

Field Electron Emission Characteristics of Single-Walled Carbon Nanotube on Tungsten Blunt Tip

Marwan S. Mousa and Samer Daradkeh

Surface Physics and Materials Technology Lab, Department of Physics, Mu'tah University, AL-Karak, Jordan.

marwansmousa@yahoo.com & mmousa@mutah.edu.jo

Abstract: Recent investigations that are presented here illustrate the initial results that were obtained from a modified technique for holding the CNT on a W clean blunt tip. Field Electron Emission (FEE) has been investigated for single walled carbon nanotube (SWCNT) mounted on tungsten tip under ($\sim 10^{-8}$ mbar) vacuum conditions. The measurements recorded presented results showed that the CNT mounted on the W tip could emit electron current of at (0.7 V/ μm) and reach up to (24 μA) of emission current at normal emission conditions. Such electron field emission tip was fabricated by electrolytically etching the high purity tungsten wire of (0.1 mm) in diameter in NaOH of (0.1) Molar solution, then mounting the single-walled carbon nanotube on the tip to be nearest to the tin oxide-coated and phosphorus glass anode. Such process was possible to be carried out under the microscope. A field electron microscope with a tip-screen separation at ($\sim 10\text{mm}$) was used to characterize the electron emitter. The system was evacuated to an ultra-high vacuum level obtained after initial backing the system at up to ($\sim 180^\circ\text{C}$) overnight. The emission characteristic has been investigated employing the I-V characteristics with Fowler-Nordheim plots and recording the emission images

1. Introduction

Carbon nanotube (CNT) have attracted much attention since their first synthesis by arc discharge method by Iijima in 1991,[1] and because their own properties like small-radius, high aspect ratio, and remarkably high electrical conductivity, CNTs offer several advantages over other material in electron field emissions like enhanced current stability, lower threshold voltage, and long life time.[2] So there are a lot of potential applications of CNTs including electron field emitters, quantum wires, transistor, molecular filter, and hydrogen storage.[3]

The electron emission from metals can be driven by temperature and applied an electric field. For high electric field and low temperature, the high field narrows the vacuum potential barrier such that electron with energies below Fermi level tunnel through the barrier and predominate the emission current[4] i.e. quantum mechanical tunneling. Which can be described by the Fowler Nordheim theory, and from the theory, the emission current I can be expressed in simplified form

$$I = 1.54 \times 10^{-6} \frac{S\beta^2}{\Phi} V^2 \exp\left(-6.83 \times 10^7 \frac{\Phi^{\frac{3}{2}}}{\beta V}\right)$$



Here, the emission current I and the applied voltage V are expressed in A and V, respectively. The work function Φ is expressed in eV and the emitting area S is expressed in cm². The field enhancement factor β corresponds to the geometry shape of the emitter, and inversely proportional to the diameter of the emitting tip.[5]

To obtain quantitative information about the microscopic properties of the emitting regime, the total electron emission current I , has been plotted as a function of the applied voltage V between the emitter and the anode. Emission characterization will be presented as $I - V$ plots and as the related FN plots. Through the experiments, electron emission images have been recorded by means of a digital camera, in order to study the spatial distribution and stability of the emission current.[6]

2. Materials and Methods

In our experiments we use SWCNTs are produced by catalytic conversion of high-pressure CO over Fe particle (HiPCO) processed at CNI, Houston, TX, mounted over blunt tungsten tip. This method showed that CNTs/W tip could emit electron at lower applied voltage comparing with individual W tip because the CNTs/W tip has a very high value of enhancement factor β .

Preparing the emitter has two stages, stage one is preparing the tungsten by electrolytically etching a 0.1 mm diameter wire at the meniscus of a 2 mol/liter NaOH solution .i.e. by the same technique used for tungsten emitters[7, 8]. Stage two is applying a thin layer of epoxy resin, which is necessary for a firm attachment of the nanotube, and then mechanically by approaching the tungsten tip to the CNTs, the CNTs will be stuck on the tungsten tip.

