

Pyrolytic synthesis of spherical carbon nanoshells

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Abstract

The methane pyrolysis on spherical SiO₂ nanoparticles with mean diameter of 40–80 nm has been studied at temperatures 550–800 °C, methane flow rate 50–660 mL/min, and process duration 20–60 min. It is shown that this process results in the formation of core/shell composites with shells having thickness of ~1–12 nm which are permeable to liquids. The dissolution of a core leads to the extraction of hollow carbon nanospheres.

Keywords: Carbon spherical nanoshells, methane, pyrolysis, template growth

Introduction

Carbon nanostructured materials have attracted the great interest due to their potential in a variety of applications in different areas of techniques, biology and medicine, such as adsorption, capacitive deionization, catalysis, electrocatalysis, photocatalysis, energy storage, sensory and biosensory systems, drug delivery, etc. A special type of carbon material are the hollow micro- and nanoparticles (shells, boxes, spheres) having low density, high values of conductivity and specific surface. The better way to form such three-dimensional (3D) nanostructures is synthesis over specific nanoparticles, viz., template growth. Metals, crystalline and amorphous oxides, carbides, silicides, and fluorides can be used as a template material.

Various templating techniques have been developed to synthesize carbon core-shell micro- and nanoparticles, such as vacuum sputtering (Hayashi, 1996), molecular beam epitaxy (Jerng, 2011 a; Jerng, 2011 b), sol-gel method (Zhu, 2009), hydrothermal approach (Xuan, 2007; Liu, 2012; Li, 2013), electrostatic interaction (Yang, 2010; Chen, 2012 a), aerosol spraying (Wen, 2013) and catalytic chemical vapor deposition (CVD).

Among the several approaches reported to-date, CVD of carbon on substrates has a great interest due to the low-cost production of graphene layers, simplicity and easy scaling-up.

The carbon shells usually represents the irregular graphene layers which can be thin (one to three layers) (Rümmeli, 2007; Wang, 2012), have up to 8–10 layers (Rümmeli, 2008; Teunissen, 2001; Rümmeli, 2010 a), or be rather thick. The number of carbon layers can be tuned by changing the growth time and the temperature.

Certain transfer-free methodologies for flat substrates have been also proposed (Ismach, 2010; Yan, 2011; Wang, 2013). Direct growth of graphene ribbons on sapphire and SiO₂ dielectric substrates using chemical vapor deposition has been studied by Ismach et al. (2010) and Wang et al. (2013). The process includes deposition of Cu or Ni films, chemical vapor deposition using hydrocarbons and metal etching. Graphene ribbons up to few millimeters long were formed along the periphery of pre-patterned Ni films (Wang, 2013).

Many oxides can encourage the carbon graphitization. Different hydrocarbons were used for the pyrolysis and covering the oxide surface. An impressive series of works on developing, testing and use of 3D composite materials has been done in Japan by M. Inagaki et al. (1998, 2004, 2006).

As a rule, the materials were produced by metal-catalyst-free pyrolysis of poly(vinyl chloride), poly(ethylene terephthalate), hydroxyethylcellulose or poly(vinyl alcohol) in contact with ceramic particles at temperatures between 700 and 1000 °C in inert atmosphere. At a definite thickness of carbon shells the values of their specific surface and porosity can be significantly increased.

Application of the CVD route in which the nanoparticles of Al_2O_3 , TiO_2 and MgO are exposed to ethanol vapor was recently explored by Bachmatiuk et al. (2013). Pyrolysis of cyclohexane vapor over MgO was also studied by Rütteli (2010 a). The growth of graphene shells on MgO and ZrO_2 particles by pyrolysis of C_2H_2 at low temperatures was studied by Rütteli et al. (2010 b; 2010 a) and Scott (2011).

