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Carbon Nanotube-based Cold Cathode for High Power Microwave Vacuum Electronic Devices: A Potential Field Emitter

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ABSTRACT

Carbon nanotubes (CNTs) can be grown in the form of small, sharp spikes capable of carrying very high current densities which suggest great potential application of CNTs as cold cathode in high power microwave vacuum device applications. These cold cathode vacuum microwave devices are expected to be ideally suited for air-borne and space applications. This paper reports the initial efforts made in the development of cold cathode using PECVD grown vertically-aligned matrix of CNTs with uniform height and optimum tip density on silicon substrate. The high aspect ratio (of the order of 10,000) and novel electrical, mechanical, and thermal properties of the CNT are found to be very attractive characteristics for emission of large and stable current densities at reasonably low field. The field emission current voltage characteristics of a typical cathode gave emission current density in excess of 35 mA/cm^2 at reasonably low field. The emission current in most of the samples is found to be stable over long period of time but is greatly effected by the vacuum condition during measurement. The initial measured data suggests great promise for achieving high current densities at practical electric fields.

Keywords: Carbon nanotubes, field emission, cold cathode, microwwave vacuum electronic devices

1. INTRODUCTION

In the case of hot filament thermionic cathodes used in medium and high power vacuum microwave devices, high electron current densities are achieved only at the cost of the useful life of the cathode. The high temperature of the hot filament puts a restriction on the proximity of the control grid to the electron source and thereby a limit on reduction of the size of the microwave devices such as TWT's. This limitation, in most of the applications, ultimately restricts the high frequency operation of the vacuum devices.

Solid-state microwave sources to a great extent have eliminated the limitations of the vacuum tubes arising mainly from the hot filaments for most of the low power applications. The availability of microwave transistors made of newer materials such as *SiC*, and *GaN* are expected to address some of the medium power application requirements at GHz frequencies. For high power applications, vacuum microwave tubes still remain the best choice due to automatic elimination of complex thermal management required in case of solid-state power amplifiers. In addition, the vacuum tubes are inherently radiation resistant and more suited at high frequency due to higher speed of electrons in vacuum. Thus the vacuum devices with cold cathode as source of electron will have the best features of both, the vacuum tubes and solid-state device. These cold cathode microwave devices can be turned on and off instantaneously and will have improved efficiency. In addition the elimination of hot cathode also removes the restriction on placement of the control grid close to the cathode. This ultimately makes the high frequency and low grid control voltage operation possible apart from the reduction in size. Such reduced size, radiation hard, and power efficient microwave device is expected to be very attractive for air-born and space communication applications. Previously good amount of efforts have been made to fabricate cold cathode microwave device with spindt type field emitter electron source using molybdenum tips[1-5]. The TWT with such type of field emitters operating at 10 GHz and emission current densities of 50 A/cm^2 at reasonably high field has been demonstrated[6].

The carbon nanotube (CNT) is a long hollow seamless cylinder (single-wall as well as multi-wall) of graphene. The diameter of these tubes is in the range of 1 to 100 nm. The tubes are normally capped with half a fullerene molecule at both ends[7]. Recently CNT having dia as low as 3 Å, has been reported[8]. These CNTs exhibit extra ordinary electrical, mechanical, chemical, and thermal properties. The CNTs are found to be mechanically very strong, chemically very stable, and show very high thermal conductivity, an ideal requirement for large current density field emitters with sustained long useful life. In addition to these desired characteristics, the CNTs have aspect ratio (h/r) greater than 1000, where h is the height and r is the radius of the tube. These large aspect ratio associated with chemical

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stability suggests use of nanotubes as an ideal electron field emitter.

