DESIGN AND FABRICATION OF A THz NANOKLYSTRON

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ABSTRACT

Recently the authors proposed a novel monolithic tube approach to THz power generation: the nanoklystron. In this presentation they report design and fabrication details of 1200 GHz nanoklystron circuits and ongoing efforts to produce low voltage cold cathodes from carbon nanotube (CNT) emitters. Both silicon-based and metal nanoklystron cavities have now been completed, and measurements on the field emission properties of several CNT cathodes have been made. In addition new techniques for growing highly ordered CNT arrays on flat evaporated surfaces have been demonstrated for the first time. This paper will include analytic design details for the 1200 GHz nanoklystron circuit, fabrication process steps for realizing the monolithic cavity, CNT emission measurements and progress on a UHV cathode and nanoklystron test chamber.

INTRODUCTION

1. Motivation

Millimeter and submillimeter-wave sensor technology has been a major thrust area at JPL for the past ten years. Instruments such as Microwave Limb Sounder, MIRO (Microwave Imager for Rosetta Orbiter), Cloude Ice and Herschel/FIRST have been enabled by the lab's efforts in this area. Future instrument opportunities will necessitate sensors at higher frequencies, greater sampling capability (arrays) and wider spectral (frequency) coverage. For all these applications, as well as for the development of THz communications systems and imagers, strong sources of submillimeter wave power will be required. The most popular technique to produce higher frequency (> 300 GHz) THz power employs low frequency oscillators coupled with nonlinear-reactance based frequency multiplier chains. These suffer from very low efficiencies as the multiplication factor increases (4 and above). The other available techniques such as THz lasers, BWOs (backward-wave oscillators) and carcinotrons are either bandwidth limited or frequency range limited along with being bulky and expensive.

A novel approach to realizing a medium power output, fixed frequency terahertz source that takes advantage of current monolithic silicon processing was recently proposed[1, 2]. This circuit, called a "nanoklystron," is actually a miniature electron tube (operating as a reflex klystron[3] [Hamilton *et al*., 1948]) with an ultra high current density (>1kA/cm^2) field emitter source for the generation of the required electron beam.

2. Nanoklystron Operating Principle

A nanoklystron consists of a high-density cathode, bunching tube, RF resonator, shaped repeller and RF output port, all fabricated monolithically on two bonded silicon wafers. Figure 1 shows a schematic sketch of such a device. For successful operation of this device a reliable, high current density emission source is of paramount importance. Low operating voltage, low power dissipation, and long operating lifetimes are desirable characteristics of electron sources for this application. Operation is identical to a traditional reflex klystron tube. Electrons emitted and focused into the beam guide travel across a narrow gap in a cavity resonator and are reflected back from a properly spaced repeller so that they interfere in phase and give up power to the resonator and output circuit. Using simplified beam analysis ala J.J. Hamilton[4] it is

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possible to show that a THz circuit operating at 500V and 3mA of beam current (micro-perveance=.268) can deliver 3mW to an output circuit with realistic losses[5]. In subsequent sections, design considerations and fabrication details for a 1200 GHz nanoklystron are given along with efforts that are underway to develop reliable, high current density, carbon-nanotubes-based electron field emitters.

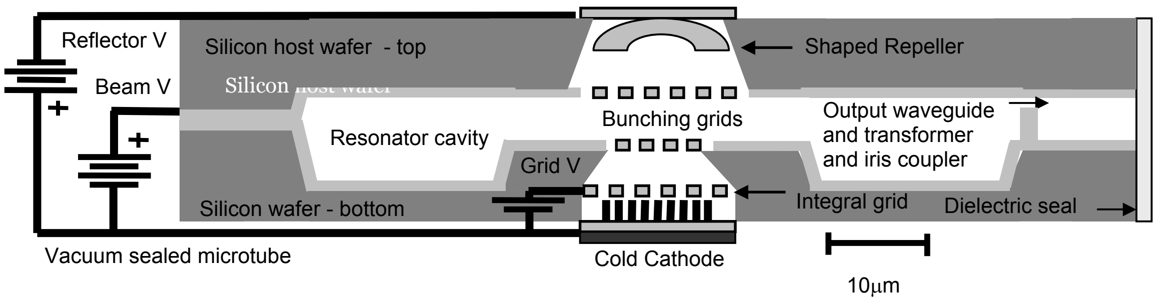

Figure 1: *Schematic cross section of a proposed nanoklystron. The cathode is composed of a carbon nanotube field emitter array with integrated grid. The cavity, beam and output waveguide are etched from two silicon wafers, which are later joined by thermocompression bonding. The repeller and cathode are drop-in parts and vacuum sealing is performed in the last step.*

DESIGN AND FABRICATION

1. Design Aspects

A reflex klystron cavity can be designed with reasonable accuracy by treating it as a capacitance loaded coaxial line. The Q is directly proportional to the ratio of volume to surface area of the cavity, as it increases the inductive element. A complete analysis has been performed[5] using the original design procedures described elsewhere[4] using 1200 GHz as the central output frequency. The analytic model predicts 50 mW of available power at 1200 GHz from a 3mA beam accelerated to 500V through a 20 μm re-entrant cavity-coupling hole. Cavity losses and iris coupling (loaded Q) cause 47 mW of the available 50mW to be lost in the re-entrant cavity (gold plated walls assumed), leaving approximately 3mW available at the waveguide output port. The simple closed form analysis shows- (1) significant output power is possible with existing cathode current densities and realistic cavity losses (Quickwave was used to simulate the actual cavity resonant frequency and resistive wall loss), and (2) the importance of reducing the cavity parasitic capacitance in order to be able to operate at the highest frequencies. A new cavity layout based on the analysis has now been completed and designs are being implemented.

