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Simultaneous formation of multi-wall carbon nanotubes and their low-resistance ohmic contacts for future ULSI via interconnects

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Abstract

As a bottom-up fabrication process for future ULSI interconnects, we have developed vertical growth of multi-wall carbon nanotubes (MWNTs) on titanium electrodes and simultaneous formation of their end-bonded ohmic contacts. We believe this is the first report of such simultaneous formation of MWNTs and end-bonded ohmic contacts with a contact resistance two orders of magnitude smaller than the current method.

1. Introduction

Carbon nanotubes (CNTs) [1] are attractive as nano-size bricks to construct devices by bottom-up fabrication. They offer unique electrical properties such as one-dimensional electrical behavior, quantum conductance, and ballistic transport characteristics allowing the passage of a huge electrical current density exceeding 10^9 A/cm^2 [2]. Therefore, they have been suggested for use as future wiring materials [3]. Even with current device dimension limitations, ultra-large-scale integrated (ULSI) semiconductor circuits have problems originating from stress and electro-migration of Cu interconnects. One problem is the existence of an open circuit of vertical Cu vias. One potentially effective solution to this problem is to use wiring materials with a large migration tolerance as vias. Therefore, we would like to use bundles of CNTs as vias. Figure 1 shows a schematic for CNT vias between Cu layers. We have already demonstrated vertically embedded CNTs in via holes [4, 5]. Forming low-resistance ohmic contacts between CNTs and metal electrodes is important for exploiting the superior features of CNTs. Generally, for this purpose, the ends of CNTs are covered with a titanium electrode and then titanium carbide (TiC) ohmic contacts are formed by annealing [6]. However, fabricating the CNT and ohmic contact to the bottom electrode simultaneously is preferable for a vertically embedded CNT structure, such as CNT bundles in via holes. To realize this requirement, we achieved simultaneous formation of CNTs and end-bonded TiC ohmic contacts.

2. Experimental

For simplicity, we grew MWNTs bridging 5-μm spaces between metal electrodes as shown in Figure 2. The metal electrodes on SiN/Si substrates were deposited by the lift-off process using photo-resist and electron beam evaporation. We compared nickel (10 nm)/titanium (100 nm) double-layer electrodes (nickel catalyst layer on titanium electrode) and nickel electrodes (100 nm) without titanium layer. Here, the nickel is a catalyst for MWNT growth. By using these samples, the MWNTs were grown by hot-filament chemical vapor deposition (HF-CVD). A mixture of C_2H_2, Ar and H_2 was used as the gas source. The substrate temperature during MWNT growth was 600ºC. The pressure of the CVD chamber was set to 1 kPa. The MWNT growth period was 1 minute. After the growth, two-terminal current-voltage measurement was performed for one nanotube bridging nickel/titanium electrodes, three nanotubes bridging nickel/titanium electrodes, and for comparison, one nanotube bridging nickel electrodes.

3. Results and Discussion

Figure 3 shows the results of the two-terminal current-voltage measurements. The sample with nickel electrodes without titanium and with one nanotube bridge exhibited a large resistance of 15–32 MΩ. This is due to the large contact resistance at the nanotube/electrode interface. On the other hand, the sample with nickel/titanium electrodes and one nanotube bridge exhibited a considerably smaller resistance of 134 kΩ than that of the sample with nickel electrodes. To check this result, we measured nickel/titanium electrodes with three nanotube bridges and obtained a resistance of 54 kΩ, which is about 30% compared to a one nanotube bridge, as expected. Consequently, we would like to emphasize that the contact resistance of the sample with nickel/titanium electrodes is two orders of magnitude smaller than that of the sample with nickel electrodes.

Figure 4 shows a cross-section scanning electron microscopy (SEM) image of the nanotubes/nickel/titanium electrode interface, and a transmission electron microscopy (TEM) image of the end of nanotubes. We estimate the MWNT diameter to be about 30 nm. We found nickel nano-clusters with a diameter of about 10 nm formed on the surface of the titanium electrodes; MWNTs with nickel nano-clusters inside the ends of the nanotubes were grown vertically on the titanium electrodes. From these observations, we propose a model for the simultaneous formation of MWNTs and end-bonded ohmic contacts. Although we could not certainly confirm TiC at the ends of

MWNTs by TEM and energy dispersive X-ray spectroscopy (EDX), our electrical measurement results suggest that low-resistance ohmic contact was achieved by TiC formation at the ends of MWNTs during growth. Figure 5 shows SEM image of CNT vias. We have succeeded to grow bundles of MWNTs in via arrays by using our method.

