

# Active Phase of Cobalt Oxide ( $\text{Co}_3\text{O}_4$ ) as a Promising Catalyst for Graphene Growth by Alcohol Catalytic Chemical Vapor Deposition



Mohd Asyadi Azam, Nor Najihah Zulkapli, Noraiham Mohamad, Mohd Shahadan Mohd Suan, Ghazali Omar

**Abstract:** The presence of active catalyst during graphene growth by alcohol catalytic chemical vapour deposition is a compulsory. This study is aimed to validate the effect of annealing temperature for the formation of active cobalt oxide ( $\text{Co}_3\text{O}_4$ ) film on the graphene growth by alcohol catalytic chemical vapour deposition technique. Active  $\text{Co}_3\text{O}_4$  film was prepared on silicon wafers by sol-gel process, using cobalt acetate tetrahydrate as the precursor compound and absolute ethanol as the solvent. The active  $\text{Co}_3\text{O}_4$  phase was achieved by annealing process at 450, 500, 550 and 600 °C. The graphene is grown from active  $\text{Co}_3\text{O}_4$  film under 900 °C of chemical vapor deposition (CVD) processing temperature for 5 minutes. The obtained  $\text{Co}_3\text{O}_4$  was characterized by x-ray diffraction and Raman spectroscopy. The as-grown graphene from active  $\text{Co}_3\text{O}_4$  film annealed at 450 °C was characterized by Raman spectroscopy and field emission scanning electron microscope (FESEM). The results demonstrate that spinel type cubic structure of  $\text{Co}_3\text{O}_4$  could be produced at the varied annealing temperatures but the optimum XRD result was at 500 °C annealing temperature. The presence of active  $\text{Co}_3\text{O}_4$  phase was supported with the exhibited peaks of four Raman-active phonon modes in the Raman spectra. The quality of as-grown graphene determined from the ratio of 2D-band over G-band intensities is 1.010; an indication of few layers of graphene. Active  $\text{Co}_3\text{O}_4$  film is able to produce good quality of graphene comparable with Ni and Cu catalysts. And graphene can be used in many devices, including electronic device, energy storage device, power device, and others.

**Keywords :** Active  $\text{Co}_3\text{O}_4$ , sol-gel process, graphene growth, alcohol catalytic CVD

## I. INTRODUCTION

Graphene is an extraordinary 2-dimensional material that has been attracting extensive attention in nanoscience and technology. Its distinctive properties such as theoretically high sheet resistance, 1000  $\Omega/\text{sq}$ , high surface area (2630  $\text{m}^2/\text{g}$ ) and high capacitance value (1954 F/g) have made graphene one of the leading candidates for various types of applications. The example application for such unique material is mobile electronic devices, back-up power supplies and hybrid electric vehicles [1-3].

There are many approaches to produce graphene such as mechanical cleavage [4-5], carbon precipitation from metals, epitaxial growth on SiC and chemical vapour deposition (CVD) [6-9]. Previously, several studies have claimed that alcohol catalytic CVD is one of the most assuring technique in carbon nanotube (CNT) growth due to its broad selectivity of substrates, good economic value and good catalytic reaction [10-12]. Due to less amorphous carbon formation, the CNT grown from this technique has high potential in developing electronic devices, and will produce high quality CNTs [13-14]. Since CNT and graphene are in the same group of materials, thus it is applicable to use alcohol catalytic CVD technique in producing graphene.

The presence of catalyst during the growth process is compulsory for alcohol catalytic CVD technique. Cobalt catalyst is the most appropriate catalyst for alcohol CVD technique [15]. The oxide layer that could be formed by air decomposition is the phase of  $\text{Co}_3\text{O}_4$ , while phases of Co and CoO can be found in the vacuum [16]. Crystalline  $\text{Co}_3\text{O}_4$  is an active phase among its well-known three polymorphs [17]. Also, the thickness of catalyst may affect the growth of graphene [18]. The amount of adsorbed carbon into the small thickness of catalyst film is not enough to enhance the precipitation of all carbon elements for a film of graphene forms on the surface. By increasing the thickness of catalyst film, the number of graphene layer will be increased. Hence, this report is prepared to validate the effect of annealing temperature for the formation of active  $\text{Co}_3\text{O}_4$  film on the graphene growth by alcohol catalytic CVD technique.