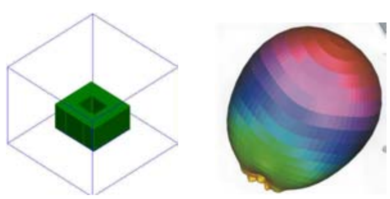

Figure 2: *Designed port geometry and predicted output beam pattern with 80% beam efficiency.*

As part of the design a new compact output horn geometry that eliminates the need for a full sized pyramidal horn was designed and integrated directly into the silicon wafer forming the nanoklystron cavity. The output circuit consists of an optimized approximately-half-wavelength-sized aperture that, when coupled with a novel dual offset inverse Cassegrain optical system produces a nice 2 degree RF beam with close to 80% beam efficiency. The design takes advantage of the loading produced by the surrounding silicon wafer on the aperture field distribution in the output port and was checked and optimized with Quickwave, a finite difference time domain program. The port geometry (left) and predicted output beam pattern (right) are shown in Figure 2 (without the inverse Cassegrain beam former).

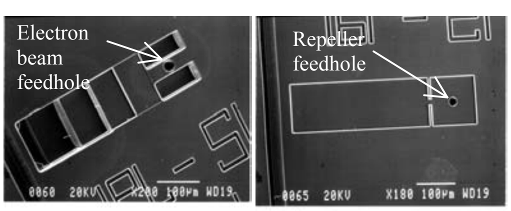

Figure 3: *SEM micrographs of top and bottom halves of a 1.2 THz monolithic nanoklystron prior to wafer bonding (α-version)*

2. Nanoklystron Fabrication

The nanoklystron is fabricated monolithically using silicon micromachining techniques. The top and the bottom halves of the device are etched in silicon separately using deep reactive ion etch (DRIE) process. The circuit consists of a reentrant resonant cavity, an emitter/repeller feedhole, and a step waveguide transformer terminating in a silicon window of half wavelength thickness at the output center frequency (reflection matched) that couples the generated THz power to the outside world. Using several lithography and DRIE processes, these parts are etched in bulk silicon in two halves and then bonded together to form the required structure. Apertures are etched at the back of the device to allow for the insertion of an electron source (in the bottom half) and a repeller (in the top half). Figure 3 shows SEM micrographs of the top and the bottom halves of a 1200 GHz nanoklystron prior to wafer bonding.

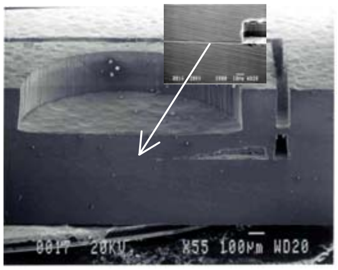

Figure 4: *SEM micrographs bonded top and bottom halves of a nanoklystron with the inset showing the bonded interface.*

After the etch step, the top and the bottom halves were coated with chromium, platinum and gold layers of 30, 60 and 250 nm thickness respectively, using e-beam evaporation. The two wafers are then aligned and bonded at a process temperature of 450° C and under a pressure of 2000 N. The total time of bonding was ~3 hours with additional 30 minutes for cooling down. The chamber pressure during bonding was maintained at 1 milliTorr. After bonding, the nanoklystrons were diced into individual devices. Figure 4 shows the cut-view of the bonded cavity and the inset shows the bonded interface at a higher magnification. The bright line indicates fused gold layers and the bond quality was excellent.

An ultra-high vacuum (UHV) test chamber is being built to test nanoklystrons as well as field emission characteristics of cold cathodes. Initially, nanoklystrons will be tested using conventional hot cathodes that are being designed by commercial vendors.

