Ageing studies for CSC detectors and ageing methodology

K. Kuznetsova (UF/INP)

DRD1 Collaboration Meeting
December 2024

Longevity studies for (wired) detectors

- ageing is a well known potential problem of all gaseous detectors

  (*summary by F. Sauli at Ageing Phenomena - 2023*)

- the nature of the ageing phenomena is chemical reactions between molecules of the detector material and/or gas mixture **in plasma conditions of the avalanche (or other) discharges**

- there is no strict theory of detector ageing processes, but quite a lot of **proved empirical experience**

- there are two directions in longevity studies

  - **methodological** - direct studies of ageing effects in their correlation to the gas and detector materials and to the detector operation condition

    Large contribution by CERN during the detector construction phase of LHC experiments

    - *for example, in this overview* (and many others)
  - **practical** – pre-production longevity tests for a given detector kind/chosen material/gas/gas equipment etc

Detector operation time

- Upon given conditions, the number of “operation cycles” of the detector is defined by **the number of avalanche discharges**, and the operation time is defined by the integral of the detector current, or so-called “**accumulated charge**”

- If the **irradiation is uniform** (GIF++ :), the characteristic value is the charge per anode wire length for wired detectors, or charge per unit of the detector area for wireless detectors

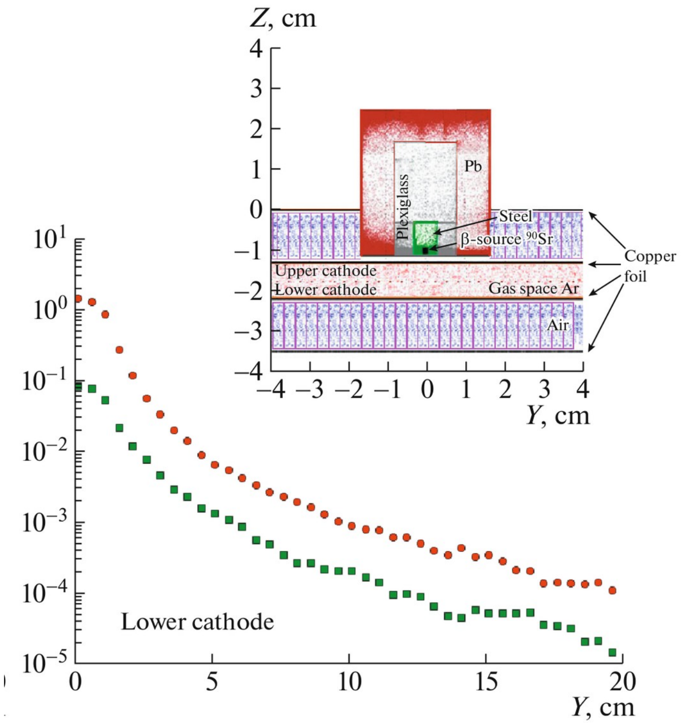
- For non-uniform irradiation (**local irradiation** with laboratory radioactive source) it is important (and a bit conditional…) to define the size of the irradiation spot to characterize the accumulated charge

