Vacuum Microelectronics Applications Using Carbon Nanotube Cathodes

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Abstract—**We will present the recent advances in carbon nanotube bundle array based field emission electron source development. These cathodes are being applied for developing new vacuum microelectronic devices. Some application issues, cathode life time, current density influencing factors, and a novel electrode integration technique will be described.**

Introduction

Background: Micro and nanotechnology development activities at JPL are directed toward enhancing the data-collection capabilities and overall science return on NASA missions to planets and planetary bodies without significantly increasing the payload. Efficient electron sources are the fundamental components of- (i) multiple analytical instruments to perform elemental and mineralogical analyses [1], (ii) vacuum microelectronic devices to develop radiation-insensitive, extreme environment withstanding electronics, and (iii) miniature vacuum tube sources for high frequency applications [2]. Each application requires specifically designed electron source in terms of beam forming optics and the emission density that spans a range of tens to hundreds of amperes per sq. cm. The state-of-the art thermionic cathodes are ill-suited for miniature instruments because of their bulkiness, high temperature operation, and high power consumption. The state-of-the-art cold cathodes [3] that are based on atomically sharp micromachined tips [4,5] are highly susceptible to poisoning when operated in non-UHV (10^{-8} to 10^{-9} Torr) environments. Such vacuum levels are not possible to attain in micromachined vacuum cavities necessary for miniaturization.

Application Specific electrode-Integrated Nanotube Cathodes (ASINCs)

Carbon Nanotube Bundle Arrays: In our pursuit of high-performance field emitters, we have found that CNTs when arranged as arrays of 1-2 micrometer (µm) diameter bundles spaced 5 µm apart (see Figure 1) give very high emission current densities [6]. 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 [7]. These tests were conducted using CNT bundle array samples that occupied a circular area of 100 µm diameter (see Figure 2(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 2(b). All emission tests were conducted in ~10^{-5} Torr vacuum.

Vacuum Packaged CNT Bundles: Field emission performance of CNT bundles inside a stand-alone vacuum package has been tested using an optimized solder-reflow process [8]. CNT chips were mounted inside COTS packages (LCC packages) and were closed off using getter (proprietary

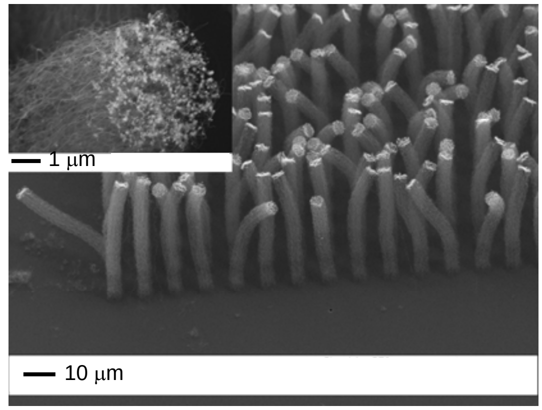

Figure 1. SEM micrograph of optimum CNT bundle arrays (1 µm diameter spaced 5 µm edge-to-edge). Inset shows the magnified view of one of the bundles containing hundreds of 20 nm-diameter

composition) patterned Kovar metal discs. The bonding was performed using Au/Sn solder reflow process at 290º C. Prior to bonding, samples were pre-baked for 96 hours and the bonding it self was conducted at 10^{-7} Torr vacuum. Figure 2-inset shows a vacuum packaged CNT chip. These samples were field emission tested for vacuum integrity after six months of shelf life (curve shown in Figure 2). The measured current corresponds to a vacuum of 10^{-6} to 10^{-5} Torr, indicating the robustness of the process. We are employing this process to produce vacuum digital electronics.