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## II. EXPERIMENTAL

Using sol gel spin-coating technique, active Co<sub>3</sub>O<sub>4</sub> films were synthesized. The precursor solution was prepared to produce a 0.05 mol / L concentration solution by diluting 124.54 mg of Co acetate tetrahydrate (Co(CH<sub>3</sub>COOCH)<sub>2</sub>·4H<sub>2</sub>O) into 10 mL of absolute ethanol. The solution was vigorously stirred for 10 min and kept in ultrasonic bath for 2 h, resulting in a light pink color solution. The silicon wafer P-type was cut in sizes of 15 mm or 15 mm. The substrates were washed by soaking in acetone, left in ethanol for sonication for 10 min, and dried with the use of nitrogen blow. The Co acetate tetrahydrate / absolute ethanol precursor solution was spin coated for 60 s at 6000 rpm on the cleaned substrates. The spin-coated wafers were then preheated to vaporize the solvent at 80 ° C for 5 min, thereby leaving Co catalyst films on the wafer. Later, for an annealing process, the preheated wafer was placed in the 450, 500, 550 and 600 ° C vacuum furnace to obtain crystalline Co<sub>3</sub>O<sub>4</sub> films.

The prepared catalyst film for the graphene growth was positioned in a horizontal quartz tube reactor (MTI-OTX 1200X). The tube was evacuated to 0.4 Pa using oil-free scroll pump. To prevent excessive oxidation of the Co catalyst, at a pressure of 400 Pa Ar gas was injected into the system simultaneously with 5 min of rapid heating and 5 min of second annealing phase. Once the annealing step completed, another Ar gas flow piping was purged into a closed-tank ethanol to vaporize the ethanol and instantly lead off at flow rates of 100–150 sccm into the system. The growth process was carried out for 5 min at an internal pressure of 4-10 kPa. The ethanol gas flow was stopped after the growth process, and the sample was left to cool to RT. The process of annealing and growth was performed at 900 ° C of CVD processing temperature.

The confirmation of the presence of active Co<sub>3</sub>O<sub>4</sub> was done by PANalytical X-ray Diffraction (X'Pert Pro MPD PW3060/60). The surface morphology and the cross section of the sample were analyzed by using field emission scanning electron microscope (FESEM, Hitachi SU8100). Raman analysis for the active Co<sub>3</sub>O<sub>4</sub> films and for the as-grown graphene was conducted by using Raman spectroscopy (Uni-RAM 3500) with 532 nm wavelength laser excitation (Nd: YAG).

## III. RESULTS AND DISCUSSION

### A. XRD Analysis

Figure 1 shows the XRD patterns of the dried Co film, the film that is prepared before annealing process and 4 samples that annealed at different annealing temperature; 450, 500, 550 and 600 °C. Dominant diffraction peaks are detected at 36.8° and 42.4° while minor diffraction peaks are detected at 52.2°, 55.9° and 61.9°, for the Co film annealed at 450 °C. For the film annealed at 500 °C, the same dominant peaks at 36° and 42.4° are observed but with more minor peaks at 31.2°, 52.4°, 55.9°, 59.4°, 61.6° and 65.3°. However, only one dominant peak is observed for the sample annealed at 550 °C with no other minor peak is presence. For Co film annealed at 600 °C, the dominant peaks are similar with the Co films annealed at 450 °C and 500 °C with three minor peaks observed at 59.5°, 61.6° and 65.3°. The Co film dried at 80 °C

shows no presence of dominant peak, which indicates amorphous phase. The diffraction peaks detected at 31.2°, 36.8°, 55.9°, 59.4°, 59.5° and 65.3° could be indexed to the spinel type cubic structure of Co<sub>3</sub>O<sub>4</sub> [19-20]. From the observation, Co<sub>3</sub>O<sub>4</sub> cubic structure can be formed at 450, 500, 550 and 600 °C annealing temperatures. Yet, this result cannot determine that the Co<sub>3</sub>O<sub>4</sub> structure produced from this sol-gel process may produce graphene structure until it undergoes graphene growth process by alcohol catalytic CVD technique.

