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Carbon nanotube technologies for future ULSI via interconnects

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1. Introduction

Carbon nanotubes (CNTs) [1] offer unique electrical properties such as highest current density exceeding 10^9 A/cm^2 [2], ultra-high thermal conductivity as high as that of diamond [3], ballistic transport along the tube [4] and an extremely high Young's modulus. Because of these remarkable properties, they have been expected for use as future wiring materials to solve the problems of stress and electro-migration [5-7] and heat removal in future ULSIs. In this paper, we demonstrate present status of CNT material technologies and the potential of metallic CNT vias for future ULSI wiring (Fig. 1)**.**

2. Results and discussions

In order to introduce CNTs to Si ULSIs for exploiting their excellent features, it is needed to lower the growth temperature about 400ºC, and control the position, direction, length and density of CNTs. One of the most probable ways to realize them should be a hot-filament CVD (HF-CVD) technology (Fig. 2(a)). In our HF-CVD system, a mixture of C_2H_2, Ar and H_2 was used as the gas source. The pressure of the CVD chamber was set to 1 kPa. We succeeded in growing vertically aligned multi-walled nanotubes (MWNTs) on an 8-inch silicon wafer (Fig. 2(b)) We also obtained MWNTs with an outer diameter of about 10 nm with well-graphitized graphen sheets using Co catalysts on Ti contact layers at 450ºC (Fig. 2(c)).

Fig. 3(a, b) shows SEM photographs and a schematic of CNT via-chains [8]. Almost vertically aligned carbon nanotubes are selectively grown in via holes. We fabricated test samples of 1000 via-chains. The diameter of via was 2 μm and the depth was 350 nm. The fabricated substrate consists of a Cu layer, a Ta barrier layer, a Ti contact layer, a Ni or Co catalyst layer, and a SiO_2 dielectric layer. Fig. 3(c) shows the total resistance of one via consisting of about 1000 tubes. The lowest resistance reaches about 5 ohm. This is still one order of magnitude higher than for a via filled with tungsten and two orders of magnitude higher than for Cu. So, it is important to produce nanotubes at a greater density and smaller diameter.

At present, the density of the nanotubes is about 10^{10}/cm^2, so we are going to try using a catalytic nano-particle technique [9] to increase the density to 10^{12} /cm^2 [8]. Because of the lower growth temperature of HF-CVD, we expect that the catalytic nano-particles will not coalesce on the substrate during CNT growth (Fig. 4(a)). Fig. 4(b) shows a diagram of our particle generation and deposition system. The nano-particles were generated by laser ablation, classified with a differential mobility analyzer, and deposited onto Si substrate. The particle size is tunable down to 2-3 nm, and particles with a mean diameter of 5.1 nm (standard deviation: 1.1) were used for MWNT growth. We confirmed that the particles did not coalesce during growth even at 550°C, and the MWNTs have outer diameters matching the particle sizes, indicating that this method can produce diameter-controlled MWNTs [9].

We also need to flatten the surface after CNT growth. We used mechanical polishing to control the length of CNTs. The CNTs were mechanically cut by polishing with diamond slurry (Figs. 6) [10].

3. Summary

We have demonstrated the feasibility of metallic carbon-nanotube vias as a future wiring technology. We presented the latest results on control of the CNT position, direction, and length by means of CVD and process technology. Although the density of CNTs needs to be increased and the growth temperature needs to be decreased at least 50°C, our results are very promising for fabricating CNT vias with a low resistance and a large tolerance to migration. We intend to introduce a catalytic nano-particle technique to solve these problems. If we solve them, it is not beyond the realms of possibility that CNTs are introduced in Si ULSIs as a new material.

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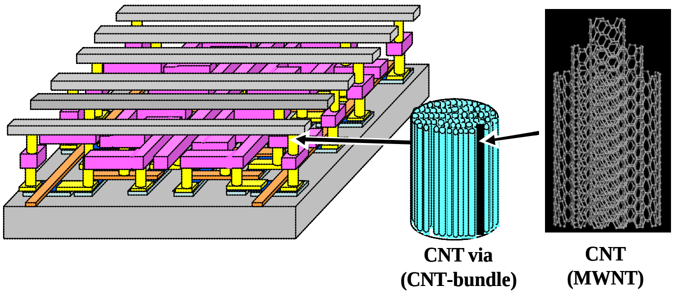
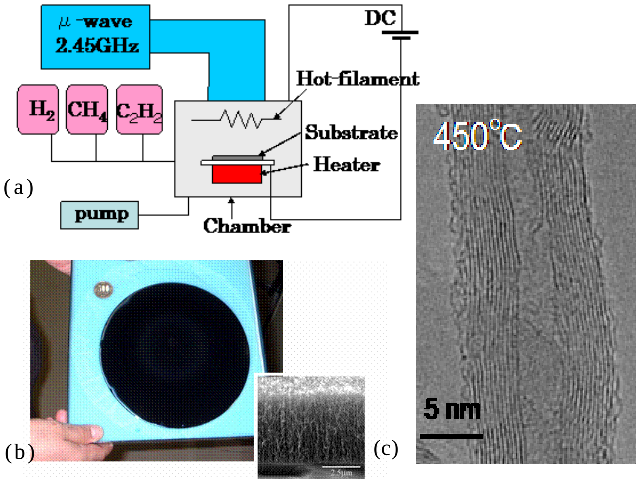
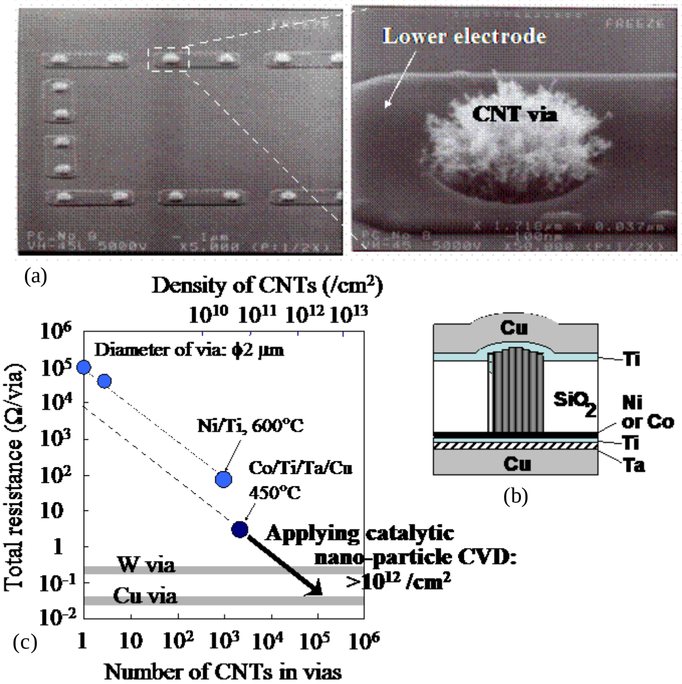


