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A truncated-cone carbon nanotube cold-cathode electron gun

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ABSTRACT

A concurrently high beam current and high current density carbon nanotube (CNT) cold cathode electron gun is herein developed. A radial electron source has been realized, formed from CNTs synthesized directly on the side walls of a stainless steel truncated-cone electron gun. Experimental results evidenced a 35 kV/50 mA electron beam can achieve a beam transparency of nearly 100% through the use of double anodes and crossed electric and magnetic fields. A maximum beam current density of 3.5 A/cm^2 was achieved. These results demonstrate the potential impact of coupling novel cold cathode gun architectures and emerging nanomaterials and their collective role in augmenting the performance of incumbent electron gun technologies, alongside allowing for the realization new types of field emission vacuum electron radiation sources.

1. Introduction

Vacuum electron radiation sources (VERS) have been applied widely throughout commerce and industry; from national security and space science, to communications and global navigation. Their many functional advantages over their solid-state counterparts, include, in particular, high output power (>1 GW) and high operation frequency (>1 THz) [1,2]. The electron gun is the central component of every VERS device, with most commercially available modern electron guns employing thermionic cathodes. Their high emission current density and stable performance make for robust electrons sources, however; thermionic cathodes suffer from the need for high temperature operation and a have therein a slow temporal response. On the contrary, field emission cold cathodes can be operated at room-temperature, and respond almost instantaneously to local fields, allowing for facile and inexpensive integration alongside aggressive miniaturization.

Carbon nanotubes have proven potential as high performance field emitters in many varied laboratory scale devices [3–5]. The continued maturity of the technology necessitates the proof of principle demonstration of higher technology readiness level devices via systems level design. CNT-based electron sources have been used in flat displays [6,7], X-ray sources [8,9], and travelling wave tubes [10,11]. Compared with Spindt-type field emitter arrays, recent advancements in nanofabrication have allowed for significant cost reductions, coupled to rapid large area manufacturing via advanced chemical vapour deposition (CVD) processes [12,13]. In the present gun the CNTs are grown directly onto the emitter without the need for any functionally deleterious, post-growth wet-chemistry processing. Careful engineering of the growth protocol has allowed us to maximize the degree of adhesion between the CNT and the SS304 substrate, thereby minimizing the degree of CNT removal during operation; an on-going challenge facing nano CVD-based VERS systems.

Nevertheless, various challenges continue to plague CNT-based cold cathode VERS. Central to this is the lack of suitable gun-level architectures that are capable of simultaneously producing high beam currents and high current densities. To date, planar CNT cold cathodes have struggled to obtain beam currents of tens of *mA*, principally due to edge effects, gate losses, emitter degradation and temporal attrition of the emitter [14–17]. In order to obtain large beam currents one viable and common approach is too increase the cathode emission area. Unfortunately increasing the emission area alone often reduces the current density. Indeed, in most cases the

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emission current density for larges area devices is often tens to hundreds of mA/cm^2. Although the emission current density of a single carbon nanotube has been shown to be >10^{10} A/m^2 [18], this is largely a product of the very low emission area rather than a concurrently high emission current and high emission area [19–24]. Thus, a second common challenge lies in beam focusing as a means to further increase the emission current density. Such beam compression will also improve the cross-sectional spatial uniformity of the electron beam, though such strategies are often computationally demanding to engineer and challenging to fabricate.

In this paper, a simultaneously high beam current and high current density truncated-cone CNT cold cathode electron gun is demonstrated. Here the CNT electron source is grown directly onto the side walls of a stainless steel truncated-cone, towards realizing a new generation of VERS. Double anodes and crossed electric and magnetic fields are used to obviate edge effects and gate losses resulting in the formation of a radially homogenous annular electron beam whilst also demonstrating the present architectures ability to provide high-compression ratios of more than two orders of magnitude.

2. Results

2.1. Truncated-cone CNT cold cathode diode experiment

In the truncated-cone CNT cold cathode diode experiment, as depicted in Fig. 1A, the anode and cathode were separated by a ceramic spacer some 1 mm thick (Fig. 1B). The right-hand side port is that through which the primary electron beam is emitted. Measurements were performed using pulsed mode operation with a typical pulse duration of 10 ms. The maximum negative output voltage was set to −15 kV, which was connected to earth through resistors R_1 (4 kΩ) and R_2 (36 kΩ), where R_1 is a protection resistor and R_2 is a high-voltage divider resistor. The cathode is connected to the negative high voltage and the anode is connected to the earth through the protection resistor R_p and a test resistor R_{test} (106 Ω). Through probing the voltage across R_{test} using an oscilloscope (HP infinium) we calculate the beam current. The truncated-cone CNT