The efforts made in the development of flat panel displays using CNTs-based field emitter has shown[9] that individual CNT can carry current up to 1 mA or current densities of about 105 A/cm^2. Recently current density of 4 A/cm^2 at an applied electric field of 60 V/mm has been obtained[10]. In fact the emission current density to a great extent depend upon many factors but is directly proportional to the number of emitters or the emitter density. Highly dense CNT emitter though will have large number of emitting tips but tips suffer from shielding effect arising due to the narrow distance between the adjacent nanotubes. The shielding effect distorts electric field, which leads to reduction in emission efficiency. Therefore in order to achieve best emission current densities, the emitters are required to have optimum tip-to-tip spacing and the emitters are to be placed perpendicular to the substrate.

This paper reports the efforts made to optimise the growth of vertically-aligned CNTs on *Si* substrate using PECVD technique[11] for realisation of field emission cathodes suitable for microwave tubes. The significant improvement in emission current density obtained in PECVD samples in comparison to the CVD samples reported earlier[12] has also been explained.

2. SYNTHESIS

Vertically-aligned CNTs were selectively grown by plasma-enhanced chemical vapour deposition technique (PECVD). Iron catalyst films of various thicknesses ranging from 5 nm to 100 nm were deposited on to pre-cleaned n-type *Si* (100) substrate of resistivity (ρ) 4-6 Ωcm using standard RF sputtering technique. In order to achieve selective vertically-aligned growth of the CNTs with optimum nano tip density, the catalyst deposited substrate was patterned using optical lithography followed by liftoff to retain iron islands of 20 μm and 100 μm diameter on to the silicon substrate with varying spacing. After cleaning of the patterned substrate the growth of the CNTs was carried out[11] using NH_3 and C_2H_2 mixture with substrate temperature kept at 670 ^{o}C. Scanning electron microscope (SEM) and transmission electron microscope (TEM) were used to characterise the grown nanotubes. Typical SEM and TEM images are shown in Fig. 1.

3. FIELD EMISSION MEASUREMENTS

The schematic of the measurement setup used for field emission measurements is shown in Fig. 2. Vertically- aligned CNT sample to be used as cathode was pasted over a

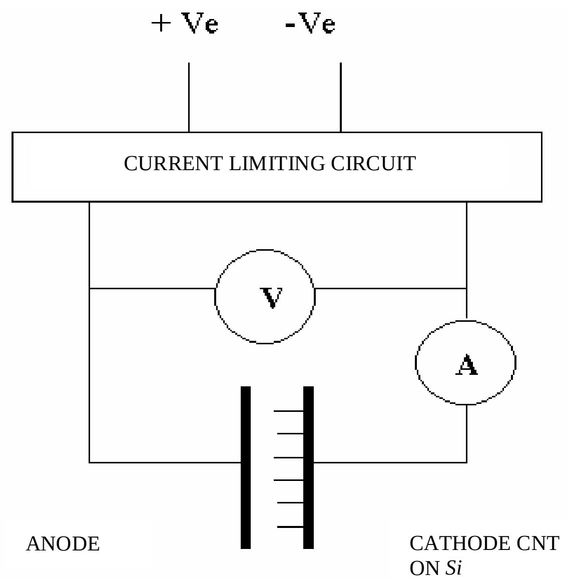

Figure 2. Field emission measurement setup.

