Effect of Local Gas Chemistry and Type of Cold Atmospheric Plasma Source on VUV Exposure

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Different cold atmospheric plasma (CAP) sources are used for a variety of applications and produce a variety of different reactive species based on operating conditions such as gas chemistry and operating voltage. Direct comparisons of these different sources and understanding of how local environment near the target can affect the flux of species and high energy photons are lacking. Experiments with a kHz driven ring-APPJ show direct interactions between the plasma and the sample surface can cause local damage to polymer films whereas more remote treatments showed uniform thickness reduction [1]. For an Ar-based kHz driven ring-APPJ the source of thickness reduction is largely due to vacuum ultraviolet (VUV). This observation is supported by increased modification of a 193 nm as opposed to a 248 nm photoresist polymer. Modification was also seen with line-of-sight by placing a mesh directly over the sample. The VUV is produced from Ar_2* at 125 nm as shown by using MgF_2 and alumina optical filters with 114 nm and 140 nm cutoff wavelengths. Fourier transform infrared spectroscopy (FTIR) of treated polymer films showed similar reductions in C-O-C and C=O bonding as for low pressure VUV treatments [2]. (See Fig. 1)

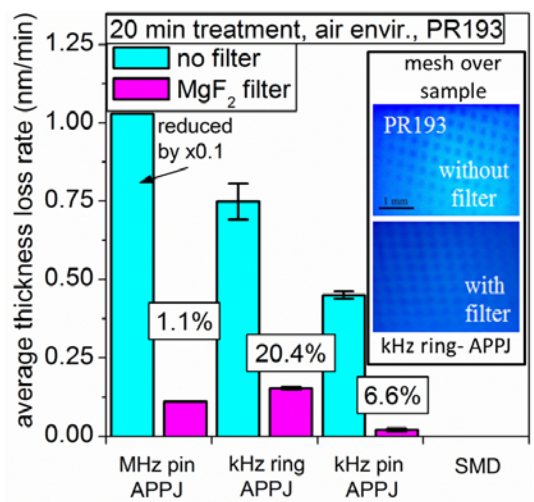


Figure 1 – Comparison of CAP sources shown with and without a MgF_2 filter in place. Insert: Mesh pattern transfer to PR193 with and without MgF_2 filter.

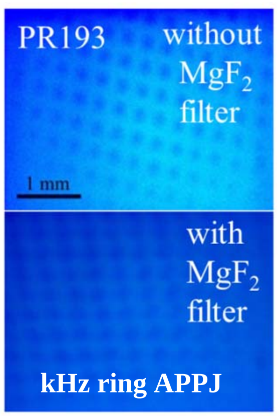
Modification rates decrease with increasing O_2 in the local gas environment. This modification rate increases over the duration of experiment as Ar becomes the dominant gas in the chamber. The VUV emission from the APPJ is absorbed by O_2 in the local environment and significantly less by N_2 and Ar. This was confirmed by using finite element modeling (COMSOL) to investigate the gas mixture over time between the APPJ and the sample. Using this O_2 concentration, the Beer-Lambert law was used to estimate the decrease of the modification with increasing O_2, which agreed with experimental data. VUV modification was different depending on the type of source. The kHz driven ring APPJ showed the largest modification through a MgF_2 filter compared to without. All jet-type sources which use Ar showed effects due to VUV reaching the surface to various degrees. In contrast, the surface microdischarge (SMD) source operates without noble gas and showed no thickness loss for either condition. Adding 1% O_2 to the Ar flow in a MHz jet source also effectively eliminated VUV effects as the O_2 strongly reduces the formation of excimers.

References

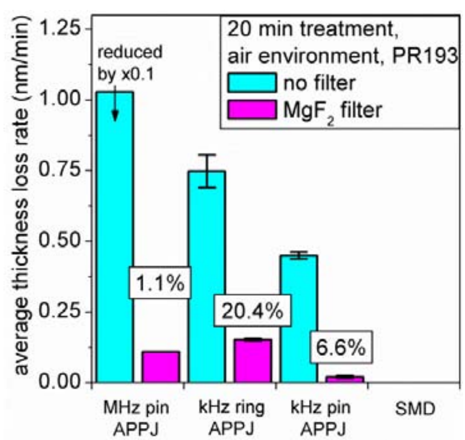
[1] A. J. Knoll, et al., Appl. Phys. Letters **17**, 105 (2014).
[2] F. Weilnboeck, et al., Journal of Vacuum Science & Technology B **3**, 30 (2012).

