April 2017

Inductively Coupled Plasma Sources at Low Driving Frequencies

Vladimir Kolobov[a] and Valery Godyak[b]

(a) CFDRC and University of Alabama in Huntsville (vik@cfdrc.com)
(b) RF Plasma Consulting and University of Michigan (egodyak@gmail.com)

Inductively Coupled Plasmas (ICPs) can be maintained over a wide range of driving frequencies, from 50 Hz to GHz. We have investigated the specifics of ICP operation at different frequencies which address: a) nonlinear plasma dynamics due to the disparity of time scales for ion transport and electron energy relaxation, b) the absence of time-varying magnetic field in plasma for certain ICP configurations, and c) the absence of a skin effect at low frequencies. Numerical simulations have been performed to demonstrate the spatial distributions of the electric and magnetic fields for different coil topologies when using ferromagnetic cores.

We investigated three regimes of ICP operation with respect to angular frequency ω, the time scale for ion transport τ_a and the electron energy relaxation time τ_ε. Since it is usually the case that $\tau_a >> \tau_\varepsilon$, one can distinguish quasi-static ($\omega\tau_a<1$), dynamic ($\tau_\varepsilon^{-1} > \omega > \tau_a^{-1}$), and high-frequency ($\omega\tau_\varepsilon >1$) regimes. An example of an ICP having ferrite cores forming a closed magnetic path is shown in Fig. 1, The calculated electron temperature and plasma density at different ω in Argon gas at a pressure of 2 Torr and coil current of 0.1 A are also shown, from $\omega = 10^2$ το 10^7. In the high-frequency regime, the electron density and the electron temperature, T_e, are essentially constant over the period. A highly nonlinear behavior is observed in quasi-static regime. In the dynamic regime, the plasma density varies slightly over the field period, but the T_e and the Electron Energy Distribution Function (EEDF) could change significantly over the field period. Detailed studies of the dynamic regime have not been performed so far, and our work [1] appears to be the first step in this direction. As an example of important kinetic effects, we have observed dynamic constriction of the ICP column at low frequencies due to Maxwellization of the EEDF by Coulomb collisions.

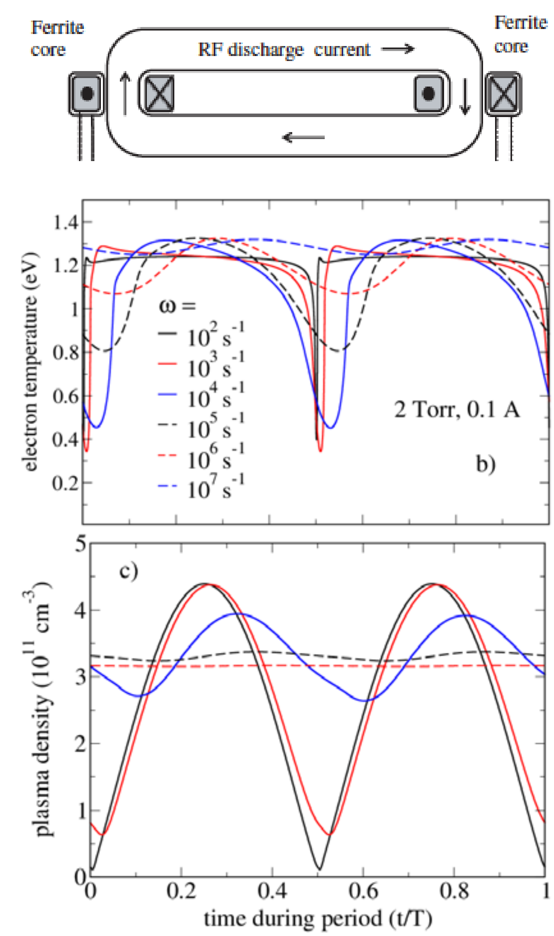
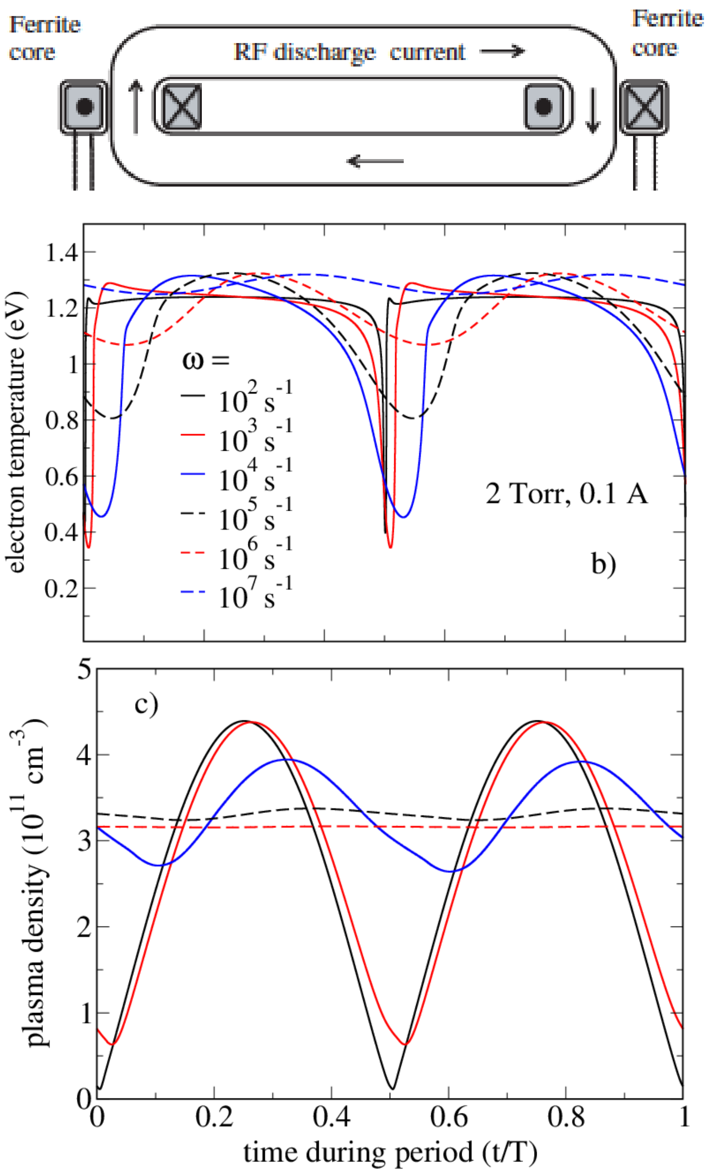


