How To Control Fluxes of Nanoparticles to a Substrate

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Recently it was reported that monocrystalline (epitaxial) silicon and germanium films could be grown by plasma-enhanced chemical vapor deposition (PECVD) at much lower substrate temperatures than normally required.[1] It was hypothesized that the key to growing such films is energetic bombardment of the film substrate by nanoparticles during film growth. If the nanoparticles are small enough (below ~3 nm), then high-velocity impact could cause them to melt, promoting sufficient atomic mobility to facilitate epitaxial growth on (100)-oriented crystalline substrates. Thus, if nanoparticles could be delivered with high velocities to a substrate during PECVD film growth, and if this process could be controlled with respect to particle size and impact energy, important applications in microelectronics and optoelectronics could be enabled.

One possible strategy to achieving such control of nanoparticle fluxes is RF plasma pulsing, combined with positive DC biasing of the growth substrate during the afterglow phase of each pulse. To explore this strategy, we adapted a previously developed 1-D numerical model that self-consistently calculates the behavior of a capacitively-coupled RF argon-silane plasma in which silicon nanoparticles nucleate and grow.[2-3]

Preliminary results indicate that pulsing frequency, duty cycle and DC bias voltage are key parameters that control nanoparticle fluxes. By correct choice of these parameters it is possible to reach a periodic state in which all of the negatively-charged nanoparticles are collected during each afterglow phase, while the size of the collected nanoparticles is limited by the plasma on-time during each pulse and their impact energy is controlled by the applied bias voltage.

Model predictions are shown in Fig. 1 for the volume fluxes of negative, neutral and positive nanoparticles to the film substrate, together with the predicted mean particle size for each of these populations. Conditions are 13.56 MHz, RF amplitude 100 V, pressure 100 mTorr, electrode gap 4 cm, 3% silane in argon, pulse frequency 50 Hz, duty cycle 50%, DC bias 100 V. These results indicate that the proposed approach has considerable promise to achieve the desired control of nanoparticle fluxes to a substrate.

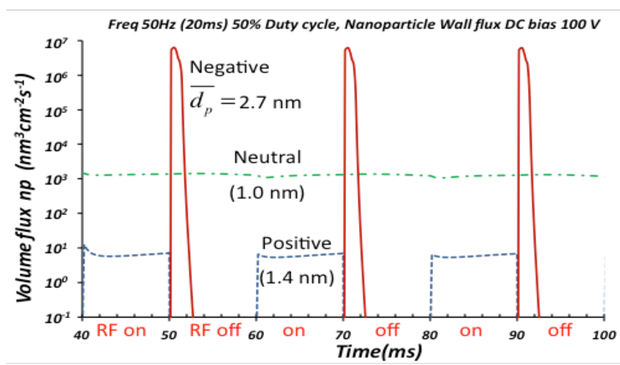


Figure 1 – Predicted volume fluxes of negative, neutral and positive nanoparticles to substrate over three RF pulse cycles. Negative particles, accelerated to biased substrate during afterglow, comprise

References

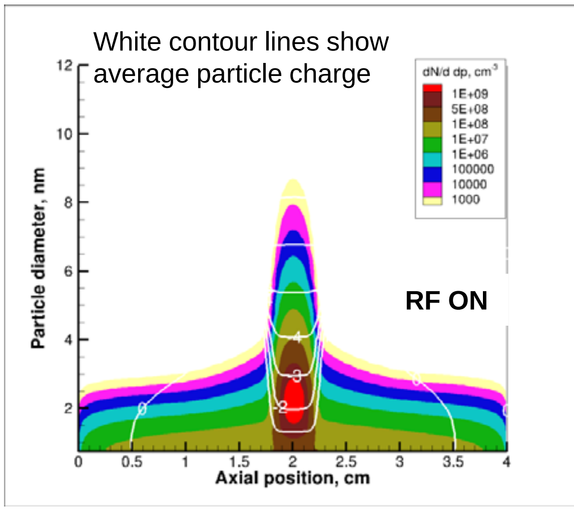
[1] M. Labrune, X. Bril, G. Patriarche, L. Largeau, O. Mauguin and P. Roca i Cabarrocas, EPJ Photovolt. **3**, 30303 (2012).

