



Citation for published version:

Cole, M, Chen, Q, Yuan, X, Zhang, YN, Xu, X, Chen, Z, Yin, Y, Li, H, Meng, L & Yan, Y 2022, 'Development on a high-beam-transparency gridded electron gun based on a carbon nanotube cold cathode', *IEEE Electron Device Letters*, vol. 43, no. 4, pp. 615-618. <https://doi.org/10.1109/LED.2022.3151714>

DOI:

[10.1109/LED.2022.3151714](https://doi.org/10.1109/LED.2022.3151714)

Publication date:

2022

Document Version

Peer reviewed version

[Link to publication](#)

© 2022 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works.

University of Bath

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Development on a high-beam-transparency gridded electron gun based on a carbon nanotube cold cathode

Qingyun Chen, Xuesong Yuan, Xiaotao Xu, Yu Zhang, Matthew T. Cole, Yifan Zu, Zexiang Chen, Yong Yin, Hailong Li, Lin Meng and Yang Yan

Abstract—We here report on the development of an improved dual-gridded electron gun based on a carbon nanotube cold cathode that enhances electron beam transparency and reduces grid interception and losses pathways. Compared with microscale tip Spindt-type the dual-gridded construction decreases difficulties of nanomaterial growth, fabrication and assembly. Our experimental findings show that this dual-gridded CNT electron gun can support anode output current (cathode emission current) of up to 700 mA, with a beam-transparency of up to ~100% and a compression ratio of 1/19. A beam spot of uniform brightness is obtained and the radius of the beam spot is 1.5 mm. In addition, the device could operate at 1/100 duty cycle continuous pulse with a stable current of around 100 mA during the testing time of 100 h.

Index Terms— Carbon nanotube (CNT), cold cathode, electron gun, field emission, high-beam-transparency.

I. INTRODUCTION

ELECTRON-OPTICAL systems are a core technology within almost every vacuum electron radiation source (VERS) though their design and effective integration remains challenging[1-5]. Carbon nanotubes (CNTs) have proven as a near ideal candidate for field electron emission (FE) cold cathodes [6-8] due to their room-temperature operation, instantaneous switch-on, ability to support large emission current densities, ease of self-assembled forming at the

This work was supported by the National Key Research and Development Program of China (No.2019YFA0210202), National Natural Science Foundation of China (No.61771096), Sichuan Science and Technology Program (No.2021YJ0096) and Fundamental Research Funds for the Central Universities (No. ZYGX2019J012). (*Corresponding author: Xuesong Yuan.*)

Qingyun Chen, Xuesong Yuan, Xiaotao Xu, Yifan Zu, Yong Yin, Hailong Li, Lin Meng and Yang Yan are members of the Terahertz Science and Technology Key Laboratory of Sichuan Province, School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China (e-mail: cqy@uestc.edu.cn; yuanxs@uestc.edu.cn).

Yu Zhang is a member of the State Key Laboratory Optoelectronic Materials and Technologies, Sun Yat-sen University, Guangzhou 510275, China. (e-mail: stszhyu@mail.sysu.edu.cn).

Matthew T. Cole is a member of the Department of Electronic and Electrical Engineering, University of Bath, Bath BA2 7AY, U.K. (e-mail: m.t.cole@bath.ac.uk).

Zexiang Chen is with the School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China. (e-mail: zxchen@uestc.edu.cn).

nanoscale, and every lower production costs [9-16]. However, several integration challenges continue to restrict the development of CNT cold cathode VERS, such as the effective and scalable integration of CNT based electron emitters into macroscopic devices [17-19].

The small modulator size of gridded electron guns with electrostatic focusing systems offer a little explored solution[20]. Nevertheless, in single grid systems the proportion of the cathode current that is intercepted by the grid can be very high, often in excess of 20-55% [18, 19, 21, 22]. The proportionally large current sank into the grid produces excessive grid heating resulting in exacerbated electro-migration within the grid which contributes towards unwanted grid deformation. This unavoidably affects the devices service life. Furthermore, due to the high electric field beneath the grid such sagging can encourage local arc discharge between the cathode and grid which further degrades the devices functional life [21, 23, 24].

