A Micromachined Vacuum Triode Using a Carbon Nanotube Cold Cathode

Chris Bower, Diego Shalóm, Wei Zhu, Daniel López, Greg P. Kochanski, Peter L. Gammel, *Member, IEEE*, and Sungho Jin

***Abstract*—A fully integrated on-chip vacuum microtriode using carbon nanotubes as field emitters was constructed laterally on a silicon surface using microelectromechanical systems (MEMS) design and fabrication principles. Each electrode in the triode was made of a hinged polycrystalline silicon panel that could be rotated and locked into an upright position. The device was operated at a current density as high as 16 A/cm^2. Although the transconductance was measured only at 1.3 μS, the dc output power delivered at the anode was almost 40$\times$ more than the power lost at the grid electrode. The technique combines high-performance nanomaterials with mature solid-state fabrication technology to produce miniaturized power-amplifying vacuum devices in an on-chip form, which could potentially offer a route of integrating vacuum and solid-state electronics and open up new applications for "old-fashioned" vacuum tubes.**

***Index Terms*—Carbon nanotubes, cold cathode, cutoff frequency, field emission, microelectromechanical systems (MEMS), micromachining, microtide, microwave power amplifiers, transconductance, vacuum microelectronics, vacuum tubes.**

I. INTRODUCTION

THE MODERN communication industry was born with the development of gridded vacuum tube amplifiers [1]. These vacuum devices made broadcast radio and television possible. From the onset, the vacuum tubes suffered from many limitations, all related to the use of thermionic cathodes, which typically had to be heated to above 800 °C for electron emission to occur. In low power applications (e.g., <10 W), the power required to heat the cathode can be greater than the power needed to operate the tubes. For high frequency applications (e.g., >1 GHz), the proximity of the hot cathode makes it difficult to stably position the control grid close enough to the cathode (e.g., <25 μm) in order to overcome the transit time limit on the operating frequency of the device [2].

The arrival of solid state transistors and integrated circuits has eliminated the use of vacuum tubes in all low power applications. However, semiconductor technologies, even using new materials such as GaAs and SiC, do not easily solve the power amplification problem, particularly at gigahertz frequencies. To generate the 50–500 watts needed in a wireless base station transmitter, for example, solid state amplifiers have to operate many transistors in parallel with complex microstrip combining circuits and bulky thermal management equipment. In contrast, vacuum tube amplifieirs can be compact and efficient for many high power and high frequency applications. This is in part due to the fundamental speed of electrons in vacuum being about three orders of magnitude faster (with correspondingly less energy loss) than in solids. They are also radiation hard and can be operated over a wider temperature range. Therefore, vacuum tubes remain the amplifier of choice for radar, electronic warfare and space-based communications.

The use of cold cathodes in vacuum devices can potentially bring together the best features of both vacuum tubes (e.g., high power) and solid state power transistors (e.g., long lifetime and miniaturization). Cold cathode devices can be turned on instantaneously, without a tedious warm-up period. They can also be operated more efficiently because of the elimination of heating power and the possible incorporation of depressed collectors in the induction output tubes (true for both hot and cold cathode devices) to recycle the kinetic energy of the spent electron beams back to the power supply. Further, in the absence of thermal distortions from the hot cathodes, the grid can now be placed very close to the cathode (e.g., < 10 μm), enabling high frequency (e.g., >10 GHz) and low control voltage (e.g., 50–100 V) operation. In beam forming tubes, density modulation of electron beams by the grid through gated emission thus becomes possible. As a result, a long beam interaction section is no longer required, and the tube length can be shortened. A cold cathode vacuum tube amplifier system is thus attractive to the commercial wireless communications industry, as the highly efficient vacuum devices can help minimize the size of the amplifier electronics in the cellular base stations. They are also especially valuable for space operation where radiation is strong, available power and space is limited, and heat can only be dissipated by radiation.