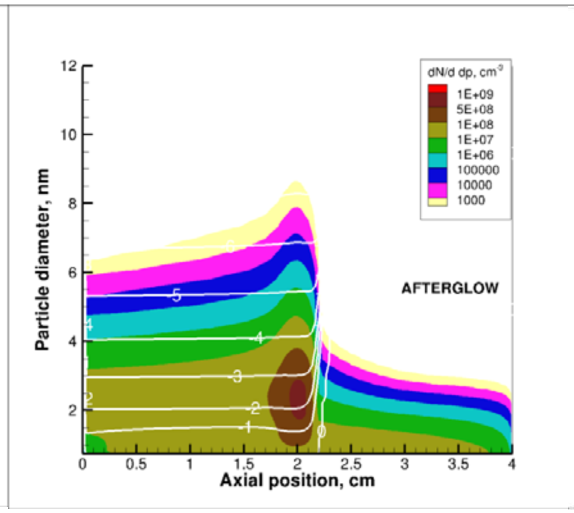
[2] P. Agarwal and S. L. Girshick, Plasma Source. Sci. Technol. **21**, 055023 (2012).

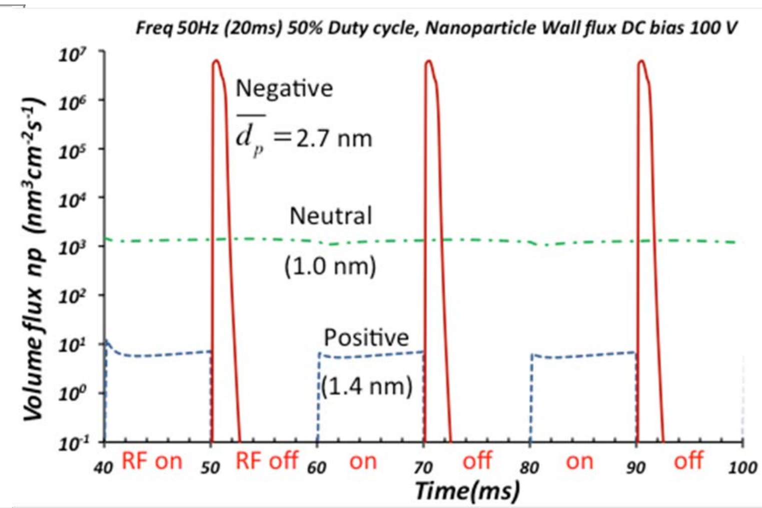
[3] P. Agarwal and S. L. Girshick, Plasma Chem. Plasma Process. **34**, 489 (2014).

PULSED DUSTY PLASMA FOR CONTROL OF NANOPARTICLE FLUXES TO A SUBSTRATE

- **Hypothesis: High-velocity impact of very small (< 3 nm) nanoparticles promotes epitaxial growth of Si films at much lower substrate temperatures than normally required**
- **Possible strategy: Pulsed RF argon-silane plasma with positive DC bias applied to substrate during afterglow phase**
- **Preliminary investigation: Developed numerical model of pulsed RF argon-silane plasma**
- **Simulation results: Negative particles are trapped in plasma during RF ON phase, then accelerated to substrate by DC bias during afterglow**







- **ON phase: negative particles trapped in center & growing**
- **Afterglow: negative particles accelerated to biased substrate**
- **Fluxes of negative, neutral & positive nanoparticles to substrate & average particle sizes**