The CNT/W emitter was characterized using the conventional field electron emission apparatus with a tip-screen separation standardized at (10 mm). The input anode is phosphored and acts as the screen of recording emission images using a digital camera. The system can be operated at pressure (10^{-10} mbar) when baked to (~ 200 °C) for (~ 12 h), with liquid nitrogen added to the trap, though the operational pressure during the present study was ($\sim 10^{-8}$ mbar). A high tension (EHT) power supply is used to apply a negative voltage to the cathode, and the emission current is measured with a Kiethley 485 auto-ranging Pico ammeter.[9]

3. Results and Discussion

We performed the tests over two samples, (C5\W) and (B5\W) under same conditions. Voltage was applied to the SWCNTs/W tip and I-V characteristics were recorded. For SWCNT\W C5, the electrons emission started at (300 V) with emission current (4 pA) to (1750 V) with emission current (6.6 μ A). By increasing the applied voltage slowly caused an increase in emission current, and by further increasing, the emission current suddenly increased to value ($I_{SW}=3.10$ μ A) at applied voltage value ($V_{SW}=1100$ V), as shown in the figure (1A); figure (1B) show the related Fowler-Nordheim (FN) plot, as well as the field electron microscope image at V_{SW} , V_{SAT} , 1700 V, and 700 V, which is shows a single spot image except at 1700 V.

