TOWARDS CMOS COMPATIBLE: INTEGRATION OF IN-SITU GROWN INDIVIDUAL VERTICAL CARBON NANOTUBES INTO FIELD EMISSION DEVICES.

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Because of their high aspect ratio, carbon nanotubes (CNTs) are recognized as ideal candidate materials for field emission (FE) applications [1]. The aim of this work was to harness the in-situ growth of individual and vertical CNTs into submicron gated FE devices (**figure 1**) and demonstrate the feasibility of an electron source manufactured on 200mm silicon wafers. This technology will pave the way to maskless lithography; massively parallel electron beams could be generated by an array of CNT electron sources individually driven by embedded CMOS electronics. The main challenges ahead were the development of a CNT growth process compatible with the following requirements: self aligned single CNT gated electron sources, highly selective growth process to avoid parasitic electrical short-circuits and low thermal budget.

A state of the art review of CNT in-situ growth techniques reveals that they do not comply with all these requirements. Contrary to thermal Chemical Vapor Deposition (CVD), Plasma Enhanced CVD (PECVD) is adopted by most of the authors as the growth process enabling vertical orientation of individual CNT, with a suitable reactor configuration, due to field alignment [2,3,4]. Moreover, PECVD appears as the most promising technique for growth at low temperatures. However, vertical alignment of the CNTs is most commonly achieved by direct current (DC) PECVD techniques [2,3], which is known for creating CMOS circuit breakdown by plasma induced arc discharge phenomena. At last, standard PECVD requires a delicate tuning of gas composition to limit the intrinsic formation of a non catalytic carbon layer that may short the device metal layers.

In this respect, an innovative “CMOS friendly” radio-frequency PECVD growth process using a solid carbon source (CS RF-PECVD) was developed during this study [5]. As Tseng et al. [4], an alternative RF plasma source was preferred to overcome the DC drawbacks. Moreover, in order to limit the carbon supply and thus create a very selective growth process with no detrimental parasitic carbon layer, the graphite RF polarized sample holder was used as the unique carbon source, without any additional hydrocarbon feedstock gas. The process was developed on unpatterned Si wafers, with a 3 nm Ni thin film catalyst, deposited on a 60 nm TiN barrier layer. At 560°C, under a pure H_2 atmosphere, the catalyst film is first reduced and splits into nano-droplets by a sintering treatment; then a RF plasma glow discharge is ignited and a forest of vertical carbon tubular structures grows from the catalyst droplets. SEM (**figure 2**) and TEM characterizations evidenced tip growth mode of vertically field aligned carbon nanofibers, as commonly observed with standard PECVD processes. A statistical study enabled us to correlate the height of the tubes to their diameters, directly related to the dimensions of the Ni seed droplets. Furthermore, the low CNTs growth rate achieved (a few $nm.min^{-1}$) allows a very tight control of the height of the tubular structures, which is a key asset for CNT device integration.

In order to integrate ‘CS RF PECVD’ grown individual CNTs into the gated FE devices, the first issue arose from the localization of a less than 100nm diameter Ni dot into each electrons source cavities (**figure 1**). That was readily achieved without e-beam lithography, by means of a lift-off technique commonly used in FE flat panel display, but a lot of work was required to find out a lift-off layer stripping process, that let the Ni nano-dot compatible with the growth of only a single nanotube. In addition, some parameters of the growth process, such as the plasma power and the growth time had to be adjusted to demonstrate the growth of individual CNTs into their cavities with a good reproducibility **(figure 3)**.

Electrical **(figure 4)** and optical characterizations carried out on the individually addressable CNT electron sources pointed out promising results: driving voltage compatible with high voltage CMOS circuits and good angular emission. The key role of the interface between the CNT and the cathode electrode on the electrical contact was evidenced by the test of samples, where the interlayer dielectric was etched by either a dry process or a wet process prior to Ni catalyst deposition. Indeed, no stable measurements or CNT burn out were exhibited on wet etched devices, whereas stable emission characteristics were displayed with a good yield on dry etched devices.

