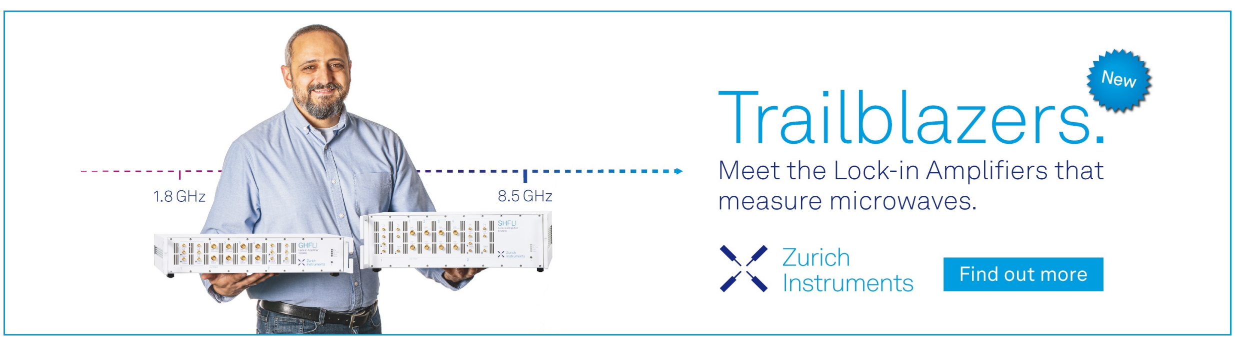
Journal of Applied Physics

Response to "Comment on 'The effects of radio-frequency bias on electron density in an inductively coupled plasma reactor'" [J. Appl. Phys. 132, 156101 (2022)]

Cite as: J. Appl. Phys. **132**, 156102 (2022); https://doi.org/10.1063/5.0109603
Submitted: 13 July 2022 • Accepted: 19 September 2022 • Published Online: 20 October 2022

M. A. Sobolewski and J.-H. Kim



AIP Publishing

Journal of Applied Physics RESPONSE scitation.org/journal/jap

Response to "Comment on 'The effects of radio-frequency bias on electron density in an inductively coupled plasma reactor'" [J. Appl. Phys. 132, 156101 (2022)]

Cite as: J. Appl. Phys. **132**, 156102 (2022); doi: 10.1063/5.0109603
Submitted: 13 July 2022 · Accepted: 19 September 2022 · Published Online: 20 October 2022

View Online Export Citation CrossMark

M. A. Sobolewski[1,a)] and J.-H. Kim[2]

AFFILIATIONS

[1]National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
[2]Korea Research Institute for Standards and Science, Daejeon 305-340, Republic of Korea

[a)]**Author to whom correspondence should be addressed:** mark.sobolewski@nist.gov

ABSTRACT

The rf-bias-induced decreases in plasma electron density observed by us [J. Appl. Phys. **102**, 113302 (2007)] and others [Fox-Lyon *et al.*, J. Vac. Sci. Technol. A **32**, 030601 (2014)] are better explained by changes in gas composition, rather than neutral gas depletion.

Published by AIP Publishing. https://doi.org/10.1063/5.0109603

In our paper,[1] we reported two kinds of rf-bias-induced changes in plasma electron density n_e. First, at low inductive source powers, in all three gases (Ar, CF_4, and 50:50 mixtures of Ar/CF_4), we saw a rapid increase in n_e, which was explained in detail, including its origin (absorption of bias power by electrons) and its dependence on source power, bias voltage, and bias frequency. Second, at both high and low source powers, we saw a slower, bias-induced decrease in n_e. It was strong in Ar, weaker in Ar/CF_4, and nearly absent in pure CF_4.

We attributed the observed decrease in n_e to changes in gas composition, in particular, a bias-induced liberation of electronegative atoms or molecules from surfaces. Because Ar plasmas have no native source of negative ions, they are sensitive to small additions of electronegative components. For example, in Ar/CF_4, the sensitivity of n_e to changes in CF_4 content is strong in argon-rich mixtures, weaker for equal mixtures, and near zero for argon-poor mixtures.[2]

In their comment,[3] Du and Ding propose a different explanation: that slow, bias-induced heating of the biased electrode heats the neutral gas, increasing its temperature and reducing its density, which in turn decreases n_e. This is a plausible hypothesis, but it does not appear to be supported by any experiment. We are aware of two studies[4,5] that have measured the effect of rf bias on the temperature of neutral gas molecules. Neither shows an increase in gas temperatures with increasing rf bias power. They show a slight decrease or no change. Nevertheless, because the gases and other experimental conditions in those studies differ from Ref. 1, the subject may merit further investigation.

The only other study that has measured the time-response of bias-induced changes in n_e is that of Fox-Lyon *et al.*,[6] in Ar plasmas. They did not observe a slow, bias-induced decrease in n_e that could be attributed to changes in wafer temperature or other slow thermal effects. They instead saw a fast decrease of n_e. It was attributed to bias-induced release of hydrocarbons from the wafer surface because it was equal in magnitude to the n_e decrease seen when the same amount of hydrocarbon was injected into the feedgas. The response of n_e to feedgas injection had a fast component (explained by gas residence times) as well as a slow component (explained by the removal of hydrocarbon residues absorbed on remote surfaces).

It remains to be explained why the bias-induced decrease in n_e was fast in Fox-Lyon's system but slow in ours. The physical and thermal characteristics of the two systems seem similar but the gases—and, presumably, the surface conditions—differ. It may be that the slow n_e decrease that we observed is caused by species released, *not* from the wafer surface but from more remote grounded surfaces, where incident ion energies are lower and sputtering is less effective. The species perhaps are desorbed thermally through bias-induced heating of the remote surfaces. This would account for the slow time-response of our n_e decrease as well as its slow reversal after the rf bias was turned off. Also, remote surfaces in our system are expected to have surface layers containing not only oxygen but also carbon and fluorine—deposited during the CF_4 measurements. Fluorocarbon deposits may behave differently than the hydrocarbons studied by Fox-Lyon *et al.*

Du and Ding invoke another mechanism to explain rapid, bias-induced decreases in n_e, the "ion loss" effect. This supposed effect was originally proposed in Ref. 7 but no valid, logical explanation of it has been given, either in Ref. 7 or in Du and Ding's comment. More work is needed to identify the actual cause of the changes seen in Ref. 7. One clue may be provided by electron energy distributions measured by Kim *et al.*[8] They indicate a bias-induced increase in effective electron temperature, which would increase the Bohm velocity, causing n_e at the edge of the sheath to decrease relative to the positive ion flux and net ionization rate. This effect merits further investigation.

REFERENCES

[1] M. A. Sobolewski and J.-H. Kim, J. Appl. Phys. **102**, 113302 (2007).
[2] A. Schwabedissen, E. C. Benck, and J. R. Roberts, Plasma Sources Sci. Technol. **7**, 119 (1998).
[3] M. Q. Du and Z. F. Ding, J. Appl. Phys. **132**, 156101 (2022).
[4] G. A. Hebner, Appl. Surf. Sci. **192**, 161 (2002).
[5] B. A. Cruden and M. Meyyappan, J. Appl. Phys. **97**, 084311 (2005).
[6] N. Fox-Lyon, G. S. Oehrlein, and V. Godyak, J. Vac. Sci. Technol. A **32**, 030601 (2014).
[7] H.-C. Lee, M.-H. Lee, and C.-W. Chung, Appl. Phys. Lett. **96**, 071501 (2010).
[8] H. Kim, W. Lee, W. Park, and K.-W. Whang, J. Vac. Sci. Technol. A **31**, 041301 (2013).