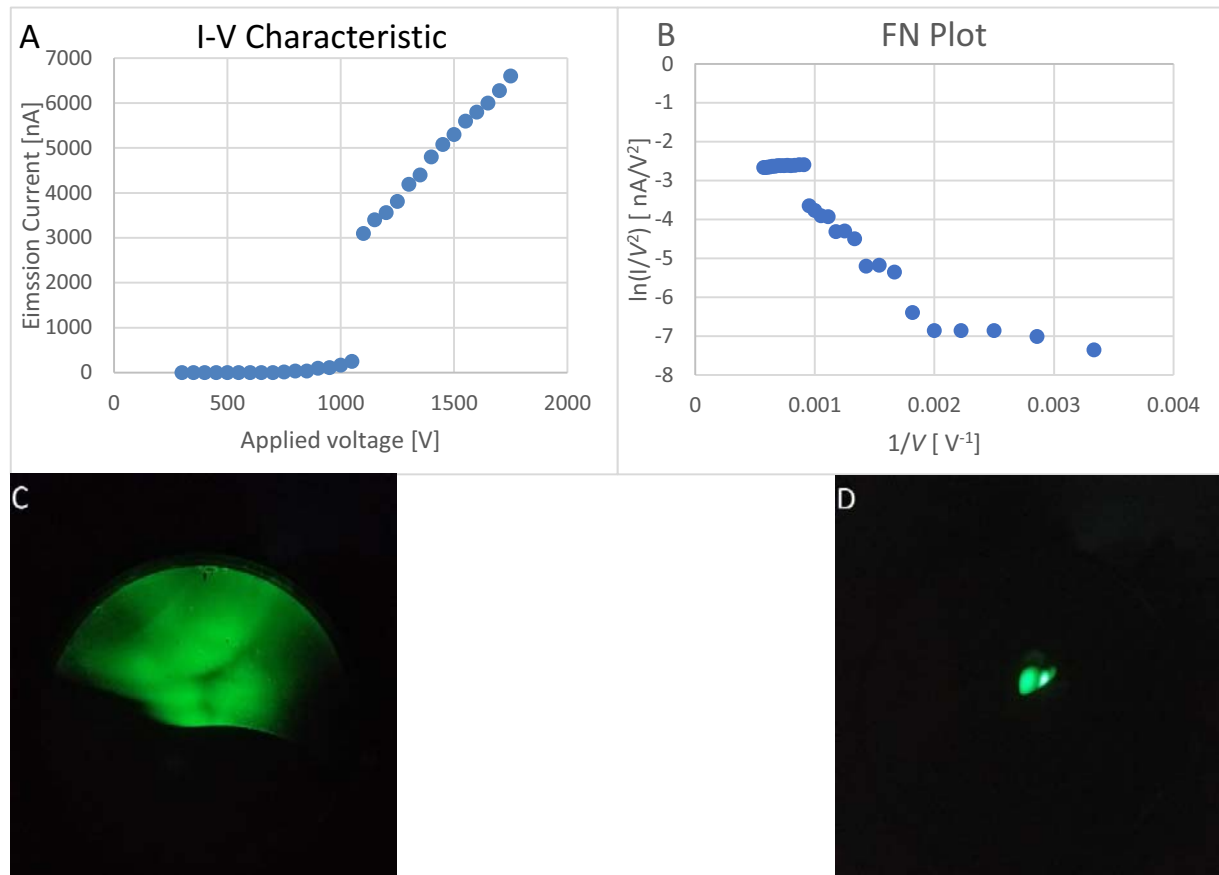


Figure 1. C5W emitter. Increasing Voltage (A) I-V Characteristic ranging from 300 V to 1750 V. (B) Related FN plot. (C) Field electron image at 1700 V, 6.28 μ A. (D) field electron image at V_{sw} =1100 V, 3.10 μ A.

By decreasing the applied voltage slowly, the saturation region extends down to value V_{SAT} =750 V, with emission current value (1.3 μ A), and by further reduction of the applied voltage, the threshold voltage (V_{TH}) has been reached which is the cathode-voltage value necessary to generate the emission current.[10]. Figure (3) shows I-V characteristic, FN plot, and field electron image at V_{SAT} , and at (700 V)