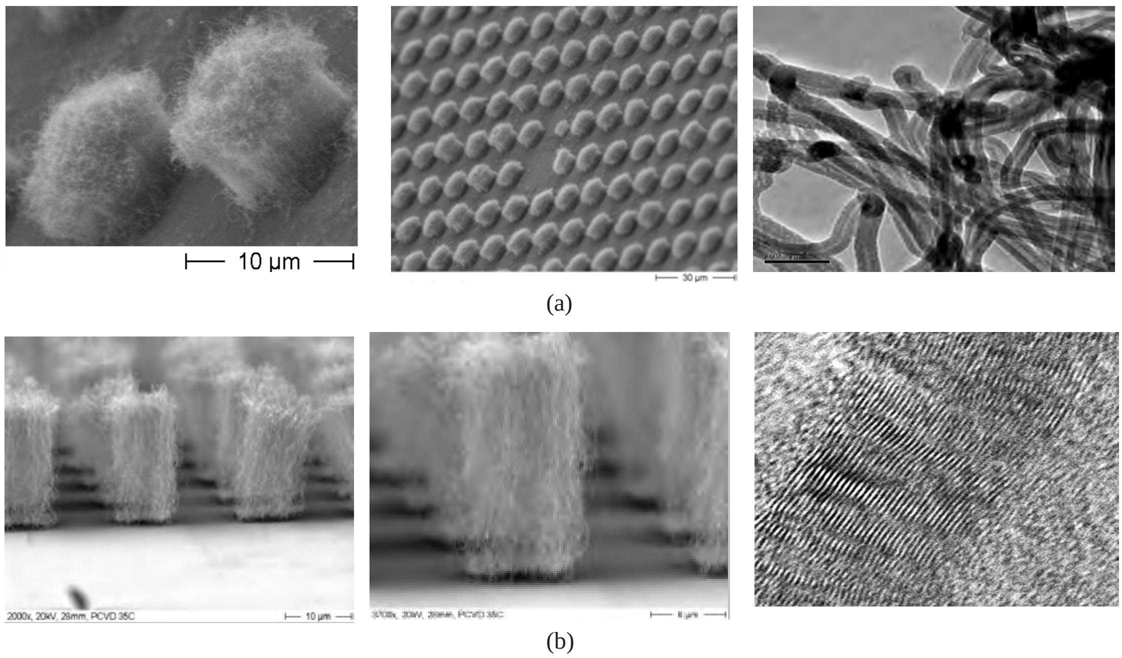

Figure 1. SEM and TEM images of CVD-grown MWNTs and (b) PECVD-grown MWNTs.

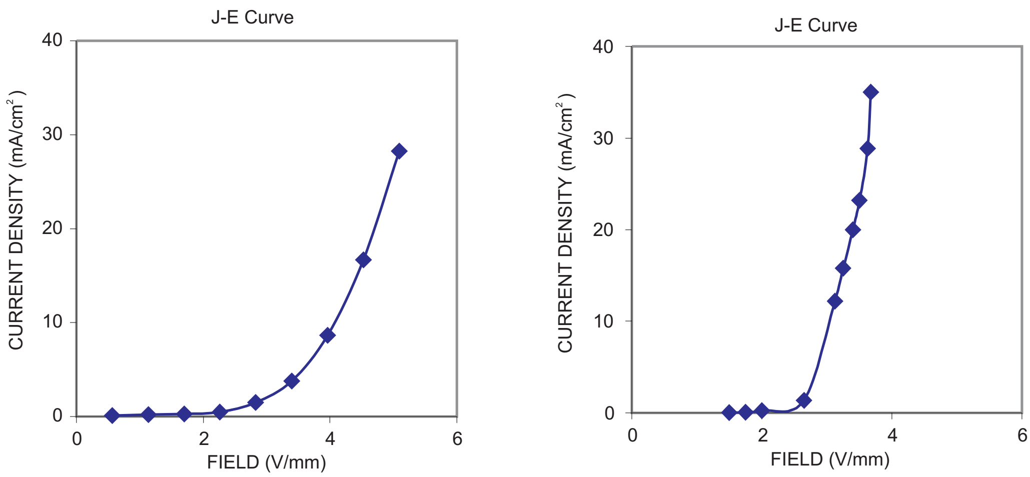

Figure 3. JE curve of: (a) CVD-grown sample and (b) PECVD-grown sample.

copper plate with conducting epoxy. An indium tin oxide (ITO)-coated glass was used as anode. Both the cathode and anode were mounted on teflon plate with double stick as guide to keep both the plates parallel to each other. The entire sample assembly was kept in side a vacuum chamber evacuated to a vacuum better than 10^{-6} torr. An over current protection circuit was also designed and added to the measurement setup so that the current can be maintained within the safe limits.

