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In-flight coating of multi-walled carbon nanotubes

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ABSTRACT

The coating of multi-walled carbon nanotubes (MWCNTs) with TiO_x and SiO_x films was demonstrated by combining MWCNT aerosolization and plasma-enhanced chemical vapor deposition. A uniform coating on the entire MWCNT surface was achieved through isotropic transport of the coating materials onto the aerosolized MWCNTs. The coating layers had different morphologies depending on the composition of the coating materials, likely due to the different wetting properties of the coating materials on the MWCNT graphite structure.

1. Introduction

Coating carbon nanotubes (CNTs) with other nanomaterials results in materials possessing the inherent characteristics of both components, as well as integrated properties, such as electronic and optical properties and catalytic activity, that are derived from specific interactions between the CNTs and the nanomaterials [1]. For example, the catalytic antibacterial activity of TiO_2/multi-walled CNTs (MWCNTs) against *Escherichia coli* bacteria under visible light irradiation was not observed for pure anatase TiO_2 or MWCNTs [2]. The TiO_2/MWCNT heterojunction of the crystalline coating with Ti–C or Ti–O–C bonds induced this activity, as an amorphous TiO_2 coating showed significantly lower activity. The size of the coating material is important for applications. An optimum nanoparticles size was observed for incident photon-to-current efficiency in Cu nanoparticle-decorated MWCNTs [3].

Hybridization of CNTs is carried out using liquid- or gas-phase processes. Two distinct approaches are used in both phases: attachment of pre-synthesized nanoparticles or direct formation of nanomaterial films on the CNT surface. In the liquid phase, the CNT surface should be functionalized to obtain efficient dispersion in the solvent and create functional groups that act as anchors for other materials. The nanomaterials coat the entire CNT surface because the coating agents are fed from all directions onto the dispersed CNTs [4]. However, the chemical treatment of CNTs increases the number of process steps and tends to damage the CNT structure. There are also concerns about contamination and waste when coating CNTs in the liquid phase.

Compared with liquid-phase processes, coating CNTs in the gas phase is simpler and more environmentally friendly because pristine CNTs are used without any chemical treatment. Deposition of nanoparticles, which were generated in the gas phase by an evaporation-condensation method [5], chemical vapor deposition (CVD) [6], or electrospray technique [7], yielded nanoparticle-decorated CNTs. Direct thin film coating of CNTs was also attempted by atomic layer deposition (ALD) [8]. However, these methods resulted in poor uniformity of the coating on the CNT surface. A uniform coating is preferred for effective electron and heat conduction from the coating materials to the CNTs. In previous studies, CNTs were fixed onto a

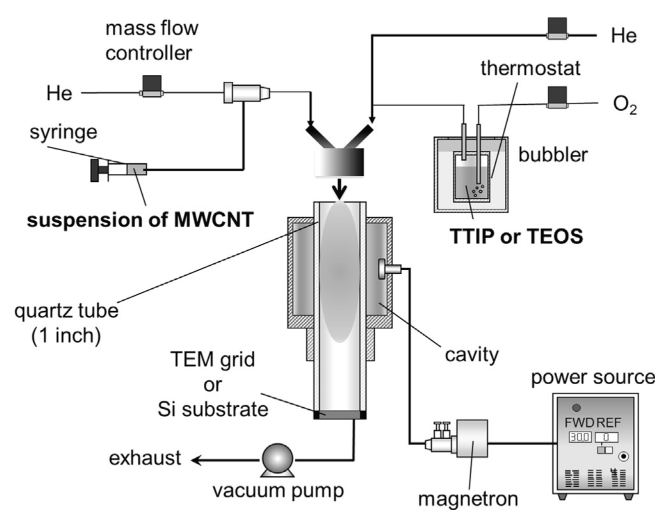

Fig. 1. Schematic of the experimental setup.