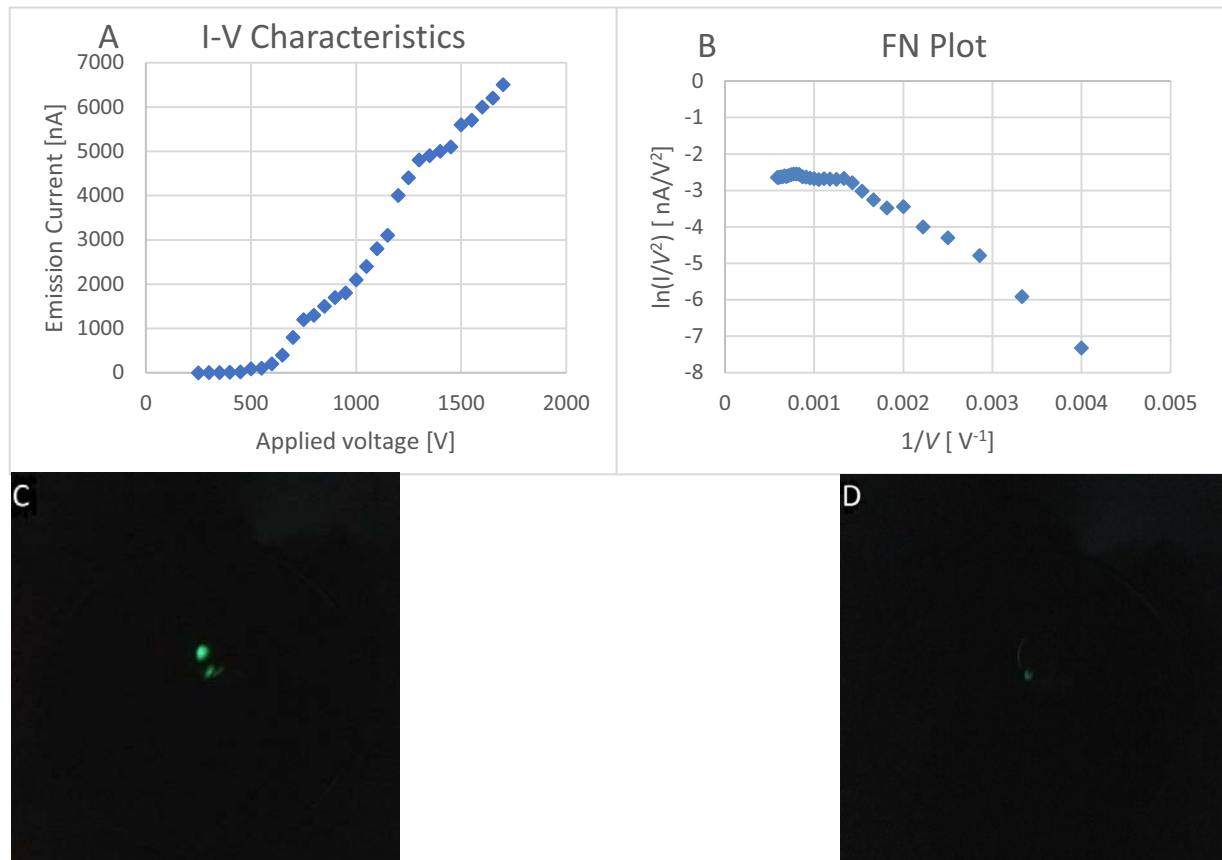


Figure 2. C5\W emitter. Decreasing Voltage (A) I-V Characteristic. (B) Related FN plot with slope -1896.79 decayed V. (C) Field electron image at $V_{SAT}=750$ V, 1.2 μ A. (D) field electron image at $V=700$ V, 0.8 μ A.

The experiment was repeated second time, under the same condition and the result as following, by increasing the applied voltage the emission current increased as well until $V_{SW}=1300$ V was reached, the emission current suddenly raised from nA range to μ A range specifically $I_{SW}=1.6$ μ A, and by further increase voltage the emission current reach to (5.2 μ A) at applied voltage value (1900 V), during this period of increased voltage there are small fluctuations in the emitted current, due to two causes, variation of local field F ($F = \beta V$, where V is the applied voltage and β is the enhancement factor) and variation of work function Φ , for which emission current I is extremely sensitive due to the exponential nature of FN equations, so 1% change in F can readily lead to 15% change in I . Local change of F are likely to occur due to geometric changes of the tip caused by surface migration in the extremely large electric field at the tip and form ion bombardment. On the other hand Φ is sensitive to adsorbates on the surface, these fluctuations can exhibit in electron field emission current in ultra-high vacuum conditions.[11, 12] Figure (3) shows I-V characteristic, its related FN plot, and emission image at V_{SW} . Then we begin slowly decreasing the applied voltage, the saturation region extends down to $V_{SAT}=950$ V, with emission current $I_{SAT}=1.2$ μ A, and then threshold value reached at $V_{TH}=210$ V, with emission current $V_{TH}=10$ pA, as figure (4) showed the I-V behavior at decreasing voltage, with FN plot for this stage.

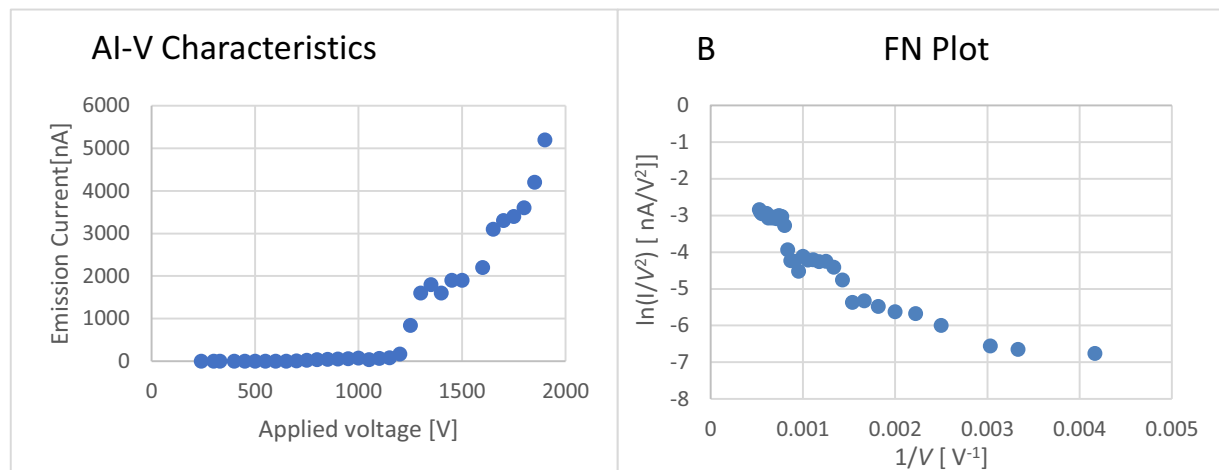


Figure 3. Cyc.2, C5\W emitter. Decreasing voltage. (A) I-V characteristic. (B) FN plot with slope -1766.14 decayed V.

