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# Simulation of field emission behavior from multiple carbon nanotubes in an integrated gate triode configuration

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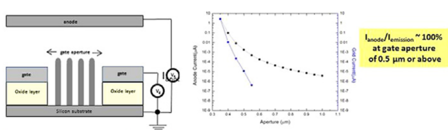
## GRAPHICAL ABSTRACT

Field emission behaviour of an integrated triode structure with multiple CNT tips has been investigated. Maximum emission can be obtained by controlling the array pitch (gate aperture) and by positioning the nanotubes slightly above the gate level. Realization of such devices will provide a miniature intense source for many vacuum microelectronic devices.




| | Position of CNT tip w.r.t gate | Electric Field (V/m) | Anode Current (μA) | Grid Current (μA) | Total Current (μA) |
|---|---|---|---|---|---|
| Top Gate | 0.2 μm below the lower gate edge | $5.99 \times 10^{8}$ | $7.5 \times 10^{-4}$ | $1.8 \times 10^{-4}$ | $9.3 \times 10^{-10}$ |
| Standard Gate | In-line with the gate | $6.97 \times 10^{8}$ | $4.8 \times 10^{-3}$ | $1.18 \times 10^{-3}$ | $5.98 \times 10^{-9}$ |
| Side Gate | 0.2 μm above the upper gate edge | $6.7 \times 10^{8}$ | $3.38 \times 10^{-3}$ | $1.96 \times 10^{-5}$ | $3.4 \times 10^{-9}$ |

Side gate configuration with optimum gate aperture most suitable for design

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## ABSTRACT

The paper investigates the simulation results of a model for Carbon Nanotube (CNT) field emitters in triode configuration with an integrated gate. Simulation studies have been carried out to analyze and evaluate the performance of a triode device with multiple CNT tips on a silicon substrate. The model has been developed using CST Particle Studio software. The modulating effect of control gate on field emission properties of the device is simulated and dc characteristics at different gate voltages are obtained. It is seen that a small change in gate voltage causes a large change in current between the anode and the cathode. The effect of gate aperture and relative position of the CNT tip with respect to the gate level on field emission is also investigated and modeled. The model helped in providing an understanding of a complete cathode device with an integrated extractor (gate) for potential applications in Vacuum Microelectronic (VME) devices.



## 1. Introduction

Vacuum tubes using thermionic electron emitters are being used since many decades in flat-panel displays, cathode ray tubes, X-ray sources and microwave sources and amplifiers. However, recently the efforts are on to use field emitters as a source of electrons in these devices [1–3]. The development of micro fabrication technology along with the use of field emitters as electron sources has led to the emergence of a new class of devices called Vacuum Microelectronic (VME) devices [1,4]. The evolution of this class of devices depends critically on the availability of a miniature, intense source. Among the earlier developed field emitters based on etched molybdenum or tungsten needles, Spindt silicon arrays etc., CNTs have emerged as a promising class of electron field emitters [4]. They have a low threshold electric field for emission and a high emission current density which make them attractive for use in these devices. [5].

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Of the two device configurations using CNTs as a field emission source, the diode configuration is the simplest consisting of two elements: a cathode at ground potential separated at a fixed gap by an anode plate with an applied positive potential [6]. However, recent research for enhancing CNT field emission has largely focused on exploiting a traditional vacuum triode structure consisting of three elements: a cathode, a gate and an anode. The gate is used to control the flow of electrons from the cathode to the anode and is much closer to the cathode than the anode. As a result, a large change in anode current can be achieved by a small change in gate voltage and the triode can be used as an amplifying device [7]. Therefore, efficient gate control along with ballistic transport makes CNT triodes important building blocks for development of high-speed vacuum microelectronics.

In this paper we report simulation results of field emission behavior from multiple carbon nanotubes in triode configuration having an integrated gate electrode. A CNT based triode where the dielectric oxide layer and gate electrode are fully integrated along with nanotubes on the silicon substrate is modeled. The triode operation is demonstrated by applying a potential to the gate which modulates the field emitted current between the anode and the cathode. DC characteristics of the triode are then calculated at varying anode and gate voltages. It is seen that the gate improves the control capability of emission currents. In the paper, it is emphasized that an optimum value of gate aperture and location of CNT tip with respect to the gate, significantly influences the emission process. Hence a proper control of these two parameters can aid in the efficient design of the actual device.

### 1.1. Simulation model

Simulations were carried out using the CST Particle Studio software which uses the finite integration technique under perfect boundary approximation and gives the numerical solution of the Laplace equation to calculate the electric field at any point around the structure. The structure of multiple carbon nanotubes in integrated gate triode mode which was used for carrying out the simulations is shown in Fig. 1. The structure consists of a silicon substrate with an oxide layer on top. Vertical CNTs are placed in a pit formed in the oxide layer. The CNTs are assumed to be ideal metallic structures with a hemispherical tip. A metal gate electrode is placed on top of the oxide layer which forms an integral part of the cathode. An anode is located at a distance'*d*' from the gate electrode which in the present simulation has been taken as 2 μm. The cathode is kept at a ground potential and fixed dc potentials are applied at the gate and anode to simulate the triode characteristics. The other simulation parameters used were CNTs of radius 20 nm, oxide thickness of 1 μm and gate thickness of 0.5 μm. The CNT height was kept 0.2 μm above the top edge of the gate.