In this paper, to overcome these restrictions, we propose a novel dual-gridded CNT electron gun which introduces a shadow grid aligned with the control grid within reasonable engineering tolerances and attached to the cathode surface that shapes the CNT FE from a whole plane into a shadowed array, thereby reducing the proportion of electrons intercepted by the control grid. In this arrangement, an electron beam system has been developed that has a high beam-transparency, uniform current density and high-compression-ratio highlighting the potential of such new device architectures in the development of emerging CNT cold cathode VERS.

II. SIMULATION

The dual-gridded CNT cold cathode electron gun has been designed as depicted in Fig. 1(a). It consists of a cathode base (oxygen-free copper), a CNT electron emitter, a stainless-steel planar shadow grid, a stainless-steel planar control grid, a focusing electrode (oxygen-free copper), an anode (SS304), an ITO (Indium-Tin Oxide) window and an observation window. The ITO window was separated from anode through ceramic insulation so that it could only obtain anode output current. The CNTs were synthesized directly by chemical vapor deposition [16, 25] on the cathode substrate (SS304) surface, as shown in Fig 1(b). The shadow grid was attached to the CNT cathode surface. The control grid extracts electrons from the CNTs by developing a local electric field of up to 4V/ μm . The control

grid and the shadow grid were aligned with one another using a light microscope.

The design parameters of the dual-gridded electron gun are given in Table I. In order to simplify fabrication in addition to shortening the processing time, the mesh-holes and wire-line widths of the shadow grid were equal to those of the control grid. Our simulations indicate that when the wire-line of grid is fixed, the mesh-hole dominates the electric field distribution at the cathode surface. The electric field distribution is relatively flat in this structure which has been reported in our previous study [13]. The electric field at the cathode surface reaches a maximum when the mesh-hole is 0.6 mm.

TABLE I
DUAL-GRIDDED ELECTRON GUN DIMENSIONS

Symbol	Quantity	Dimension
r_c	Cathode substrate radius	6.5 mm
h_1 (h_2)	Mesh hole of grid	0.6 mm
w_1 (w_2)	Mesh wire of grid	0.1mm
t_1 (t_2)	Thickness of grid	0.06 mm
D_{c-g}	Distance between the two grids	0.4 mm
D_{c-a}	Distance between cathode and anode	18 mm

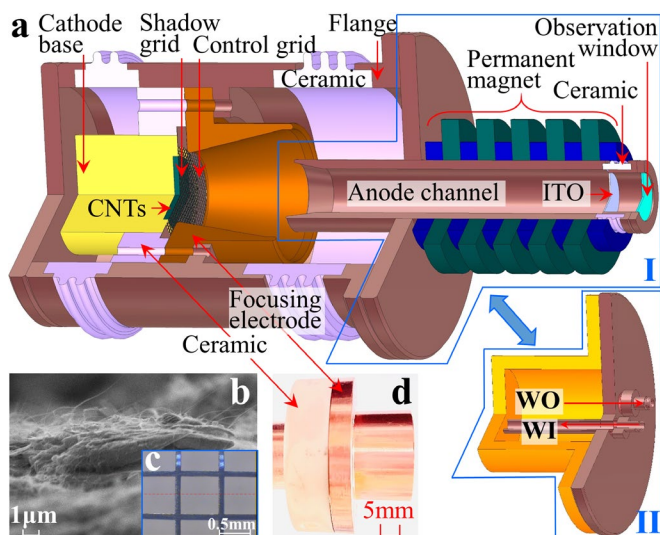


Fig. 1 (a) Scheme of dual-gridded CNT cold cathode electron gun and anode block with water circulation system (II), (WO-water output, WI-water input). (b) Edge-view SEM of as-grown CNT thin film on a stainless steel substrate dense CNT forest, consisting of CNTs with mean diameter of 10nm and mean length of 5 μ m, as measured elsewhere [13], [21], (c) Optical micrograph of grid, (d) Photo of dual-gridded structure with focusing electrode.

