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DECLARATION

This dissertation contains the results of research performed by the author between October 2004 and February 2008 in the Department of Engineering, University of Cambridge. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

This work has not been submitted in whole or in part for any other University degree or diploma except where specifically indicated in the text.

Permission is granted to consult or copy the information and results contained within this dissertation for the purpose of private study only, and not for publication.

In compliance with regulations, this dissertation contains 39,638 words and 116 figures.

Mark Mann
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CARBON NANOTUBES AS ELECTRON GUN SOURCES

Mark Mann

This dissertation presents the development of a manufacturable carbon nanotube (CNT) electron source for specific application to high-quality electron beam equipment. It first details the advantages CNTs have over other electron sources and then describes the various methods used to fabricate carbon nanotubes.

For an effective electron source, it is important that the electrons come from one CNT, because if there are two, they will interfere with each other. After controlling the geometry of the tungsten wire during etching so that the apex diameter is less than 100 nm, a new process was developed to grow one multi-walled carbon nanotube typically 50 nm in diameter and a few hundred nm in length at the apex by plasma-enhanced chemical vapour deposition (PECVD). This process resulted in a 49% yield of single CNT tips aligned with the optical axis; a significant improvement on methods mentioned elsewhere [1]. The process was then modified so that CNTs could be grown on etched wires mounted on hairpins and by putting an entire electron source module into the reaction chamber. These modified processes gave similar yields.

Field emission experimentation was carried out on the CNT tips. CNTs need to undergo a rapid thermal anneal to remove adsorbed gaseous species and to complete the cap structure at the top. Stability, poorly defined elsewhere, has been replaced by *drift* and *instability* to describe peak to peak and standard deviation fluctuations in emission currents respectively. Instability was found to be less than 1% after three weeks of emission, comparable to that measured by De Jonge [1], but was found to increase if not annealed rapidly frequently. It was also found that the CNTs should not be operated at pressures of 10^{-8} mbar and above because instability was found to be too high. Kinetic energy spread was found to be as little as 0.28 eV at 20 nA total current. The CNT could be as much as three times as bright as current commercially available Schottky emitters.

On placing the CNT source in an electron microscope, micrographs were taken to compare it with a typical Schottky source. With the same system geometry, the resolution of the CNT was found to be twice that of the Schottky indicating a smaller virtual source size.

This work shows that CNTs are a viable electron source and in performance are at least equal and in some cases better than state-of-the-art electron sources currently available.

[1] N. de Jonge, M. Allioux, M. Doytcheva, M. Kaiser, K.B.K. Teo, R.G. Lacerda and W.I. Milne. "*Characterization of the field emission properties of individual thin carbon nanotubes*", Applied Physics Letters **85**, (2004).

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NOTATION

Units

As a general rule, S. I. units are used throughout this dissertation. The only exceptions to this rule are where accepted practice dictates otherwise. The two exceptions are gas flow rate, which is measured in standard cubic centimetres per minute (sccm), and gas pressure, which is measured in millibar (mbar). 1 sccm = 1.6667 x 10^{-8} m^3sec^{-1}, and 1 mbar = 100 Pa.

References

References to published literature are given in the text in the form [$Author^n$], where Author is the surname of the first-named author, and n is a reference number which refers to the list of references to be found at the end of each chapter.

Abbreviations

All abbreviations are written in full at their first occurrence in the text, with the abbreviation given next to it in brackets, for example Plasma Enhanced Chemical Vapour Deposition ("PECVD").

Keywords

Carbon Nanotube

Field Emission

Plasma Enhanced Chemical Vapour Deposition

Electron microscopy