Carbon-Nanotube Growth in Alcohol-Vapor Plasma
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Abstract—We have successfully grown carbon nanotubes (CNTs) by plasma-enhanced chemical vapor deposition (PECVD) using alcohol. When 0.01-wt% ferrocene was added to the alcohol, vertically aligned CNTs grew at 650 °C. By contrast, a few CNTs and mostly carbon nanoparticles were obtained by pure alcohol PECVD even though the Fe catalyst was coated on Si substrates. Comparing this PECVD experiment with thermal alcohol CVD showed that only the PECVD method can be used to grow CNTs under the reported experimental conditions. To understand the plasma properties for CNT growth, particularly plasma species contained in a gas phase of alcohol plasma, the plasma was analyzed using optical-emission spectroscopy (OES) and quadrupole mass spectrometry (QMS). From the OES measurement, emission peaks from the excitation states of C₂, CH, CHO, CH₂O, CO, H₂O, C⁺, and CO⁺ were identified, while the QMS measurement also showed the existence of H₂, O, and CO. These results indicate that, in alcohol plasma, oxidants and reductants exist together and potentially promote/suppress CNT growth depending on the process conditions. The contribution of C₅Hₓ (x ≥ 1, y ≥ 3) radicals, which were produced by decomposition reactions in alcohol plasma as a CNT precursor, is discussed.

Index Terms—Carbon nanotube (CNT), ferrocene, mass spectrometry, optical-emission spectroscopy (OES), plasma-enhanced chemical vapor deposition (PECVD).

I. INTRODUCTION

CARBON nanotubes (CNTs) have attracted significant interest due to their unique properties, e.g., high chemical stability, mechanical strength, and current density. Based on these properties, our group has focused on the application of CNTs as nanoscale interconnections in large-scale integrated (LSI) circuits [1], [2]. Plasma-enhanced chemical vapor deposition (PECVD) is superior to other techniques including arc discharge, laser ablation, and CVD for the low-temperature operation of CNT growth (~390 °C). The PECVD approach meets the condition for the LSI fabrication process (≤ 400 °C)

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup for alcohol PECVD. The details of the experimental setup and CNT growth procedure are described in earlier reports [7]–[9]. The ribbon heater was equipped to provide a stable alcohol-vapor feed. To compare CNT growth, pure C₂H₅OH and C₂H₅OH containing 0.01-wt% ferrocene (C₁₀H₅Fe) were used. We prepared the catalyst/support materials on a Si substrate using the electron-beam (EB)-evaporation approach. The substrates used were Si...
wafers with a 20-nm-thick SiO₂ layer. In the EB evaporation, the Fe (catalyst) and Al₂O₃ (support) were deposited on the substrates to form sandwichlike structures (Al₂O₃/Fe/Al₂O₃ = 1/1/1 nm), which can then form small nanoparticles [9], [14]. The pretreatment and growth conditions including pressure, power, process temperature, and process time are listed in Table I.

The procedure of CNT growth is briefly described. First, substrates with catalyst and support materials were set on the center of the grounded electrode. The reactor was pumped down to below \(10^{-4}\) Pa. Using an infrared heater, the substrates were heated and kept at 550 °C in 666-Pa H₂ plasma for 4 min. The H₂ gas was removed, and C₂H₅OH (water content \(\leq 0.2\%\), with/without 0.01-wt% ferrocene) was introduced. The pressure was maintained at 133 Pa, while the temperature was maintained at 650 °C for 10 min. During CNT growth by PECVD, plasma optical-emission spectra were acquired using a photonic multichannel analyzer (PMA: Hamamatsu Photonics K.K., PMA-11) in the wavelength range of 300–800 nm. A quadrupole mass spectrometer (QMS: ANELVA, M-QA200TS) was used to analyze the plasma species. The QMS tube was connected with the PECVD chamber through a 50-cm-long 1/8-in-diameter stainless-steel pipe and a variable leak valve. Pressure inside the QMS tube was carefully controlled by the valve, and the QMS spectra of CH₄/H₂ gas with/without plasma were evaluated. The CNTs obtained were characterized using a scanning electron microscope (SEM: Hitachi High-Technologies Corporation, S-4800) and a transmission electron microscope (TEM: JEOL, 2000FX).