Over the years, there have been considerable efforts spent in building cold cathode microwave power tube amplifiers [3]–[15]. All devices have been based on Spindt-type field emitter array (FEA) cathodes that were used as the electron source for triodes, klystrodes and traveling wave tubes (TWT). TWT devices operating at 10 GHz with molybdenum FEAs emitting at current densities of 50 A/cm^2 for a period of 5000 hours (at 1% duty cycle) have been demonstrated [12]–[14], and a highly stable unmodulated FEA-TWT has also been fabricated that operated at a current density of 11.5 A/cm^2 with a transmission ratio of 99.5%, output power of 55 W and efficiency of 17.2% at 4.5 GHz [15]. However, density modulation at microwave frequencies through gated emission has proven to be difficult, and no practically useful triodes have been reported.

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Carbon nanotubes have recently emerged as promising field emitters that can emit large current densities at relatively low electric fields [16]. They are composed of cylindrically arranged graphitic sheets with diameters in the range of 1–30 nm and length/diameter aspect ratios greater than 1000 [17]. Of particular interest is the capability of nanotube emitters to stably deliver very high emission currents, as individual nanotubes can emit up to 1 μA [18] and nanotube films can generate current densities in excess of 4 A/cm^2 [19].

We report here a novel method for fabricating fully integrated, on-chip, vacuum microtriodes using carbon nanotubes as field emitters via silicon micromachining processes. In contrast to the conventional vertical structures based on Spindt field emitter arrays [7], [8] or metal nanopillar cathodes [20] that involves multi-layer deposition and precision alignment, our triodes are constructed laterally on a silicon substrate surface using microelectromechanical systems (MEMS) design and fabrication principles. This approach offers greater flexibility in designing sophisticated microwave devices and circuitries, employs simpler, more reliable and more precise fabrication processes, and produces completely integrated structures. The technique combines high-performance nanomaterials with mature solid-state microfabrication technology to produce miniaturized vacuum tube devices in an on-chip form, which could have important and far-reaching scientific and technological implications. To our knowledge, this is the first demonstration of incorporating carbon nanotube field emitters in a MEMS design intended for on-chip power-amplifying vacuum devices.

II. Experiments

Our new microtriode was fabricated using a three-layer polysilicon micromaching process on a silicon nitride coated silicon substrate [21]. The triode structure was chosen because, despite its simple device geometry, its characterization can be easily parameterized and its behavior can provide important insight to the design and performance of more sophisticated devices. The triode here is a micrometer-scale version of a conventional vacuum triode, consisting of a cathode, a grid, and an anode. Each electrode here was made of a hinged polysilicon panel that can be rotated and locked into position. Well-aligned carbon nanotubes were selectively grown on the cathode regions by first depositing a thin, nanotube-nucleating catalyst layer of iron (50 Å) through a shadow mask, and then growing the nanotubes in a microwave plasma of ammonia/acetylene mixture at 750 °C (for details, see [22], [23]). Fig. 1(a) presents an optical micrograph of a triode structure following carbon nanotube growth, in which the cathode, grid, and anode have not yet been rotated and locked into place. The nanotubes were typically patterned on the cathode according to the grid geometry in order to minimize the intercepted grid current (I_g). Fig. 1(b)–(d) shows scanning electron microscopy (SEM) micrographs of a completely assembled microtriode. The structure here was assembled under a microscope using a mechanical microprobe. Various self-assembly techniques could be used to achieve better manufacturability for future devices [24]. The carbon nanotubes grown here were multi-walled and highly oriented, with diameters ranging from 20–50 nm. The nanotube length was determined by controlling the growth time (typical growth rates were $\sim$10 μm in length per minute), which, in turn, controlled the spacing between the cathode and grid (and hence the emission field), as shown in Fig. 1(e)–(f).

