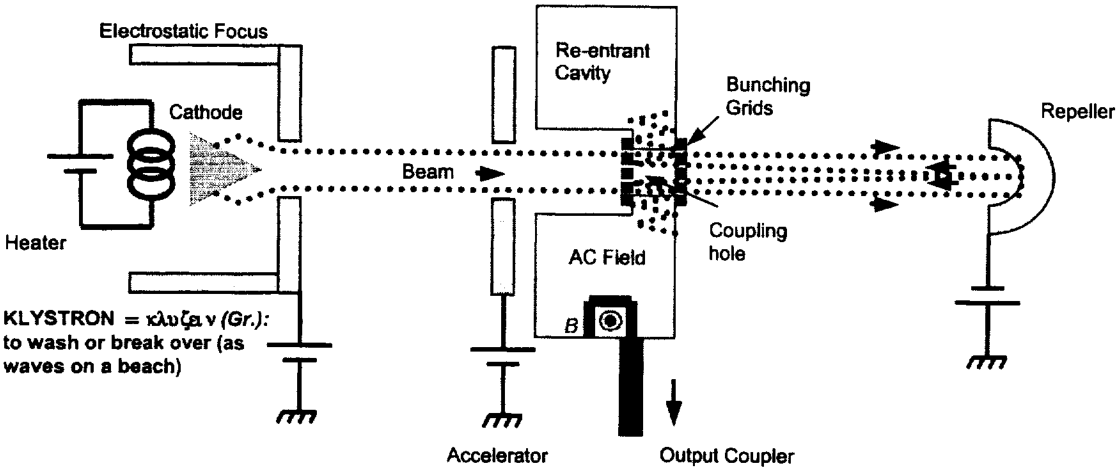


Fig. 1. Schematic cross-section of a simple reflex klystron. All items are cylindrically symmetric. Output coupling is shown via a magnetic field loop. For scale the cavity diameter can be taken as approximately one half wavelength. Actual millimeter wave klystron geometries are significantly more complicated and, at least in the case of Varian designs, still proprietary.

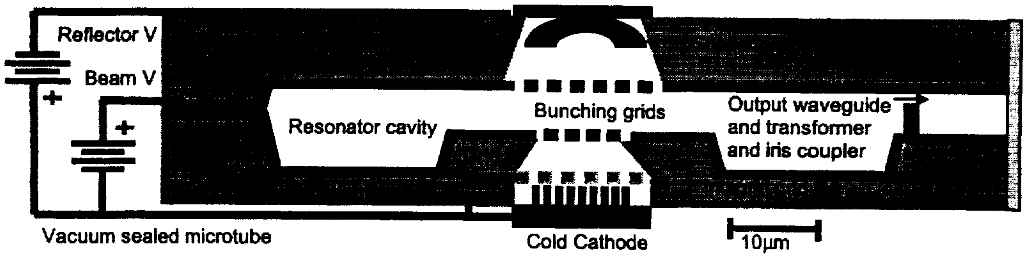


Fig. 2. Schematic cross section of proposed nanoklystron. The cathode is composed of a carbon nanotube field emitter array (Fig. 7) with a built-in grid. The cavity, beam and output waveguide are etched from two silicon wafers which are later joined by thermocompression bonding. The wiring and grid layers are formed lithographically. The repeller and cathode are drop-in parts and vacuum sealing is performed in the last step.

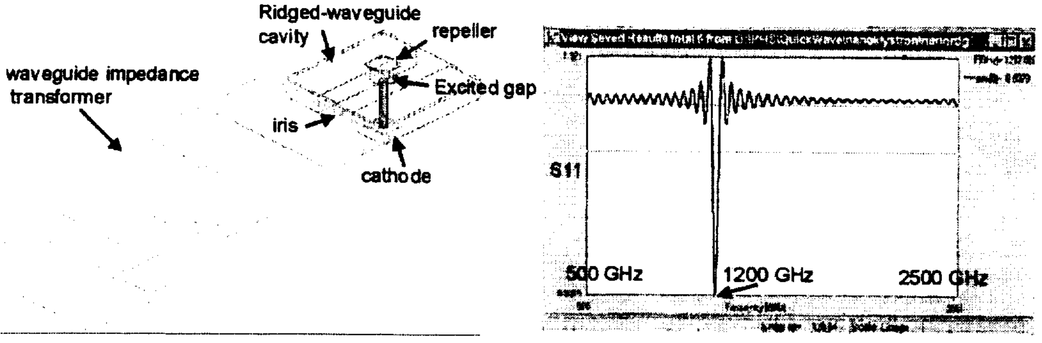


Fig. 3. Left: Transparent construction of nanoklystron re-entrant cavity, coupling iris and output waveguide stepped transformer. Excitation for the S parameter plot (right) is via a coaxial probe that produces a Z oriented field across the cavity grid gap. Right: $S_{11}$ vs. frequency from 500-2500 GHz for gap excited ridged waveguide resonant cavity shown at left. The ripple and greater than unity excursions are an artifact of not waiting for full program convergence. The sharp resonance is due to the fact that the cavity is assumed to be lossless. The resonant frequency is≈ 1200 GHz. The analysis was performed using Quickwave [15].