HIGHLIGHT

UNIVERSITY OF MINNESOTA

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

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Control of Plasma Kinetics

Coupled Transport in Plasma-Liquid Interactions

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The study of atmospheric pressure plasmas interacting with liquids involves many complex issues that have yet to be resolved.[1,2] One of these important issues is the role of plasma-induced (or imposed) gas flow in altering transport phenomena associated with the plasma-liquid interface. The present highlight shows recent results from finite element simulations of an assumed gas flow (associated with, for example, a pulsed corona discharge that induces flow from the 'ionic wind.') The gas phase advection induces a flow in the liquid due to gas-liquid viscous stress and momentum transfer between the gas and liquid. The liquid is assumed to be water in this example. The water will also evaporate into the gas phase at a rate determined by coupled heat and mass transfer. Both transfer processes depend strongly on gas flow.

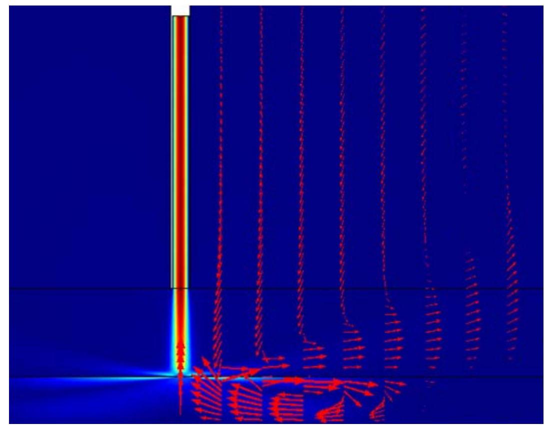


Figure 1 – Velocity vectors in the liquid and gas phases. Note that the magnitude of the velocity vectors in the gas phase and liquid phase are scaled differently for clarity.

The gas and liquid phase velocity vectors in the example studied are shown in Fig. 1. Recirculating currents are induced in the liquid adjacent to the interface by the impinging gas flow. The liquid-phase convection induced by the gas flow can have profound effects on transport between phases. The difference in concentration profiles calculated for nitric acid (HNO_3) transport into the liquid phase when convective as well as diffusive forces are present are shown in Figure 2. The total quantity of reactive species transferred from the gas to the liquid phase, as well as spatial concentration profiles, can be a strong function of convection.

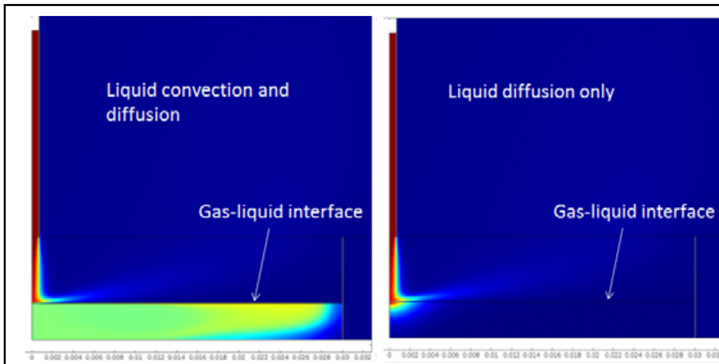


Figure 2 – Concentration profiles of nitric acid (HNO_3) in the gas and liquid phases considering (left) convective and diffusive forces, and (right) diffusive transport only.

