Carbon Nanotube-Based Vacuum and Semiconducting Devices for Micro-Instrumentation and Electronics.
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Introduction: High-current density field emission electron sources are the essential components to enable multiple miniature instruments for planetary probe missions, which include, XRD/XRF, XPS, miniature mass spectrometers, UV-Lasers for Raman spectroscopy, advanced THz sources for heterodyne spectroscopy, and vacuum microelectronics. Such sources increase the data collection rate, and reduce mass and power budgets, which makes them attractive for probe missions, especially to extreme environments such as Venus, where the mission lifetime could be very short.

Carbon nanotube (CNT)-based electronics are inherently radiation hard and find applications in high frequency as well as in control and communication electronics. It is possible to realize logic gates and zero-power consuming non-volatile memories using CNTs that can be employed for electronic applications in probe missions to high radiation Jovian environment.

This work focuses on the field emission and the electronics technology development using both multi-walled nanotubes (MWNTs) and single-walled nanotubes (SWNTs).

CNT Bundle Array Field Emitters: Using specific array architecture of CNT bundles (see Figure 1) we have demonstrated field emission sources [1] that are capable of generating current densities greater than 10 A/cm^2 on a routine basis (see Figure 2). These are large area sources, meaning the over all CNT covered

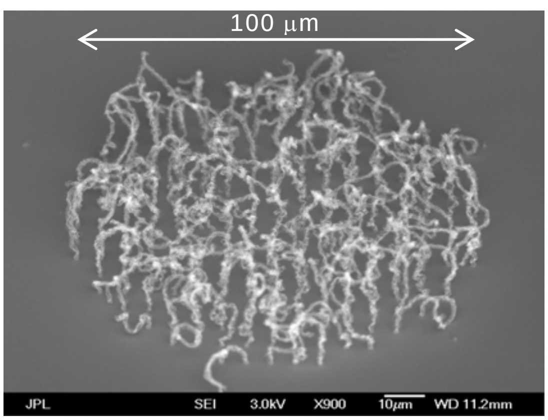

Figure 1. The CNT bundle arrays architecture. The CNT bundles are 1-μm diameter spaced 5-μm apart (edge-to-edge), and ~ 20 μm tall. The overall bundle area is 100 μm.

area is at least 100 μm in diameter. The high current

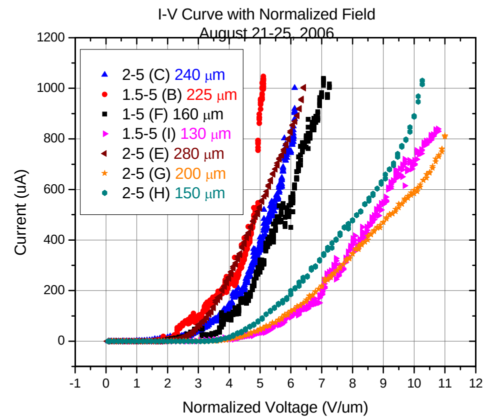

Figure 2. I-V characteristics of different CNT-bundle array field emission samples that show > 10 A/cm^2 current densities at applied fields in the range of 4 to 10 V/μm.

density measurements were done in a diode mode using anodes of various materials such as, copper, pyrolytic carbon, glassy carbon, and ITO-coated glass. The applied fields were in the range of 4 to 10 V/μm. We have for the first time verified the correlation between the CNT bundle aspect ratio and the field enhancement factor, which is an important metric to quantify high efficiency emitters. The life time of emission (see Figure 3) is a concern at high current densities due to anode material sputtering at poor vacuums or due to space charge effects. We have partly remedied this by using low sputter yield anode material such as graphite. This work will also show the results of emission

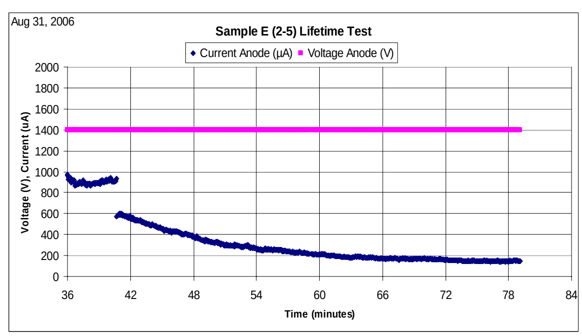

Figure 3. The emission life time curve showing a gradual degradation of high current density (~14 A/cm^2) over a few tens of minutes to settle down at a lower current density (~ 2 A/cm^2)

reliability, and uniformity of field emission. These issues are of high importance in realizing functioning micro-instruments whose vacuum cavities will, more than likely, be devoid of any active pumping. We have found that the CNTs are robust emitters that operate well in vacuums of 10^{-5} Torr or better, a typical vacuum in a microfabricated sealed micro-cavity.

