EXPERIMENTAL STUDY OF EMISSION PROPERTIES OF CARBON NANOTUBES

Jan PEKÁREK\textsuperscript{1,2}, Radim VRBA\textsuperscript{1,2}, Martin MAGÁT\textsuperscript{1}, Jana CHOMOUCKÁ\textsuperscript{1,2}, Petra BUŠINOVÁ\textsuperscript{1,2}, Jana DRBOHLAVOVÁ\textsuperscript{1,2}, Radim HRDÝ\textsuperscript{1,2}, Jan PRÁŠEK\textsuperscript{1,2}, Ondřej JAŠEK\textsuperscript{2,3}, Lenka ZAJÍČKOVÁ\textsuperscript{2,3}

\textsuperscript{1} Department of Microelectronics, Faculty of Electrical Engineering and Communication, Brno University of Technology, Technická 3058/10, 616 00 Brno, Czech Republic, EU, pekarek@feec.vutbr.cz
\textsuperscript{2} Central European Institute of Technology, Brno University of Technology, Technická 3058/10, 616 00 Brno, Czech Republic, EU
\textsuperscript{3} Department of Physical Electronics, Faculty of Science, Masaryk University, Kotlářská 267/2, 611 37 Brno, Czech Republic, EU

Abstract

This paper describes a new approach to study the emission properties of carbon nanotubes in low distances between two electrodes. Each electrode consists of high doped silicon substrate. The field emission works on the principle that the field emission current is correlated with the electrical field intensity, i.e. the anode-emitter distance when the applied voltage is fixed. This means that the CNTs array serves as the emitter source of electrons between the cathode and the anode in the electric field. The measurement of emission current density flowing through the electrodes is carried out in a vacuum iron-glass vessel pumped by a turbomolecular pump and equipped with feedthroughs for voltage application and current measurement. The vacuum vessel is equipped with a new vacuum compatible linear nano-motion drive SmarAct that enables precise changes of the distance between two electrodes inside the vacuum chamber (step width from 50 nm to 1000 nm, sub-nanometer resolution). Special software, enabling to set up the step size, number of the steps and speed of the motion, is developed for its control. Additionally, a measurement control unit and the software are prepared for an automatic electrical measurement. For this experiment, carbon nanotubes (CNTs) are deposited using a microwave (mw) torch at atmospheric pressure or using a thermal chemical vapour deposition.

Keywords:
Emission properties, carbon nanotubes, thermal chemical vapour deposition, deposition using a microwave torch

1. INTRODUCTION

Carbon nanotubes (CNTs) are molecular-scale tubes of graphitic carbon with outstanding properties. They are among the stiffest and strongest fibers known, and have remarkable electronic properties and many other unique characteristics. For these reasons they have attracted huge academic and industrial interest, with thousands of papers on nanotubes being published every year. The diameter of a nanotube is on the order of a few nanometers (approximately 50 000 times smaller than the width of a human hair), while they can be up to several millimeters in length [1] [2].

Field emission involves the extraction of electrons from a solid by tunnelling through the surface potential barrier. The emitted current depends directly on the local electric field at the emitting surface $E$, and on its work function, $\phi$. Fowler-Nordheim model shows that the dependence of the emitted current on the local electric field $E$ and the work function $\phi$, is exponential like. As a consequence, a small variation of the slope or surrounding of the emitter and/or the chemical state of the surface has a strong impact on the emitted current. The small diameter of carbon nanotubes is very favourable for field emission, the process by which a device emits electrons when an electric field or voltage is applied to it [3].
Several techniques have been developed to produce nanotubes in sizeable quantities, including arc discharge, laser ablation, high pressure carbon monoxide and chemical vapour deposition (CVD). Most of these processes take place in vacuum or with process gases. Large quantities of nanotubes can be synthesized by CVD methods; advances in catalysis and continuous growth processes are making CNTs more commercially viable [4-6].

2. THEORY - EMISSION MECHANISM

Large field amplification factor, arising from the small radius of curvature of the nanotube tips, is partly responsible for the good emission characteristics. It is however still unclear whether the sharpness of the nanotubes is their only advantage over other emitters, or if intrinsic properties also influence the emission performances.

