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Growth and integration challenges for carbon nanotube interconnects

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ABSTRACT

This paper discusses the current status and the challenges associated with the fabrication of carbon nanotube (CNT) interconnects. This application needs innovative technological solutions for realizing high quality CNT growth at low growth temperatures. In addition, the CNT integration process should be CMOS compatible while at the same time it should preserve the quality of the CNT. We show that the CNT length at low growth temperatures is limited as a result of growth termination. Moreover, the carbon forest population below 500 °C contains predominately multi-walled CNT (MWCNT). We show that generating Ni catalyst particles from a thin film only reaches densities of 10^{12} cm^{-2} on TiN. Under the assumption that each particle yields a CNT, the resulting CNT density is still at least one order of magnitude too low to compete with Cu vias in local interconnects. For DRAM and Flash contacts, one MWCNT per contact hole is sufficient to satisfy the contact resistance requirement set by the ITRS roadmap. In order to protect the CNTs during the integration process, we evaluated different oxide encapsulations of the CNT and its impact on the electrical performance for 150 nm CNT contacts metallized with Cu single damascene top contact. The yield plots show an improved yield and contact resistance when using an additional Al_2O_3 layer to encapsulate the CNT. The comparison of our electrical results with theory indicates there is still room for improvement in CNT quality and contact resistance.

1. Introduction

The ongoing downscaling of the dimensions of the integrated circuit (IC) building blocks forces the semiconductor industry to search for new material combinations and innovative technological solutions in order to satisfy the requirements set for future generations. The fabrication of interconnects is no exception to this trend. The current technologies used to metallize interconnect contacts are facing their limits as the dimensions of the contacts become increasingly smaller. One alternative technology that could meet the requirements set by the ITRS roadmap [1], is a carbon nanotube (CNT) based interconnect.

CNT have unique electrical, thermal, and mechanical properties that make them ideal candidates for future interconnect material [2–4]. A CNT interconnect can consist of a bundle of single-walled or multi-walled CNT. From theoretical calculations, it follows that depending on the interconnect length the electrical resistance of a CNT bundle can compete with Cu for CNT shell densities between 10^{13}–10^{14} shells/cm^2 [5]. Also the current carrying capacity of CNTs is order of magnitudes higher compared to Cu, providing a better resistance towards electromigration [2]. From a technological perspective, CNTs offer an additional advantage as the growth process is truly bottom-up. Therefore no void issues are expected in the fill of the contact hole. However, before CNTs can be used as an interconnect material, a CMOS-compatible process yielding high quality CNTs on metallic substrates has to be demonstrated.

CNT interconnects face several challenges for which innovative technological solutions are needed before this technology can be applied in microelectronics. This paper discusses the growth and integration challenges for CNTs for future generation interconnects. The main challenges are: (1) high quality CNT growth at CMOS compatible growth temperatures, (2) high CNT shell density on metallic substrates, and (3) non-destructive integration of CNTs in contacts using processes commonly used in a CMOS fab. We will discuss each of these technological challenges in more detail and place them in a realistic perspective.

2. Experimental

The blanket CNT growth studies were carried out using a 70 nm TiN on 200 mm Si wafers. The catalyst film (Ni or Co), was sput-

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tered without breaking the vacuum after the deposition of TiN. The film thickness was measured with Rutherford backscattering spectroscopy (RBS). CNTs were grown with remote-plasma (microwave) enhanced CVD using a two-step recipe. First, the film was transformed into particles using a 200/1000 sccm H_2/Ar plasma at 470 °C (1 kW, 3 Torr). In the second step, a carbon precursor gas was added (12 sccm C_2H_2 or C_2H_4) to the gas flow. The growth and integration of CNT in 150 nm holes was done using the same procedure as described in [6].

3. Results and discussion

One of the main challenges for CNT interconnect technology is the fabrication of high quality CNT at a low process temperature (<400 °C). Typically, when lowering the growth temperature, the CNT growth rate decreases. Fig. 1a shows the length of the CNT forest grown at 470 °C as a function of time for both Ni and Co catalysts. Although the Ni and Co nanoparticles have the same size and density, the CNT growth is different for both cases. For Ni catalyzed CNT growth, the CNTs grow faster compared to Co in the initial stage of growth. In contrast, termination of CNT growth occurs earlier for Ni, resulting in longer CNT for Co at extended growth times. Fig. 1b shows the CNT length after 30 min of growth (at or close to termination) as a function of temperature. Lowering the substrate temperature decreases the CNT length. Interestingly, there is a cross-over in CNT length between Ni and Co at 460 °C, as the decrease in CNT length with temperature is steeper for Co than for Ni. The decrease in CNT length is mainly due to a faster termination process rather than a decrease in growth kinetics as the initial growth rate doesn't change significantly in the inspected regime. This is in agreement with the low activation energies reported for plasma enhanced CNT growth in literature [7]. The early termination of CNT growth at lower temperatures imposes a limit to the length of a CNT bundle. This has an impact for CNT interconnect applications that require long CNTs, such as Through-Silicon-via (TSV) technology [8]. Here, long CNTs (∼50 μm) grown at low temperatures are needed. Therefore, preventing the termination of growth at lower temperatures remains a challenge for TSV.

