

# Self-Organization of Atmospheric Pressure Carbon Arc Discharges

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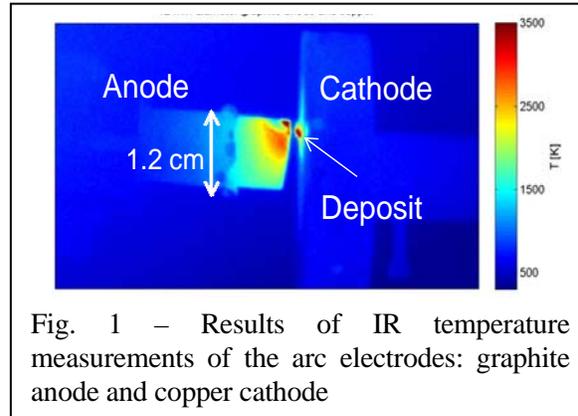
The atmospheric pressure carbon arc in inert gases is an important method for the production of nanomaterials [1]. Typical nanosynthesis arcs operate in a dc mode between a graphite anode, which is consumed, and a cathode which can be made from either graphite or a lower melting point material [2]. In spite of many studies, the basic physical processes in this discharge such as cathode electron emission, evaporation and deposition of the anode material, particle and heat transport, and arc instabilities are still not well understood. A lack of understanding of these processes limits predictive capabilities of existing arc models and their application for nanosynthesis modeling. Our current research involves integrated experimental and modeling efforts aimed at developing an understanding of the plasma processes and their synergy with material processes.

In recent arc experiments, measurements of evaporation and deposition rates, electrodes temperatures, arc discharge characteristics, and material characterization of the deposit revealed self-organization of plasma and material processes in the arc discharge [3,4]. In particular, during the arc operation, a carbon deposit is formed on the cathode surface. Electrons emitted from this deposit heat the graphite anode, which evaporates. The carbon ions and atoms travel to the cathode and condense to form the deposit, which is at sufficient high temperature (Fig. 1) for thermionic emission to support the arc current of 50-100 A [4].

Our results suggest that for the same operating conditions (gas, pressure, current), the arc can operate in two different regimes of evaporation and deposition of the anode material. The transition between these regimes is determined by the anode diameter (in our experiments  $\sim 0.8$  cm). For larger anodes, the evaporation and deposition rates are relatively small and independent on the anode diameter. For smaller anodes, both evaporation and deposition increase dramatically as the anode diameter decreases. This regime is favorable for high yield nanosynthesis. It was suggested that the transition to this regime is due to the formation of the positive anode sheath leading to enhanced power deposition on the anode [5]. This regime is also characterized by the enhanced contribution from the latent heat to the cathode energy balance [3]. Future studies will include detailed plasma measurements and numerical simulations of these arc regimes and self-organization which can be important for controlling of nanosynthesis material processes.

## References

- [1] C. Journet *et al.*, *Nature* **388**, 756 (1997).
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- [3] J. Ng and Y. Raitses, "Self- organization processes in the carbon arc" submitted (2014).
- [4] J. Ng and Y. Raitses, "Role of the cathode deposit in the carbon arc" submitted (2014).
- [5] A. Fetterman, Y. Raitses, and M. Keidar, *Carbon* **46**, 1322 (2008).



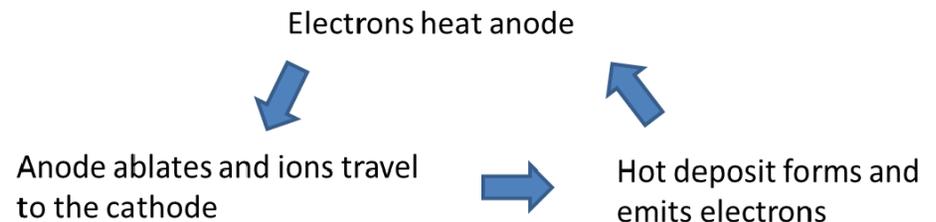
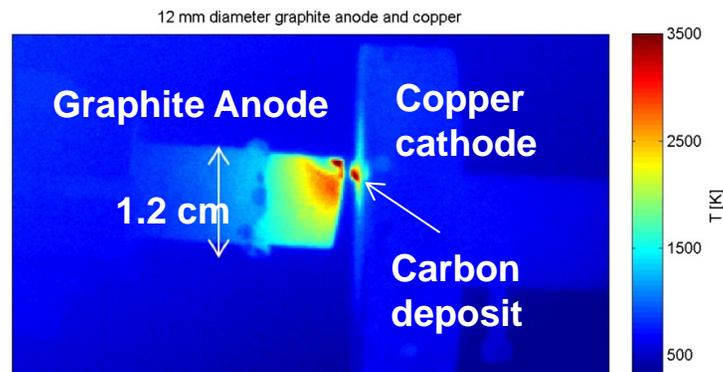
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**Highlight**