III. Results and Discussion

We have obtained the dc characteristics of the triodes by measuring how the anode current (I_a) changes as a function of both the grid voltage (V_g) and the anode voltage (V_a). These measurements were performed at room temperature within a vacuum chamber with a base pressure of 10^{-8} torr. A triode is the vacuum equivalent of a field effect transistor, in which electrons are emitted from the cathode into vacuum, and a grid (or gate) electrode varies the electric field between the cathode and grid to control the emission current. Some of the electrons pass through apertures in the grid, accelerate toward the anode, and are collected to give a current through the device. The devices can have a substantial output current gain (I_a) if the grid intercepts only a small fraction of the emitted current. As this grid-controlled current goes to the anode and passes through an external load, it can produce a voltage larger than the control voltage at the grid, resulting in a voltage gain ($\Delta V_a/\Delta V_g$). Therefore, if the device geometry is designed correctly, this can yield an overall power gain.

Fig. 2(a) shows how the grid current (I_g), anode current (I_a), and transconductance ($g_m = \delta I_a/\delta V_g$) vary with grid voltage while the anode voltage was held at 100 V for the triode shown in Fig. 1(a)–(e). We observed that the grid and anode currents increase exponentially with the grid voltage, as is expected from the Fowler–Nordheim emission tunneling theory [25]. Under reverse bias conditions, no current was observed until electric breakdown of the insulating silicon nitride layer occurred at approximately 200 V. The plateau in the Fowler–Nordheim plot, shown as region 2 in the inset in Fig. 2(a), is associated with the desorption of adsorbates present at the nanotube tips, as described in detail elsewhere [18], [26]. The grid and anode currents were observed to follow each other closely, with a current ratio (I_a/I_g) of roughly 3 for this particular device tested but varying between 1–10 from device to device. The anode current was plotted only up to 28 μA in the figure; however, the maximum currents we have measured so far were $I_a = 100\,\mu$A and $I_g = 50\,\mu$A, meaning a total emission current of 150 μA from the cathode. This corresponds to a peak, macroscopic emission current density (J_{peak}) generated by the cathode [effective emission area of nanotubes = (the number of gate holes) $\times$ (the area of each gate hole) = $9 \times (10 \times 10)$ μm^2] of 16 A/cm^2, exceeding the previously published record emission current density from carbon nanotubes [19]. The device was run continuously without degradation for 24 hours at a current density of approximately 2 A/cm^2 ($I_a = 12\,\mu$A). The device was further operated at an elevated pressure of 10^{-6} torr, and the emission current ($I_a = 12\,\mu$A) remained stable for a period of 6 h. This robustness of our microtriode may be attributable to the excellent chemical and mechanical properties of carbon nanotubes. The use of small-area (i.e., $\sim\mu$m^2) cathodes in our microtriode