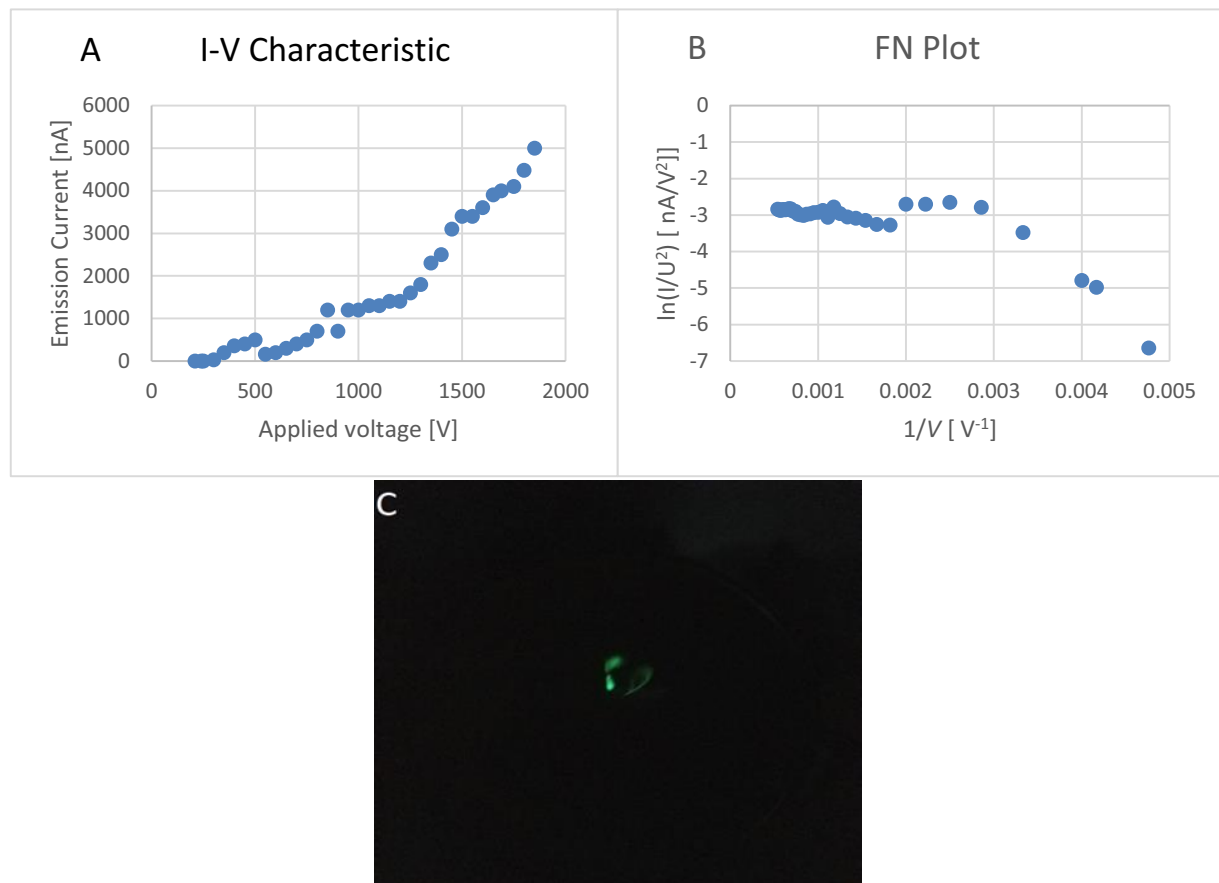


Figure 4. Cyc.2, C5\W emitter. Increasing voltage. (A) I-V characteristic. (B) FN plot. (C) Field electron image at $V_{sw}=1300$ V, $1.6 \mu A$.

The second emitter (B5\W) was investigated under same conditions, with same way of cycling the applied voltage up and down two times, and the result as following; in the first cycle, by increasing the applied voltage, the emission current increased until it reaches $V_{SW}=1250$ V, where its value has become ($2.9 \mu A$), we continue increase the voltage until it reaches $V=2850$ V, with emission current value ($17.9 \mu A$), after that we decrease the applied voltage, while the value of the emission current remained in range of (μA), until the applied voltage reaches $V_{SAT}=650$ V, where the emission current was ($1.06 \mu A$), then it falls to (nA) range. The emission current vanishes at $V_{TH}=350$ V, $I_{TH}=1$ pA, the figure (5) shows the behavior of I-V in first cycle, and its related FN plot, and field electron emission at V_{SW} , and V_{SAT} .