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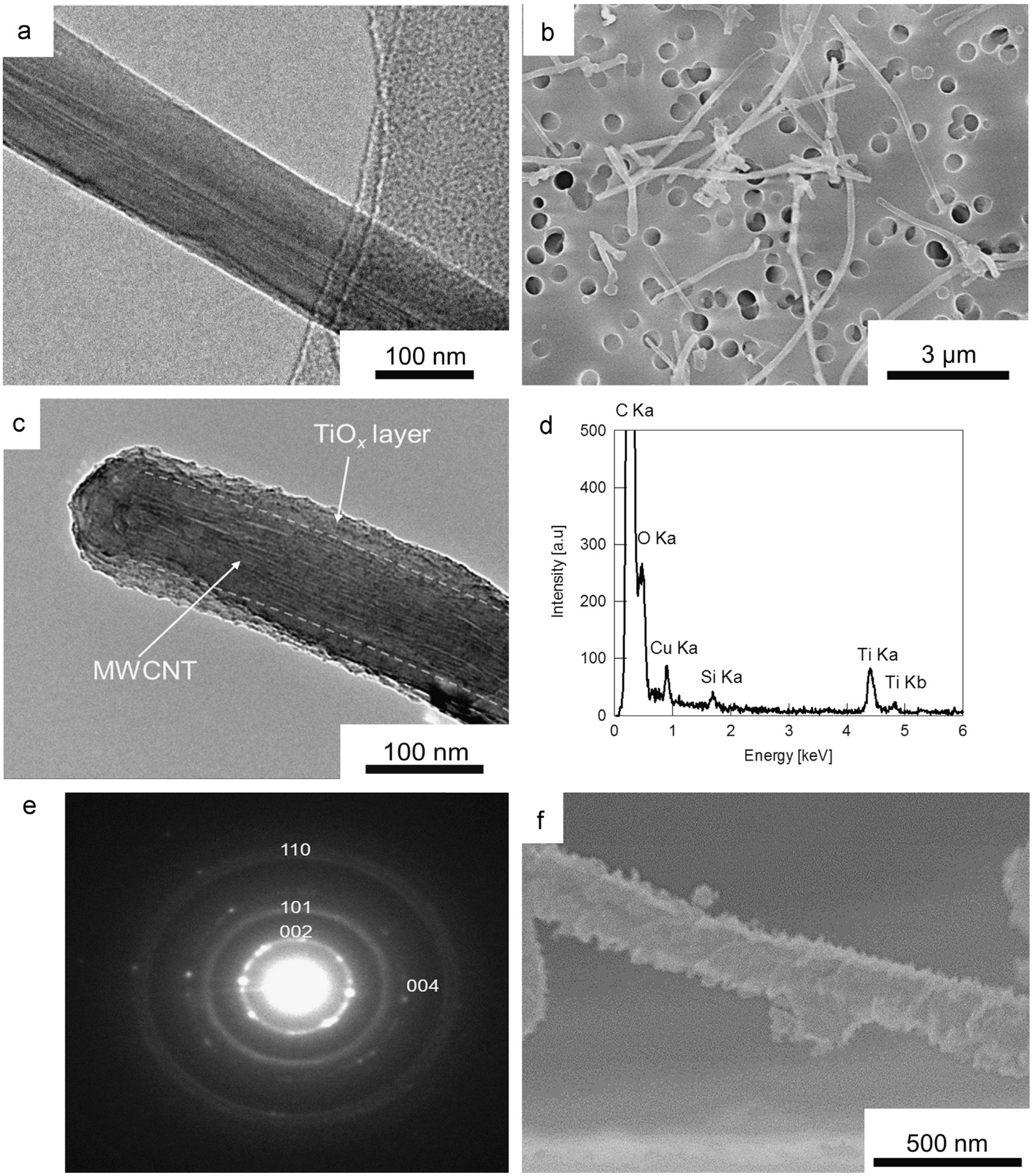

Fig. 2. (a) TEM and (b) SEM images of pristine MWCNTs; (c) TEM image, (d) EDS spectrum, and (e) SAED pattern of a TiO_x-coated MWCNT; (f) SEM image of the side view of a coated MWCNT collected on the Si substrate.

substrate for coating in the gas phase, which induced a concentration gradient of nanoparticles or precursors between the top and bottom of the fixed CNTs. This anisotropic transport of coating materials onto the CNTs caused non-uniform coatings on the CNTs.

CNT aerosolization is considered a possible solution for achieving isotropic transport of coating materials onto the CNTs, as all surfaces of the aerosolized CNTs are exposed. Mixing aerosolized MWCNTs and Ag nanoparticles was reported to result in uniform decoration of Ag nanoparticles onto MWCNTs [9]. However, thin film coatings on CNTs have not been previously achieved. In this study, we prepared thin metal oxide films on aerosolized MWCNTs by combining MWCNT aerosolization and plasma-enhanced CVD (PECVD).

2. Materials and methods

Preparation of MWCNT suspension: MWCNTs (Aldrich) were dispersed in deionized water with Triton-X (TCI Co. Ltd.) as a dispersing agent. The suspension of 0.1 mg/mL MWCNTs and