The emission current measurement as a function of electric field was carried out under dynamic condition of vacuum over number of samples having different catalyst thickness, dot size and spacing. The current density (J) versus electric field (E) plot is shown in Fig. 3. The emission current measurements were also carried out at different anode to cathode spacing but keeping the field constant. Measurement at higher fields could not be carried out due to the existing vacuum setup. However the theoretical estimation of FE current at higher fields were carried out by extracting the Fowler Nordheim (F-N) parameters from the experimentally obtained F-N curves. The following F-N equation[13] was used to extract the parameters to estimate the current density values at higher fields.

$$J(E) = \frac{\eta a}{\varphi}(E_1)^2 \exp\left(-\frac{b\varphi^{3/2}}{E_I}\right)$$

where the local electric field E_1 is connected with the external macroscopic electric field E_1 as $E_1 = \beta E$, φ is the work function, and β is the field enhancement factor (likely related to the geometry); a =1.54 × 10^{-6} AeVV^{-2} and b = 6.83 × 109 eV$^{-3/2}$ Vm^{-1} are universal constants. The factor η describes the effective emitting area.

4. RESULT AND DISCUSSIONS

The SEM micrograph observation reveals that the CNTs grown by PECVD technique are comparatively smaller in dia with very less amorphous carbon deposition and graphitic particles presence on the sample. The PECVD grown sample is also observed to have less dense growth in comparison to the nanotubes grown by CVD technique for the samples having same catalyst condition[13]. The field emission current measurement results of two typical CNT sample each having patterned growth on iron catalyst dots of thickness 10 nm is reported. These samples were grown on patterned catalyst film having 10 μm diameter iron dots with 10 μm spacing. In the CVD sample[13] an emission current density of 8 mA/cm^2 at a field of 3.7 V/μm was measured where as an emission current density of 35 mA/cm^2 at same field was obtained in the PECVD grown sample [Figs 3(a) and 3(b)]. This observed increase in the emission current density in case of the PECVD sample could be attributed to much less dense growth of CNTs of smaller diameter. These geometrical factors are expected to improve the geometrical field enhancement factor by way of increased aspect ratio and reduced shielding effect of one emitter (CNT) over other. The increased geometrical field enhancement factor ultimately results in lowering of the threshold field and improved field emission current.

Efforts are being made to optimise the size of the iron dots and spacing in between them to get an emission current density of about 1 A/cm^2 at practical field, which is evident from the estimated current density with field curve (Fig. 4). It was also observed that initially during I-V measurements of field emitters some non-uniformity in the emission current was observed which make the device unstable. But this issue was resolved by giving a high field treatment to device for longer duration[14]. At a fixed electric field the measured emission current densities were found to be independent of the spacing between cathode

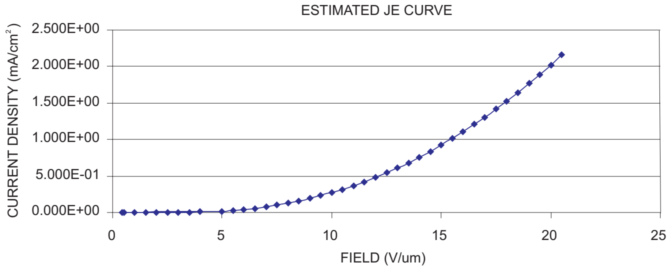

Figure 4. Estimated JE curve.

and anode. The stability of the emission current was also found to depend upon the vacuum conditions during the measurement. This could be because of degradation of the CNT emitter tips due to ion bombardments at poor vacuum conditions[15].

5. CONCLUSIONS

Initial measurement results of emission current data obtained on selectively grown CNT cathode samples by PECVD technique in diode configuration, show great potential for cold cathode application in microwave tube. With fine refinement of the growth process leading to the most optimum nanotip density it should be possible to get a stable current density in excess of 1 A/cm^2 at reasonable field. Further improvement in current densities at much lower field is expected to be made possible by using triode configuration wherein a control grid placed much closure to the emitter tips shall be able to extract electrons at much lower gate voltage. Established semiconductor processing techniques can be exploited to fabricate triode type of structure.

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