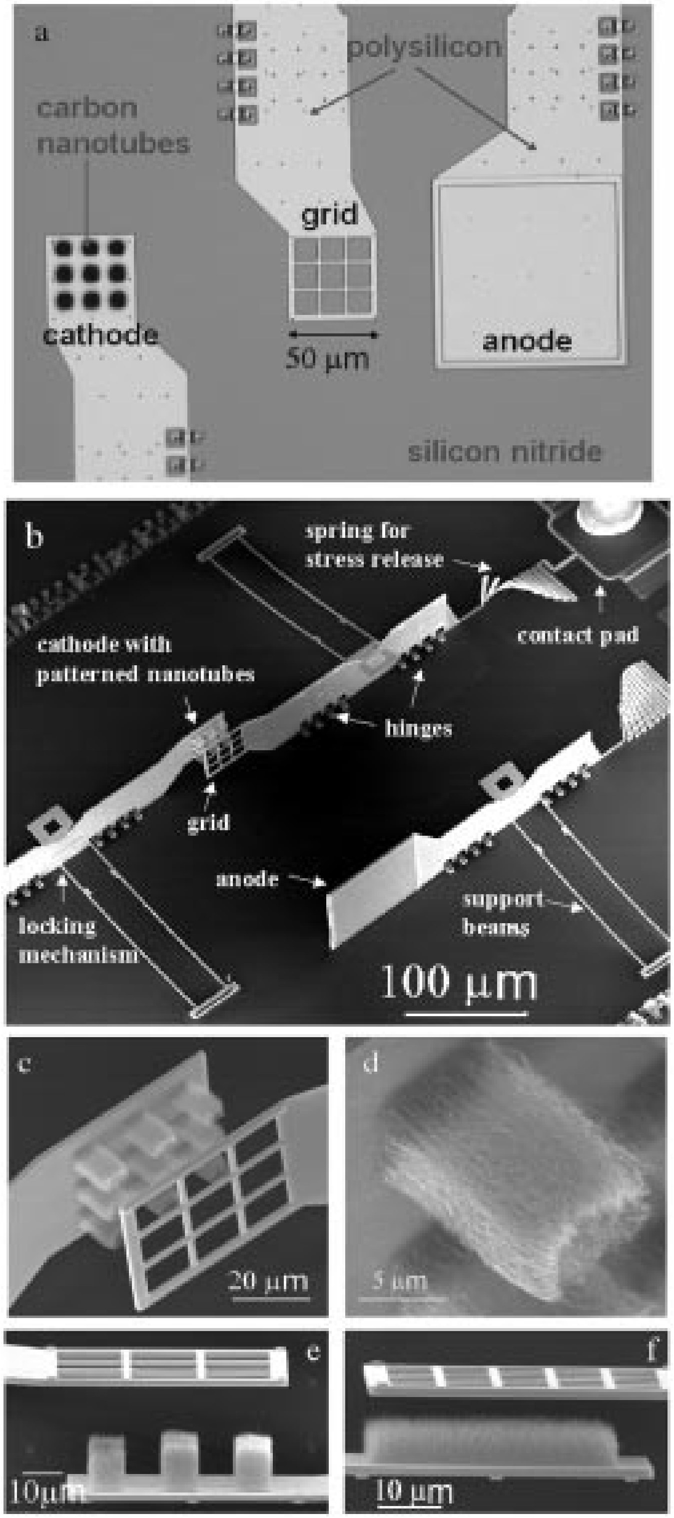


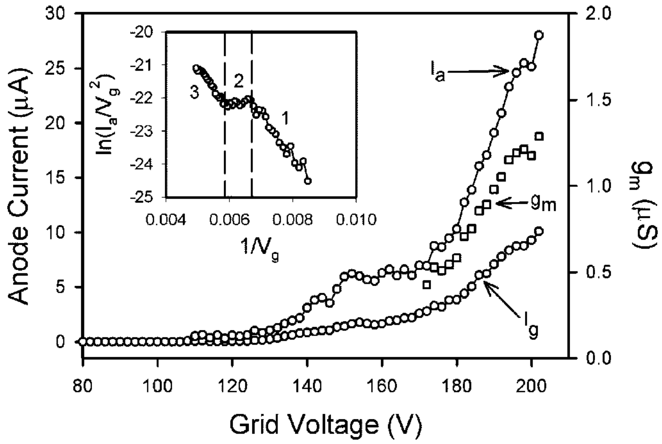
Fig. 1. (a) An optical micrograph showing an unassembled micromachined triode structure. (b)–(d) SEM micrographs of a completely assembled triode and its nanotube cathode structure. (e) and (f) SEM micrographs illustrating that the spacing between the nanotube cathode and grid can be controlled by the length of nanotubes.

also contributes to the emitter stability by reducing the impact of extreme emission nonuniformity (i.e., hot spots) that is frequently encountered and often unavoidable in large-area (e.g., ~mm^2 and larger) cathodes [26]–[28]. It should be noted that even at the observed maximum current of 150 μA, only a very small number of nanotubes were actually emitting electrons, considering that each nanotube is capable of generating 1 μA of emission current. The nonuniformity in tube height as exemplified in the "dishing" effect in the surface profile of nanotubes shown in Fig. 1(d) and the "screening" effect in field concentration among neighboring tubes that are bundled tightly together are two possible contributing factors to the scarce number of active emitters.

