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SCIENCE DIRECT
Diamond & Related Materials 15 (2006) 334 – 340
DIAMOND AND RELATED MATERIALS
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Fabrication of aligned convex CNT field emission triode by MPCVD

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Available online 26 October 2005

Abstract

In this work, vertically aligned carbon nanotubes (CNTs) were used to form a gated microcathode with a convex surface profile, being selectively synthesized from Microwave Plasma Chemical Vapor Deposition (MPCVD) with nickel (Ni) as a catalyst. A single-mask microfabrication process achieved an array of 10 μm × 10 μm CNT microtriodes with self-aligned gate. The convex profile is important in preventing cathode-gate leakage without resorting to more complicated fabrication processes or utilizing a gate over-etching approach. The main mechanism for the formation of the convex-shaped CNT microcathodes was investigated and is proposed to be the result of plasma etching of CNTs near the gate opening region due to higher plasma density during the growth process, leading to slower growth rate or shorter CNTs at the circumferential area. Additionally, previous simulation work has predicted that this type of surface profile is beneficial for more quasi-uniform electric field distribution on CNT tips. Field emission characteristics of the triode device were investigated, whereby a gate turn-on voltage as low as 25 V was achieved. The low turn-on of the device is mainly due to the smaller gate aperture made possible by the convex-shaped CNT microcathodes.

Keywords: MPCVD; Carbon nanotubes; Field emission; Electrical properties characterization

1. Introduction

Recently, gated CNTs field emission microcathodes or triode devices have caught attention of researchers [1–11] due to their low turn-on voltages and potential for high current, high frequency and high power applications in vacuum microlelectronics. Unlike diode devices, a field emission triode is a three-terminal device. Due to the proximity of the gate electrode to the electron emitting cathode, a gate voltage, often less than 50 V is sufficient to cause a high electric field on the emitters for the extraction of electron into vacuum, i.e. the tunneling phenomena termed as field electron emission. The field emission triode is an indispensable building block in the development of high-speed, radiation, and temperature-immune vacuum microelectronics and field emission displays (FEDs).

Most of the reported CNT triode results thus far do not test or reveal DC or AC transistor characteristics such as amplification factor (μ), transconductance (g_m), anode resistance (r_a) and voltage gain (A_v) of the device. The reported gate turn-on voltages range from 10 to 60 V for as-grown CNT on microfabricated triode [1–11]. Previously, we successfully fabricated a CNT triode with a gate turn-on voltage of ~40 V by thermal CVD [1]. Since the CNTs grown were randomly oriented, an over-etched gate structure [1] was adopted in order to avoid cathode-gate leakage problems. As a result, the large cathode-gate spacing (~12 μm) led to high turn-on voltage and triode characteristics of amplification factor ~10 and transconductance ~47 nS when configured as a triode amplifier.

In order to overcome the gate leakage problems, which limits the performance of the CNT triode, three approaches have been suggested in the literature, namely (i) over-etched gate electrode or reduced gate overhang [1,2], (ii) sidewall protector [3–6], and (iii) post-growth processing which includes utilizing chemical mechanical polishing (CMP) technique [7], or plasma trimming of the grown CNTs [8]. In this respect, the over-etched gate and sidewall protector techniques did alleviate the gate leakage problems but at the expense of higher gate turn-on voltages. Apart from the above,

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0925-9635/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.diamond.2005.09.022

potential solution to the cathode-gate leakage problems is a gated triode structure with a second gate or focus electrode [9]. This dual-gate configuration is capable of reducing gate-leakage currents as well as providing focused electron beams but more complicated and costly fabrication processes are involved. In addition, by operating the field emission triode in a "collector-assisted" mode [12] or biasing the anode such that the cathode is on the verge of emission [13] also improves electron emission uniformity and gate current leakage problem.

In this work, an alternative approach with gated convex CNT microcathodes was performed to minimize cathode-gate leakage problems. The CNT microtriode was fabricated with self-aligned gate utilizing a single-mask microfabrication process. Vertically aligned CNTs were synthesized selectively inside the triode structure by MPCVD method with Ni as a catalyst and without shorting the gate electrode. H_2 plasma pretreatment of the catalysts prior to the CNT synthesis process was successfully employed to obtain a convex-shaped surface profile, which is important in preventing cathode-gate leakage without resorting to more complicated fabrication processes or utilizing a gate over-etching approach. Field emission characteristics of the aligned CNTs field emission triode were investigated.