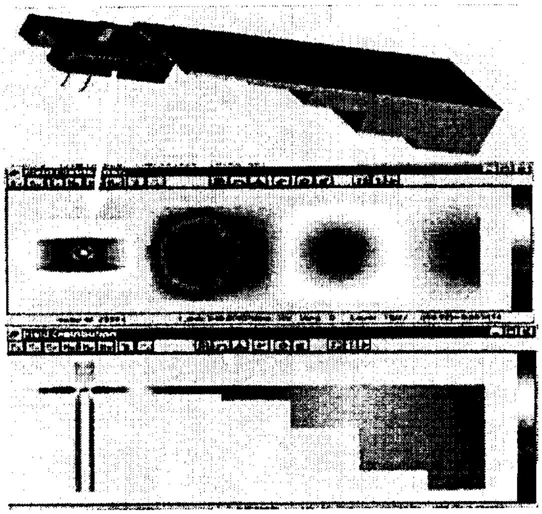


**Fig. 4.** Top: Solid view of nanoklystron cavity and output waveguide. Middle: Top view field plot showing $E_z$ at the height of the grid gap. Bottom: Side view field plot showing $E_z$ through the center of the cavity ridge and output waveguide. The coax excitation used to set up the fields can be seen at the left in the bottom plot.

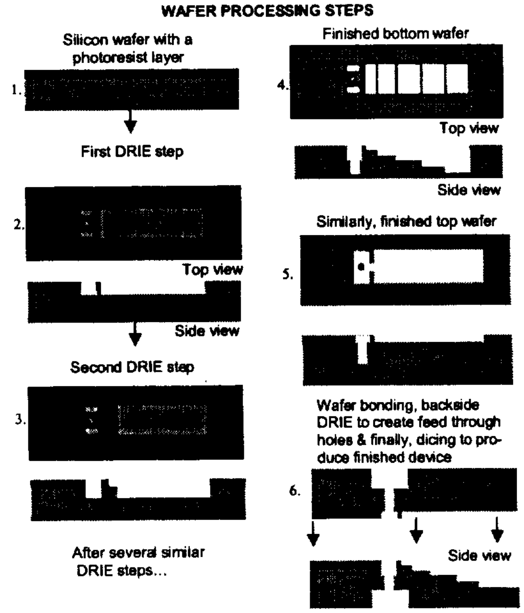


**Fig. 6.** Wafer processing steps needed to realize nanoklystron cavity, iris and output waveguide transformer from two SI silicon wafers. Each cell is approximately 1x2 mm for circuits between 600 and 1200 GHz allowing many hundreds of variations/wafer.

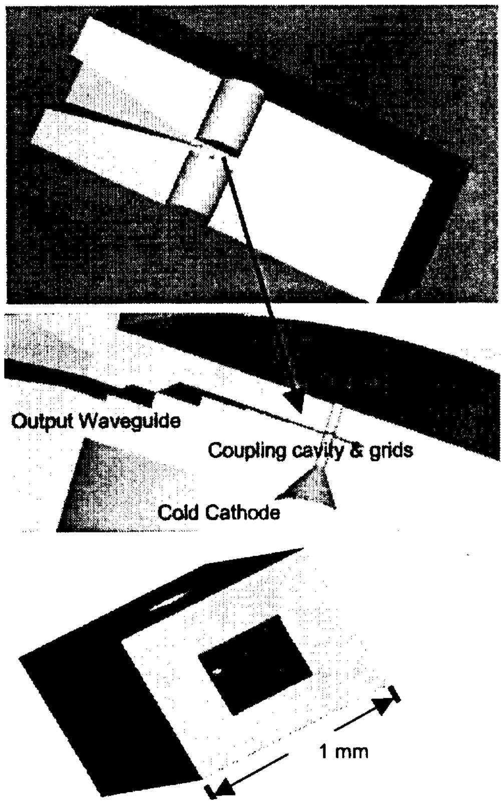


**Fig. 5.** Cross section and assembled view of 640 GHz machined nanoklystron. The smallest features are the 40μm diameter electron beam hole and the 10μm deep ridged waveguide cavity.

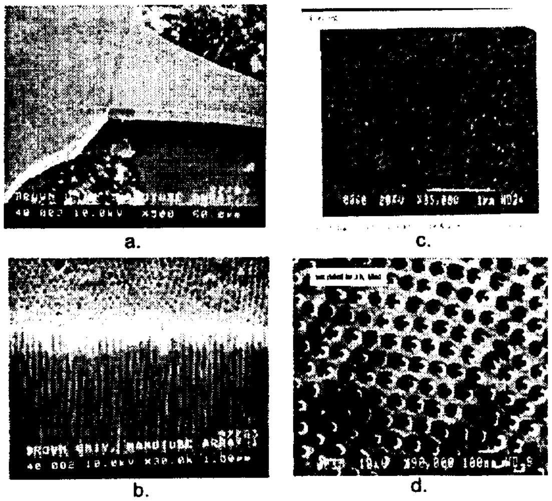


**Fig. 7.** Brown University highly ordered nanotube array at different magnifications. a. 500 X, b. 30 kX (tilted), c. 35kX (top), d. 90kX (top).