Some high frequency tube sources require even higher current densities than 10 A/cm^2 [2], such as tending to hundreds of amperes per square centimeter. Simply driving CNTs at higher fields to obtain these higher current densities is detrimental to individual emitters. Therefore, using a five grid electrode system we have devised a miniature electron column that can focus the beam from CNT bundle arrays to a much smaller spot size, in essence, enhancing the achievable current density. We have developed a monolithic gate-integration scheme using silicon-on-insulator (SOI) substrates, and vacuum packaging technique using COTS packages. These results will be summarized in this work.

CNT Schottky Diodes: In the CNT-Schottky diode development, we have produced devices with Pt or Pd Ohmic contacts and Ti Schottky contacts using angled evaporation technique [3] as shown in Figure 4. After annealing the devices have exhibited ideality factors (n) of 1.3 to 1.5 (see Figure 5). They still suffer

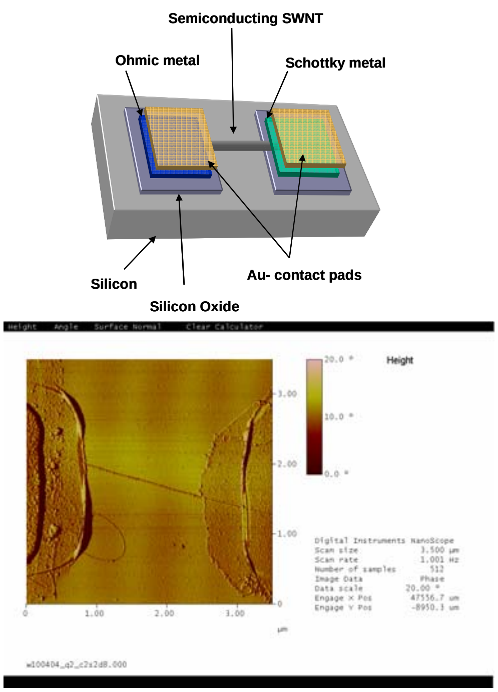

Figure 4. The CNT Schottky diode schematic (top), and the AFM image of a fabricated device (bottom).

from hundreds of kOhms series resistance and the aging effect when tested after a prolonged storage. Again, annealing was seen to restore/improve the device performance. Details of these results along with their application modes for planetary probe missions will be discussed.

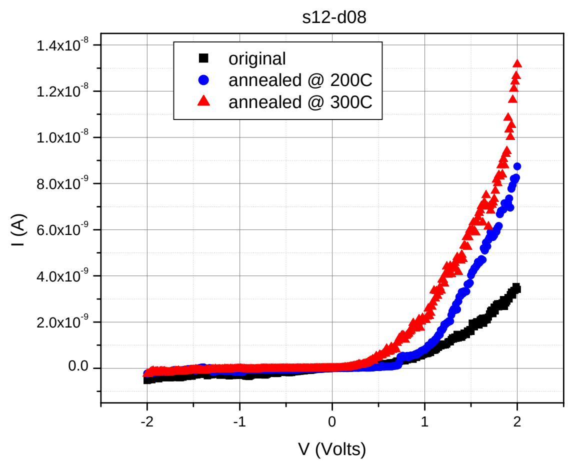

Figure 5. CNT Schottky diode DC characteristic curves showing the effect of annealing on the non-linearity in the forward bias region. These diodes are inherently radiation hard and can be used to form logic gates.

References: [1] Manohara H. M. et al. (2005) *J. Vac. Sci. Technol. B*, *23*, 157-161. [2] Manohara H. M. et al. (2004) *Proc. SPIE*, *5343*, 227-234. [3] Manohara H. M. et al. (2005) *Nano Lett. 5*, 1469-1474.