1. DOE Award number: **DE-SC0001169**
2. Recipient: **George Washington University**
3. Title: **Mechanism of Synthesis of Ultra-long Single Wall Carbon Nanotubes in Arc Discharge Plasma**
4. PI-**Michael Keidar**
5. **Accomplishments**

Summary

In this project fundamental issues related to synthesis of single wall carbon nanotubes (SWNTs), which is relationship between plasma parameters and SWNT characteristics were investigated. Given that among plasma-based techniques arc discharge stands out as very advantageous in several ways (fewer defects, high flexibility, longer lifetime) this techniques warrants attention from the plasma physics and plasma technology standpoint. Both experimental and theoretical investigations of the plasma and SWNTs synthesis were conducted. Experimental efforts focused on plasma diagnostics, measurements of nanostructures parameters, and nanoparticle characterization. Theoretical efforts focused to focus on multi-dimensional modeling of the arc discharge and single wall nanotube synthesis in arc plasmas.

It was demonstrated in experiment and theoretically that controlling plasma parameters can affect nanostucture synthesis altering SWNT properties (length and diameter) and leading to synthesis of new structures such as a few-layer graphene. Among clearly identified parameters affecting synthesis are magnetic and electric fields. Knowledge of the plasma parameters and discharge characteristics is crucial for ability to control synthesis process by virtue of both magnetic and electric fields.

New graduate course on plasma engineering was introduced into curriculum. 3 undergraduate students were attracted to the project and 3 graduate students (two are female) were involved in the project. Undergraduate student from Historically Black University was attracted and participated in the project during Summer 2010.

A single-step simultaneous synthesis and magnetic separation of high-quality graphene flakes and SWNTs in magnetically-enhanced arc discharge plasmas as it is summarized in Fig.1.

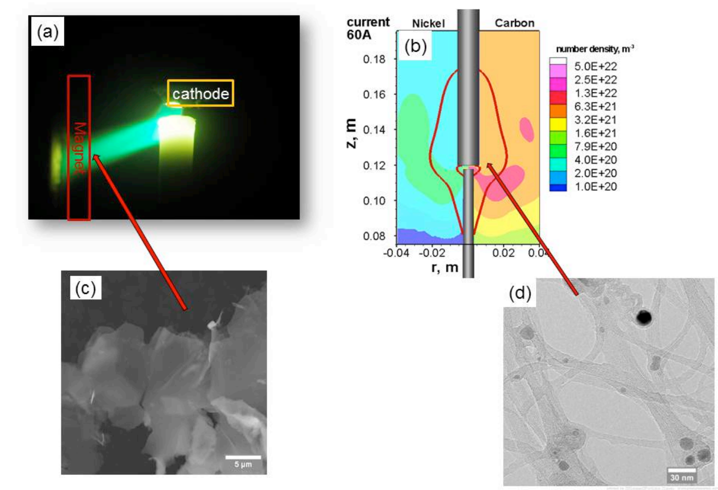

Figure 1. *(a) photo of the arc plasma in the case of a magnetic field applied, (b) computed carbon and catalyst particle density distribution showing the regions with preferable conditions for synthesis, (c) SEM image of graphene sheets, (d) TEM image of SWNT bundles.*

1. Major research and education activities

In this project fundamental issues related to synthesis of single wall carbon nanotubes (SWNTs), which is relationship between plasma parameters and SWNT characteristics are investigated. Given that among plasma-based techniques arc discharge stands out as very advantageous in several ways (fewer defects, high flexibility, longer lifetime) this techniques warrants attention from the plasma physics and plasma technology standpoint. Both experimental and theoretical investigations of the plasma and SWNTs synthesis are conducted. Experimental efforts focus on probe measurements of plasma and nanostructures parameters, optical spectroscopy, SWNT characterization using SEM, TEM, AFM, UV-viz-NIR and photoemission spectroscopy. Theoretical efforts continue to focus on 3D modeling arc discharge and single wall nanotube synthesis in arc plasma.

2. Major findings resulting from these activities

It was demonstrated in experiment and theoretically that controlling plasma parameters can affect nanostuctures synthesis altering SWNT properties (length and diameter) and leading to synthesis of new structures such as a few-layer graphene. Among clearly identified parameters affecting synthesis are magnetic and electric fields. Knowledge of the plasma parameters and discharge characteristics is crucial for ability to control synthesis process by virtue of both magnetic and electric fields.

Fast shielded probe was developed to access plasma parameters during the carbon nanotube synthesis. It was found that probe voltage-current characteristic is symmetrical during the carbon nanotube synthesis indicating possible effect of the helium under atmospheric pressure conditions.

It was demonstrated in experiment and theoretically that controlling plasma parameters can affect nanostuctures synthesis altering SWNT properties (length, chirality and diameter) and leading to synthesis of new structures such as a few-layer graphene. Among clearly identified parameters affecting synthesis are magnetic and electric fields.

It was determined that formation of the plasma jet in a magnetic field leads to synthesis of the graphene. Knowledge of the plasma parameters and discharge characteristics is crucial for ability to control synthesis process by virtue of both magnetic and electric fields.

3D numerical model of the arc discharge was developed. Numerical simulations demonstrate that in order to describe properly arc physics one needs to take into account coupling between processes in interelectrode plasma and electrodes, current continuity at electrodes and thermal regime of electrodes.

3. Opportunities for training, development and mentoring

New graduate course MAE 6255 “Plasma engineering in aerospace and nanotechnology” was introduced into curriculum. This course will be taught in Fall 2011 for the first time.

3 undergraduate students were attracted to the project and 3 graduate students (two are female) were involved in the project.

