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Model calculation and empirical investigation of enhanced field emission behavior of branched carbon nanostructures

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ABSTRACT

In this paper, we propose the novel branched carbon nanotubes (B-CNTs) as efficient candidate for field emission applications. We believe that the double-stage structure of B-CNTs, beside formation of multiple thin branches at the apex of each vertical CNT, is responsible for the observed enhanced field emission behavior in B-CNTs. In this regard, we have derived an analytical model to evaluate the field enhancement factor (β) of the B-CNTs in comparison with CNTs, as the most popular cathode for field emission applications in the scientific society. The presented model also allows investigating the effect of different structural parameters on the field emission characteristic. We have also, compared the field emission characteristics of the B-CNTs with vertical CNTs experimentally. We observed a β value for B-CNTs which was around three times higher than CNTs. The observed enhancement in the experimental data was in good agreement with the presented analytical model.

1. Introduction

High aspect ratio, high electrical conductivity and thermal stability are among the most interesting characteristics of the carbon nanotubes (CNTs) which have always attracted the scientific attention for field emission applications [1–3]. Nano-scale curvature of the tip and the geometric characteristics of CNTs are supposed to be the main factors leading to enhanced local electric fields in the vicinity of CNT-tip. Many research activities have been concentrated on the field enhancement value as the key parameter to evaluate the emission efficiency of the CNTs or other nanostructures [4–7]. In this regard, there are simulations and analytical approaches in the literature [8,9]; however the analytical approaches have always helped to clarify the effect of different structural factors simpler and more feasible. Similar investigations have shown that field enhancement factor of a single CNT in a uniform electric field depends directly on the value of aspect ratio (length to radius of the CNT), in the case of large anode–cathode distances [5].

On the other hand, there are many experimental and simulation researches in the last few years, which have reported enhanced field emission behavior from the double/multi-stage cathodes [10–13]. The investigated multi-stage structures were generally realized by settling/growing a high aspect ratio nanostructure on an upholding tip with a larger dimension. The observed enhancement has been attributed to the increment of the field enhancement factor depending on the multi-stage geometry. In this regard, Huang et al. have investigated the emission behavior of the Si nanowires grown on the carbon cloths [13], while Niemann et al. have studied the effect of cathode structure by comparing the field enhancement factor of a CNT grown on the parallel plate with a CNT grown on a micro-tip [11]. In our previous work, we have also reported enhanced field emission behavior of ZnO-nanowires grown on the base of CNTs (branched-ZnO/CNT nanostructures) [14]. Seelaboyina et al. have, specifically, studied the emission behavior of double-stage CNTs and reported a lower threshold field and higher emission current in comparison with single-stage CNTs [15].

In this line of research, branched carbon nanostructures (B-CNTs) have been grown and developed for the first time in our research group [16–18]. B-CNTs have presented tree-like structure and they are achieved from a double-stage growth of CNTs in DC-PECVD system. The utilized catalyst was Ni and the secondary growth takes advantage from the catalyst present at the tip of the initial CNTs. B-CNTs showed great potential for different application fields including field emission. Tree-like structure and numerous highly emissive tips of the grown B-CNTs can lead to efficient field emission behavior, which has been studied experimentally in our previous work [19]. Here we have derived an analytical model to evaluate the field enhancement factor of the B-CNTs, as a bright characteristic in field emission application fields. The resulted approach simplifies studying the effect of different structural

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parameters on the field emission characteristics of these nanostructures. We also compared the field emission characteristics of the B-CNTs with vertical CNTs, by both the model results and experimental results.

2. Calculation and method

2.1. Model solution

To calculate the field enhancement factor of the carbon nanotubes, assuming the CNT as a cylinder shape (with the height of h) perpendicular to the cathode plane is a general assumption [4]. We can also assume a hemisphere cap with the radius ρ for the CNT, and the anode–cathode distance is much larger than the CNT height in this model system. Fig. 1a displays the applied 2D model system schematically. Here we have investigated a B-CNT structure with an average number of 3 branches which seems sensible by considering the SEM image of the grown B-CNTs (Fig. 7b).

From the experimental point of view in the B-CNT growth procedure, the number of branches is inversely proportional to the diameter of branches. This assumption has been applied because the seed present at the initial CNT tip is divided into separate parts, which serve as the seed for secondary growth, individually [16–18]. So, we can consider ρ as the branch radius and 3ρ as the base radius. h, a, ω and d represent base length, branch length, inter-branch angle and anode–cathode distance, as shown in Fig. 1b.

We assumed the CNTs being conducting, so that the potential value on the B-CNT's surface is the same as the external potential applied to the cathode plate. Thus, we can assume CNTs as spheres which are connected to the cathode plate by ultra thin wires (Fig. 1b). The assumed wires can also be neglected, for the sake of simplicity, because they can hardly affect the potential distribution at the apex of a CNT with high aspect ratio. Calculations have also shown that electric charges are mostly induced at the top of the CNTs when they are exposed to the electric field [20]. Thus, it is a sensible approximation to model the B-CNT as floating spheres which are placed in a tree-like arrangement, as depicted in Fig. 1c. The induced charge on the spheres can also be approximated by dot charges (Q) and electric dipoles (P). Due to high aspect ratio of the CNTs (both in the base and the branches) we have neglected the higher powers of the factors ρ/d and h/d in the following derivations. It is worth mentioning that the presented analytical model can be applied to similar branched structures/heterostructures, however one should take different physical characteristics of the materials into account.