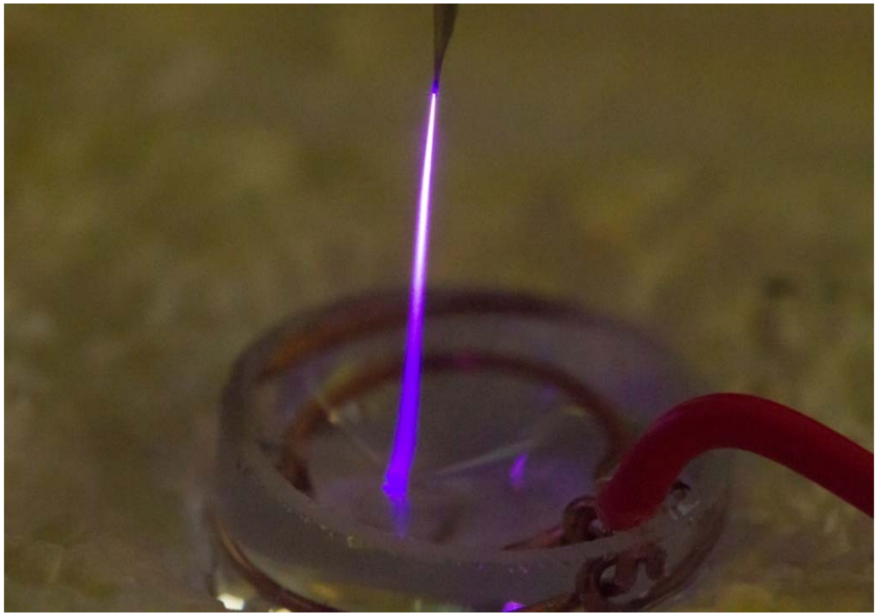
References

[1] P. Bruggemann and C. Leys, J. Phys. D: Appl. Phys. **42**, 053001 (2009).

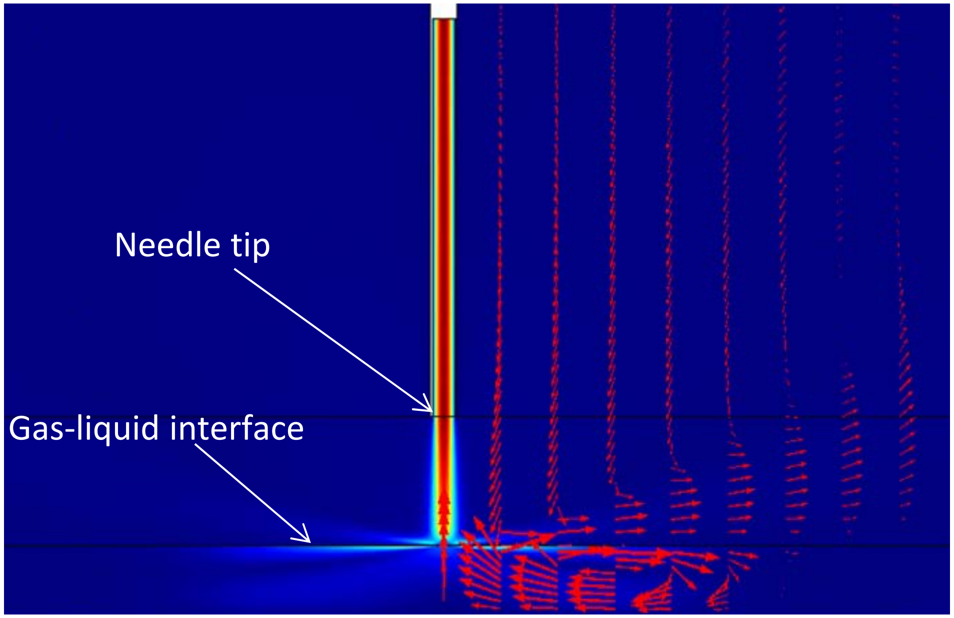
[2] B. Locke and K.-Y. Shih, Plasma Sources Sci. Tech. **20**, 034006 (2011).

TRANSPORT IN PLASMA-LIQUID INTERACTIONS

- Plasma-activated-liquids in biotechnology are produced by transport of gas-plasma species into the liquid.
- Ionic wind from pulsed atm. pressure treamer induces convection in liquid.
- Coupled heat & mass transfer in water evaporation → water vapor above liquid & significant cooling of liquid.
- Observe strongly inhomogeneous distributions of reactive species (OH, ONOOH) in liquid phase despite convective mixing.



- Pulsed streamer over water



- Simulation of gas & liq. convection

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