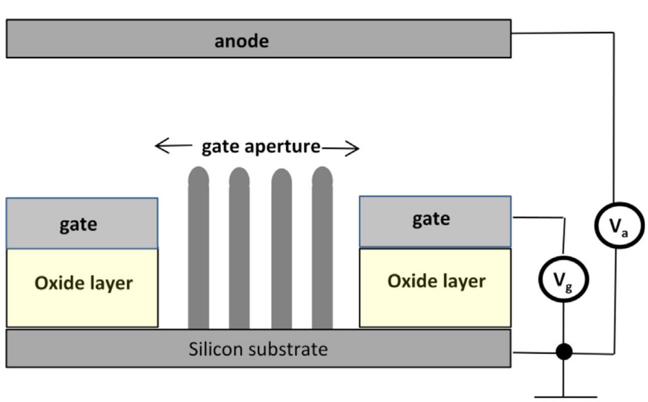


**Fig. 1.** Model of multiple tip CNT triode with an integrated gate.

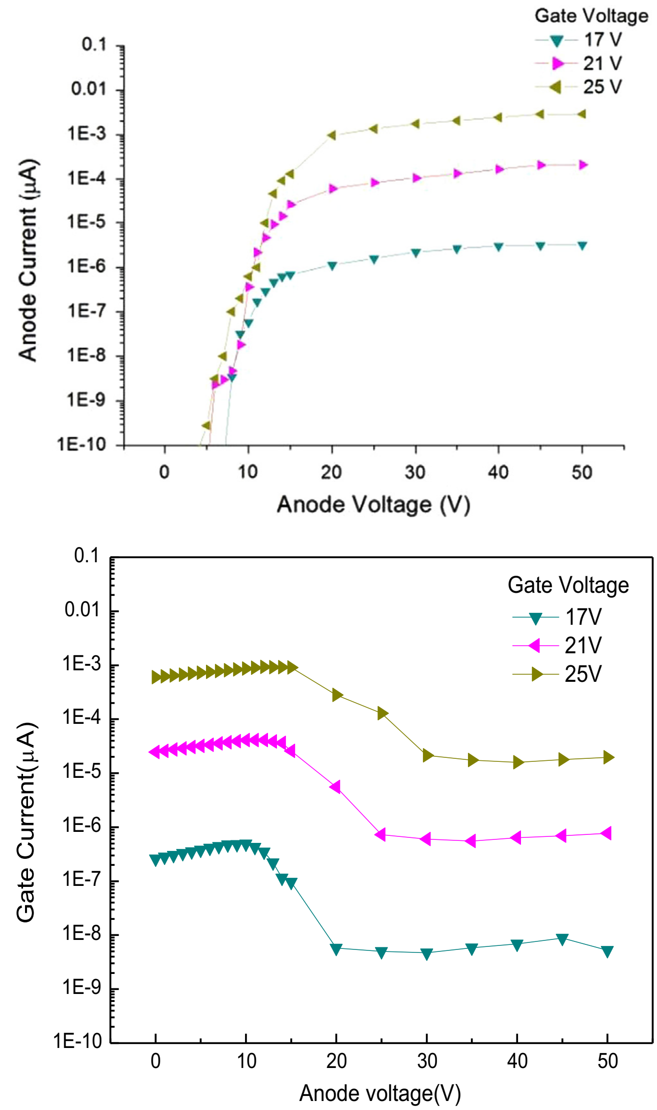


**Fig. 2.** (a) Total emission current as function of anode voltage for three different gate voltages and (b) gate current as a function of anode voltage for three different gate voltages.

### 1.2. Simulation results

#### 1.2.1. Triode characteristics

Anode and gate characteristics were simulated for 3 gate voltages of 17, 21 and 25 V as shown in Fig. 2(a and b). The anode voltages were varied from 0–50 V. Fig. 2(a) shows variation of emission current with anode voltage at a gate aperture of 0.5 μm. As the anode voltage increases and becomes comparable to the gate voltage, the anode current increases with the anode voltage. As the anode voltage is increased further and it becomes significantly higher than gate voltage, the anode current saturates and is almost independent of anode voltage. When a gate is interposed between the anode and cathode, it tends to screen the cathode from the anode field. If the gate is made positive with respect to the cathode, the gate significantly increases the electric field at the CNT tips, thus drawing a larger emission current. Hence, the gate voltage variation causes the total emission current to increase as seen in Fig. 2(a). However the gate current also increases slightly as seen in Fig. 2(b).