First Disclosure of a Viable Semi-Commercial Single CNT-Based FE Device

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ABSTRACT

Several disclosures covering Carbon Nanotube (CNT) based devices for Field Emitter (FE) applications have been published, none of which have shown commercial viability. As a result of our research and development, El-Mul Technologies has recently gained knowledge of some critical factors which enable semi-commercial manufacturing of single CNT-based FE devices that are useful for a wide variety of applications. We present here this novel device and discuss its key characteristics. Our proprietary technology combines conventional semiconductor manufacturing processes with nanoscale innovations to yield scalable, high performance electron micro-gun emitters and emitter arrays.

Keywords: carbon nanotube, CNT, field emitter, FE, electron micro-gun array, commercial

1 MANUFACTURE OF CNT-BASED FIELD EMITTERS

Although there have been numerous disclosures covering Carbon Nanotube (CNT) based devices for Field Emitter (FE) applications have been published[1] [2], none of these have shown commercial viability. As a result of our research and development, El-Mul Technologies has recently gained knowledge of some critical factors which enable semi-commercial manufacturing of single CNT-based FE devices that are useful for a wide variety of applications.

The fabrication methods we have developed overcome the difficulties of two critical capabilities for CNT integration inside a gating structure: (1) mastering growth of single, vertically aligned CNTs and (2) patterning techniques at the nanoscale. We are now able to produce micro-gun based devices such as single beam emitters with well-characterized fine beams or multi-beam emitter arrays with high current broad beams.

2 METHODOLOGY

As the basis for our technology, we employ a stack of silicon, silicon oxide and conductive poly silicon layers. A cathode well (a cavity measuring 2 µm in diameter and depth) is etched through the poly and oxide layers to the silicon substrate, using conventional semiconductor processing techniques, resulting in formation of a capacitor-like gating structure.

This structure is further processed to place either single or multiple CNTs in each well, depending on the catalyst seed pattern which is deposited during the pre-growth stage. Additional etching into the silicon is possible in order to form a structure which enables the creation of a narrow-spreading beam.

The resulting proprietary, patented structure[3] [4] creates a focusing field-line regime which, when applied to the CNT apex, produces a narrow electron beam, as demonstrated in the 2D simulation presented in Figure 1.

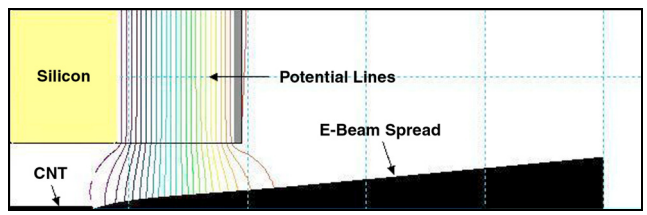

Figure 1: Simulation of electron trajectories focused by field line regime, based on our proprietary structure. Note that the diagram is rotated clockwise here.

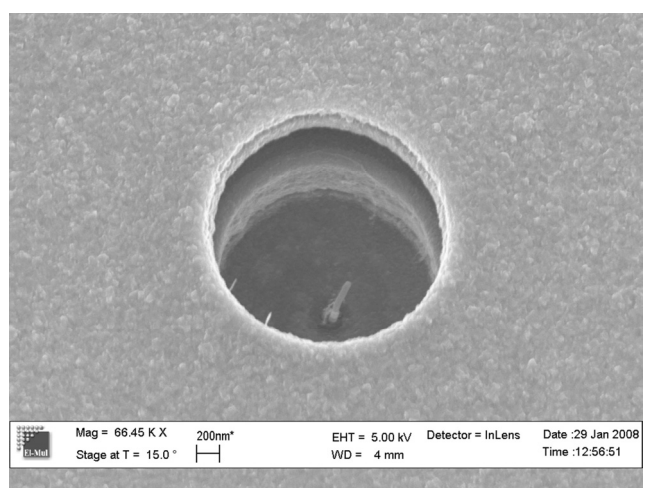

Figure 2: Completed structure with single MWCNT that results in a narrow beam spread. In this version, gate electrode and CNT apex are 2 µm apart.

