An Empirical Study of Field Emission Properties of a Single Toroid Carbon Nanotube Pillar Electron Source

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In recent years there have been tremendous advancements in understanding the fundamentals of carbon nanotube (CNT) structures. This is particularly true for electron source applications. Still, many aspects that contribute to optimal emission current are not fully understood [1, 2]. Phenomena such as field screening, local field enhancement and the edge effect have received significant attention in the last few years. Despite the current advanced state of the research, this current understanding is not at a level sufficient for large scale manufacturing [3-5].

Recently, our laboratory has developed cold field emitters consisting of CNT pillar arrays (CPAs) and toroid CNT pillar arrays (tCPAs) fabricated on bulk metal as well as silicon wafers sputtered with metal catalyst substrates [6, 7]. Our CPA and tCPA technology rely heavily on mature micro-scale lithographic processing. For the first time, CPA based structures make uniform CNT emitters an economically viable option. As seen in Fig. 1a, a CNT pillar can be described as a uniform, highly dense, vertically aligned, and compact bundle of CNTs. Vertical self-alignment of CNTs results from the van der Waals interaction between neighboring CNTs and contributes to the excellent structural stability of CNT pillars [8]. While having the same structural stability as the CNT pillar, the toroid CNT pillar differs in that it has an open-center, as shown in Fig 1b. These CNT emitter structures exhibit exceptional field emission properties which are directly related to the electric field enhancement along the edges of the structure. This effect is called the "edge effect". At an applied field of 7.45 V/μm, a current of 50 mA/cm^2 and 22 mA/cm^2 were achieved for the tCPA and the CPA, respectively. In this experiment, the only change to the structure was the removal of the CNTs at the center of tCPA. Thus, we attribute the increase in current density for the tCPA when compared to the CPA to a larger emission area. This effect is directly related to the reduced field screening at the additional inner edge of the toroid pillar structure [9].

In this paper, we investigate the effect of ring thickness, R, indicated in Fig.1b, on the field emission of a tCPA. This is accomplished by varying the inner radius, r, of the toroid at 5 μm, 7.5 μm, and 10 μm while keeping the outer radius, d, constant at 15 μm. Here, we investigate the field emission characteristics for three tCPA emitters with R values of 10 μm, 7.5 μm, and 5 μm. First, we employ finite element electrostatic simulations using COMSOL Multiphysics to extract the electrostatic field in close proximity to the structures. As seen in Fig. 2, when R is 5 μm, the electric field enhancement is strongest. Thus, this structure will achieve the highest current density. This leads us to believe that that an optimal current density can be achieved by selecting the value of R that minimizes field screening while maintaining structural stability.

Experimental field emission I-V characteristics for the three toroid CNT pillar emitters will be presented at the conference. In addition, we will also present the results of cathode stability tests for these tCPAs.

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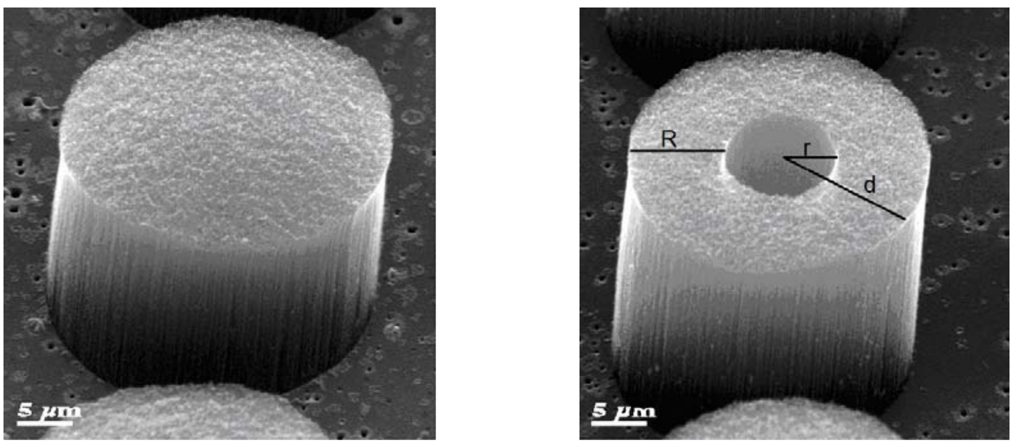

(a) (b)

Figure 1. SEM images at a tilted viewing angle of 45° of the a) CPA b) tCPA.

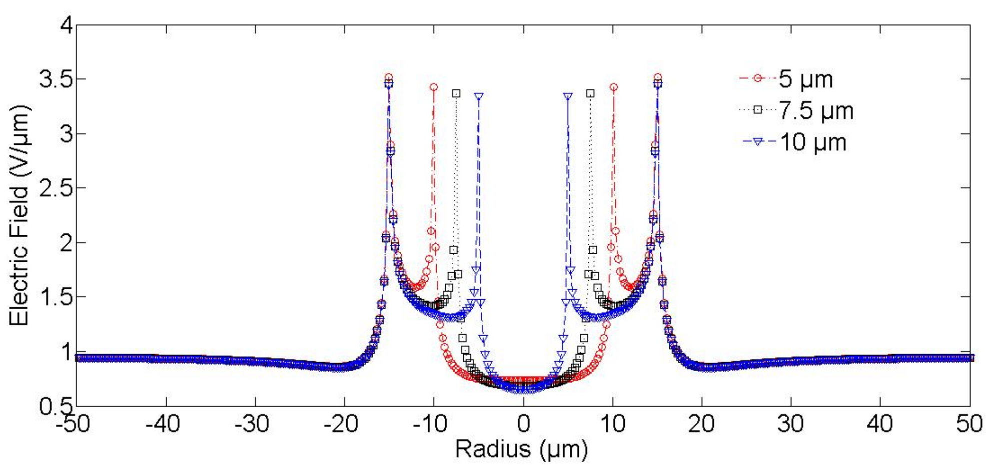

Figure 2. Simulated data for electric field versus radius for toroid pillars with varying ring thicknesses of 5 μm, 7.5 μm and 10 μm.