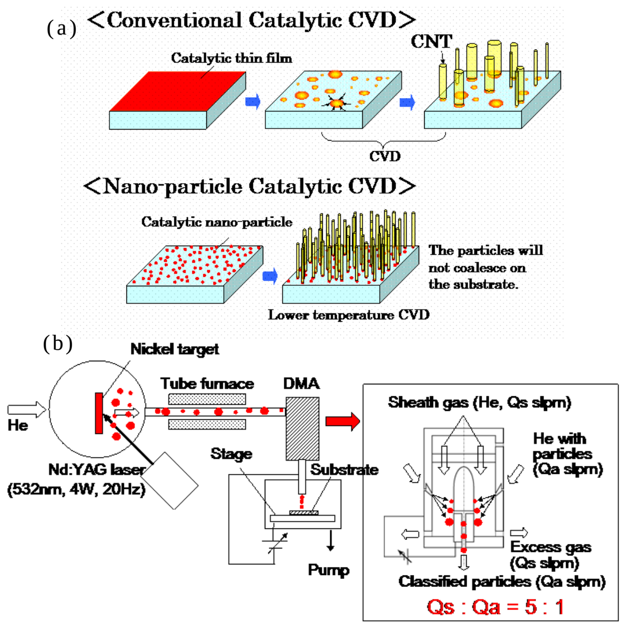
Fig. 1 Schematic of future LSI interconnects consisting of CNT vias



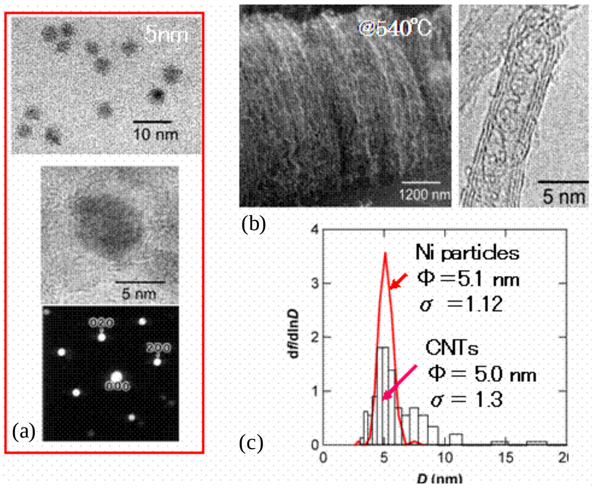
Figs. 2 (a) Schematic of our multi-mode CVD system, (b) MWNTs grown by the HF-CVD on 8-inch Si wafer at 540°C using Ni catalyst thin film, and (c) TEM images of MWNTs grown by the HF-CVD at 450°C using Co catalyst thin film



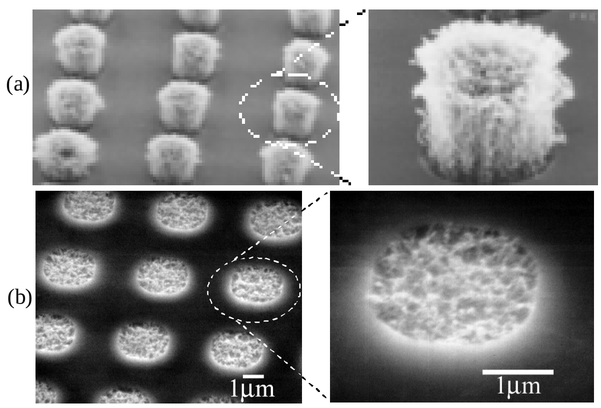
Figs. 3 SEM images (a) and schematic (b) of CNT-via structure, and total resistance of CNT-via with a diameter of 2μm



Figs. 4 Schematic of nano-particle catalytic CVD and our particle generation and deposition system



Figs. 5 (a) TEM images and electron diffraction pattern of size-classified Co nano-particles, (b) SEM and TEM images of MWNTs using the nano-particle catalysis CVD and (c) the distributions of catalytic particle and CNT diameters



Figs. 6 SEM images of CNTs via just after CVD growth (a) and those of CNT vias cut by mechanical polishing (b)