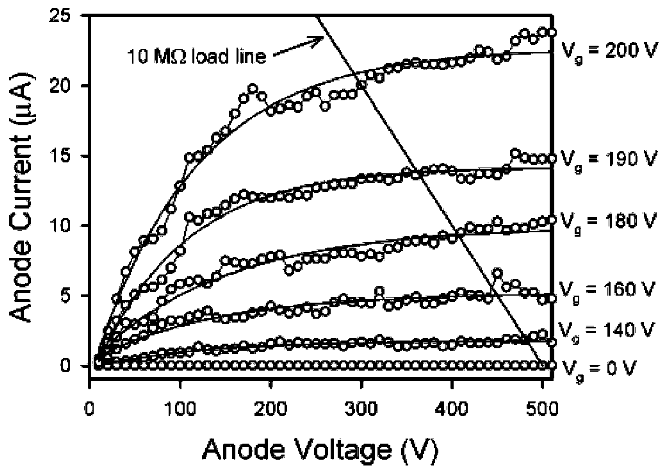
The transconductance of this triode, as shown in Fig. 2(a), was 1.3 μS at the anode current of 28 μA. It should be correspondingly much higher at the maximum anode current level of 100 μA that we observed. On a normalized basis with respect to the cathode area, our number (0.15 S/cm^2 at $I_a = 28\,\mu$A) is about half of that from the thermionic triode (0.3 S/cm^2) [2], but can be significantly better at higher current levels. If normalized by the emission current, our number (0.05 S/A) is comparable or even better than Spindt cathode-based structures (~0.03 S/A). While it is important to have a high transconductance for successful high frequency device operation, such a high transconductance is desirably achieved at relatively low emission currents and voltages in order to reduce the probability of emitter failure due to overheating or arcing and to minimize the heat dissipation at the anode. Because the fields required for emission from nanotubes are typically low (<10 V/μm), our nanotube based triode structure is likely to perform well in this regard.

Fig. 2(b) shows the measured anode characteristic curves. As noted earlier, electric breakdown occurred across the thin silicon nitride layer on the Si substrate at voltages above 200 V. To circumvent this problem, an external metallic anode was brought into close proximity to the original polysilicon anode, and data at voltages above 200 V were subsequently collected. The internal anode resistance ($R_a = \delta V_a/\delta I_a$), measured in the linear region above anode voltages of 200 V, was approximately 100 MΩ. Also included in the figure is a 10 MΩ load line. Operating at the point of $V_a = 325$ V and $I_a = 16\,\mu$A, a peak-to-peak voltage swing of 10 V on the grid induces a peak-to-peak anode voltage change of 75 V, resulting in a voltage gain of 17.5 dB. We can also conveniently calculate the amount of output power delivered at the anode (P_a) compared to the power lost at the grid (P_g) by $P_a/P_g = (I_a^2 R_l)/(I_g V_g) = (I_a/I_g) g_m R_l$. Using a current ratio (I_a/I_g) of 3, a transconductance (g_m) of 1.3 μS, and a load resistance (R_l) of 10 MΩ, we obtain $P_a/P_g = 39$, suggesting that the dc output power is almost 40 times more than the power lost (or intercepted) at the grid. Because of the breakdown of the silicon nitride layer, the total output power at the integrated anode is currently limited in the range of 1–10 mW, corresponding to an output power density of 10–100 W/cm^2 of anode area. Assuming that these devices will eventually be built on a better substrate with a much larger breakdown voltage, and the considerable challenges in thermal management can be met, we expect that an output power of 100 mW (100 μA at 1000 V) per device is obtainable. In a distributed amplifier system [6], this would require only 100 devices to generate 10 W of power.

Based on the results of the dc measurements, it is possible to discuss the predicted frequency performance of this device.