2. Experimental method

In this study, vertically aligned CNT microcathodes with self-aligned gate were synthesized selectively inside the triode mold utilizing MPCVD method. The single-mask microfabrication process achieved an array of 10 μm × 10 μm CNT microtriodes with 2856 array cells and 20 μm array spacing. As illustrated in the schematic fabrication process in Fig. 1, the process began with a low-pressure CVD deposition of polysilicon as the gate electrode on thermally oxidized highly doped n-type silicon (100) substrate. A spin-on-diffusion source was utilized to dope the polysilicon gate at high-temperature (1050 °C) for good conductivity. The thickness of the thermal oxide and the polysilicon gate layers was ~1.5 μm and 0.8 μm, respectively.

After conventional photolithography patterning, the polysilicon gate was subsequently dry-etched by a gas mixture of sulfur hexafluoride (SF_6) and oxygen (O_2) at 150 mTorr in a reactive-ion-etch system (MRC). Next, the thermal oxide was isotropically wet-etched with buffered-oxide-etch (BOE) to obtain an undercut structure as illustrated in Fig. 1. A thin film of titanium (Ti) ~20 nm, a diffusion barrier layer and Ni ~5–10 nm, acting as nanocluster catalytic centers for CNT nucleation growth catalyst, were sputter deposited in sequence

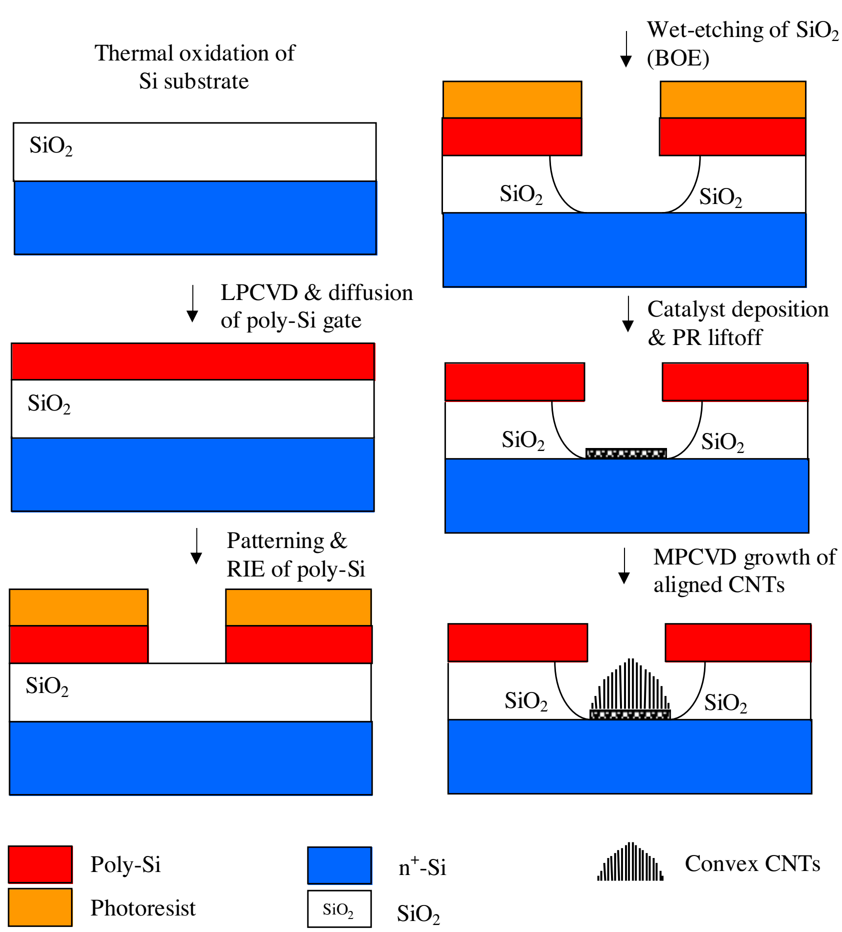

Fig. 1. Schematic diagrams of the single-mask fabrication process for the aligned CNT field emission triode amplifier with a convex-shaped surface profile.