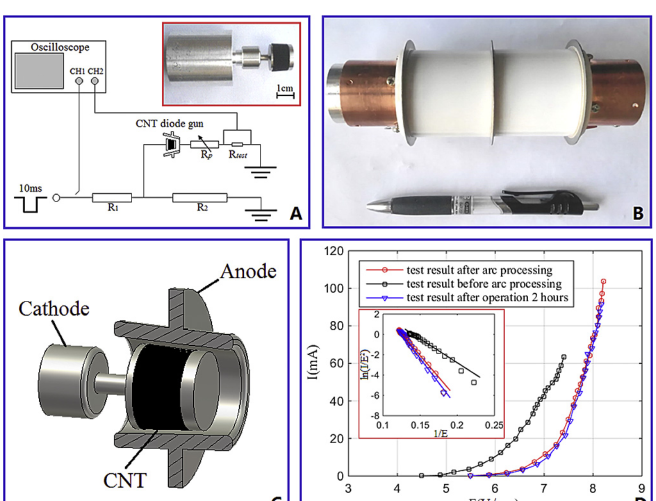

Fig. 1. Truncated-cone CNT cold cathode diode experiment. (A) Experimental schematic, inset: photo of a typical fabricated truncated-cone CNT cold cathode. (B) Photo of the complete truncated-cone CNT cold cathode diode gun. (C) Scheme of the truncated-cone CNT cold cathode coaxial diode. (D) Experimental field emission current as a function of anode voltage, inset: Fowler-Nordheim plots. (A colour version of this figure can be viewed online.)

diode source in mounted in a vacuum chamber at 9 × 10^{-5} Pa. U_a is the actual voltage applied on CNT cold cathode, which can be calculated by:

$$U_a = U_0\frac{R2}{R1 + R2} - I(R_p + R_{test}) \quad (1)$$

where U_0 is the power supply output voltage, and I is the field emission current given by U_{test}/R_{test}, where U_{test} is the oscilloscopes second channel monitor. Using this method we observe clear emission stabilization characteristics in single high voltage pulse process. Fig. 1C shows the experimental setup. The cathode height was 9.8 mm, with a top and bottom radii of 8.0 mm and 8.5 mm, respectively. The total area of the CNT cold cathode was 5.08 cm^2. The inner wall of the anode lies parallel to the outer wall of the cathode, with the cathode lying coaxial within the anode. The distance between anode and cathode was 1 mm. By changing the cathode position along the axis, the inter-electrode separation can be accurately adjusted with a resolution of 50 μm per mm of lateral travel. Fig. 1D shows typical emission currents as a function of the applied voltage. The three typical test profiles correspond to; before the forming processing (square), after the forming processing (circle), and after 2 h continuous operation (triangle). The low initial field emission performance is a result of but a few carbon nanotubes (approx. 10% of the population) emitting. The subsequent forming processing profile is associated with the CNT cathode that has been processed with short high voltage pulses (7.5 kV/100 μs). The maximum emission current achieved was 103 mA for the treated samples, where this treatment effectively activated a greater proportion of the CNT population. The continuous operation profile shows the emission performance after 2 h pulsed operation. Here, the operation current was about 70 mA at 1 Hz. To investigate the robustness of the present sources, we increased, significantly, the operation voltage of the continuous samples following the 2 h experiment. Notable high voltage arcing occurred for fields in excess of 8.3 V/μm, with post-SEM analysis showing serious degradation of the CNT.

2.2. Truncated-cone CNT cold cathode electron gun experiment

The CNT truncated-cone gun was mounted in a ceramic (99% Al_2O_3), fully-sealed vessel evacuated to a base pressure of <10e^{-7} *Pa* prior to sealing in a double-vacuum baked device. The distance between the cathode and control anode is 1.3 mm. The length of the anode is 245 mm. At the gun output port a sapphire (Al_2O_3) window was used to seal the unit. To observe the electron beam spot dimensions, an ITO-coated glass electrode was fixed in the front of the output window with a single lens reflex camera mounted some 5 mm distant. Fig. 2A shows the electron gun scheme. The CNT-coated truncated-cone was produced by directly synthesising the CNT by thermal chemical vapour deposition on the catalytically active stainless steel (SS304) substrate. Type SS304 was selected over other steel types given its low cost and its high proportion of CNT suitable catalytically active species; chiefly, iron (60%), and nickel (8%). Fig. 2C shows a photograph of the sealed CNT cold cathode. In order to decrease edge effects along the tubes long axis, the CNT cold cathode is sandwiched between two stainless steel truncated-cones. To avoid contamination, the CNT was grown on the central section independently, which was latterly installed in the tube. Fig. 2D shows a typical SEM micrograph of the as-grown CNT. The CNT had a uniform areal coverage and had a typical diameter between 20 and 50 nm.

Experiments were performed using high voltage pulses some 100 μs in duration, operated at a pulse frequency of 1 Hz. The electron gun was installed in a custom-built 9.2 T superconducting