SPIE MOEMS and Miniaturized Systems IX, Vol 7594 (2010)

Invited

Carbon nanotube-based digital vacuum electronics and miniature instrumentation for space exploration

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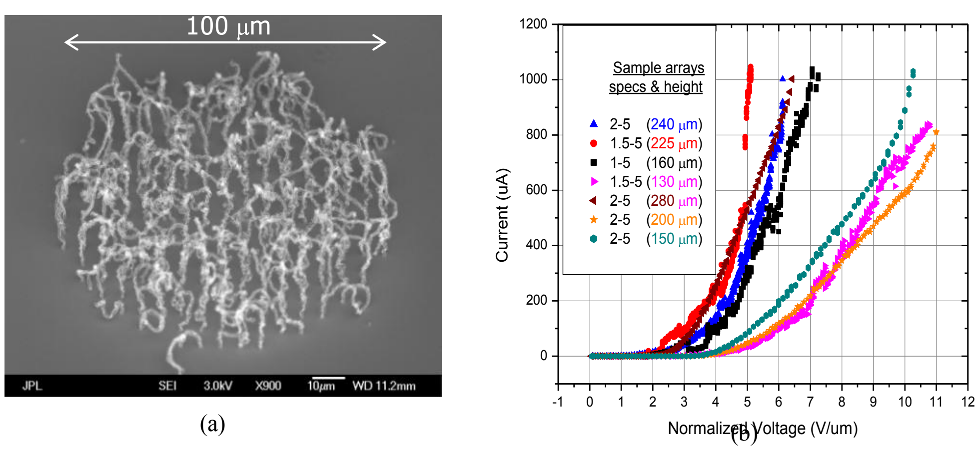
ABSTRACT

JPL has developed high performance cold cathodes using arrays of carbon nanotube bundles that produce > 15 A/cm^2 at applied fields of 5 to 8 V/μm without any beam focusing. They have exhibited robust operation in poor vacuums of 10^{-6} to 10^{-4} Torr- a typically achievable range inside hermetically sealed microcavities. Using these CNT cathodes JPL has developed miniature X-ray tubes capable of delivering sufficient photon flux at acceleration voltages of <20kV to perform definitive mineralogy on planetary surfaces; mass ionizers that offer two orders of magnitude power savings, and S/N ratio better by a factor of five over conventional ionizers. JPL has also developed a new class of programmable logic gates using CNT vacuum electronics potentially for Venus *in situ* missions and defense applications. These "digital" vacuum electronic devices are inherently high-temperature tolerant and radiation insensitive. Device design, fabrication and DC switching operation at temperatures up to 700° C are presented in this paper.

Keywords: Field Emission; Carbon Nanotube; CNTs; Vacuum Electronics, X-rays

1. INTRODUCTION

High-performance field emitters have been developed using CNT arrays of 1-2 micrometer (μm) diameter bundles spaced 5 μm apart. After initially achieving > 2 A/cm^2 at 4 V/μm, we have optimized the CNT growth process and the architecture in recent times to routinely produce 10 to 25 A/cm^2 at applied fields of 5 to 10 V/μm [1-3] . These tests were conducted using CNT bundle array samples that occupied a circular area of 100 μm diameter (see Figure 1(a)), which is considered a large area source for our applications. The repeatability of this current production was achieved over multiple samples as shown in Figure 1(b). All emission tests were



(a) (b)

Figure 1. (a) SEM micrograph of 100-μm diameter sample with 1-μm diameter bundles. (b) An example of field emission data from multiple samples producing 10 to 15 A/cm^2 at fields ranging from 4 to 9 V/μm.

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conducted in ~10^{-5} Torr vacuum. Such high-current density, poor-vacuum tolerant field emitters are useful for multiple applications involving miniature spectroscopic instruments and high-temperature tolerant, radiation-insensitive vacuum electronic devices. Using combination of CNT field emitters, Si micromachining, and microassembly techniques, electron beam-based microsystems can be developed for *in situ* planetary exploration. While high-current density facilitates miniature X-ray tubes and mass ionizers [2-10], high-temperature tolerance and inherent radiation insensitivity of the field emission process allows the development of vacuum electronic-based logic gates that are compatible for operation in extreme environments such as on the surface of planet Venus whose surface temperature is 470° C, or in the Jovian environment that is rich in radiation. This demonstrated digital vacuum electronics technique also allows device densities that can be comparable to that achieved using CMOS technology.

