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Fowler Nordheim theory of carbon nanotube based field emitters

Shama Parveen[a], Avshish Kumar[a], Samina Husain[b], Mushahid Husain[a,*]

[a] Department of Physics, Jamia Millia Islamia (Central University), New Delhi, India
[b] Centre for Nanoscience and Nanotechnology, Jamia Millia Islamia (Central University), New Delhi, India

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ABSTRACT

Field emission (FE) phenomena are generally explained in the frame-work of Fowler Nordheim (FN) theory which was given for flat metal surfaces. In this work, an effort has been made to present the field emission mechanism in carbon nanotubes (CNTs) which have tip type geometry at nanoscale. High aspect ratio of CNTs leads to large field enhancement factor and lower operating voltages because the electric field strength in the vicinity of the nanotubes tip can be enhanced by thousand times. The work function of nanostructure by using FN plot has been calculated with reverse engineering. With the help of modified FN equation, an important formula for effective emitting area (active area for emission of electrons) has been derived and employed to calculate the active emitting area for CNT field emitters. Therefore, it is of great interest to present a state of art study on the complete solution of FN equation for CNTs based field emitter displays. This manuscript will also provide a better understanding of calculation of different FE parameters of CNTs field emitters using FN equation.

1. Introduction

After the most influential discovery of fullerenes by Kroto and Co-workers in 1985 [1] followed by the subsequent discovery of carbon nanotubes (CNTs) by Iijima [2] in 1991, a completely new class of carbon nanomaterials has taken a toll worldwide. Iijima discovered multi-wall carbon nanotubes (MWCNTs) in a carboneous soot found as a by-product of fullerene on an electrode produced by a carbon arc. These MWCNTs consist of up to tens of graphitic shells with adjacent shell separation of (~0.34) nm and diameter more than 1 nm. Two years later, in 1993 Iijima and Ichihashi [3] synthesized single-wall carbon nanotube (SWCNTs). These two types of CNTs are shown in Fig. 1. SWCNTs were considered as result of rolling a single graphene sheet which makes the cylindrical shape often closed at the two ends by fullerene caps. The discovery of CNTs created much excitement and stimulated extensive research into the properties of nanometer scale structure of carbon network [4–6]. These cage-like forms of carbon have been shown to possess fascinating material properties that are a consequence of their symmetric structure [7].

Many researchers have reported excellent properties of CNTs that exceeds those of any previously existing materials. Although, there are varying reports in the literature on the exact properties of CNTs, theoretical and experimental results have shown that this nanostructure of carbon exhibits exceptional morphological, physical and chemical properties [8]. CNTs possess high aspect ratio (a length to diameter ratio greater than 1000 and as high as 13200,000), superior thermal and electric properties such as thermally stable up to 2800 °C in vacuum, thermal conductivity about twice as high as diamond and electric current carrying capacity 1000 times higher than copper wire [9]. With these amazing properties, CNTs are considered as entirely new class of most advanced nanomaterials.

Many applications of these most advanced nanomaterials have already been demonstrated in field emission displays [10], nanoscale electronic devices [11,12], chemical/biosensors [13–16] and hydrogen storage mediums. The proposed applications of CNTs are in micro-electronics/semiconductors, conducting composites, controlled drug delivery/release, artificial muscles [17,18]. In addition, CNTs are posing to be a promising candidate in medicine, providing better contrast agents for MRI and localized heaters that can induce a target cell health. They also offer a new approach to gene therapy, broken bone treatment, killing cancer cells and preserving healthy cells [19–33]. The peculiar geometry of CNTs is attracting the increasing interest of researchers whose work is focused in investigating basic properties of such exotic material for various potential applications, particularly, for field emission based display devices [32,33] as shown in Fig. 2. Therefore, CNTs represent a very attractive subject for nanotechnologist because of their blessed combination of nanoscale properties with high aspect ratio, good electrical-thermal conductivity and high mechanical stability [34,35].

High aspect ratio of CNTs leads to large field enhancement factor

* Corresponding author.
E-mail address: mush_reslab@rediffmail.com (M. Husain).

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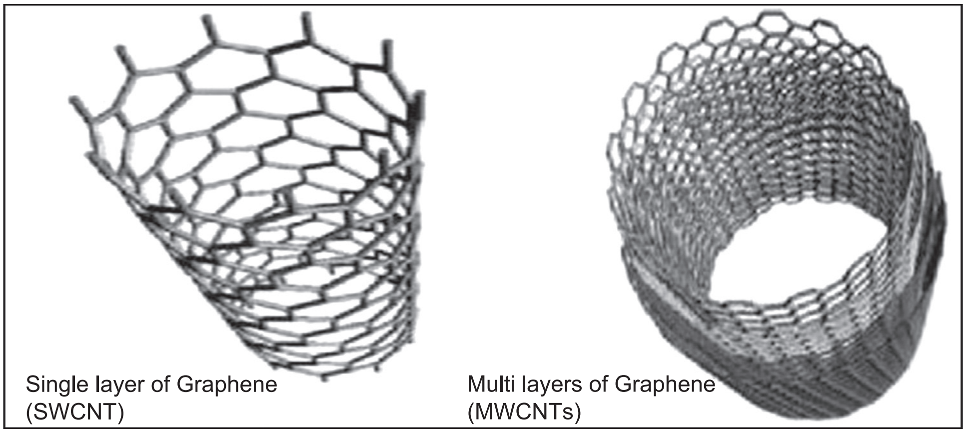