Figure 1 – ICP geometry (a) and time dependence of the electron temperature (b) and plasma density (c) at different driving frequencies.

References

[1] V. I. Kolobov and V. A. Godyak, "Inductively Coupled Plasma at Low Driving Frequencies", Plasma Sources Science Technology, in press (2017).

INDUCTIVELY COUPLED PLASMAS AT LOW FREQUENCIES



- Plasma properties are governed by differences in ion transport τ_a and electron energy relaxation τ_ε times.
- Since $\tau_a >> \tau_\varepsilon$, there are three regimes:
  - a) quasi-static: $\omega\tau_a < 1$
  - b) dynamic: $\tau_\varepsilon^{-1} > \omega > \tau_a^{-1}$
  - c) high-frequency: $\omega\tau_\varepsilon > 1$
- ICPs with ferrite cores forming closed magnetic paths were investigated at different frequencies at constant current.
- In quasi-static and dynamic regimes, nonlinear transport results due to the disparity in ion and electron transport times, shown by behavior of electron temperature and density.

HIGHLIGHT

UNIVERSITY OF MICHIGAN

UAHuntsville

CFDRC Delivering Breakthrough Solutions

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems

PSC Department of Energy Plasma Science Center

DOE Plasma Science Center
Control of Plasma Kinetics

Micro-plasma Surface Treatment of Luminescent, Water-soluble Silicon quantum dots

Jeslin J. Wu, V. S. Santosh K. Kondeti, Peter J. Bruggeman and Uwe R. Kortshagen
University of Minnesota, Department of Mechanical Engineering
(pbruggem@umn.edu, Kortshagen@umn.edu)

Silicon quantum dots (SiQDs) were synthesized in a low pressure, nonthermal plasma reactor using silane SiH_4 as a precursor [1]. An atmospheric pressure, nonthermal micro-plasma jet was used to treat the hydrophobic SiQD surface. The micro-plasma jet has a maximum electron density of 10^{20} m^{-3} but can produce reactive species densities such as atomic oxygen in excess of 10^{22} m^{-3} while maintaining a gas temperature not exceeding 50 K above room temperature at a few mm from the nozzle [2,3]. The hydrogen-terminated hydrophobic SiQDs were first wetted in ethanol to aid initial dispersion into water and dispersed in distilled water. The micro-plasma-treated SiQDs demonstrated several characteristics that are highly attractive. For the first time, efficient size-tunable luminescence, with photoluminescence quantum yields exceeding 50%, was observed from water-soluble SiQDs. The stability of the micro-plasma-treated SiQDs is likely the result of the formation of a stable oxide shell.

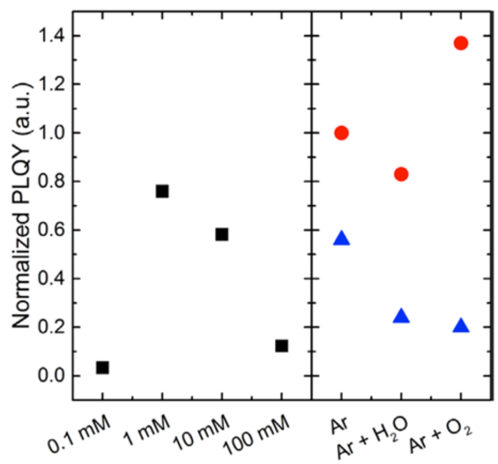


Figure 1 – Normalized photoluminescence quantum yield (PLQY) of SiNCs after Fenton's reaction as a function of molar concentration of H_2O_2 and iron(II) sulfate (black squares) and of SiNCs treated with Ar, Ar +0.25% H_2O, and Ar +1% O_2 micro-plasma with the nozzle placed 3.5 mm (red circles) and 12 mm (blue triangles) away from the liquid surface.