2. APPLICATIONS

The development of CNT bundle array-based miniature X-ray tubes and miniature mass spectrometers has been described in detail elsewhere [2,3]. Here we focus on the development of digital vacuum electronic devices for high temperature.

2.1. Digital Vacuum Electronics

A programmable logic gate based on a four-gate transistor (G^4-FET) design has been presented in an earlier work [11]. By controlling the conduction characteristics of the device using combined interaction of these gates a universal and programmable logic device was demonstrated. It was shown that the logic function it implements is the inverse of that of a Majority gate (the output of the Majority gate is „1‟ if more than half of its inputs are „1‟), and hence it was called the "Inverse Majority Gate."

This work adapts the Inverse Majority logic Gate (IMG) concept to carbon nanotube (CNT) field emitter-based vacuum microelectronics [12]. This device consists of three gates and a common anode. By controlling the electron emission from CNT to either the anode or to one, two or all of the three gate electrodes, logic operation of a 2-input NAND and a 2-input NOR gate can be realized from a single device. This allows programmability to achieve functionally versatile logic devices. Because the electron transport in these devices occurs in vacuum, they are inherently high-temperature tolerant and radiation insensitive unlike their solid-state counter parts. By achieving critical dimensions of electrodes in the range of 1 to 2 µm, nanosecond-level switching speeds can be achieved, which are comparable to those of solid-state devices.

2.1.1. Description of the Concept: Figure 2 shows schematic of an IMG device. Operationally, it is a simple structure that relies on the switching of electron current from anode to gates and vice-versa depending on where a stronger field is applied. To accomplish switching, the electron emitter tips are placed below the plane of gate electrodes. The electron emitters employed here are CNT bundles that have been shown to be efficient, high current density field emitters that turn on at fields < 1 V/µm. Anode is placed at a larger gap (typically 5 to 10 µm) from the CNT tips and the gates are placed significantly closer (typically 1 to 2µm). When a field higher than the threshold is applied between the anode and the cathode, current flows into the anode. By connecting a pull-up resistor to the anode, a corresponding voltage drop can be recorded, which is assigned a logic state. Thus, a non-zero current at the anode constitutes the logic state of "1" and vice-versa. The anode current is made zero when a similar or a higher voltage is applied between the gates and the emitters (because of higher field) as the electron flow switches from anode to gates. Because the CNT tips are well below the plane of gate structures, they do not act as extraction electrodes but instead suppress current flow to the anode.

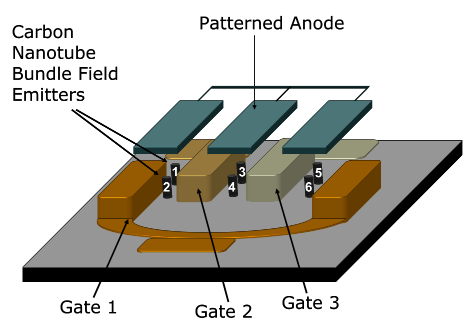

Figure 2. Tri-grid (gate) Inverse Majority Gate design. Six CNT bundles are fabricated as electron emitters.

The uniqueness of the IMG structure shown in Figure 1 is that it requires at least two of the gates to be turned on to make the anode current "zero." For example, if only gate 1 is on, electron emission from CNT bundles 1, 2, 5, and 6 are diverted from anode to gate 1, but the emission from 4 and 5 will continue to anode unless gate 2 or 3 is turned on. This case holds for any set of gate combinations. Applying the above-mentioned convention for logic states, a truth table can be generated as shown in Table 1. Notice that the output state is always the inverse of the majority state of the gates (hence the name Inverse Majority Gate). The truth table shows states of both a NAND and a NOR gate. Hence, by selecting a particular sequence of gate states the IMG can be programmed to operate either as a NAND or as a NOR gate.

Table 1. Logic truth table of an Inverse Majority Gate (IMG)

Sl. No.	Gate 1	Gate 2	Gate 3	Output
1	0	0	0	1
2	1	0	0	1
3	0	1	0	1
4	1	1	0	0
5	0	0	1	1
6	1	0	1	0
7	0	1	1	0
8	1	1	1	0

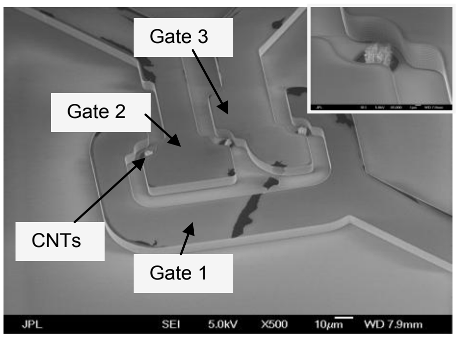

Figure 3. SEM micrographs of IMG device with single emitter bundle design.