Lifetime Issues: We have found that, when operated in a continuous mode, the performance of ASINCs is affected by

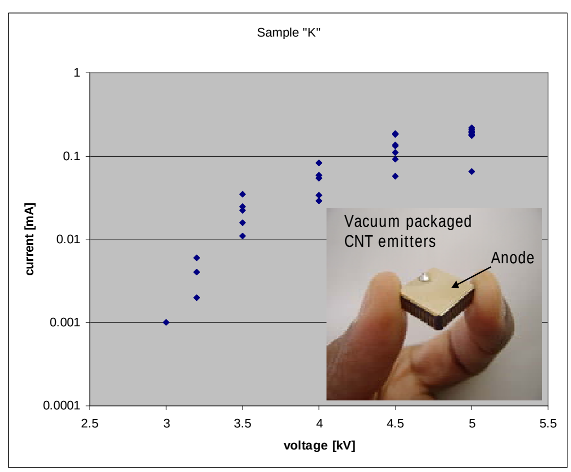

Figure 2. A field emission curve that was measured by biasing a vacuum packaged CNT chip. Inset: Vacuum packaged CNT using LCC-package and solder reflow bonding technique.

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two effects- (i) a gradual decay of emission due to anode sputtering at lower fields (< 10 V/µm), and dislodging of CNT bundles from the substrates at higher fields (> 10 V/µm). The former effect has been observed in traditional cold cathodes [9]. But, the latter is unique to CNT field emitters. Figure 3(a) shows a gradual decay of field emitted current from > 1 mA to ~200 µA within 20 minutes. Over several samples we have observed that the emission current eventually settles down to around 200 µA. These experiments were conducted using copper and glassy carbon anodes. EDX analysis of a CNT sample tested using Cu showed sputtered copper particles settled on CNTs. Similarly, SEM micrograph of glassy carbon anode showed a circular etched region (see Figure 3(b)) corresponding in dimension and location to that of cathode.

When the field is increased to > 10 V/µm, we start seeing the second failure mechanism. The force exerted at these fields appears large enough to dislodge individual CNT bundles (presently measured adhesion strength of CNT bundles to the Si substrate is ~ 35 to 65 kPa). This is shown in Figure 3(c). The graph shows a continuously increasing emission current even though the bias voltage is kept constant, indicating slowly rising CNT bundle(s) that have been dislodged but are held down by surrounding bundles. A sharp drop in the emission current indicates the bundle(s) completely losing any contact with the cathode. The inset of Figure 3(c) shows SEM micrograph of an anode tip that has dislodged CNT bundles attached to it. We are currently developing techniques to mitigate both of the effects mentioned above. Initial tests have shown continuous high field operation for tens of hours.

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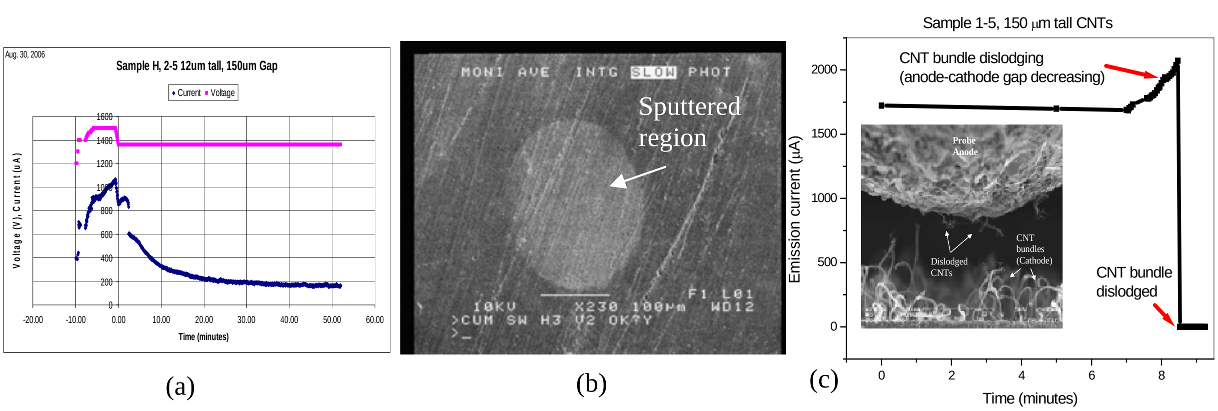

Figure 3. (a) Graph showing a gradual decay of field emission current in continuous bias mode. Top curve indicates bias voltage (held constant after t=0); (b) SEM micrograph of glassy carbon anode showing etched circular region corresponding to CNT cathode area; (c) Graph showing the high field failure of field emission due to CNTs dislodging from the surface. The inset shows SEM micrograph of dislodged CNTs stuck to the probe anode.

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