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Plasma Processing for Carbon Nanomaterials. Syntheses of Nanostructures and Their Process Control by Numerical Simulation of Plasma

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SUMMARY

Plasma is a useful tool to synthesize carbon nanomaterials, including diamonds, fullerenes, nanotubes, and graphenes. This review gives an overview of these carbon nanomaterials produced by thermal or nonthermal plasmas and of the authors' work related to plasma-enhanced chemical vapor deposition of carbon nanotubes, along with an analysis and numerical simulation of CH_4/H_2 feedstock gas plasmas. The amount of carbon atoms in the grown carbon nanotubes and that calculated by simulation showed good agreement. © 2013 Wiley Periodicals, Inc. Electron Comm Jpn, 96(6): 1–8, 2013; Published online in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/ecj.11504

Key words: plasma-enhanced chemical vapor deposition (PECVD); carbon nanotube (CNT); catalyst; numerical simulation; chemically active species (radical species); flux.

1. Carbon Nanomaterials

1.1 Classification of carbon nanomaterials

The carbon atom contains four unpaired electrons and can have three types of hybrid orbitals: sp^1, sp^2, and sp^3 [1]. Therefore, there are various types of carbon allotropes. Carbyne, with sp^1 bonds, graphite, with sp^2 bonds, and diamond, with sp^3 bonds, are naturally produced [2]. As electron microscopy technique has developed, new carbon allotropes with nanometer-scale structure have been discovered since the 1980s. They are called carbon nanomaterials, referring to their size. In this paper, we select some carbon allotropes and describe their characteristics and the techniques of their synthesis by plasma processing. We have studied plasma-enhanced chemical vapor deposition (PECVD) of carbon nanotubes (CNTs) and the prediction of CNT growth by plasma simulation. Experimental and simulation results are introduced.

1.2 Diamond

Diamond has the highest hardness, Young's modulus, and thermal conductivity of all materials on the earth. The optical transparency of diamond is also high. Taking advantage of these attractive properties, diamond has been regarded as promising for applications in industrial fields, and artificial synthesis methods have been studied for many years. Spitsyn and colleagues in 1981 [3] and Matsumoto and colleagues in 1982 [4] successfully synthesized diamond on a nondiamond substrate in a vapor phase. In the vapor-phase synthesis of diamond, plasma makes a great contribution to the generation of hydrocarbon radicals and atomic hydrogen.

1.3 Fullerene

Fullerene has a spherical shell structure of several tens of carbon atoms, and its shell is composed of five-membered and six-membered rings of carbon atoms. In 1985, Kroto and colleagues synthesized a fullerene with 60 carbon atoms (C_{60}) by laser ablation; this was the discovery of fullerene [5]. Laser ablation is a phenomenon in which atoms and molecules near a solid target are explosively

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