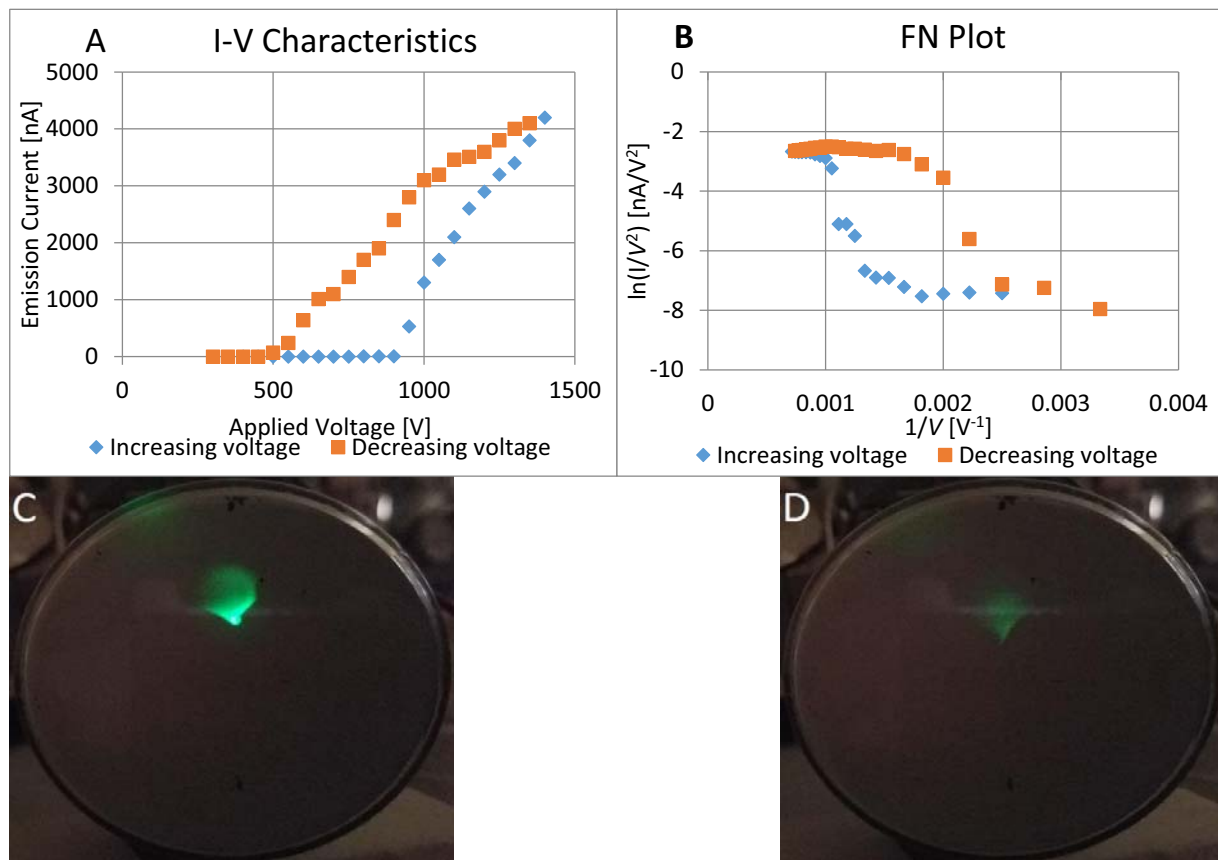


Figure 5. First cycle. B5/W emitter. Increasing and Decreasing voltage (A) I-V characteristics. (B) FN plot with slope -1872.79 decayed V. (C) field electron image at V_{SW} . (D) Field electron image at V_{SAT} .

