Fe/Ge Catalyzed Carbon Nanotube Growth on HfO$_2$ for Nano-Sensor Applications

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1. Introduction
Carbon nanotubes (CNTs) are gaining much attention for device application, especially bio-sensing [1]. The main advantage of CNTs for this application is a very high sensitivity due to the large surface to volume ratio of a CNT. The use of a high-$k$ dielectric as a gate insulator for a CNTFET is valid because it delivers improved performance due to an increased $I_{on}/I_{off}$ ratio. CNTFETs with a HfO$_2$ gate dielectric have also recently been researched for application in high-speed non-volatile memory [2]. CNTs can be introduced onto HfO$_2$ using dispersion techniques, but CNT growth by CVD would be more compatible with mainstream Si technology. However, CVD growth of CNTs on HfO$_2$ appears to be very difficult and to our knowledge no work has been reported so far.

In this paper, a CNT growth process on HfO$_2$ is reported and this growth process is used to produce back gate CNTFETs with Al source/drain (S/D) contacts. The novel growth process uses a combination of Ge nanoparticles and ferric nitrate dispersion to achieve a dramatic increase in CNT yield compared with the use of ferric nitrate dispersion alone. Electrical measurements on completed CNTFETs show p-FET behavior, an excellent $I_{on}/I_{off}$ ratio of $10^5$, and a steep sub-threshold slope of 130 mV/dec.

![SEM images after CNT growth on HfO$_2$ substrates](image)

Fig. 1. SEM images after CNT growth on HfO$_2$ substrates using (a) Fe nanoparticles only and (b) a combination of Ge and Fe nanoparticles. CNT area densities are 0.15 and 6.2 µm length/µm$^2$ respectively.

2. Experimental
A p'$+$ Si substrate (0.005 Ω·cm) was employed as a back gate and a passivating SiO$_2$ layer was thermally grown, followed by the deposition of a HfO$_2$ layer by atomic-layer deposition. A 30nm SiO$_2$ layer was then deposited by PECVD on top of the HfO$_2$ and densified at 950 °C. The SiO$_2$ layer was then implanted with $5 \times 10^{15}$ cm$^{-2}$, 20 keV Ge and annealed in N$_2$ at 600 °C for 40 min to create Ge nanoparticles. The SiO$_2$ layer was then removed using a HF vapor etch to expose the Ge nanoparticles on top of the HfO$_2$ layer. Then the HfO$_2$ substrate was dipped in ferric nitrate solution for 1 min and rinsed with hexane. The CNT growth was performed using CVD in a hot-wall reactor at atmospheric pressure. CNTs were grown at 850 °C for 20 min using a mixture of methane (1000 sccm) and H$_2$ (300 sccm) immediately after a pre-anneal in H$_2$ (1000 sccm) at 900 °C. For comparison, CNT growth on HfO$_2$ without Ge nanoparticles was also carried out.

Back gate CNTFETs were fabricated with Al S/D contacts. Al was deposited by sputtering and the S/D electrodes were formed using direct write laser lithography and lift-off. The use of Al instead of the more common Pd can both reduce the cost and improve the yield, as Pd has poor adhesion to HfO$_2$. The gap between the S/D electrodes was 2.0 µm and the width was 5.0 µm. After Al patterning, the devices were annealed in H$_2$ at 400 °C for 30 min.

3. Results and Discussion
The Ge nanoparticles were evaluated by means of atomic force microscopy. These results showed a high density of particles (460 ± 30 particles/µm$^2$), with particle

![I-V characteristics of an Al contacted CNTFET](image)

Fig. 2. I-V characteristics of an Al contacted CNTFET with channel length $L_g = 2.0$ µm after H$_2$ anneal. Sub-threshold characteristics for $V_d = -0.1$ and -1.0 V and output characteristics for $V_g = -1.0$, -1.5, -2.0, -2.5 V.
We have developed a novel CNT growth process on HfO₂ using a combination of Ge nanoparticles and ferric nitrate dispersion. The synthesized CNTs were successfully applied to fabricate back gate CNTFETs with Al S/D contacts for application in nano-sensors. The CNTFETs have an excellent on/off current ratio of 10^3 and a steep sub-threshold slope of 130 mV/dec. The sub-threshold characteristics including threshold voltage shift after exposure in air indicate that the CNTFETs are suitable for application as nano-sensors.

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References