



# Growth of Inner Carbon Nanotubes inside Cobaltocene-Filled Single-Walled Carbon Nanotubes <sup>†</sup>

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**Abstract:** In this work, the single-walled carbon nanotubes (SWCNTs) were filled with cobaltocene. The growth properties of individual chirality nanotubes were studied with Raman spectroscopy. It was shown that the larger nanotubes grow slower. The growth of inner nanotubes becomes faster with increasing annealing temperature. These results are of high importance as they stimulate research on carbon nanotubes, and bring ideas from laboratories into factories.

**Keywords:** Raman spectroscopy; growth properties; cobaltocene

## 1. Introduction

Filling of single-walled carbon nanotubes (SWCNTs) is important for applications [1–4]. Metalloenes are promising filler material as they modify the chemical and physical properties of SWCNTs. Metalloenes inside SWCNTs represent a unique system for the growth of inner carbon nanotubes. The electronic properties of filled SWCNTs are also modified [5,6]. In this work, I filled the SWCNTs with cobaltocene, and I investigated the growth of inner carbon nanotubes. Raman spectroscopy allowed me to trace the process of growth with high precision. The growth of inner SWCNTs with chiralities of (13,1), (12, 3), and (11, 1) was detected. The chirality-specific growth curves of SWCNTs were obtained at different temperatures to compare kinetics.

## 2. Experiments

I performed the filling of SWCNTs with cobaltocene in gas phase. The filling was performed in glass ampoule at low temperature (~59 °C). The filled SWCNTs were annealed at different temperatures to investigate kinetics. This system is very interesting for investigation of these properties as it gives a clean environment for highly precise study of growth of SWCNTs.

## 3. Results

Figure 1 shows the growth curves of inner nanotubes inside cobaltocene-filled SWCNTs at temperatures of 540 °C (a), 560 °C (b), 580 °C (c), 600 °C (d), 620 °C (e) and 640 °C (f). With these lots of data, it is visible that the larger nanotubes grow slower. The growth of inner nanotubes becomes faster with increasing annealing temperature. This is because the kinetics of growth of inner SWCNTs depends on their chirality. Here, I present the chirality-specific kinetics, which is important knowledge for applications. For example, this will allow decreasing the growth temperature of SWCNTs to make the preparation processes easier, simpler, and low cost. It should be noted that the growth kinetics of SWCNTs in this system should be investigated with different conditions, i.e., precursor types, which lead to new results, and important information on synthesis protocols is implemented in industry. The kinetics experiment is time-consuming, but the established fundamental dependencies



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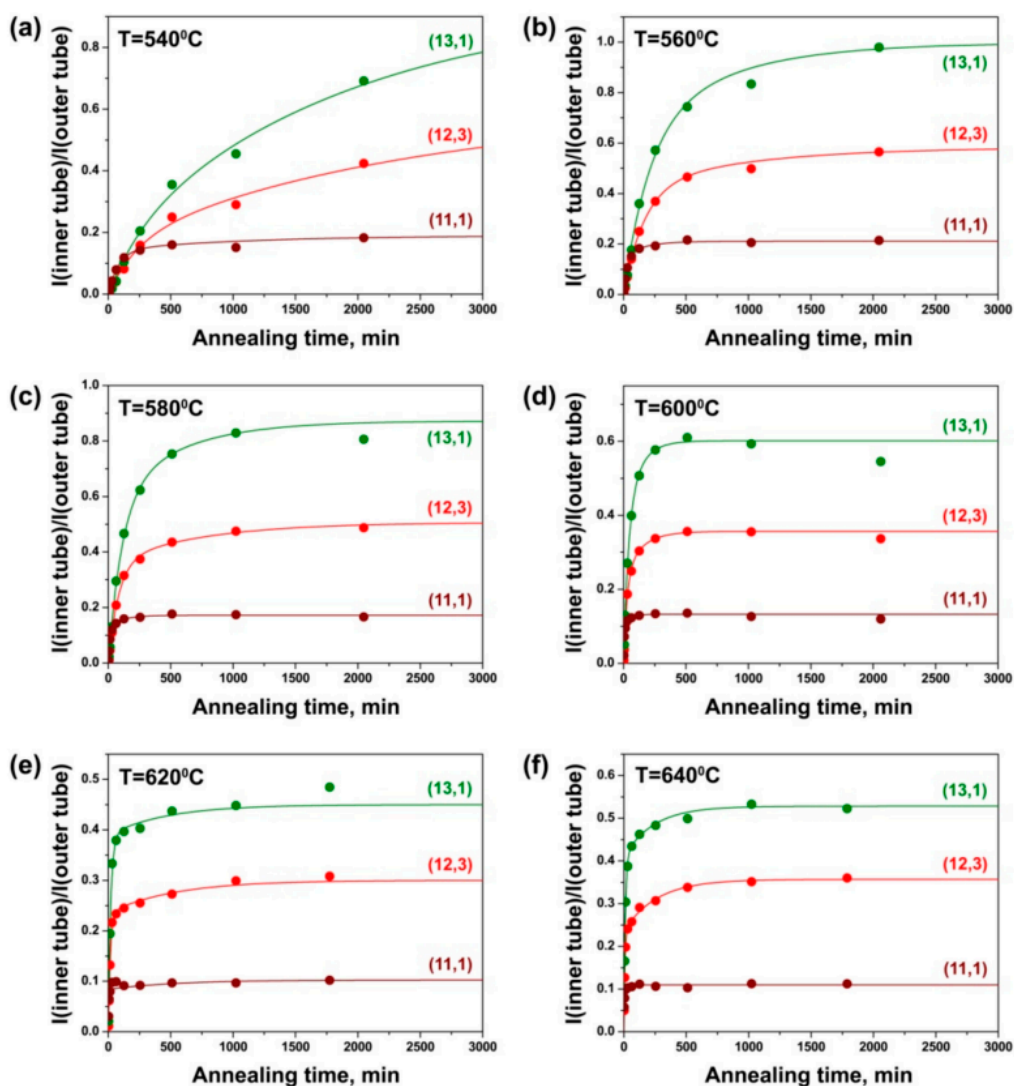
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and trends lead to quick modernization of preparation processes. I expect that this data will be involved in factory process developments soon.



**Figure 1.** The growth curves of inner nanotubes inside cobaltocene-filled SWCNTs at temperatures of 540 °C (a), 560 °C (b), 580 °C (c), 600 °C (d), 620 °C (e) and 640 °C (f) [2]. Copyright 2021 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

#### 4. Conclusions

In this work, the growth properties of individual chirality nanotubes were studied. It was shown that the larger nanotubes grow slower. The growth of inner nanotubes becomes faster with increasing annealing temperature. The high importance of this data is caused by the necessity of a driving force for researchers to study. With these materials obtained, research on carbon nanotubes is going faster.

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