If the nanotubes seem to follow the Fowler-Nordheim law they can be thought of as metallic emitters. Nanotube emissions deviate from Fowler-Nordheim model. Such deviations are usually attributed to space-charge effects, which induce a diminution of the F-N slope at high fields. Thus nanotubes cannot be considered as usual metallic emitters [7].

Also for nanotubes electrons are not emitted from a metallic continuum as in usual metallic emitters, but rather from well-defined energy levels of ~0.3 eV half width corresponding to localized states at the tip. The energy spread of nanotubes is typically half that of metallic emitters (~0.2). And the shape of the energy distribution suggests that the electrons are emitted from narrow energy levels. Greatest part of the emitted current comes from occupied states with a large density of states near the Fermi level but the other deeper levels also contribute to the field emission.

The greatest part of the emitted current comes from occupied states below the Fermi level. The position of these levels the with respect to the Fermi level, which depends primarily on the tip geometry (i.e. tube chirality, diameter and the eventual presence of defects), would be, together with the tip radius are the major factors that determines the field emission properties of the tube. Finally it is worth noting that the presence of localized states influences the emission behaviour greatly. Local density of states at the tip reaches values at least 30 times higher than in the cylindrical part of tube increasing the carrier density for strong emission.

Fig.1 Theory of emission mechanism (Fowler-Nordheim law) [7]
3. EXPERIMENTAL

A new approach to study the emission properties of carbon nanotubes in low distances between two electrodes was used in this paper. Each electrode consists of high doped silicon substrate. The field emission works on the principle that the field emission current is correlated with the electrical field intensity, i.e. the anode-emitter distance when the applied voltage is fixed. This means that the CNTs array serves as the emitter source of electrons between the cathode and the anode in the electric field. The measurements were fifth-times repeated and the same results were obtained.

![Fig. 2 Schematic illustration and principle of measuring the emission properties](image)

The measurement of emission current density flowing through the electrodes was carried out in a vacuum iron-glass vessel pumped by a turbomolecular pump and equipped with feedthroughs for voltage application and current measurement. The vacuum vessel was equipped with a new vacuum compatible linear nano-motion drive SmarAct that enables precise changes of the distance between two electrodes inside the vacuum chamber (step width from 50 nm to 1000 nm, sub-nanometer resolution). Special software, enabling to set up the step size, number of the steps and speed of the motion, was developed for its control. Additionally, a measurement control unit and the software were prepared for an automatic electrical measurement.

![Fig. 3 The workplace for emission measuring and the linear nano-motion drive SmarAct](image)

For this experiment, carbon nanotubes (CNTs) were deposited using a microwave (mw) torch at atmospheric pressure or using a thermal chemical vapor deposition. The typical deposition conditions in torch were: flow rates of argon, methane and hydrogen $Q_{Ar} = 1000$ sccm, $Q_{CH_4} = 50$ sccm and $Q_{H_2} = 200$ to 300 sccm, respectively, microwave (mw) power of 400 W, substrate temperature 900 to 1100 K, deposition time 1 minute. A detailed study of the microwave torch for deposition of CNTs and their characterization were published in Ref.[8], [9]. The typical depositions for thermal CVD were: the substrate was heated under
mixture of Ar, flow rate 2800 sccm, and H₂, flow rate 500 sccm, to 800 °C with ramp rate of 25 °C.min⁻¹. The CNTs were grown at 800 °C under mixture of Ar (1400 sccm) and C₂H₂ (30 sccm). Deposition time was 20 minutes. After the deposition the substrate cooled down under Ar flow (1400 sccm).

4. RESULTS AND DISCUSSION

Fig. 4. SEM analysis of the CNTs

Measurements were performed for ten electrode distances – from 84 µm to 100 µm. For this ten distances were obtained several times the same results. The basic dependency was measured by the emission current in dependence on the applied voltage. Graphs of these dependences are shown below.

Fig. 5 Result of measured emission current in dependence on the applied voltage (and the detail for higher voltages)
In the set of experiments on the array with CNTs with dimension of 4x4mm, the field emission results show that in the small electrode distance is the low turn-on field (smaller than 1 V/µm) and achieved a high current density at 1.8 V/µm.

ACKNOWLEDGEMENT

This research was supported by the Czech Science Foundation under 102/09/1601 and 205/10/1374 project, by project Prospective applications of new sensor technologies and circuits for processing of sensor signals, No. FEKT-S-11-16.

REFERENCES