Fig. 1. Two types of carbon nanotubes.

and lower operating voltages because the electric field strength in the vicinity of the nanotube's tip can be enhanced by thousands of times [36,37]. This peculiarity in turn, manifests itself in the possibility at a moderate magnitude of the applied voltage which is required to eject large number of electrons from the tip of CNTs [38–48].

Field emission (FE) behaviour of any type field emitter is explained in the frame work of Fowler Nordheim (FN) theory. It is very suitable theory because it provides complete information not only for microstructures but also for nanostructures like CNTs. With the help of FN equation, many parameters can be calculated such as field enhancement factor, effective emitting area and work function of electron emitting material [49]. Turn-on field, maximum current density can also be found from FE data.

The present manuscript is focused to provide the complete explanation of FN theory and solution of derivative of FN equation which could not be derived by any researcher. Their different FE parameters have been derived on the basis of FN equation particularly for CNTs. We have worked with reverse engineering to calculate the work function of nanostructure using FN plot. With the help of modified FN equation, an important formula for effective emitting area (active area for emission of electrons) has been derived and employed to calculate the active emitting area for CNTs field emitters. These studies are useful for future technologist those are doing dedicated work to make the CNT based electron emitting devices. The complete solution of FN equation will help researchers to understand the parameters on which FE characteristics of field emitting materials particularly CNTs, may be improved.

2. Electron field emission phenomenon and Fowler Nordheim theory

Field Emission is defined as extraction of free electrons from the surface of metal caused by external energy source in the form of electrostatic field. In the absence of a strong electric field, free electrons must acquire a certain minimum energy, called the work function, to escape through the surface of a material, which acts as a potential barrier for electron passage [50–52]. If the source material is placed in an electric circuit that renders it strongly negative electrode with respect to a nearby positive electrode (i.e., when it is subjected to a strong electric field), the work function is so lowered that some electrons will have sufficient energy to leak through surface potential barrier [53]. The resulting current of electrons through the surface of electron emitting material under the influence of a strong electric field is called field emission [54–58]. Most commonly, FE phenomenon occurs from metal surface into vacuum. However, FE can take place from metal, semiconductor, liquid, polymers and also non-conducting or weak conducting dielectrics. Zener effect can also be regarded as a form of FE in which induced field promote the electron from the valence band to conduction band. There are variety of names that are used for FE phenomena; field electron emission, field induced electron emission, electron field emission and also cold emission, cold cathode emission [59–64]. In spacecraft engineering, the name field emission is applied to field induced emission of ions (field ion emission) rather than electron while FE is used as general name covering both field electron emission and field ion emission. Material science is confined itself only for electron field emission which is more appropriate than any other available terminology. In the beginning of twentieth century and also the starting period of quantum mechanism, it was distinctly explained on the basis of quantum tunnelling by R. H. Fowler and L. Nordheim in 1928 and this theory is known as FN theory [65].

2.1. Fowler nordheim theory

An electron field emission phenomenon was first observed in 1897

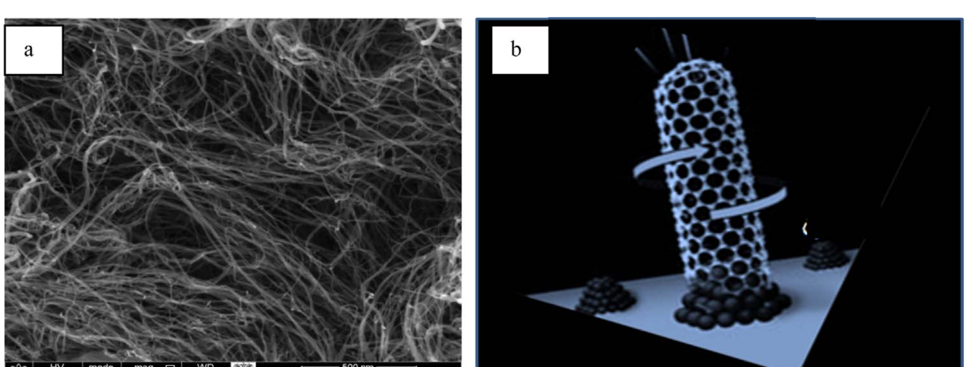

Fig. 2. (a) As-grown SWCNTs on Si substrate (b) SWCNTs as electron field emitters.