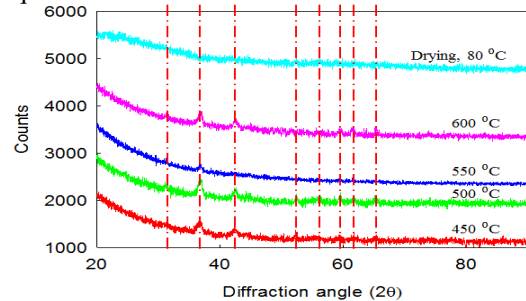


Fig. 1. XRD patterns of the Co film dried at 80 °C and annealed Co<sub>3</sub>O<sub>4</sub> films at 450, 500, 550 and 600 °C.

### B. Raman Analysis

Another analysis to confirm the formed of spinel cubic structure Co<sub>3</sub>O<sub>4</sub> is an active Co<sub>3</sub>O<sub>4</sub> is by Raman analysis. Theoretically, the normal spinel structure for Co<sub>3</sub>O<sub>4</sub> crystal is Co<sup>2+</sup> (Co<sup>3+</sup>)<sub>2</sub> O<sub>4</sub> (space group O<sub>h</sub><sup>7</sup>) with Co<sup>2+</sup> and Co<sup>3+</sup> located at tetrahedral and octahedral sites [21]. Raman analysis is considered to be based on the interaction of molecular vibrations, phonons or other excitations in the system with laser light, resulting in the energy of the laser photons being moved up and down, thus giving information to the vibrational modes in the system [22]. Previously, it is mentioned that the reduction of the 42-dimensional representation  $\Gamma$  of the vibrational modes at k=0 into irreducible representations of the factor group O<sub>h</sub> gives A<sub>1g</sub>, E<sub>g</sub>, 3F<sub>2g</sub>, 5F<sub>1u</sub>, 2A<sub>2u</sub>, 2E<sub>u</sub> and 2F<sub>2u</sub> [23]. The A<sub>1g</sub>, E<sub>g</sub> and 3F<sub>2g</sub> is the fingerprint for Raman active of Co<sub>3</sub>O<sub>4</sub>. Raman spectrum of active Co<sub>3</sub>O<sub>4</sub> film annealed at 450 °C clearly displayed Raman-active phonon modes located approximately at 196, 480, 619 and 684 cm<sup>-1</sup>, that correspond to the F<sub>2g</sub><sup>1</sup>, E<sub>g</sub>, F<sub>2g</sub><sup>2</sup> and A<sub>1g</sub> (Fig. 2). F<sub>2g</sub><sup>3</sup> might be overlapped with Si peak. This indicates complete crystallization of the Co<sub>3</sub>O<sub>4</sub> phase [19]. However, the crystallization of Co<sub>3</sub>O<sub>4</sub> phase depends on the thickness of Co film spin-coated on the substrate since 1 layer spin-coated Co film shows weak intensity as compared with 5 layers of coating.