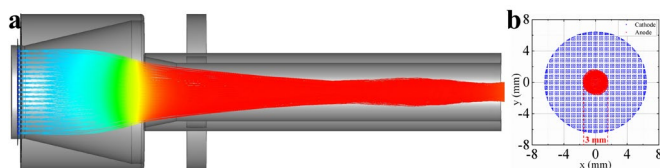


Fig. 2 (a) Beam trajectories within the dual-gridded, CNT-based electron gun. (b) CNT cold cathode emission area and electron beam spot size in the anode plane.

The dual-gridded electron gun has been simulated herein using commercially available 3D simulation software. In our simulations the voltages of cathode and shadow grid, control grid and focusing electrode, and anode were set up to 0, 4, and

22 kV, respectively. The emission current from the CNT surface was 500 mA. Analysis of individual electron trajectories suggested that few electrons were intercepted by the grid. Fig. 2 (b) depicts the simulated beam spot cross-section at the cathode surface and anode output port plane of the electron gun. The electron beam cross-section is compressed from the cold cathode area of 42.25π mm² into a beam spot approximately 2.25π mm² under the action of an electrostatic and magnetic lens. A small-scale permanent magnet (maximum magnetic field 0.13 T) was adopted as shown in Fig.1(a).

III. EXPERIMENT

Experimentally, the CNT cold-cathode dual-gridded electron gun was sealed in a ceramic and measured in an ultrahigh-vacuum system operated at a base pressure of 1×10^{-7} Pa. The measurements were performed using computer controlled power supply that generates negative voltage pulses with a duration of 100 μ s at a repetition frequency of 100 Hz. Triode mode experiments were performed in order to investigate the beam transparency and the beam focusing. During triode measurements, the maximum negative output voltage of power supply was 22 kV. A resistance network was used to provide negative high voltage for the cathode, control grid and anode as shown in Fig. 3. As the power supply output voltage U_s increased, the negative high voltage on the cathode and the shadow grid were ramped from 0 to 22 kV. The voltage difference between the cathode and the control grid was 0-5 kV by adjusting the tunable resistor R_1 . The ITO window was connected to earth through a testing resistor R_{test} . The anode was connected to the earth directly. The ITO window was separated from the anode through ceramic insulation. The anode output current collected on the ITO window was obtained by testing the voltage on resistor R_{test} using an oscilloscope. The cathode emission current and the anode output current were simultaneous measured by using the same specification current transformers (CT1 and CT2). The anode output current measured by CT2 (CTS-current transformer signal) and R_{test} (TRS-testing resistor signal) were equal. A typical profile of anode current, emission current and high-voltage signal is shown in Fig. 4(d). The signal amplitudes of emission current and anode output current were equal and the beam transparency was up to $\sim 100\%$. Fig. 4(a) shows the anode output current (emission current) as a function of the cathode surface electric field, namely typical $I-E$ characteristics of the CNT cold cathode. The experimental data were obtained after 1% duty cycle continuous pulse of aging processing. A fitted emission profile was obtained by applying our fitting produce, as reported elsewhere [15, 17] across the samples and the generalized Fowler-Nordheim equation[26]: $J=AE^2 \exp(-B/E)$, where A and B are 9.5116×10^{-7} A/V² and 7.3849×10^7 V/m, respectively ($R^2 = 0.997$). In the triode mode measurements, a maximum anode output current of 700 mA was obtained at an electric field of 8.1 kV/mm. The resulting electron beam spot image, as circled, is shown in Fig. 4(c). The diameter of the nominally circular electron beam is ~ 3 mm. The compression ratio of the electron beam was $\sim 1/19$ and the

operating current density was $\sim 10\text{A}/\text{cm}^2$ comparing favorably to more complex device structures [19, 21]. The brightness intensity distribution of the measured beam is shown in Fig. 4(b). The brightness uniformity of the circle spot of 96.5% is obtained by the formula [25] indicating that the electron beam is extremely uniform on current density according to the luminance signal in the beam spot image.