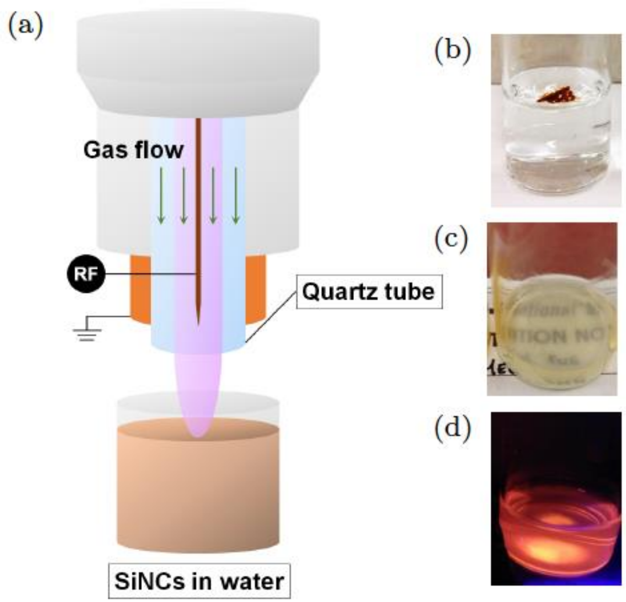
A goal of this work was to assess the underlying plasma properties that enable the exceptional photoluminescence quantum yields. The plasma-induced chemistry has been changed drastically by admixing O_2 and H_2O in the micro-plasma jet. A combination of modeling and laser diagnostics showed that for these different gases a large variation in OH and O density flux towards the liquid occurs [3]. As shown in Fig, 1, comparison of the micro-plasma treatment with Fenton's reaction indicates that the OH species generated in the liquid-phase can play a significant role in surface passivation. However, the remarkable result is that the highest photoluminescence quantum yield is found for the plasma conditions corresponding with the highest flux of atomic oxygen. This result suggests the importance of atomic oxygen in high density atmospheric pressure plasmas for the SiQD surface passivation that has up to now mainly been attributed to the OH radicals.

References

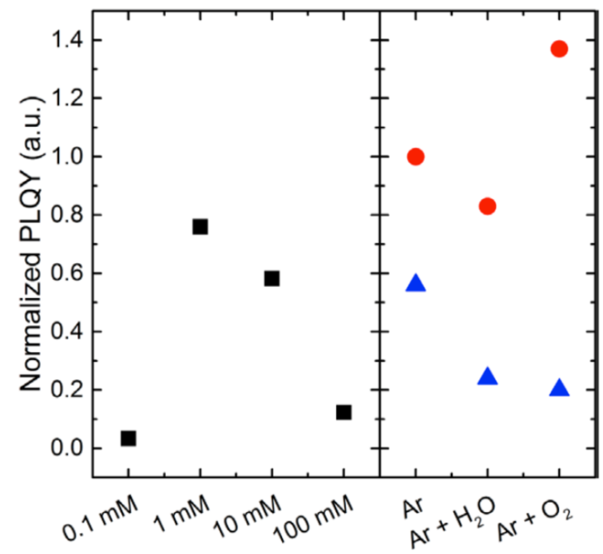
[1] Mangolini L, Thimsen E and Kortshagen U, Nano Lett. **5**, 655-659 (2005).
[2] van Gils C A J, Hofmann S, Boekema B K H L, Brandenburg R and Bruggeman P J, J. Phys. D. Appl. Phys. **46** 175203 (2013).
[3] Wende K, Williams P, Dalluge J., van Gaens W. et al. Biointerphases, **10**, 029518 (2015).

LUMINESCENT, WATER-SOLUBLE SILICON QUANTUM DOTS VIA MICRO-PLASMA SURFACE TREATMENT

- **A micro-plasma jet treated silicon quantum dots (Si QDs) suspended in water; and produced size-tunable luminescence, with photoluminescence quantum yields exceeding 50% from these water-soluble Si QDs.**
- **OH in the liquid-phase generated by the plasma jet is believed to be important for surface passivation. However, here highest quantum yields occurred for the maximum atomic O flux to the liquid, indicating an important role of atomic O.**



- **Microplasma jet treatment of Si quantum dots**



- **Photoluminescence quantum yield with micro-plasma nozzle (red) 3.5 mm and (blue) 12 mm from liquid surface.**

April 2017 **HIGHLIGHT**

University of Minnesota — Driven to Discover

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems

PSC — Department of Energy Plasma Science Center

DOE Plasma Science Center

Control of Plasma Kinetics