4. Outreach activities

Undergraduate student (Enoch Ilufoye) from Historically Black University (Howard University) was attracted and will participate in the project during Summer 2010. In addition another student from Columbia University (Y. Dachman) participated in summer REU opportunity.

Journal Publications during the reporting period

1. I. Levchenko, O. Volotskova, A. Shashurin, Y. Raitses, K. Ostrikov and M. Keidar, The large scale production of graphene flakes using magnetically-enhanced arc discharge between carbon electrodes, *CARBON*, Vol. 48, issue 15, pp. 4570 – 4574, 2010.
2. 1. M. Keidar and I.I. Beilis, Modelling of atmospheric-pressure anodic carbon arc producing carbon nanotubes, *Journal of Applied Physics,* vol. 106, 103304, 2009.
3. 2. O. Volotskova, A. Shashurin, M. Keidar, Y. Raitses, V. Demidov, S. Adams, Ignition and temperature behavior of a single-wall carbon nanotube sample, *Nanotechnology*, vol. 21, 095705, 2010.
4. 3. M. Keidar, A. Shashrin, O. Volotskova, Y. Raitses and I.I. Beilis, Mechanism of carbon nanostructure synthesis in arc plasma, *Physics of Plasmas*, Vol.17, Issue 5, 057101, 2010
5. O. Volotskova, J. Fagan, J.Y. Huh, F. Phelan Jr., A. Shashurin, M. Keidar, Tailored Distribution of Single-Wall Carbon Nanotubes from Arc Plasma Synthesis using Magnetic Fields, *ASC NANO*, Vol. 4, No. 9, pp. 5187–5192, 2010.
6. O. Volotskova, I. Levchenko, A. Shashurin, Y. Raitses, K. Ostrikov and M. Keidar Single-step synthesis and magnetic separation of graphene and carbon nanotubes in arc discharge plasmas, *Nanoscale*, Vol. 2., pp. 2281-2285, 2010. This paper was listed among 17 outstanding papers and reviews on Graphene to commemorate the 2010 Nobel Prize in Physics on graphene by Nanoscale.
7. M. Keidar and I.I. Beilis, On a model of nanoparticle collection by an electrical probe, *IEEE Transaction on Plasma Science*, vol. 38, pp. No. 11, 2010, pp. 3249-3251.
8. S. Kumar, I. Levchenko, M. Keidar, and K. Ostrikov, Plasma-enabled growth of separated, vertically-aligned copper-capped carbon nanocones on silicon, *Appled Physics Letters*, Vol. 97, 151503, 2010.
9. M. Keidar, A. Shashurin, J. Li, O. Volotskova, M. Kundrapu and T. Zhuang, Arc plasma synthesis of carbon nanostructures: where is the frontier? *J. Phys. D: Applied Physics*, 44 (2011) 174006.
10. M G Kong, M Keidar and K Ostrikov, Plasmas meet nanoparticles—where synergies can advance the frontier of medicine, *J. Phys. D: Applied Physics*, 44 (2011) 174018.

11. M. Kundrapu, I. Levchenko, K. Ostrikov, and M. Keidar, Simulation of Carbon Arc Discharge for the Synthesis of Nanotubes, *IEEE Transaction on Plasma Science*, Vol. 39, No. 11, 2011 pp. 2876-2877.

12. J. Li, O. Volotskova, A. Shashurin, and M. Keidar, Controlling Diameter Distribution of Catalyst Nanoparticles Arc Discharge, *J. Nanoscience and Nanotechnology*, vol. 11, No. 11, 2011, pp. 10047-10052.

13. J. Li, A. Shashurin, M. Kundrapu, M. Keidar, "Simultaneous synthesis of single-walled carbon nanotubes and graphene in a magnetically-enhanced arc plasma", *Journal of Visualized Experiments*, 60, 3455, M. Kundrapu and M. Keidar, Numerical simulation of carbon arc discharge for nanoparticle synthesis, *Physics of Plasmas*, vol. 19, 073510, 2012.

14. M. Kundrapu, J. Li, A. Shashurin and M. Keidar, Model of the carbon nanotube synthesis in arc discharge plasmas, *Journal Physics D: Applied Physics*, vol. 45, 315305, 2012.

15. J. Li, M. Kundrapu, A. Shashurin and M. Keidar, Emission spectra analysis of arc plasma for synthesis of carbon nanostructures in various magnetic conditions, *Journal of Applied Physics*, vol. 112, 024329, 2012.

16. J. Li, X. Cheng, A. Shashurin and M. Keidar, Review of electrochemical capacitors based on carbon nanotubes and graphene, *Graphene*, vol. 1, pp. 1-15, 2012.

Collaborations

New collaborations were established:

Loughborough University (UK) on medical application of nanoparticles (Prof. M. Kong)
NIST on SWNT characterization and arc technique standardization (Drs. F. Phelan and J. Fagan)
Air Force Research Laboratory on SWNT application for thermal management (Dr. S. Adams)
University of Sydney on SWNT synthesis simulations (Prof. Ken Ostrikov)
Princeton Plasma Physics Laboratory on graphene synthesis (Dr. Y. Raitses)

Research Highlights

Our research in this area was recently highlighted by American Physical Society (http://www.aps.org/publications/apsnews/201001/dppmeeting.cfm) as one of 3 major research areas such as Black Holes and Fusion.

Single-step synthesis and magnetic separation of graphene and carbon nanotubes in arc discharge plasmas was listed among 17 outstanding papers and reviews on graphene, put together to commemorate the 2010 Nobel Prize in Physics on graphene.