Plasma Science for Modern Nanotechnology

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Revolutionary Nanosynthesis Technologies

- Nanomaterials have the potential to revolutionize many fields, including electronics, energy storage, and environmental and pharmaceutical applications.

- Many existing methods of nanosynthesis use low pressure ($10^{-3}$-$10^{1}$ torr) and higher pressure ($\leq 1$ atm.) plasmas to produce a broad range of nanomaterials with various nanostructures:

  - Low pressure plasma synthesis of silicon nanoparticles. *Mangolini and Kortshagen, Advanced Materials 2007 Univ. of Minnesota*

  - Magnetically controlled arc synthesis of graphene at 500 torr. *Volotskova et al, Nanoscale, 2010 GWU-PPPL-CSIRO*

  - Microplasma synthesis of nano diamonds at 1 atm. pressure *A. Kumar et al., Nature Comm. 2013 Case Western Reserve Univ.*
Challenges of Plasma-Based Nanosynthesis

• Low-pressure methods use non-equilibrium plasma ($T_e \sim 1-10$ eV, $T_{i,a} < 0.1$ eV) to support non-thermal synthesis processes:
  • Plasma kinetics and gas-phase chemistry are important, but not well understood, which explains the absence of validated predictive modeling capabilities.

• Atmospheric pressure methods use higher-density non-thermal and thermal plasmas to achieve higher synthesis yield at lower cost as compared to low-pressure plasma methods.
  • Role of the plasma in nucleation and growth of nanoparticles is poorly characterized and not understood.
  • A critical issue – poor control of synthesis processes.

• Fundamental research of plasma synthesis is needed to address these challenges.
Emerging Plasma-Based Nanotechnologies

- Use low-pressure magnetized plasmas to produce new nanomaterials:

- Synthesis of nanostructural functional coatings using magnetized plasmas

  a) Sputtering magnetron discharge: (a) High power impulse magnetron (HiPIMS); (b) Plasma non-uniformity rotating in $E \times B$ direction (DC Magnetron). A. Anders et al., IEEE TPS to appear in 2014, APL 2013

- Functionalization of nanomaterials by magnetically filtered cold plasmas

  a) NRL Electron-beam plasma source for functionalization of graphene. Baraket, Walton et al. 2014; (b)PPPL DC-RF plasma-beam system and rotating spoke instability. Raitses et al., DOE PSC meeting 2012

- Need understanding of relevant plasma instabilities and plasma-surface interactions at nanoscale level to control quality of synthesis and functionalization processes and nanomaterials.
Current Plasma Nanotechnology Research

• EU funds several multimillion projects related to plasma nanotechnology. Examples of such projects:
  
  • BUONAPART-E project involving partners from universities as well as industry, focused on atmospheric pressure arc and spark discharges for synthesis of nanoparticles. ([www.buonapart-e.eu](http://www.buonapart-e.eu))
    ~ $2.5M/year for 4 years + cost share from participants.

  • German DFG funds (from *Jahresbericht 2012 - Programme und Projekte*):
    - Collaborative Research Center “Pulsed High Power (Magnetized) Plasmas for the Synthesis of Nanostructural Functional Layers”.
      ~ $3.8M/year since 2012, up to 12 years.
    - Collaborative Research Center "Fundamentals of Complex Plasmas“, topics relevant to dusty plasmas and plasmas synthesis of nanoparticles.
      ~ $2M/year since 2008, up to 12 years.

• US DOE Basic Energy Science supports 5 Nanoscale Science Research Centers at national labs (~ $100M/year) focused on materials sciences nanotechnology and applications, but no focus yet on the role of plasmas in producing nanomaterials.
Concluding Remarks

• Coordinated DOE FES and DOE BES program on plasma nanotechnology research is essential to maintaining US leadership in this area of science and technology.

• For the FES/BES joint program, we might expect that BES would provide the main push for this, but that FES should participate (and get credit) for some of the plasma contributions.

• Key objectives of this research program:
  – Better understanding of the underlying physics of the plasma synthesis and functionalization processes and synergy between plasma and materials sciences.
  – Predictive multiscale modeling capturing the entire range of synthesis and functionalization processes.
  – In-situ diagnosing and monitoring of plasma, nanoparticles and nanostructures during the synthesis and functionalization processes.
PPPL Plasma Nanotechnology Research

- Plasma-Based Nanotechnology Laboratory (PBNL) built with internal laboratory support, LDRD, approved by DOE and now fully operational.
- PBNL incorporates unique experimental facilities for studies of plasma nanosynthesis and functionalization—leverage from other PPPL PS&T projects supported by DOE FES and DOD.\(^1\)
- Initial efforts on modeling of plasma synthesis supported by LDRD.\(^2\)
- Collaboration with leading materials science and nanotech experts.

\(\text{MAPX for synthesis of B-C-N nanomaterials.}\)

\(\text{DC-RF plasma-beam system for synthesis, functionalization, and hydrogenation of nanomaterials.}\)

\(^1\)FESAC talks by Igor Kaganovich on Wednesday and Phil Efthimion on Thursday

\(^2\)FESAC talk by Predrag Krstic on Thursday
Collaborators

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Advantages of Plasma-Based Nanosynthesis Methods Over Other Methods (e.g. CVD)

• Higher throughput, shorter nanostructure growth time, lower cost (especially for atmospheric pressure plasma methods).

• Greater versatility - capable of bottom-up (i.e. taking material away) and top-down (i.e. building material) production of nanoparticles.

• Better control of size distribution and some properties (for low pressure plasma methods).

• Non-thermal synthesis (potentially at room temperature)

• Broader range of nanomaterials with high and low melting temperatures.

• Higher quality of nanomaterials (e.g. less structural defects of nanotubes, a fewer layer graphene).
Atmospheric Pressure Plasma NanoSynthesis: Plasma Science Questions

1. What are the plasma characteristics where nucleation and growth of nanoparticles occurs? What are the physical mechanisms, governing these plasma characteristics?

2. What is the role of the plasma characteristics in nanomaterial synthesis?

3. What are the effects of the mutual interactions of nanoparticles with plasma on nucleation and growth processes?

4. Why structural properties of nanoparticles synthesized in plasma are better than without plasma?

5. What are the optimum system parameters influencing the selectivity of plasma synthesis for various kinds of nanostructures?

6. What are suitable diagnostic tools for measurements in plasmas with nanoparticles?

7. Can nucleation and growth of nanoparticles in plasma be diagnosed in-situ?