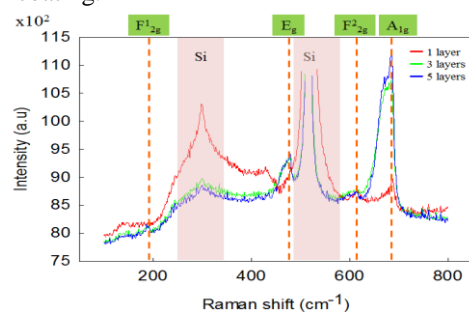
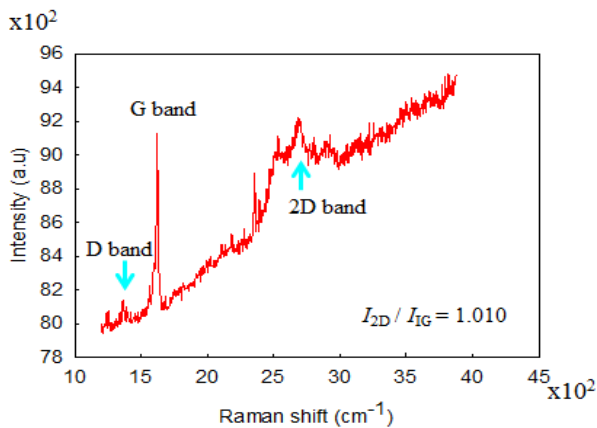


Fig. 2. Raman spectra of active Co<sub>3</sub>O<sub>4</sub> films.

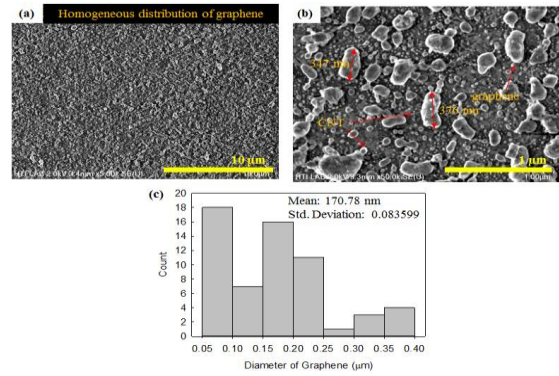
Further study has been conducted to confirm the spinel cubic structure of  $\text{Co}_3\text{O}_4$  is an active catalyst for graphene growth by alcohol catalytic CVD. Since theoretically  $\text{Co}_3\text{O}_4$  structure can be formed at  $450^\circ\text{C}$ , thus the Co film annealed at  $450^\circ\text{C}$  was used for this purpose (Fig. 3). With absolute ethanol as the carbon feedstock, graphene is indicated by the presence of G-band and 2D-band in the Raman spectrum at  $1621\text{ cm}^{-1}$  and  $2680\text{ cm}^{-1}$ , respectively. G-band is specified as the graphitic structure and 2D-band is secondary peak indicates the number of graphene layers [24]. These bands are the fingerprint for the existence of graphene on the sample. The intensity ratio of 2D-band over intensity of G-band was calculated in order to qualitatively ascertain the structures of the produced graphene. The  $I_{2D}/I_G$  ratio was calculated to be 1.010. This indicates the growth of a few layers of graphene. Hence, even though the existed bands are not strong enough to overcome the intensity of Si peak, it is proved that the active  $\text{Co}_3\text{O}_4$  is able to synthesize graphene layer by alcohol catalytic CVD.



**Fig. 3. Raman spectrum of graphene grown from active  $\text{Co}_3\text{O}_4$  film annealed at  $450^\circ\text{C}$ .**