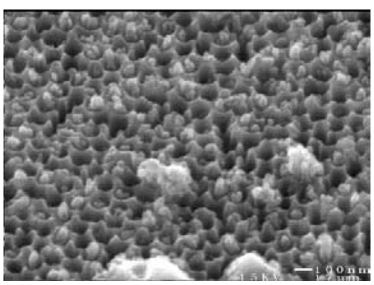

Figure 5: *SEM micrographs ordered carbon nanotube array grown inside the ordered pores of alumina. Inset shows the opened CNT tips*

3. Carbon Nanotube Field Emitters

The electron source for the nanoklystron must be capable of generating current densities of at least 100-1000 A/cm^2. Such current densities at low operating voltages may be generated by employing cold cathodes, especially carbon nanotube-based field emitters. The small diameter of carbon nanotubes (diameter of a 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. Figure 5 shows an SEM micrograph of ordered nanotube arrays[6] that are being tested to be used as an electron source for the nanoklystron. These are multi-walled nanotubes that are grown inside ordered pores of alumina that are produced from the anodization of high-purity aluminum substrates. Typical tip density is about 100 tips/µm^2 with typical tube diameter of ~ 40nm. To test the emission characteristics of these tips special grids were fabricated. Figure 6 shows an SEM micrograph of such grid structures. The grid is fabricated on silicon with an integrated insulating spacer layer made of hard-baked photoresist. This layer thickness is ~ 1.5 µm. The grid itself is made of gold, 1-µm thick with 2-µm line, 4-µm space mesh (transparency of ~ 45%). Grids were first formed using a lift-off process on a silicon substrate with 0.5 µm of oxide layer on it. This was followed by patterning and hard-baking the spacer layer. In the final step, backside etch was performed using DRIE to open up the beam channel and also to isolate the individual grid structures. By dissolving the oxide layer in BOE (buffered oxide etchant), individual grid chips with suspended mesh were released. For field emission measurements, a 3 mm × 4 mm piece of the CNT array was hard mounted on a TO5 transistor base. A grid structure was placed on top with its spacer layer facing down and

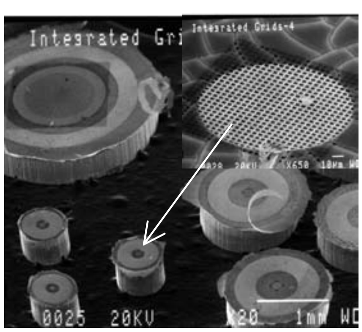

Figure 6: *SEM micrograph of custom-made grids with inset showing close-up of the gold mesh.*

was held in place by non-conductive glue while grid bias contact was made. CNTs were case grounded. Measurements were conducted in a UHV chamber in 7×10^{-9} Torr vacuum. Figure 7 shows the variation of emission current (I_g) with respect to grid bias (V_g). Although anode bias voltages of 200 V, 600 V and 800 V were used during the course of the experiment, no anode current was recorded. All of the emission was measured through the grid electrode. Initially, there was a high electron emission at very low V_g. We measured ~ 2.5 μA at 5 V of V_g which increased close to 100 μA at 50 V (inset data). This high current lasted for about ten minutes before dying down. When we restarted the measurements, we could not recover this region again, but consistently measured the second set of data over three different trials (curve that resembles an Fowler-Nordheim or an F-N plot) with a maximum current of ~ 35 μA at V_g =300 V. At this point we had to stop the experiment as the grid and the CNTs short-circuited.

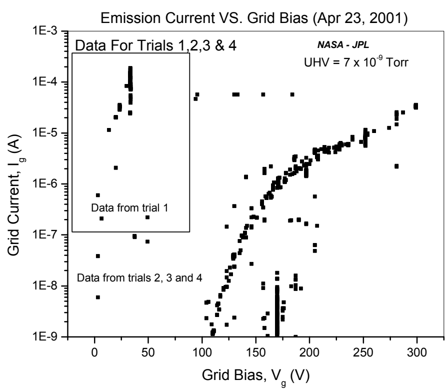

Figure 7: *Field emission measurement data of ordered CNT arrays using custom-made grids. Inset data shows the initial burst of emission followed by a data that follows the F-N curves.*

CNTs used in this experiment were grown on commercially available high-purity aluminum foils. These foils are highly prone to wrinkles, which make the surface of the CNT sample non-uniform to the order of few tens of microns (as measured by SEM). This results in significant variation of the gap distance between the grid and the CNT surface in spite of having a uniform insulation layer of 1.5-μm thickness. The initial burst of emission at low V_g can be attributed to this surface non-uniformity, which causes a few nanotube tips very close to the grid to emit freely at low biasing potential. It was also noticed that the ratio of emitting tips to the total present was quite low. A sampled count gives ~ 10^8 tips in the emission area of 1 mm dia (0.78 mm^2) and at a projected emission of 300 nA/tip, our emission data accounts for only a few hundreds of tips actually participating in the emission! To eliminate obvious problems resulting from the non-uniformity of the emitting surface, ordered arrays of carbon nanotubes have been successfully grown on aluminum-deposited, flat, degenerately doped silicon wafers. In the near future emission properties of these samples will be tested. One other major advantage of such CNTs grown on Al-on-Si substrate is their conduciveness for micromachining, which allows for shaping the emitter cross section to any suitable geometry. The emission measurements presented here are very encouraging for applying CNTs as low-operating voltage cold cathodes.

SUMMARY

The nanoklystron is a promising new approach to the generation of direct power at THz frequencies. Although no working circuits have yet been tested, progress both on the circuit fabrication and high density cathodes is being made. Prelimnary analysis shows no insurmountable obstacles, although there is still much development work ahead.

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