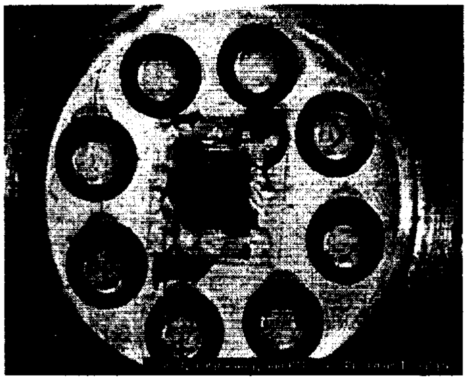
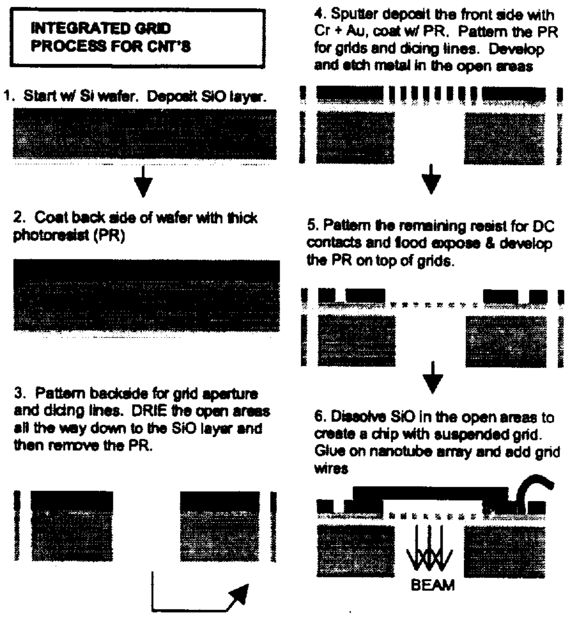


**Fig. 8**. Nanotube cathode and separate commercial emitter grid (1500 LPI) mounted on a fused quartz spacer for testing in a high vacuum emission test chamber. The grid and cathode are mounted on a T0-5 transistor header. Grid and anode current vs. voltage can be determined. The chamber has been assembled by Colleen Marrese of JPL.



INTEGRATED GRID PROCESS FOR CNT'S

1. Start w/ Si wafer. Deposit SiO layer.

2. Coat back side of wafer with thick photoresist (PR)

3. Pattern backside for grid aperture and dicing lines. DRIE the open areas all the way down to the SiO layer and then remove the PR.

4. Sputter deposit the front side with Cr + Au, coat w/ PR. Pattern the PR for grids and dicing lines. Develop and etch metal in the open areas

5. Pattern the remaining resist for DC contacts and flood expose & develop the PR on top of grids.

6. Dissolve SiO in the open areas to create a chip with suspended grid. Glue on nanotube array and add grid wires

**Fig. 9**. Steps for fabricating integral grid nanotube cathode.

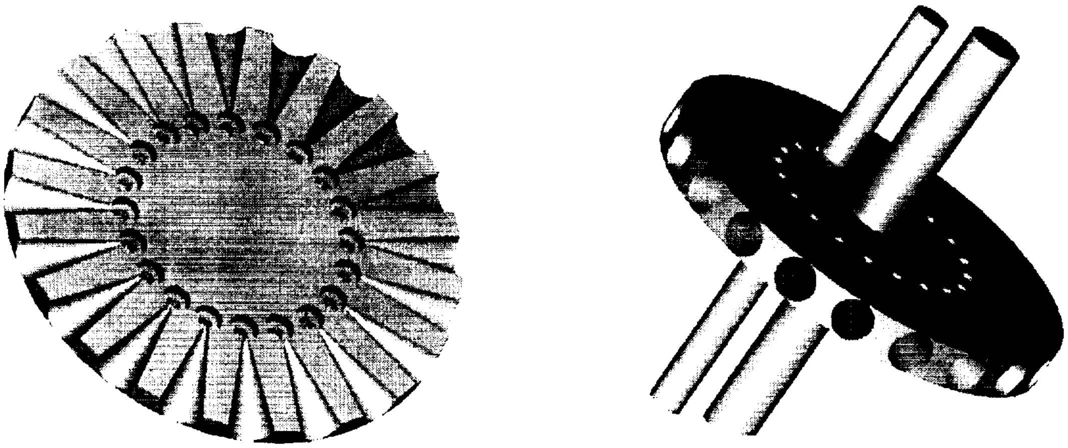


**Fig. 10.** Left: Possible nanoklystron array for multiple frequency or multiple power output. Right: Frequency switching or redundancy is obtained by mechanical indexing.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.