The same procedure of testing followed with B5/W emitter (second cycle), as we increase the applied voltage, the emission current increase with it from (6 pA) at applied voltage value (400 V) to ($4.2 \mu A$) at applied voltage value (1400 V), during this interval of increasing the applied voltage V_{SW} was (1000 V), with emission current ($1.3 \mu A$), in decreasing voltage phase, the saturation extends to $V_{SAT}=650$ V, with $I_{SAT}=1.01 \mu A$, and the lowest emission current value was (1 pA) at (300 V). Figure (6) shows the I-V characteristics, FN plot during increasing and decreasing applied voltage, and field electron image at V_{SW} .

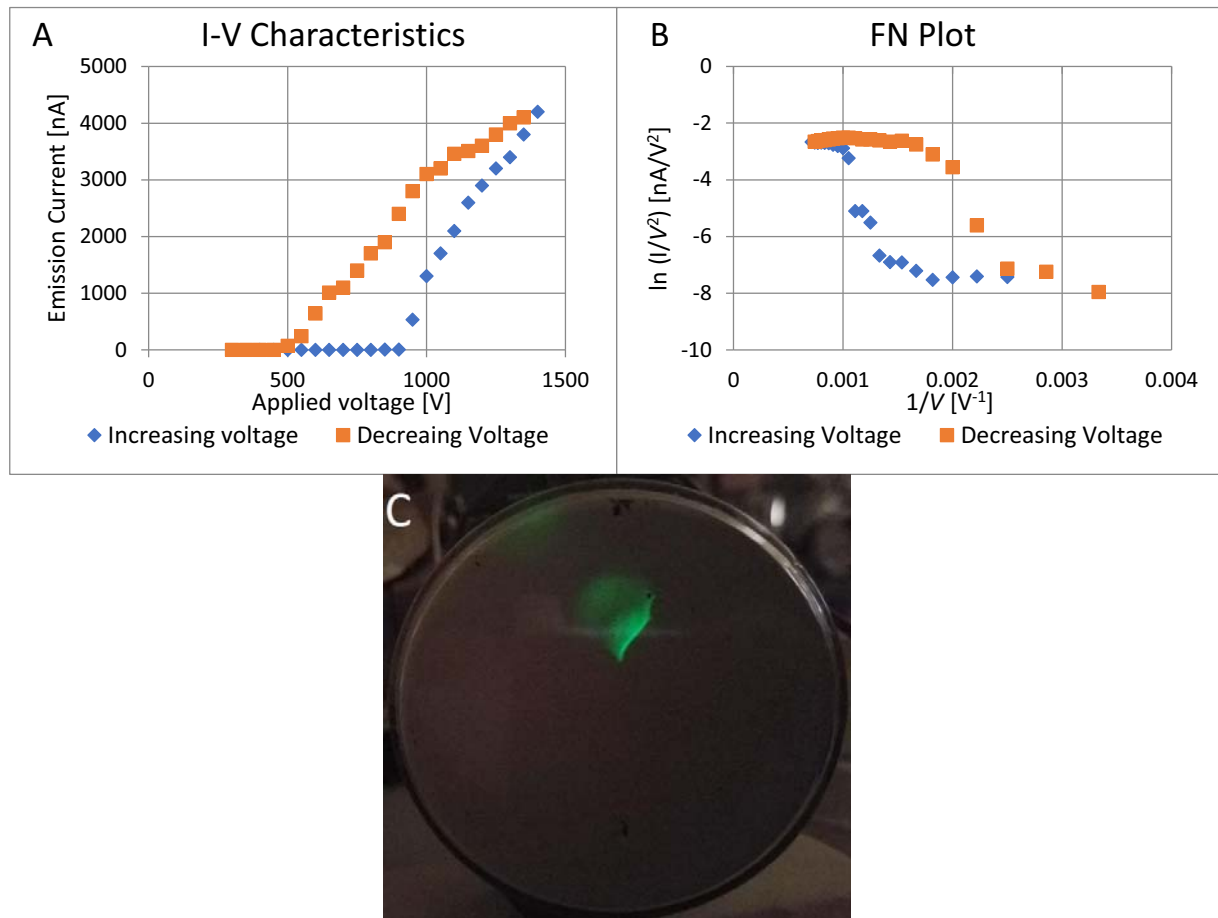


Figure 6. Second cycle. B5/W emitter. Increasing and Decreasing voltage (A) I-V characteristics. (B) FN plot with slope - 1766.14 decayed V. (C) field electron image at V_{sw} .