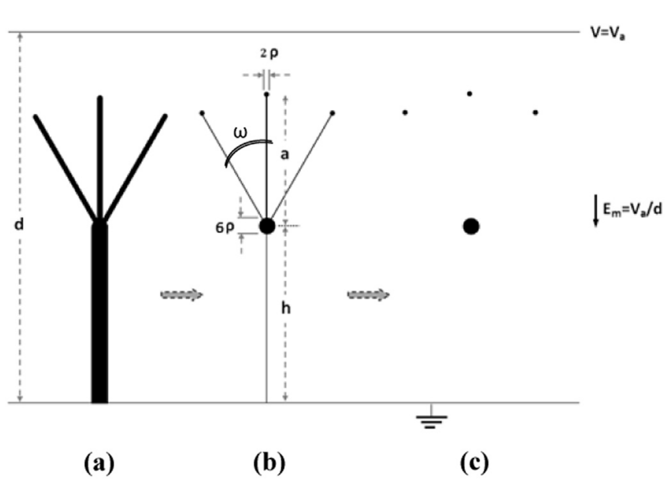

Fig. 1. Model schematic of (a) B-CNT structure; (b), (c) simplified models applied for calculation, wherein h, a, ρ, ω and d are base length, branch length, branch radius, inter-branch angle and anode–cathode distance.

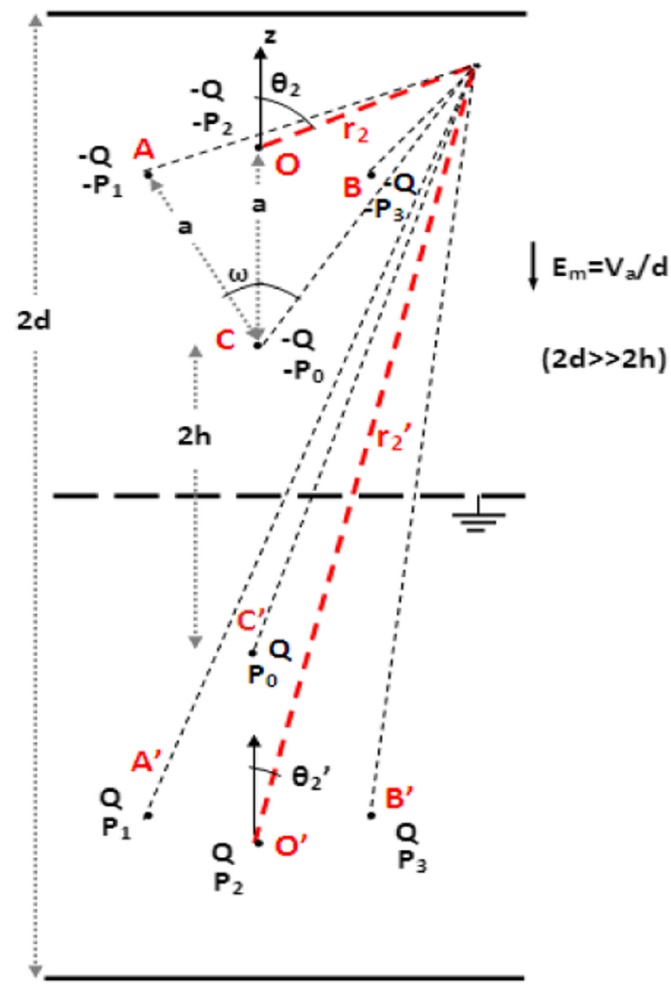

Fig. 2. A B-CNT on the cathode plate is simplified by the method of images; thus replaced by the equivalent charges and dipoles ($-Q$ and $-P_i$), when an electric field is applied.

2.2. Calculation of field enhancement factor for B-CNTs

To calculate the field enhancement factor, we are going to calculate the electric field at the proximity of B-CNT apex. For this purpose, we calculated the induced electric potential at the tip of the central branch, as shown in Fig. 2. It can be observed in this figure that we have assigned an image charge and dipole ($-Q$ and $-P$) for each sphere, to satisfy the boundary condition at the conductor surface. Then, the potential value has been determined by:

$$\begin{aligned}\varphi(r,\theta) = & \left(-\frac{Q}{r_2}-\frac{P\cdot\cos\theta_2}{r_2^2}+\frac{Q}{r_2'}-\frac{P\cdot\cos\theta_2'}{r_2'^2}\right)\\ & +\left(-\frac{Q}{r_1}-\frac{P\cdot\cos(\theta_1+\omega)}{r_1^2}+\frac{Q}{r_1'}-\frac{P\cdot\cos(\omega-\theta_1')}{r_1'^2}\right)\\ & +\left(-\frac{Q}{r_3}-\frac{P\cdot\cos(\omega-\theta_3)}{r_3^2}+\frac{Q}{r_3'}-\frac{P\cdot\cos(\omega+\theta_3')}{r_3'^2}\right)\\ & +\left(-\frac{Q}{r_0}-\frac{P\cdot\cos\theta_0}{r_0^2}+\frac{Q}{r_0'}-\frac{P\cdot\cos\theta_0'}{r_0'^2}\right)\\ & +E_m(h+a+r_2\cdot\cos\theta_2)\end{aligned} \tag{1}$$

Here, (r_i, θ_i) denotes the coordinate of any charge in space, while (r_i', θ_i') denotes the coordinate of the image charge. It can be