The emission stability and lifetime of the CNT cold cathode in the dual-grid structure was measured by using an anode block equipped with a water circulation system. In Fig. 1 (a), the anode block with water circulation system (II) replaced the original anode channel (I) through a flange. After 160 hours of pulse-mode testing (100 μs , 100 Hz), the device showed 118.5 mA/3 h, 115.2 mA/18 h, 114.4 mA/16 h, and 112.5 mA/100 h as shown in Fig 4(e). The FE current decreased by only 5% throughout this entire duration. After the short pulse-mode processing, the device operated at long pulse (25 s) with current of 300 mA as shown in Fig. 4(h). Fig. 4(f) shows the device operated at DC mode with a stable current of 75 mA during the testing time of 1 h.

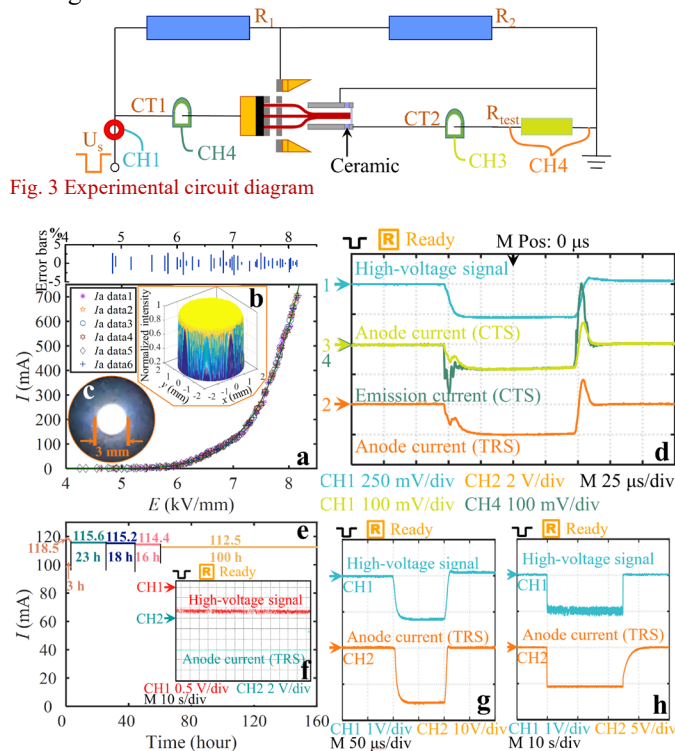


Fig. 4 (a) Typical experimental current (I)-electric field (E) characteristics of the dual-gridded CNT cold-cathode, inset: the analysis of measurement data error. (b) Brightness distribution along the circle spot. (c) Photo of electron beam spot collected on the ITO window. (d) Typical temporal switching emission profile of the anode current, emission current and high-voltage signal at 100 μs pulse. (e) Emission stability of CNT cold cathode (100 μs /100Hz continuous pulse). Typical profile of the anode current and high-voltage signal at (f) DC mode, (g) 100 μs pulse and (h) 25 s pulse.

IV. CONCLUSION

A dual-gridded CNT cold cathode electron gun with a large anode current has herein been realized, and that has been shown capable of providing beam transparencies $\sim 100\%$. Compared with microscale tip Spindt-type structures, the macroscale CNT

forest cathodes used here are shaped by the shadow grid removing the need for complex and time consuming lithographic processing of the CNTs, whilst also providing increased spatial uniformity. The proposed dual-gridded electron gun is simple to fabricate and assemble. The present structure demonstrates the feasibility of dual-gridded CNT cold-cathode electron guns and highlights their potential deployment in millimeter-wave VERS.