From figure (5C, 5D, and 6C), it shows that the field electron emission image formed in approximately single spot, it seems with higher applied voltages, it will activate a new emission sites on the tip, and that's will make the electron emission image spread on screen.

We see that there are a deviation from FN theory, such deviation are usually attributed to space-charge effect, which induce a diminution of the FN slope at high field,[11] and the electronic properties of the emission behavior may be significantly influenced by the electronic properties of the SWCNT, and to non-metallic density of states at the tip of the tubes.[13]. The emission current fluctuations of conventional nanotube emitter have been found to be caused by head shaking, temperature change, vacuum alteration, or adsorption/desorption of gas molecules, all of these can be divided to two major kinds, the first is a variation in local field F , the second is a variation in local work function Φ , and I is very sensitive to the changes in these two factors[14].

4. Conclusion

We investigate the electron field emission properties of SWCNTs mounted on blunt tungsten substrate. The Fowler-Nordheim analysis for the emission current-voltage curves provided that we could get single electron field emission bright spot from SWCNTs/W in low applied voltage. In our experiment we use the mentioned tools, and that effect on the quality of the results, like; to perfectly mount the individual SWCNT on the tungsten or other suitable material, using a Nano-manipulator in SEM that could be very precise, and the carbon material is extremely strong and it can only be broken by brute force, and the breaking occurs by joule heating with a current through the tube of more than 20mA, or by apply a mechanical force, and this way would not give you a uniform length to the nanotubes and that will effect on the enhancement factor β and in turn effect on the local field and the emission current I .

References

- [1] S. Iijima, Helical microtubules of graphitic carbon, *Nature* (1991) 56-58.
- [2] T.T. D. Ferrera, I. Matsuya, G. Zhong, S. Okamoto, and H. Kawarada, Enhancement of field emission characteristics of tungsten emitters by single-walled carbon nanotube modification, *Applied Physics letter*, vol.88, issue 3 (2005).
- [3] C.-s.L.a.S.-H.S.a.G.-T.C.a.Y.-H.L.a.M. Yokohama, the synthesize of carbon nanotube on tungsten wire for field emission cathode, *proceedings of asia display*, vol.2 (2007).
- [4] a.L.C. Shi-Dong Liang, Theories of field and thermionic electron emissions from carbon nanotubes, *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena* 28(2) (2010).
- [5] R. Gomer, *Field Emission and Field Ionization*, Harvard University Press, Cambridge 1961.
- [6] E.S.B.A.n.M.S. Mousa, Switch-on phenomena and field emission from multi-walled carbon nanotubes embedded in glass, *Applied Microscopy* 46 (2016) 244-252.
- [7] E.W. Müller, Electron microscope observation of field cathodes, *Zeitschrift für Physik* 1937.
- [8] M.S.Mousa, Field electron emission studies on zinc oxide coated tungsten microemitters, *Surface Science* 266(1-3) (1992) 110-120.
- [9] K.O.M.M.S.M.a.A. Fisher, M.S. Mousa, Information extraction from FN plots of tungsten microemitters, *Ultramicroscopy* 132 (2013) 48-53.
- [10] N.E. Evgeny Sheshin, *Field Emission Electronics*, Springer 2017.
- [11] W.W.D. J. P. Barbour, J. K. Trolan, E. E. Martin, and W. P. Dyke, Space-Charge Effects in Field Emission, *physical review* 92(1) (1953).
- [12] a.J.T.L. K.SYeong, Effects of adsorbates on the field emission current from carbon nanotubes, *Applied Surface Science* 233(1-4) (2004) 20-23.
- [13] J.-P.S. Jean-Marc Bonard, Thomas Stöckli, Walt A. de Heer, László Forró, and André Châtelain, Field emission from single-wall carbon nanotube films, *Applied Physics Letters* 73(7) (1998).
- [14] F.A. Lixin Dong, T. Fukuda, Field emission of telescoping multi-walled carbon nanotubes, 4th IEEE Conference on Nanotechnology, IEEE, Munich, Germany, 2004.