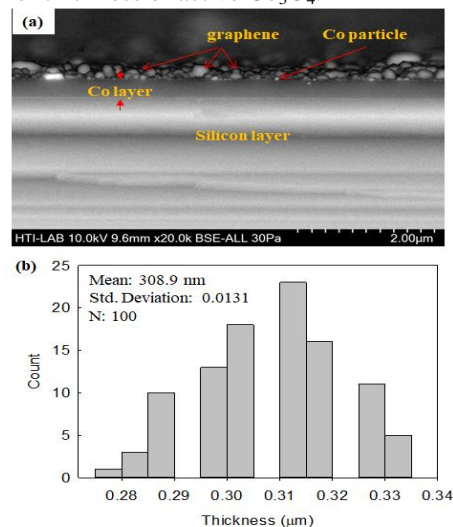
**C. Surface Morphological Analysis**

For the morphology of the as-grown graphene from the active  $\text{Co}_3\text{O}_4$ , again, the sample that annealed at  $450^\circ\text{C}$  was used for this study. The sample was characterized by field emission scanning electron microscopy (FESEM). Fig. 4a displays the homogeneous distribution of graphene on the sample surface. Closed-image at 50k magnification shows that the graphene structure is well-formed (Fig. 4b). Along with the presence of graphene structure, CNT structure is also observed on the surface. This indicates that the CVD processing temperature at  $900^\circ\text{C}$  is not enough to eliminate the CNT growth. Higher CVD processing temperature is needed to make sure there is only graphene structure formed on the surface. Somehow, the existence of CNT might be helpful in a certain application. This is an interesting finding for those who may need both graphene and CNT in their composition. The graphene which appears to be particle-like with irregular shapes and sizes has the average diameter of graphene formed on the surface is  $170.78\text{ nm}$  (Fig. 4c).



**Fig. 4. (a)-(b) FESEM images of as-grown graphene from the active  $\text{Co}_3\text{O}_4$  film. (c) Histogram of the graphene diameter distribution captured from the image.**

Morphology of the cross-section of the as-grown graphene is also examined by FESEM image, as shown in **Figure 5a**. From the image, the graphene layer is grown on the rough surface of active  $\text{Co}_3\text{O}_4$ . Therefore, from this result, it can be specified that the exhibited Raman spectrum is affected by the surface roughness of the active  $\text{Co}_3\text{O}_4$ . Smooth surface with small surface roughness, may result in good formation of graphene layer. There is a claim that the thickness of catalyst film may affect the growth of graphene [5, 19]. This is because the amount of adsorbed carbon into the small thickness of catalyst film is not enough to enhance the precipitation of all carbon elements out on the surface to form graphene layer. In this study, the average thickness of active  $\text{Co}_3\text{O}_4$  is  $308.9\text{ nm}$ . This implies that the thickness is enough to ignite the precipitation of carbon elements onto the surface. However, it is not a conclusion to decide that the measured thickness is the optimum to ignite the precipitation of carbon elements onto the surface. Generally, higher annealing temperatures might introduce smaller thickness due to the shrinkage that happens during the process. It is much easier to ignite the precipitation of carbon elements onto the surface with smaller thickness of active  $\text{Co}_3\text{O}_4$ .



**Fig. 5. (a) FESEM cross-section image of the as-grown graphene from active  $\text{Co}_3\text{O}_4$  film. (b) Histogram of the thickness of active  $\text{Co}_3\text{O}_4$  film distribution captured from the image.**



#### IV. CONCLUSION

This study aims to validate the effect of annealing temperature for the formation of active Co<sub>3</sub>O<sub>4</sub> film on the graphene growth by alcohol catalytic chemical vapor deposition (CVD) technique. Active Co<sub>3</sub>O<sub>4</sub> film was prepared on silicon wafers by sol-gel process, using cobalt acetate tetrahydrate as the precursor compound and absolute ethanol as the solvent. The active Co<sub>3</sub>O<sub>4</sub> phase was achieved by annealing process at 450, 500, 550 and 600 °C. The graphene is grown from active Co<sub>3</sub>O<sub>4</sub> film under 900 °C of CVD processing temperature for 5 minutes. The obtained Co<sub>3</sub>O<sub>4</sub> was characterized by X-ray diffraction and Raman spectroscopy. The as-grown graphene from active Co<sub>3</sub>O<sub>4</sub> film annealed at 450 °C was characterized by Raman spectroscopy and field emission scanning electron microscope (FESEM). The results demonstrated that spinel type cubic structure of Co<sub>3</sub>O<sub>4</sub> could be produced at the varied annealing temperatures but the optimum XRD result was at 500 °C annealing temperature. The presence of active Co<sub>3</sub>O<sub>4</sub> phase was supported with the exhibited peaks of four Raman-active phonon modes in the Raman spectra. The quality of as-grown graphene determined from the ratio of 2D-band over G-band intensities is 1.010; an indication of few layers of graphene. Overall, Co<sub>3</sub>O<sub>4</sub> is a promising transition metal catalyst for graphene growth.

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