EFFECT OF GAS FLOW AND TYPE OF ATMOSPHERIC PRESSURE PLASMA ON VUV EXPOSURE

- **Different responses of 193 nm and 248 nm photoresist (PR) to VUV with cut-off wavelength optical filters were used to examine the importance of VUV surface modification for different cold atmospheric plasma (CAP) sources.**
- **VUV surface modification is highly dependent on source type – major modification by Ar plasma, and absent for surface microdischarges (SMD) using O_2/N_2 .**
- **Local environment has a large impact on polymer modification from VUV emission as O_2 readily absorbs the 125nm Ar excimer wavelength. This was shown experimentally and by modeling the gas flow from the CAP jet source.**

a)


mesh over sample

b)


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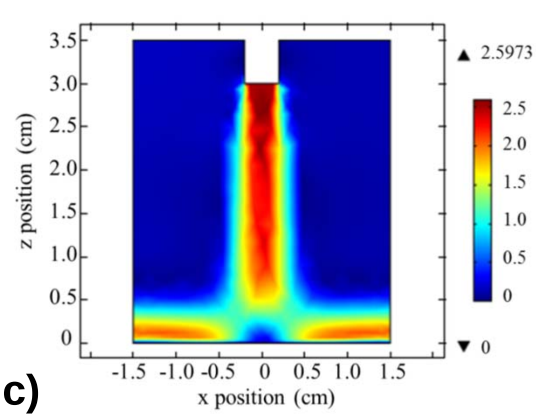

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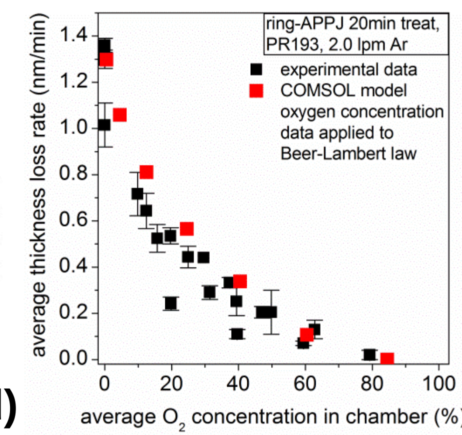

a) Line-of-sight VUV effect on PR
b) Comparison of VUV effect vs CAP source

c) Model of gas flow from jet source
d) Comparison of model with experiment

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HIGHLIGHT

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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

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Global Modeling for Rare Gas Metastable Lasers

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Diode-pumped alkali vapor lasers (DPAL) convert the broad band, poor optical quality, incoherent radiation from diode lasers into narrow band, high quality coherent radiation from alkali vapor. Previous studies extended the concept of DPAL to show that rare gas metastable states, np^5 $(n+1)s[3/2]_2$, can operate as the base of a three-level laser with excitation of the $(n+1)s \rightarrow (n+1)p$ transitions.[1] The electronic structure of the metastable states of rare gases is similar to that of alkali atoms. Though both rare gas lasers (RGLs) and DPALs are pumped with incoherent optical pumping, RGLs do not suffer from the highly reactive behavior of alkali metals. As opposed to working from the vapor pressure of the metal for DPALs, the metastable rare gases are produced with pulsed electric discharges and are relatively inert with respect to buffer gases and materials. Since metastable populations are maintained via electric discharges, we proposed that a tuned electron energy distributions (EEDs) can improve RGL efficiency and potentially drive the gain mechanism without the need for intense optical pumping.

To better understand the consequences of system variables, we used the kinetic global modeling framework (KGMf), a newly implemented laser module, and three different gas systems (pure argon, and helium buffered argon or krypton) to map the possible parameter space.[2] The laser dynamics are addressed using a two-way averaged intracavity laser intensity model introduced for studying DPAL systems.[3]

The resulting global models were then validated with previously published studies employing both experimental and computational data.[4] The results obtained through the KGMf identified gain and energy efficiency baselines for each gaseous system being optically pumped. Preliminary result-search methods were utilized to identify optimized EEDs and system parameters for metastable production, generation of a lasing population inversion, and improving RGL operation efficiencies. (See Fig. 1.) Finally, we aim to determine if a RGL can efficiently operate without optical pumping using a different reaction pathway.