Porous hollow carbon@sulfur composites were formed earlier using silica particles 200 nm in diameter (Jayaprakash, 2011), 500 nm in diameter (Shin, 2013) and 150 – 200 nm (He, 2014) as template. Spherical SiO_2 matrix with diameter more than 100 nm were used for the carbon shells by pyrolysis of different organic compounds, but not methane (Yoon, 2002; Kim, 2003; Su, 2006; Kim, 2009; Chen 2012, b; Bottger-Hiller, 2013; Qiao, 2013).

The synthesis of carbon/ MgO core/shell and pure carbon shell particles at CH_4 decomposition using MgO as a template was described by Davydov et al. (2012).

Here we report on the formation of hollow carbon nanoshells by pyrolysis of methane on spherical SiO_2 nanoparticles.

Experimental part

A. Sample preparation

Nanoparticles of SiO_2 produced by plasma pyrolysis of SiF_4 have been used as a matrix. The size distribution of SiO_2 particles is shown in Fig. 1. It is seen that the most part of them has diameter 30–90 nm with average value of 50–70 nm.

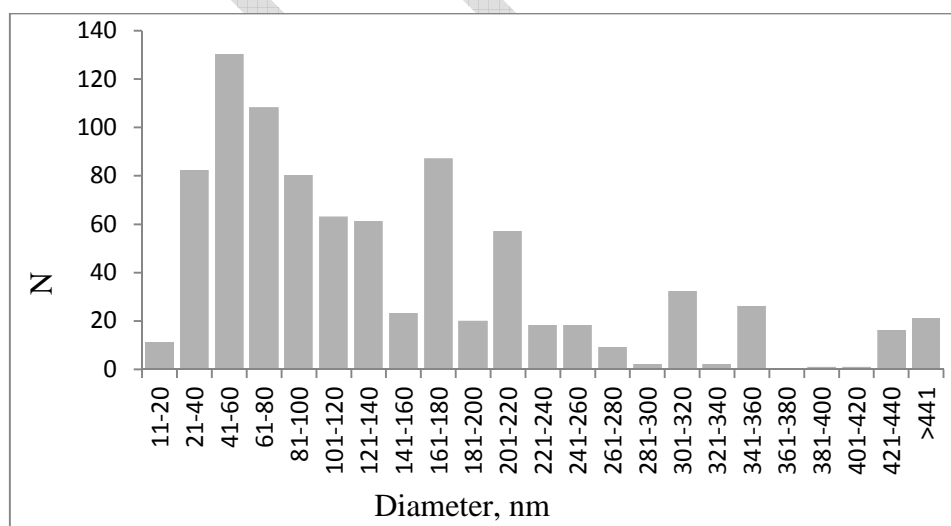


Fig. 1. Distribution of silica particles by size.

Domestic gas with 99 % of methane content is used without any cleaning for the experiments. 3D carbon networks are prepared on SiO₂ by CVD at ambient pressure.

The carbon-encapsulated SiO₂ nanoparticles are synthesized in a horizontal tube furnace (Fig. 2). The reactor consists of a sectioned quartz tube 55 mm in outer diameter. The tube has

working area heated by electric furnace, and cold area, with a sealing leg between the areas. We introduce methane into quartz tube 1 h before the pyrolysis to achieve the full displacement of air