# SELF-ORGANIZATION IN ATMOSPHERIC PRESSURE CARBON ARC DISCHARGES

- Material evaporation and deposition processes in arc discharges are critically important for arc synthesis of nanomaterials.
- Experiments with carbon arcs demonstrated a two-fold role of the cathode carbon deposit:
  - The deposit is hot enough ( $> 3000$  K) to support the arc by thermionic emission.
  - The deposit is a good thermal insulator ( $\sim 1$  W/m/K) that protects the cathode bulk material under deposit.
- The results revealed self-organization of the carbon arc discharge.



- Self-organization of the carbon arc

- IR camera measurements of the arc electrodes

PLSC\_0414

**HIGHLIGHT**

# NO<sub>3</sub> Formation on Surfaces by Atmospheric Pressure Plasma Jet Treatment

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Atmospheric pressure plasma jets (APPJs) have attracted substantial attention due to the variety of plasma-generated reactive species that can deactivate bacteria and biomolecules or modify surfaces under mild conditions. In this work, lipopolysaccharide (LPS), a toxic biomolecule, 193 nm photoresist (PR193), 248 nm photoresist (PR248), and polystyrene (PS) were exposed to an Ar APPJ with small O<sub>2</sub>/N<sub>2</sub> admixtures. LPS biological activity was monitored by an immunosorbent assay and PR193 etch rates were measured by *in situ* ellipsometry. After treatments, the surface chemistry was measured by x-ray photoelectron spectroscopy (XPS). The APPJ is mounted inside a vacuum chamber that can be evacuated and then refilled with a controlled environment. We regulate the interaction of the plasma with the ambient by confining the plasma inside an alumina tube or allowing it to extend out of the tube as a plume.

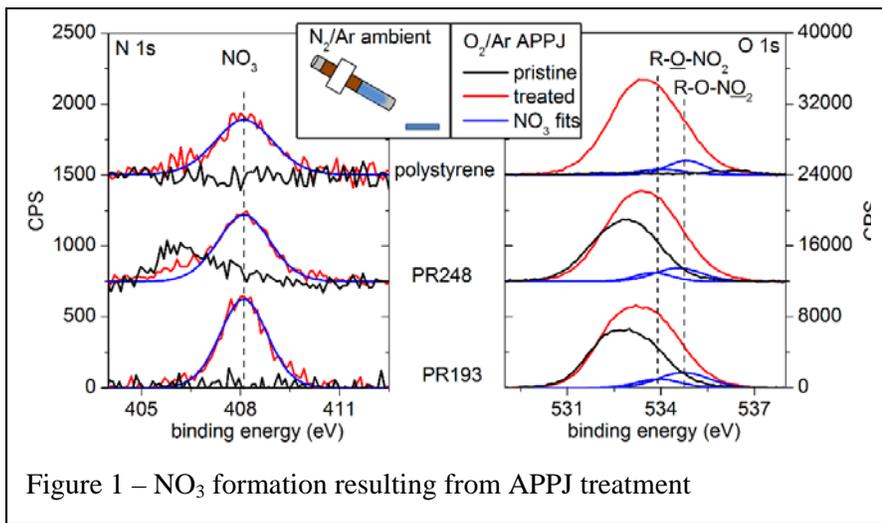


Figure 1 – NO<sub>3</sub> formation resulting from APPJ treatment

For exposure conditions that lead to high levels of biodeactivation and oxygen uptake, we observed the formation of a transient surface species that has been stoichiometrically identified as NO<sub>3</sub>. Additionally, NO<sub>3</sub> forms on polymers even if the film contains neither oxygen nor nitrogen i.e. polystyrene. As the feed gas contains only O<sub>2</sub> and Ar for these conditions, the NO<sub>3</sub> must result from plasma-generated species interacting with ambient N<sub>2</sub>.

When the plume is exposed to N<sub>2</sub>/Ar environments, surface modifications such as oxygen uptake and formation of surface-bound NO<sub>3</sub> increase with decreasing ambient N<sub>2</sub> concentrations in N<sub>2</sub>/Ar environments. This results from the plasma exciting ambient N<sub>2</sub>, which quenches reactive oxygen species that would otherwise modify the films. Consistent with this quenching role, N<sub>2</sub> addition to O<sub>2</sub>/Ar feed gas results in decreased bioactivity, ozone densities, and atomic O emission. Despite the surface modification, ellipsometry shows that O<sub>2</sub>/Ar plasma treatments produce quite low PR193 etch rates.