III. RESULTS AND DISCUSSION

Fig. 2 shows the CNT growth results obtained using C₂H₅OH plasma. The substrate with Al₂O₃/Fe/Al₂O₃ showed CNT growth over the whole substrate area, resulting in a high production yield of CNTs. The effect of adding ferrocene can be clearly seen. As shown in Fig. 2(b2), vertically aligned CNTs were obtained when ferrocene was added, although Fig. 2(b1) and (b2) revealed that CNT growth occurred over the whole substrate area. To confirm the effect of the Al₂O₃/Fe/Al₂O₃ catalysts, we observed the CNT deposition on a Si substrate. Without catalyst, no CNTs were obtained on a Si substrate even though ferrocene was supplied with the alcohol. This clearly indicated that a carbon source containing a ferrocene molecule can be activated on the catalyst surface and used to grow CNTs. Eres et al. [15] used a substrate that was catalyzed using a Mo/Fe/Al multilayer and found that the introduction of ferrocene into the acetylene-gas stream enhanced the growth of vertically aligned CNTs. In addition, CNT growth has been achieved using ferrocene-containing ethanol solutions in spray pyrolysis [12] and inductively coupled plasma [13] techniques. However, the concentrations of ferrocene in these reports (i.e., 1000 mg/100–800 mL by Su et al. [12] and 5 mg/10 mL by Xu et al. [13]) are higher than the levels used in our experiment (8 mg/100 mL). TEM analysis showed the effect of the addition of ferrocene (Fig. 3). In the absence of ferrocene, a large...
number of carbon nanoparticles and nanocapsules were formed on the Al$_2$O$_3$/Fe/Al$_2$O$_3$-catalyzed substrate. By contrast, a bundle structure composed of CNTs with a diameter of $\sim$5 nm was formed by the ferrocene-assisted reaction.

To ensure the effect of plasma, we confirmed that no CNTs were obtained at a substrate temperature of 650 $^\circ$C without plasma. Chiashi et al. [16] who performed single-walled CNT (SWCNT) growth in a cold-wall CVD reported that the effective reaction temperature of alcohol CVD was estimated to be slightly higher than 850 $^\circ$C, whereas a low-temperature reaction caused the generation of amorphous carbon.

Fig. 4 shows the OES spectra obtained using a 133-Pa C$_2$H$_5$OH plasma. The measurements were performed at room temperature to avoid the detection of light from the heating system. As a result of this OES measurement, optical peaks from C$_2$, CH, CHO, CH$_2$O, CO, H$_2$ (H atom in the Balmer series), O$_2$, C$^+$, and CO$^+$ were identified. Fig. 5(a) shows the QMS result obtained using a 133-Pa C$_2$H$_5$OH plasma. From the QMS analysis, peaks corresponding to each molecular weight were observed: H$_2$ (between 1 and 3), CH$_4$ (between 12 and 18), CH$_3$OH (between 24 and 31), and C$_2$H$_5$OH (between 38 and 46). Since the ionization process of particles by electron collision is absolutely necessary for QMS detection, the decomposition of the C$_2$H$_5$OH molecule occurs. We measured the QMS peaks obtained in the 133-Pa C$_2$H$_5$OH atmosphere [without plasma, Fig. 5(b)]. Fig. 5(c) shows the subtraction of the spectral intensity of plasma-off [Fig. 5(b)] from that of plasma-on [Fig. 5(a)]. The result indicates that the peaks of C$_2$H$_5$OH-derived molecules (CH$_4$, CH$_3$OH, and C$_2$H$_5$OH) decreased by igniting the plasma. This shows that the decomposition of C$_2$H$_5$OH is promoted by generating plasma. By contrast, the species of H$_2$, O, CO, and C$_2$H$_4$ (atomic/molecular weight = 2, 16, 28, and 28, respectively) increased by the recombination/dissociation processes. These results reflect the observation that plasma processes can promote the production of several species by plasma reactions.