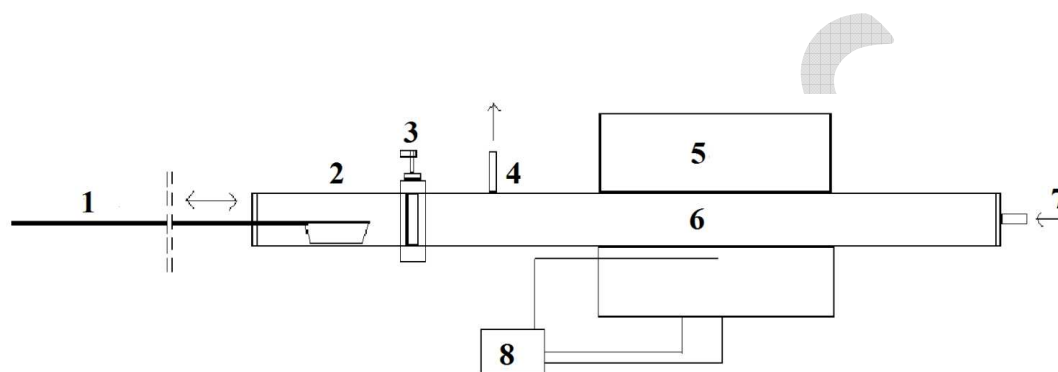


Fig. 2. Reactor for pyrolysis: 1 – metal stick for introducing of the boat to hot area; 2 – boat with SiO₂ nanoparticles in cold area; 3 – sealing leg; 4 – tube for exhausted gases; 5 – electric heating furnace; 6 – quartz tube; 7 – tube for gas input; 8 – equipment for measuring and adjustment of temperature.

from the reactor. The boat with 250 mg of SiO₂ was put into reactor by means of a special stick after heating the working area. The boat is held for a definite time in the hot area, then moved to the cold area, cooled and drawn out. The product is weighted and analyzed. Gas flow (100–800 mL/min) is preliminary calibrated at room temperature. The flow rate is controlled precisely by volume flow controller.

B. Product characterization

For the determination of deposited carbon mass, the samples were calcined at 750–800 °C during 3 h in air, cooled in closed exiccator and weighted. The thickness of carbon shells is estimated using total mass gain of deposited carbon and the mean size of the encapsulated SiO₂ particles. Scanning electron microscopy (Chem JEOL, JSM-6510LV) and transmission electron microscopy (FEI Tecnai G² 30 ST) were used to study the morphology of the starting SiO₂ particles, encapsulated nanoparticles and hollow shells. The specific surface of start materials and the products is measured by BET method (Sorbi MS).

Results and discussion

The CH₄ pyrolysis is observed at the temperature 500–900 °C. The typical dependencies of mass change on the process duration and gas flow rate at relatively high temperatures are represented by the curves with saturation (Fig. 3 and 4).

By analogy with the results of hydrocarbon pyrolysis over Cu, Ni and other metals, one can suppose that the surface of oxides exerts a catalytic influence on pyrolysis reaction. With increasing deposit thickness and process duration this influence weakens and finally ceases. Ceramic materials also has been used as catalysts of methane decomposition, e. g. by Hussain and Iqbal (2011). The activity of SiO₂ was found to be much lower than MgO/SiO₂ or Ni doped MgO/SiO₂.

It would be noted that at the highest temperatures, along with the carbon deposition on the tested samples, it takes place on the walls of quartz reactor. This uncontrolled deposition follows by the increasing of hydrogen content in reaction gases and some distortion of calculated data. The increasing of H_2 concentration in reaction gases delays the pyrolysis reaction too.

The final mass gain due to formation of carbon deposit on SiO_2 depends on the temperature (Fig. 5), and at 850–900 °C rises up to 72 mass %.