Experiments in ozone-rich environments produced using an air-fed corona discharge have shown that NO<sub>3</sub> formation on surfaces decreases rapidly with discharge-sample distance even though the O<sub>3</sub> concentration at the polymer surface remains high.

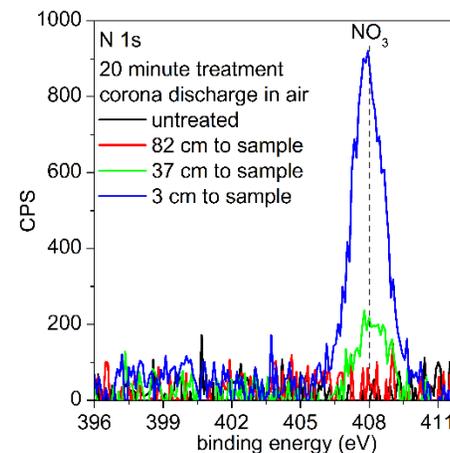
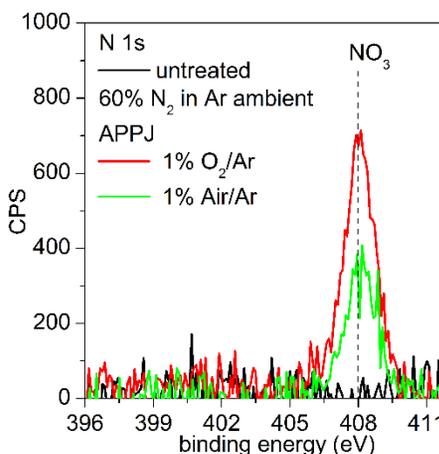
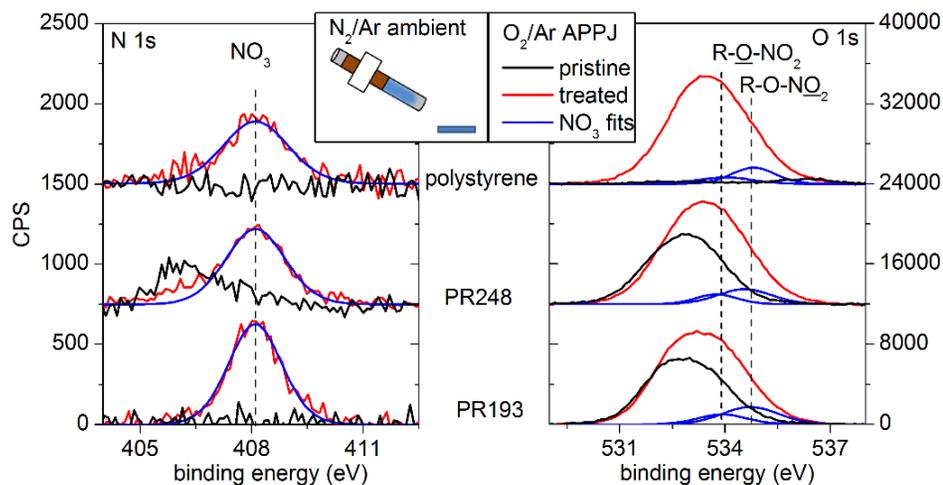
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**Highlight**



# NO<sub>3</sub> FORMATION ON SURFACES BY ATMOSPHERIC PRESSURE PLASMA JET (APPJ) TREATMENT

- An APPJ mounted in a controlled environment vacuum chamber (N<sub>2</sub>/Ar) was used to study plasma-ambient interactions on surface modification
- A new transient surface species, NO<sub>3</sub>, has been observed that leads to significant oxygen uptake & biodeactivation of biopolymers
- NO<sub>3</sub> forms even if polymer surfaces contain neither O nor N. N<sub>2</sub> admixtures to O<sub>2</sub>/Ar plasma reduce NO<sub>3</sub> formation. N<sub>2</sub> quenches reactive oxygen species necessary for NO<sub>3</sub> formation, which do not include O<sub>3</sub>.



- NO<sub>3</sub> forms on a variety of surfaces and is accompanied by major oxygen uptake.
- O<sub>2</sub>/Ar plasma forms more NO<sub>3</sub> than N<sub>2</sub>/O<sub>2</sub>/Ar plasma
- O<sub>3</sub> is not responsible