REFERENCES

- [1] J. Swegle, E. Schamiloglu, and J. Benford, "High Power Microwaves, Second Edition," *High Power Microwaves, Second Edition. Series: Series in Plasma Physics, ISBN: 978-0-7503-0706-2. Taylor & Francis, Edited by John Swegle, Edl Schamiloglu and James Benford, 02/01, 2007, doi: 10.1201/9781420012064.*
- [2] R. J. Umstatt, D. Abe, J. Benford, D. Gallagher, R. M. Gilgenbach, D. M. Goebel, M. S. Litz, and J. A. Nation, "Cathodes and Electron Guns," in *High-Power Microwave Sources and Technologies*, J. B. Robert and S. Edl, eds., Piscataway, NJ: Wiley-IEEE Press, 2001, ch. 9, pp. 284-324.
- [3] C. Abdallah, R. J. Barker, R. M. Gilgenbach, D. M. Goebel, Y. Y. Lau, R. M. Phillips, E. Schamiloglu, and A. Singh, "Beam Transport and RF Control," in *High-Power Microwave Sources and Technologies*, J. B. Robert and S. Edl, eds., Piscataway, NJ: Wiley-IEEE Press, 2001, ch. 8, pp. 250-283.
- [4] G. Faillon, G. Kornfeld, E. Bosch, and M. K. Thumm, "Microwave Tubes," in *Vacuum Electronics: Components and Devices*, J. A. Eichmeier and M. K. Thumm, eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 1-84.
- [5] A. S. Gilmour, and I. Ebrary, *Klystrons, traveling wave tubes, magnetrons, crossed-field amplifiers, and gyrotrons*, Fitchburg, USA: Artech House, 2011, p. 21.
- [6] Y. Di, M. Xiao, X. Zhang, Q. Wang, C. Li, W. Lei, and Y. Cui, "Large and stable emission current from synthesized carbon nanotube/fiber network," *Journal of Applied Physics*, vol. 115, no. 6, pp. 064305, 2014/02/14, 2014, doi: 10.1063/1.4864431.
- [7] W. Lei, X. Zhang, J. Chen, Z. Zhao, Y. Cui, and B. Wang, "Very High Field Emission from a Carbon Nanotube Array With Isolated Subregions and Balanced Resistances," *IEEE Transactions on Electron Devices*, vol. 58, no. 10, pp. 3616-3621, 2011, doi: 10.1109/TED.2011.2162520.
- [8] Q. Wang, C. Yu, Y. Di, Z. Zhu, X. Zhang, C. Li, and W. Lei, "High-Current-Density field emission from self-heating printed carbon nanotubes," *Fullerenes, Nanotubes and Carbon Nanostructures*, vol. 24, no. 4, pp. 273-277, 2016/04/02, 2016, doi: 10.1080/1536383X.2016.1152470.
- [9] A. S. Berdinsky, A. Shaporin, J. B. Yoo, J. Park, P. S. Alegaonkar, J. Han, and G. H. Son, "Field enhancement factor for an array of MWNTs in CNT paste," *Applied Physics A*, vol. 83, pp. 377-383, 01/06, 2006, doi: 10.1007/s00339-006-3482-7.
- [10] D. S. Bethune, C. H. Kiang, M. S. de Vries, G. Gorman, R. Savoy, J. Vazquez, and R. Beyers, "Cobalt-catalysed growth of carbon nanotubes with single-atomic-layer walls," *Nature*, vol. 363, no. 6430, pp. 605-607, 1993/06/01, 1993, doi: 10.1038/363605a0.
- [11] J.-M. Bonard, J.-P. Salvetat, T. Stöckli, W. A. d. Heer, L. Forró, and A. Châtelain, "Field emission from single-wall carbon nanotube films," vol. 73, no. 7, pp. 918-920, 1998, doi: 10.1063/1.122037.
- [12] Z. Chen, G. Cao, Q. Zhang, P. Lan, B. Zhu, T. Yu, and Z. Lin, "Large current carbon nanotube emitter growth using nickel as a buffer layer," *Nanotechnology*, vol. 18, no. 9, pp. 095604, 2007/01/24, 2007, doi: 10.1088/0957-4484/18/9/095604.
- [13] Q. Chen, X. Yuan, M. T. Cole, Y. Zhang, L. Meng, and Y. Yan, "Theoretical Study of a 0.22 THz Backward Wave Oscillator Based on a Dual-Gridded, Carbon-Nanotube Cold Cathode," *Applied Sciences-Basel*, vol. 8, no. 12, pp. 2462, 2018.
- [14] X. Yuan, Q. Chen, X. Xu, M. T. Cole, Y. Zhang, Z. Chen, and Y. Yan, "A Carbon Nanotube-Based Hundred Watt-Level Ka-Band Backward Wave Oscillator," *IEEE Transactions on Electron Devices*, pp. 1-6, 2021, doi: 10.1109/TED.2021.3066144.
- [15] M. Cole, K. Teo, O. Gröning, L. Gangloff, P. Legagneux, and W. Milne, "Deterministic Cold Cathode Electron Emission from Carbon Nanofibre Arrays," *Scientific reports*, vol. 4, pp. 4840, 05/02, 2014, doi: 10.1038/srep04840.