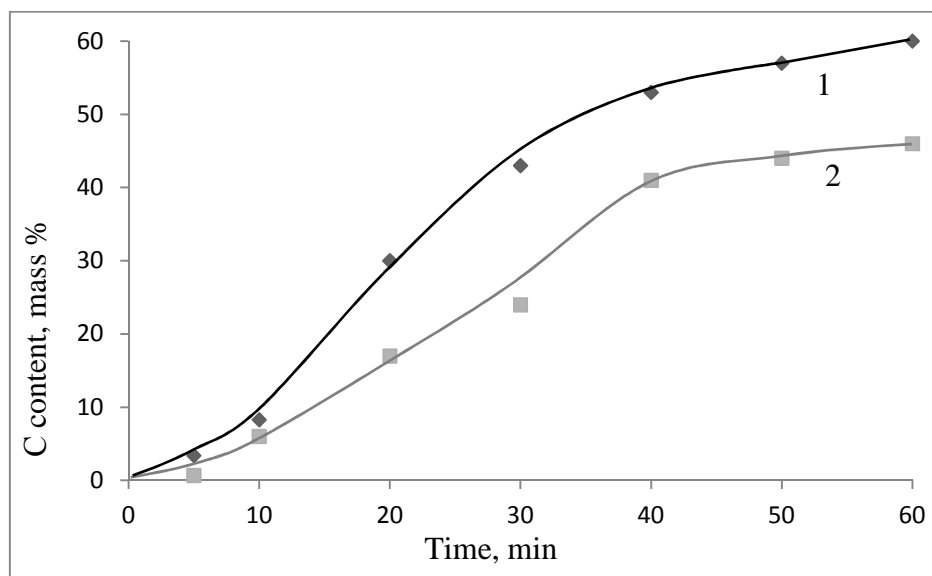


Fig. 3. The influence of pyrolysis time on mass of carbon deposit on SiO_2 at CH_4 flow rate of 330 mL/min and temperature of 800 °C (1) and 700 °C (2).

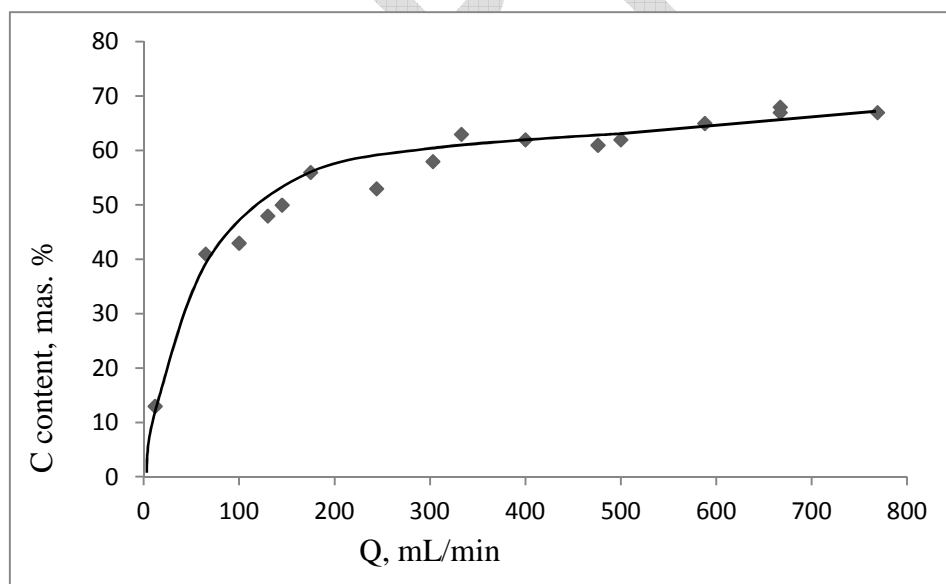


Fig. 4. The influence of CH_4 flow rate on mass of carbon deposit on SiO_2 at temperature of 850 °C and process duration of 60 min.

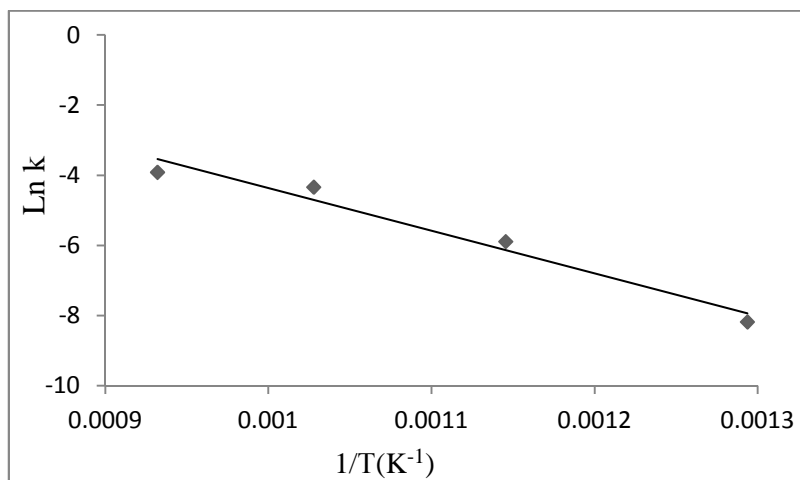


Fig. 5. The Arrhenius plot of carbon deposition on SiO₂ matrix.