Acknowledgments: This work was supported by the Micro and Nanotechnology Program from French Ministry of research under the grant Basic Technology Research, « maskless nanolithography ».

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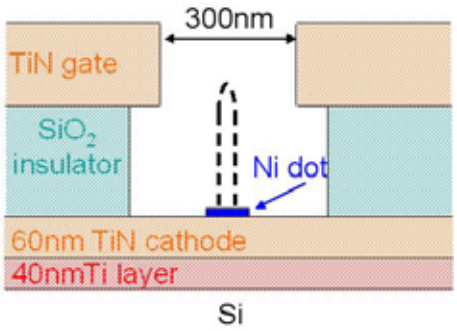

Figure 1: Cross section schematic of the gated FE submicron cavity with a single vertical CNT used as electrons emitter.

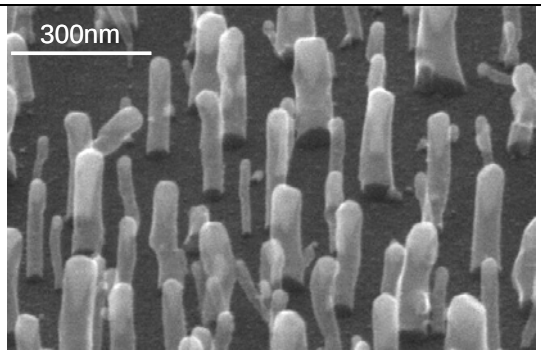

Figure 2: SEM characterization of vertically aligned carbon nanofibers obtained on unpatterned substrate after a 1h growth process under 300W H_2 plasma at 560°C (45° tilted sample).

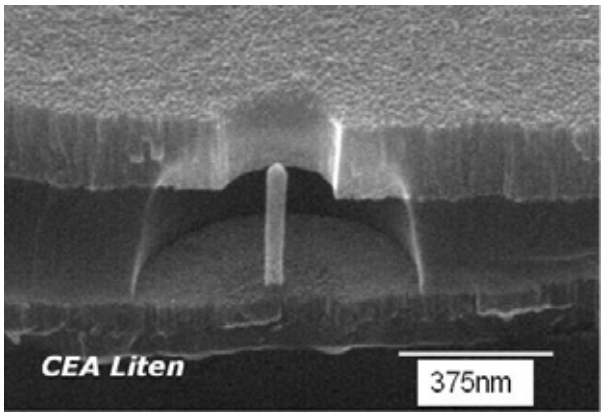

Figure 3: SEM image of a single free standing 45nm diameter CNT in-situ grown in a FE gated cavity by 'CS RF PECVD' growth process (45° tilted sample).

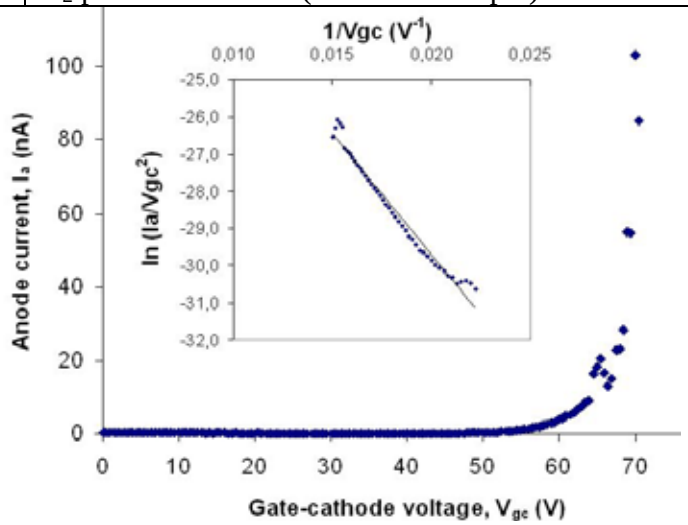

Figure 4: FE measurements obtained from an individual CNT grown in a gated cavity, where the SiO_2 insulator was dry etched. Collected current on the anode (1kV, 3mm distant from the cathode) versus gate-cathode voltage and Fowler-Nordheim plot (inset).