Figure 2 presents a manufactured instance of the proprietary structure that is described in Figure 1. Our work confirms prior efforts[5] that report the need for a catalyst

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site in the diameter range of 200-300 nm in order to yield single MWCNT growth.

In our work Ni catalyst is deposited by means of electron beam evaporation and is confined to form such sites on the well bottom. Then, a Plasma Enhanced Chemical Vapor Deposition (PECVD) process is applied to yield a vertically aligned CNT with the desired dimensions.

We have already achieved good control over our patterning and growth processes, enabling us fully reproducible manufacturing of cathodes with a ±200 nm precision in CNT centricity and height. A top-down image of our CNT is presented in Figure 3.

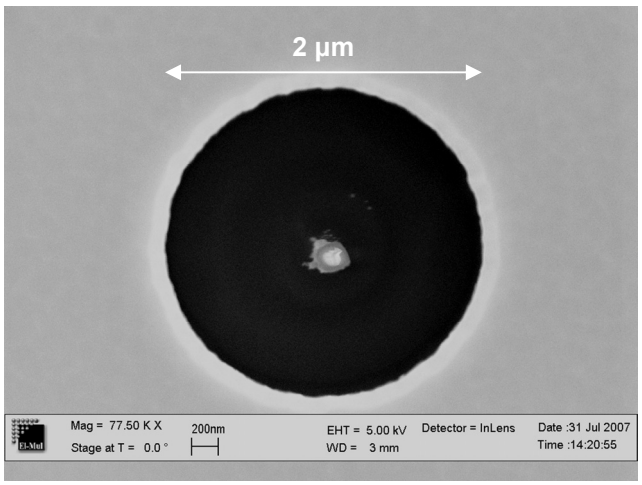

Figure 3: Cathode well with single MWCNT, as viewed directly from above.

3 CHARACTERIZATION

CNT cathode devices are characterized by two principle parameters: current characteristics and beam optics behavior.

3.1 Device Current

Direct current measurements are performed, including I-V profiling, beam stability and gate leakage testing. Our devices are characterized by a low turn-on voltage of (a) 20-50 V for cathodes where the gate electrode and CNT apex are on the same level, as presented in Figure 4; and (b) 100-150 V for cathodes where the gate electrode and CNT apex are 2 µm apart, as already presented in Figure 2.

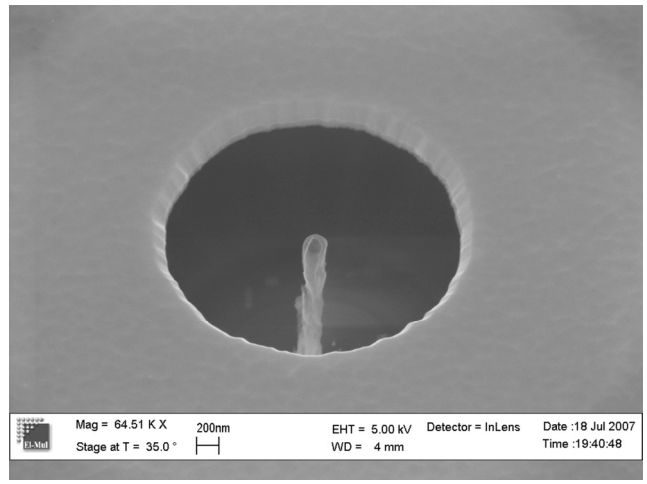

Figure 4: Cathode well with single MWCNT, as viewed at slight angle from above.

All cathodes show typical field emission behavior expressed by an exponential rise of current versus voltage and a good fit to the Fowler-Nordheim model, as depicted in Figure 5.