2.1.2. Fabrication of IMG: IMG was fabricated using silicon-on-insulator (SOI) substrates with 9-µm thick device layers of ~0.01 Ω.cm resistivity. The fabrication process consists of four lithography steps and a combination of wet and dry etching steps to pattern three gates in the device layer followed by 2-µm diameter catalyst (Fe) dot deposition at center of each gate halves for CNT synthesis. CNT bundles with 20 nm diameter nanotubes were synthesized using a CVD process. Figure 3 shows SEM micrographs of an IMG.

2.1.3. Test Set-Up: We designed a ceramic sample mounting chip with Au contact pads for IMGs (inset of Figure 4). Gap-welded Au-ribbons were used to make electrical contacts. The IMG chip was mounted at the center of the ceramic chip and a micromachined anode in the shape of a "plus" sign was placed on top at a distance of ~ 50 µm. The tests were conducted inside a vacuum chamber. The ceramic chip with IMG sample was placed at the center of a 25-mm diameter Tantalum-Tungsten heater coil (see Figure 4).

2.1.4. DC Switching Results: DC switching experiments to generate the IMG logic states was performed at both room temperature as well as at different elevated temperatures up to ~ 700° C. The base level or the noise current with all instruments off was measured to be 0.3-0.5 nA. This is set as the current for the OFF state of the logic gate. Tests were conducted at threshold field level of 1 - 2 V/µm, and the non-zero current measured at the anode due to field emission was recorded for different gate combinations. Output is considered logic ON when the current is > 1 nA, and the gates are considered logic ON when their bias is at 10 V. Using this convention, the operation of an IMG was tabulated at different temperatures. Both two-gate and three-gate operations were recorded for several devices over a range of 25° C to 700° C. Table 2 lists the operational values at ~ 400° C, as an example. Note that the output logic states in Table 2 match those in the truth-table (Table 1).

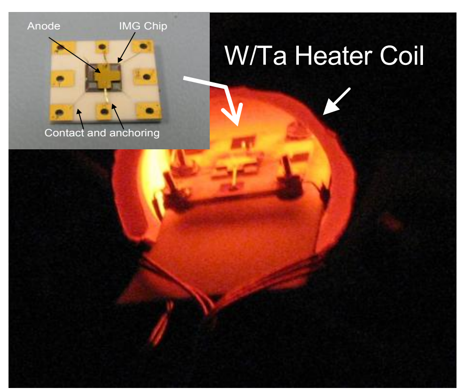

Figure 4. IMG chip during test inside a W/Ta heater. Inset: Ceramic IMG mount with "+" shaped anode.

Table 2. Results of DC switching at high temperature. Current at the anode of < 1 nA is regarded as the "0" state, as that corresponds to no field emission from CNTs

Va (V)	Vg1 (V)	Vg2 (V)	Vg3 (V)	Ia (nA)	O/P State
50	0	0	0	3.2	1
50	10	0	0	2.8	1
50	10	10	0	0.7	0
50	10	10	10	0	0
50	0	10	0	3.6	1
50	0	10	10	0.27	0
50	0	0	10	2.5	1
50	10	0	10	0.35	0

3. CONCLUSIONS

A new logic gate device concept using CNT vacuum electronics has been successfully demonstrated from room temperature to 700° C. The switching speed depends predominantly on the intrinsic device capacitance, load capacitance, and the electron transit time. The first two quantities can be decreased to values < pF by adapting smaller line widths and dedicated measurement circuits. Then the operational frequency becomes predominantly electron transit time dependent and can tend towards GHz range. Low voltage and low current operation can ensure prolonged device life time.

4. ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with National Aeronautics and Space Administration (NASA). This work was funded by the Defense Advanced Research Project Agency. We thank Dr. Mark Rosker and Dr. Amit Lal of DARPA for their support, and Dr. Ken Dean of Motorola, Dr. Elizabeth Kolawa and Dr. Linda Del Castillo of JPL for valuable discussions.

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