The quality of the CNTs grown at these low temperatures is important as it determines the electron transport through the tube. In case of defective CNT shells, additional electron scattering events occur lowering the conductivity of the tube. Fig. 2 shows the graphitization of different CNT/CNF grown at 470 °C. Within the same CNT forest, high quality MWCNT (see Fig. 2a), but also defective MWCNT and bamboo-like tubes are found (see Fig. 2b and c). The ratio between CNT and bamboo-like tubes depends greatly on gas conditions and shifts in favor of fibers at lower growth temperature with close to 100% bamboo-like tubes at 400 °C.

Apart from the CNT quality, also the total number of conducting shells will determine the resistance of the CNT bundle. In the case of ballistic transport, each conducting shell contributes a quantized amount (i.e. quantum conductivity) to the conductivity of the bundle. Therefore, for a low bundle resistance a high shell density is required. Typically, about 10^{13}–10^{14} shells cm^{-2} are needed to compete with Cu. The quest for high CNT shell densities has been typically linked to the search for closely packed catalyst particles. This stems from the fact that in an ideal yield situation, there is a one-to-one relation between the number of CNTs and the number of catalyst nanoparticles. A commonly used technique to form catalytic nanoparticles is by breaking up a sputtered thin film upon thermal anneal [3]. Fig. 3 shows the density of Ni nanoparticles on a TiN substrate as a function of deposited film thickness. The particle density increases with decreasing film thickness. The thinnest film of 0.7 nm yields a particle density of 7.5×10^{11} cm^{-2} with average particle size close to 6 nm. The number of shells is then estimated to be five, based on the empirical correlation between MWCNT diameter d (in nm) and the number of CNT shells N_{shell} [10]:

$$N_{shell} \approx d - 1 \tag{1}$$

Together with the assumption that all particles yield a MWCNT, the maximum obtained shell density is estimated to be 4×10^{12} cm^{-2} in this case. Previously, Yamazaki et al. [11] reported a similar CNT packing density on TiN around 1×10^{12} cm^{-2} with an average diameter around 6 nm. This is still at least one order of magnitude too low (for CNT with ideal resistance) to compete with copper vias at the local interconnect level. Particle densities up to 10^{13} cm^{-2} have been demonstrated in literature, however on oxides rendering them inappropriate for interconnect technologies [12]. The difficulty to obtain high CNT densities on conductive substrates currently imposes a constraint to the application of CNT as interconnects.

Yet, not all interconnects require closely-packed CNT bundles. For example, at the contact level for DRAM and Flash technology, the contact diameter will decrease below 10 nm while aspect ratios (AR) above 50 are expected for future generations [1]. For these applications, a shell density of one MWCNT per contact hole will suffice, as illustrated in Fig. 4. The minimum number of conducting CNT shells to achieve the contact conductivity requirement

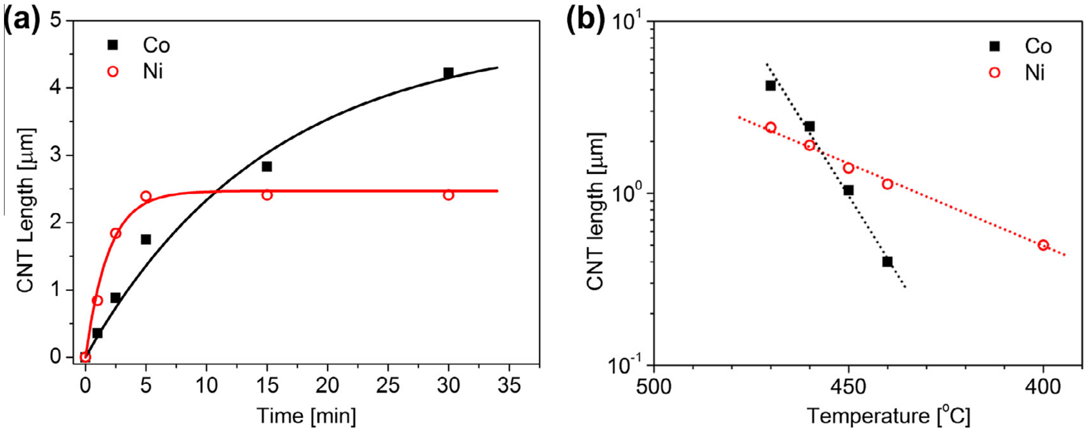

Fig. 1. (a) CNT length as a function of growth time from Ni and Co nanoparticles (particle density ∼4×10^{11} cm^{-2}, particle size ∼7 nm) using 12/84 sccm C_2H_2/H_2 mixture diluted with 1000 sccm Ar at 470 °C. The experimental data are fitted according to an empirical equation used by Futaba et al. [9]. (b) CNT length after 30 min as a function of growth temperature for Ni and Co catalysts.