- [16] M. T. Cole, K. Hou, J. H. Warner, J. S. Barnard, K. Ying, Y. Zhang, C. Li, K. B. K. Teo, and W. I. Milne, "In-situ deposition of sparse vertically aligned carbon nanofibres on catalytically activated stainless steel mesh for field emission applications," *Diamond and Related Materials*, vol. 23, pp. 66-71, 2012/03/01, 2012, doi: 10.1016/j.diamond.2011.12.039.
- [17] X. Yuan, Y. Zhang, M. Cole, X. Li, R. Parmee, J. Wu, N. Xu, W. Milne, and S. Deng, "A truncated-cone carbon nanotube cold-cathode electron gun," *Carbon*, vol. 120, pp. 374-379, 03/01, 2017, doi: 10.1016/j.carbon.2017.03.046.
- [18] X. Yuan, Y. Zhang, H. Yang, X. Li, N. Xu, and S. Deng, "A Gridded High Compression Ratio Carbon Nanotube Cold Cathode Electron Gun," *IEEE Electron Device Letters*, vol. 36, pp. 1-1, 04/01, 2015, doi: 10.1109/LED.2015.2401593.
- [19] G. Ulisse, C. Ciceroni, F. Brunetti, and A. D. Carlo, "Electrostatic Beam Focusing of Carbon Nanotubes Electron Source," *IEEE Transactions on Electron Devices*, vol. 61, no. 7, pp. 2558-2563, 2014, doi: 10.1109/TED.2014.2324171.
- [20] Y. Di, Q. Wang, X. Zhang, W. Lei, X. Du, and C. Yu, "A vacuum sealed high emission current and transmission efficiency carbon nanotube triode," *AIP Advances*, vol. 6, no. 4, pp. 045114, 2016/04/01, 2016, doi: 10.1063/1.4948263.
- [21] G. Ulisse, F. Brunetti, E. Tamburri, S. Orlanducci, M. Cirillo, M. L. Terranova, and A. D. Carlo, "Carbon Nanotube Cathodes for Electron Gun," *IEEE Electron Device Letters*, vol. 34, no. 5, pp. 698-700, 2013, doi: 10.1109/LED.2013.2250247.
- [22] W. Knapp, and D. Schleußner, "Special features of electron sources with CNT field emitter and micro grid," *Applied Surface Science*, vol. 251, no. 1, pp. 164-169, 2005/09/15/, 2005, doi: 10.1016/j.apsusc.2005.03.200.
- [23] Y. S. Di, Q. L. Wang, X. B. Zhang, W. Lei, X. F. Du, and C. R. Yu, "A vacuum sealed high emission current and transmission efficiency carbon nanotube triode," *Aip Advances*, vol. 6, no. 4, Apr, 2016.
- [24] Q. Chen, X. Yuan, Y. Zhang, H. Li, B. Wang, Y. Yan, and L. Meng, "Study on a High Beam Transparency Gridded X-ray Electron Gun Based on Carbon Nanotube Cold Cathode," *Journal of Nanoelectronics and Optoelectronics*, vol. 13, no. 9, pp. 1265-1270, 11 April, 2018, doi: 10.1166/jno.2018.2364.
- [25] X. Yuan, W. Zhu, Y. Zhang, N. Xu, J. Wu, Y. Shen, J. Chen, J. She, and S. Deng, "A Fully-Sealed Carbon-Nanotube Cold-Cathode Terahertz Gyrotron," *Scientific Reports*, vol. 6, pp. 32936, 09/09, 2016, doi: 10.1038/srep32936.
- [26] L. W. Nordhiem, and R. H. Fowler, "The effect of the image force on the emission and reflexion of electrons by metals," vol. 121, no. 788, pp. 626-639, 1928, doi: doi:10.1098/rspa.1928.0222.