In this paper, we discuss the decomposition/dissociation reactions of C$_2$H$_5$OH plasma. Several groups [17]–[21] have reported the chemical-reaction processes of C$_2$H$_5$OH plasma.

\begin{align}
C_2H_5OH &\rightarrow C + CO + 3H_2 \quad (1) \\
C_2H_5OH + 3H_2O &\rightarrow 2CO_2 + 6H_2 \quad (2) \\
C_2H_5OH + H_2O &\rightarrow 2CO + 4H_2 \quad (3) \\
C_2H_5OH &\rightarrow C_2H_4 + H_2O \quad (4) \\
C_2H_5OH &\rightarrow C_2H_5 + OH. \quad (5)
\end{align}

Reaction (1) is a collision-impact process between electrons and radicals in plasma [17] as well as a typical reaction occurring on a catalyst surface for CNTs growth by nonplasma alcohol CVD. However, the CNT formation in this experiment could not be explained simply by this reaction, since no carbon
The addition of a small amount of H$_2$O (175 ppm) in the carbon source (C$_2$H$_4$) [5], the oxidation of the catalyst by existing OH radicals [6], and the optimization of the carbon/hydrogen ratio by O atoms [4]. Among the aforementioned molecules (CO$_2$, H$_2$O, OH, CO, and H$_2$), only CO can be used as a carbon source for CNT by a CO disproportionation reaction below 900 °C [26]. These species produced in the plasma have a strong influence on the catalyst state and CNT growth by varying their concentration in the gas phase.

A recent experiment by Oshima et al. [27] showed that C$_2$H$_5$OH thermally decomposed at 840 °C without plasma and a metal catalyst, and C$_2$H$_4$, C$_2$H$_2$, C$_2$H$_4$O, CH$_4$, CO, CO$_2$, and H$_2$O were generated through the thermal reactions. This paper suggested that hydrocarbons such as C$_2$H$_4$ and C$_2$H$_2$ can be used as a CNT precursor. Our previous work using CH$_4$/H$_2$ plasma concluded that C$_2$H$_4^+$ and C$_2$H$_2^+$ ($x, y \geq 2$) are the main precursors [7], [8], [10] and that Al$_2$O$_3$/Fe/Al$_2$O$_3$ catalyst resulted in high yields of CNTs. According to the present QMS measurement, the radicals derived from the C$_2$H$_5$OH molecule are the major species in the plasma. The species observed by QMS are different from those by OES because the emission peaks of hydrocarbon radicals are located in the infrared region and outside the measurement range. Considering these results, we speculate that C$_2$H$_4$ and C$_2$H$_2$, which were generated by electron impact collision with C$_2$H$_5$OH would be CNT precursors in this system. Since the molecular weight of CO and C$_2$H$_4$ are equivalent, it is difficult to distinguish between these two species [Fig. 5(c)]. The presence of CO indicates that carbon is provided by the CO disproportionation reaction [26]. By employing plasma, the electron-collision process in the plasma reduces the effective temperature for CNT growth by approximately 200 °C, when compared with the nonplasma CVD process [27].

IV. CONCLUSION

In this paper, we reported multiwalled CNT growth by alcohol PECVD at 650 °C. By adding 0.01-wt% ferrocene in C$_2$H$_5$OH, the yield of CNTs increased, and well-aligned CNTs were grown on an Al$_2$O$_3$/Fe/Al$_2$O$_3$ substrate. Using plasma OES, the spectral peaks from the resulting atoms and molecules (C$_2$, CH, CHO, CH$_2$O, CO, H, O$_2$, C$^+$, and CO$^+$) were identified. In the QMS measurement, the peaks of H$_2$, CH$_2$, CH$_3$OH, and C$_2$H$_5$OH were detected, and a decrease in intensity of CH$_4$, CH$_2$OH, and C$_2$H$_5$OH by generating plasma was shown. By utilizing the plasma dissociation process for alcohol, oxidants (such as CO$_2$, H$_2$O, OH) and reductants (CO, H$_2$), as well as C$_x$H$_y$ ($x \geq 1, y \geq 3$) that are precursors for CNT growth, can be effectively produced at a lower temperature in plasma.

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