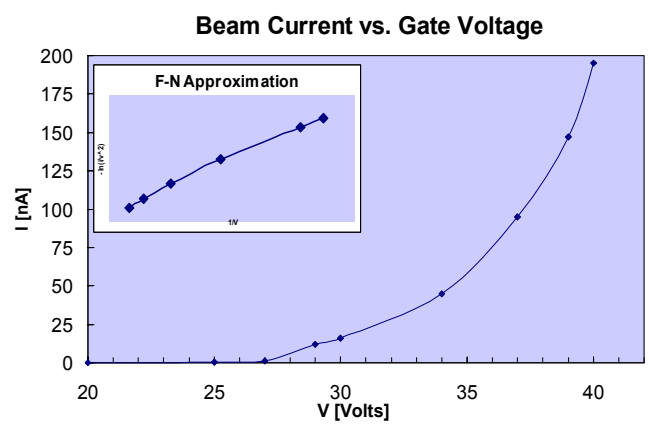

Figure 5: Sampled CNT emission data showing the exponential behavior which characterizes field emitters. Inset shows data coordinates fit to Fowler-Nordheim model, resulting in a straight line.

Currents of 200 nA per source are easily surpassed for extended time periods, without causing any apparent damage to the CNTs. Stability tests, performed at ultra high vacuum levels of 1E-9 Torr show an unsteady behavior expressed by current fluctuations sometimes exceeding 50%. (Measures to resolve this undesired behavior are being taken currently.)

Gate-to-source leakages during operation measure as high as 10-20% of the beam current. Such leakages do not affect operating lifetimes, as no visual damage to the source or performance degradation has been identified over time. However, these leakages may still affect the beam stability.

3.2 Beam Optics

Characterization is performed using Field Emission Microscopy (FEM) where a Multichannel Plate (MCP) and phosphor screen are placed in front of the emitter chip to facilitate imaging of the beam profile. Our electrical design allows imaging at conditions where voltages on the face of the detector (MCP input) and the gate electrode are equal, thus imposing a "field free zone" for electrons during flight. These conditions enable measurement of the intrinsic emitting angle of the device without the distortion that would be imposed by external electrical fields. Typical divergence angles vary from 10-15 degrees for emitters where the CNT tip is located below the oxide level, to 30-40 degrees for emitters where the CNT extends to the gate level.

4 DEVICE YIELDS IN SEMI-COMMERCIAL CONFIGURATIONS

As stated above, our current process successfully addresses critical demands of semi-commercial manufacturing. As presented in Figure 6, we currently produce CNT FE devices in various array sizes with high yields, achieved on the die level. For purposes of our target applications, *e.g.*, next generation e-beam tools, microscopy and other electron field emission systems, our preliminary results confirm the potential for high volume device production with very good yields and repeatability.

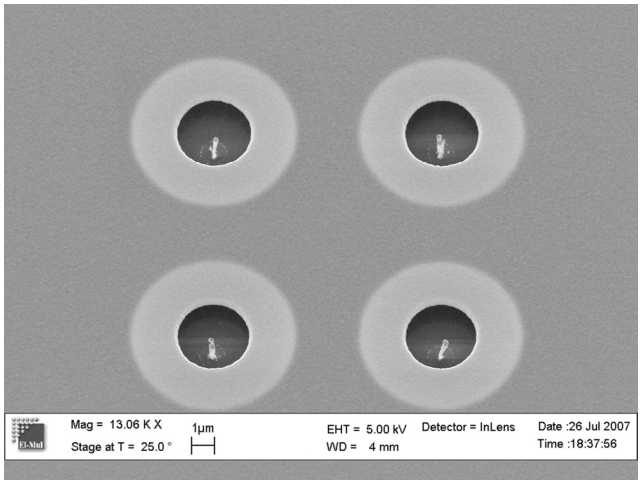

Figure 6: Sample micro-gun emitter array manufactured using our proprietary structure and conventional semi-conductor manufacturing processes.

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