4. Conclusions

We have successfully formed MWNTs and end-bonded TiC ohmic contacts to titanium electrodes simultaneously by using HF-CVD. This result will enable us to fabricate CNT vias with a low resistance and a large resistance to electro-migration for future ULSI interconnects.

Acknowledgements

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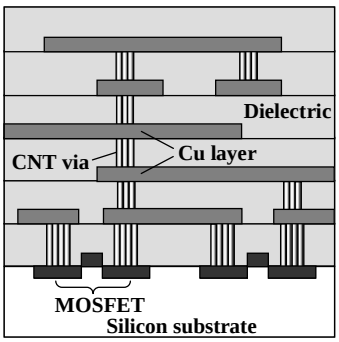

Fig. 1. Schematic of CNT vias for future ULSI interconnects.

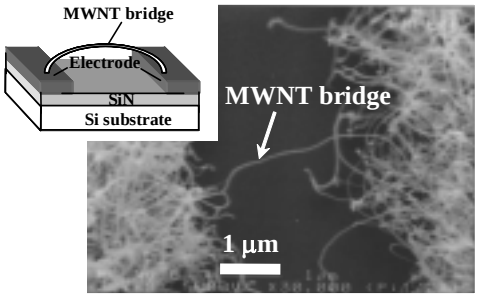

Fig. 2. MWNTs bridging 5-μm spaces between metal electrodes.

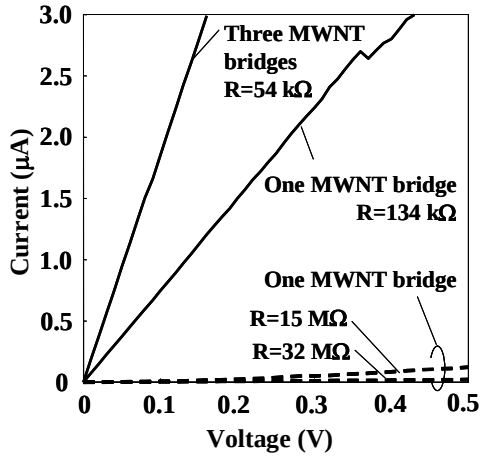

Fig. 3. Two-terminal I-V characteristics. (a) Solid line: Ni/Ti electrodes, (b) Dotted line: Ni electrodes without Ti.

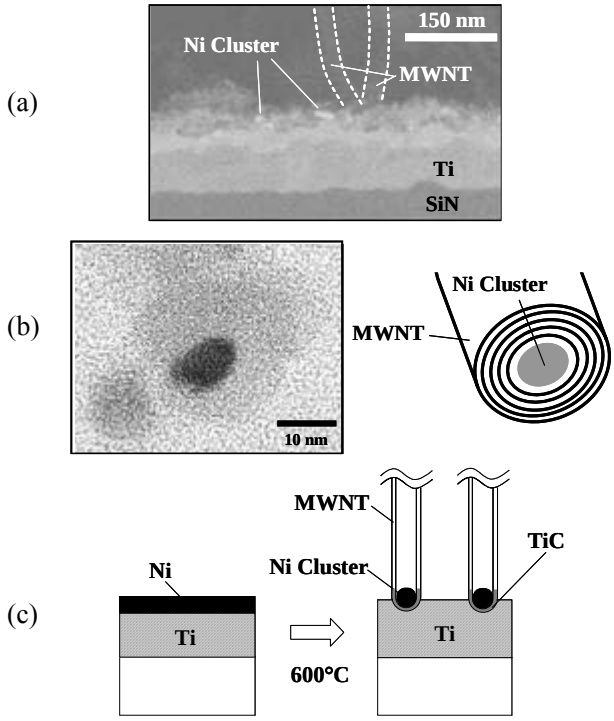

Fig. 4. (a) Cross-section SEM image of MWNTs/Ni/Ti electrode interface, (b) TEM image of end of MWNTs, and (c) model of simultaneous formation of MWNTs and end-bonded ohmic contacts.

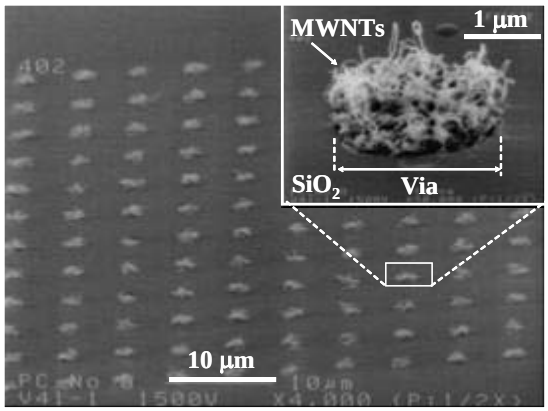

Fig. 5. SEM image of bundles of MWNTs grown in via arrays.