(a)



(b)

Fig. 2. (a) Grid current, anode current and transconductance as a function of grid voltage with the anode held at 100 V. The inset is a Fowler–Nordheim plot for the anode current showing three distinctive regions associated with surface adsorbates that are described in detail elsewhere [18], [26]. (b) Anode current as a function of anode voltage at various grid voltages. The 10 MΩ load line indicates the voltage gain that can be achieved by this device.

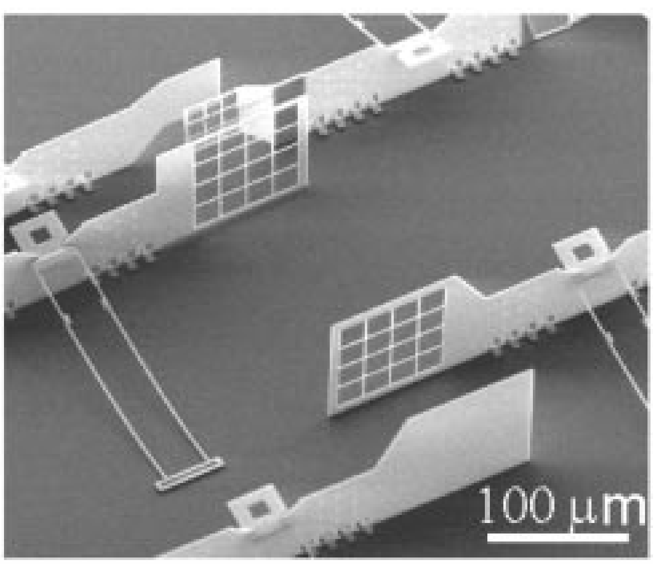


Fig. 3. SEM micrograph showing an assembled micromachined pentode structure. Carbon nanotubes have not been grown on the cathode.

Because the current structure is primarily designed to test the feasibility of the MEMS device concept, not for high frequency operation, the actual frequency performance is currently dominated by stray capacitance and lead inductance. In theory, the cutoff frequency of a triode depends critically on the transconductance and the interelectrode capacitance ($f_t = g_m/2\pi C_g$). For the microtriode, the cathode-to-grid capacitance can be roughly approximated using parallel plate geometry. Using a cathode area of (50 × 50) μm^2 and a cathode-to-grid distance of 25 μm, the capacitance [$C = \varepsilon_o$ (A/d)] can be calculated to be 8.85×10^{-4} pF. Note that this is likely an overestimation of the true capacitance, because we did not take into account the grid holes or the true area of the carbon nanotube cathode that is substantially smaller. Using this C_g and a transconductance of 1.3 μS, we derive the cutoff frequency to be 234 MHz.

IV. Conclusion

We have demonstrated a completely integrated, laterally built, on-chip microtriode that incorporates carbon nanotube field emitters and provides substantial dc output power. The design allows multiple devices to be integrated on a single chip, which can be used to form a part of complex microwave circuits to meet various power amplification needs. We are encouraged by the fact that the MEMS structure and materials withstood the high-temperature nanotube growth processing and the resulting device still demonstrated impressive dc power characteristics. Based on the dc data already obtained, we will perform rf modeling and design optimization on both the device and circuit levels and further explore device structures that are more compatible with high frequency operation. With the use of better breakdown-resistant substrates and improved electrode designs, we expect to achieve transconductances of at least 100 μS per device, which would increase the power gain and cutoff frequency by two orders of magnitude. We will take advantage of the MEMS design flexibility to add more functionality into the device structure. For example, a micropentode structure, shown in Fig. 3, has been fabricated without requiring any additional processing steps. The design and fabrication of inductive output type vacuum tube devices such as klystrodes, klystrons and TWTs via such solid-state-based MEMS technologies is also clearly within reach. More importantly, the powerful combination of nanomaterials with MEMS technology, as demonstrated in this work, will likely stimulate further advances in creating new and unique devices useful for a variety of other applications.

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