The value of apparent activation energy that is estimated using medium part of the curve, is near 100 kJ/mole. This value is appreciably lower than the activation energy determined by Hussain and Iqbal (2011), which is equal to 186 kJ/mole, and defined in the work of Brüggert et al. (1999) – 446 kJ/mole. The difference may be related to the lower temperatures in our experiments and to the lower activity of SiO₂ catalyst. Also, it is likely that our data are influenced by carbon deposition process on the walls of quartz tube.

The results of electron microscopy analysis are evident of thin carbon layer formation on SiO₂ particles. As it is seen in Fig. 6 b - e, the shells covered whole surface of particles. The diameters of produced hollow carbon spheres closely repeats the size of initial SiO₂ particles.

Some of the empty shells are slightly distorted. To calculate medium diameter of SiO₂ particles, we takes into account overall numbers of particles in definite fractions of 20 nm in size at the interval of 21–210 nm. Assuming the mean diameter of particles equal to 60 nm and considering mass gain during deposition of carbon shells, it is possible to calculate the conventional thickness of the shells. The calculated thickness values are shown in Table 1.

Table 1. The calculated thickness of the shells at different experimental conditions

Temperature, °C	Duration, min	Carbon content, mass %	Shell thickness, nm, at SiO ₂ diameter, nm			
			50	60	70	80
550	60	5.0	0.5	0.6	0.7	0.8
600	30*	7.5*	0.6	0.9	1.0	1.2
600	60	10	0.8	1.2	1.4	1.6
650	60	34	3.0	3.6	4.2	4.8
700	60	47	3.5	4.2	4.9	5.6
750	60	65	5.5	6.6	7.7	8.8
800	60	72	5.6	6.7	7.8	8.9

* Gas flow rate 466 mL/min, in other cases 330 mL/min.

As it is seen, the value of the shell thickness can be controlled by alteration of pyrolysis temperature and duration.

SiO₂ matrixes covered by carbon shells can be easily dissolved in HF aqueous solution, thus the shells are microporous and permeable to solutions. Therefore, the calculated values are

approximate and underestimated by 15 – 20 %. The real thickness of shells produced at 600 °C and pyrolysis duration of 30 min, measured in micrographs (Fig. 6), is 1–12 nm. This interval coincides with calculated values. At lower temperature and process duration, the thickness less than 1 nm can be achieved.