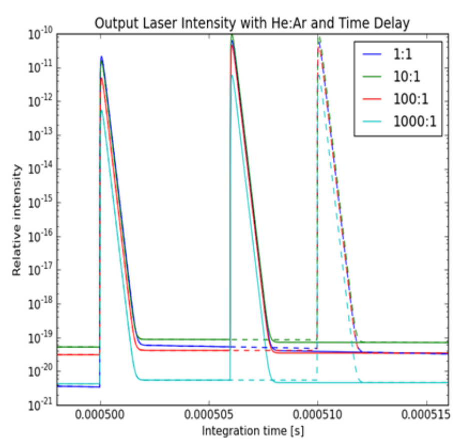

Figure 1 – Non-linear relationship between gas ratios, optimal RF to optical pulse delay, and laser output.

References

[1] J. Han and M.C. Heaven. Opt. Lett., **37**, 2157 (2012).
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[3] N. D. Zameroski, G. D. Hagar, W. Rudolf and D. A. Hostutler. J. Opt. Sc. Am. B, **28**, 1088 (2011).
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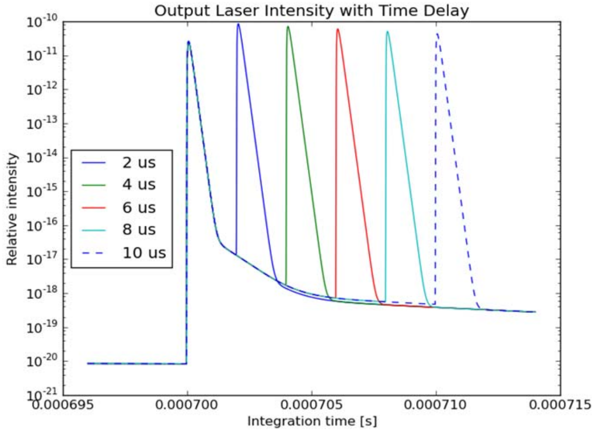
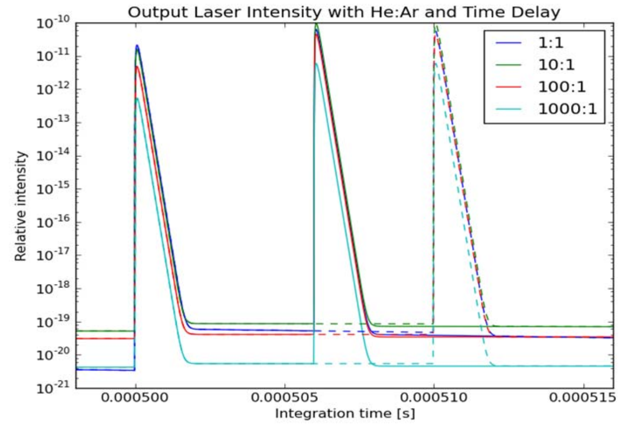
GLOBAL MODELING OF RARE GAS METASTABLE LASERS

- **Extending experiments of 3-level laser using rare gas metastables, a laser module was implemented in the Kinetic Global Modeling framework (KGMf) to optimize performance using parameter-scanning methods**
- **KGMf was validated for multiple gases (Ar, Ar/He, Kr/He) enabling testing of tuned EEDFs and quantified sensitivity to system/module inputs.**
- **Current system requires electrical (plasma) and optical pumping. Work addresses indirect methods of achieving population inversion with a minimum of optical pumping and emphasis on plasma pumping.**



- **Effect of delay between RF and optical pulses**



- **Non-linear relationship between buffer gas ratio and output intensity**

- **G. Parsey, Y. Güçlü, J. Verboncoeur, A. Christlieb. "A kinetic plasma-pumped rare gas laser", 68th Gaseous Electronics Conference, Honolulu, Oct. 2015**