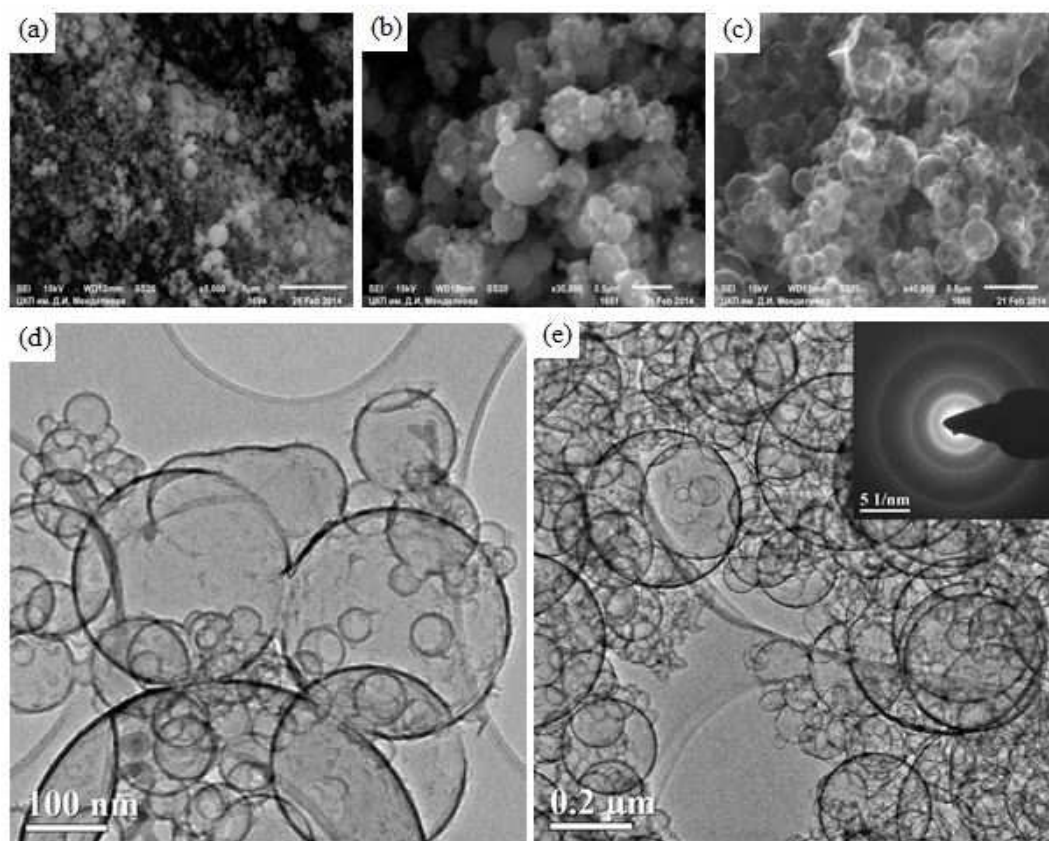


Fig. 6. Carbon shells produced by CH₄ pyrolysis over spherical SiO₂ particles (SEM): a – silica particles (SEM); b – silica particles with carbon shells (SEM); c – carbon shells (SEM); d – carbon shells (TEM); e – carbon shells (TEM) and their diffraction pattern.

The carbon spherical shells with the thickness of some nanometers become not strong and do not keep their habitus. Therefore destroyed spheres are seen on some of the pictures (Fig 6 d), but its number is negligible. Coalescent particles are also observed.

In 1959 Cullis et al (1959) has showed that carbon deposited from methane on silica substrate had a normal graphite structure, in other words represented graphene (which was not yet discovered).

The electron diffraction pattern (Fig 6 e) corresponds to the polycrystalline graphite structure of carbon deposit.

The lower is the pyrolysis temperature, the higher are porosity and specific surface values of shells. The specific surface of shells synthesized at 600 °C was 175 m²/g, whereas specific surface value of a matrix SiO₂ particles was equal to 12–13 m²/g.

Carbon shells having thickness lower than 5–7 nm in the case of individual particles must be transparent or semitransparent, as it was shown earlier by Kaplas and Svirko (2012). Our shells are transparent in electron beam, however as a whole they retain black color.

The unique spherical carbon shells synthesized here have high electrical conductivity and can be used as electrode material for capacitive deionization (electrosorption) of waste water effluents.

Conclusion

A simple method for the preparation of 3D architectures is developed via a pyrolytic process. The methane pyrolysis at temperatures of 500–900 °C on the spherical nanoparticles of SiO₂ allows to get a core-shell hybrid composites, and the consequent dissolution of SiO₂ matrix leads to formation of isolated hollow carbon shells. The main part of these shells have diameters of 40 – 80 nm with a shell thickness of 1–12 nm. The values of shell density and specific surface are temperature dependent: The lowering of synthesis temperature leads to the reduction of density and to the increasing of specific surface.

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Conflict of interests

The authors have declared that no conflict of interest exists.

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