Local irradiation – definition of the irradiation zone

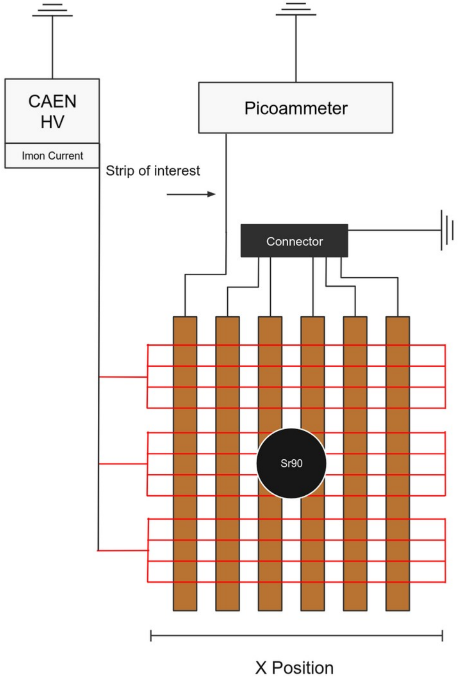
Can be defined different ways

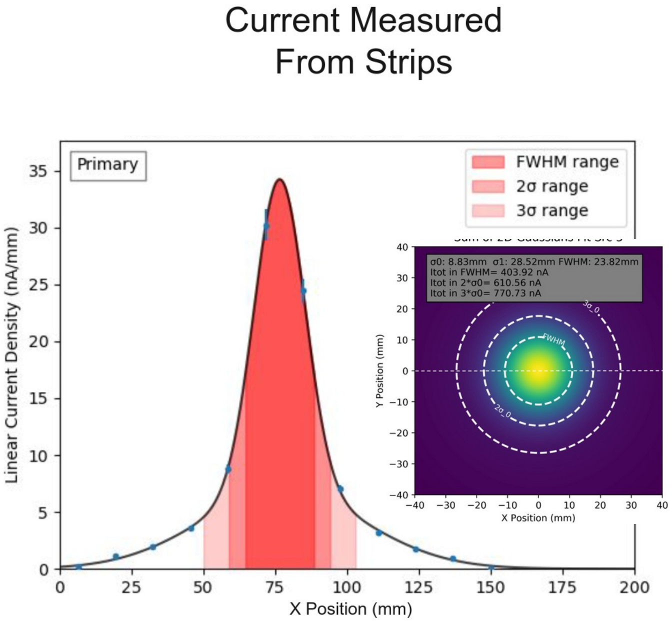
- **MC**

BUZOVERIA et al.
PHYSICS OF ATOMIC NUCLEI Vol. 82 No. 9 2019



- **Measurements**
  - Usually no way to use electronics read-out due to too high rate
  - Current measurement – if possible (for example, CSC :)
  - Emulsions? Other detectors?





Accelerated longevity tests

- Upon given conditions, the number of “operation cycles” of the detector is defined by **the number of avalanche discharges…**

- We never have possibility to perform one-to-one irradiation study
  - Have to irradiated with higher intensity (so-called **accelerated longevity test**)

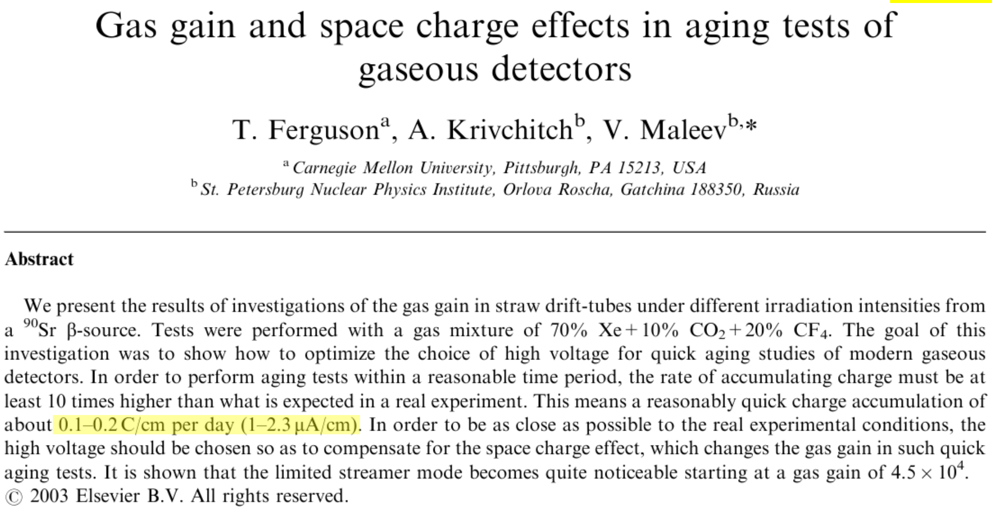
- Many factors will influence reliability of the (always!) accelerated longevity test. Just some of them:

  - Even if the production of the reactive radicals/ions/molecules is proportional to the irradiation intensity (not always), **the distribution of their concentration (non-uniform!) depends on…** presence of other molecules/ions/radicals (recombination), gas flow, electrical field, etc (can not be avoided)

  - Sometimes the high irradiation intensity results in presence of the **space charge** → lower gas gain → different distribution of the reactive species around the anode wire (can be checked and, probably, avoided)

  - Some of the detectors have relatively large resistance in the HV circuit and **high irradiation current** causes the voltage drop changing the actual operation voltage (can be easily avoided)

Accelerated longevity tests



Gas gain and space charge effects in aging tests of gaseous detectors

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Abstract

We present the results of investigations of the gas gain in straw drift-tubes under different irradiation intensities from a ^{90}Sr β-source. Tests were performed with a gas mixture of 70% Xe + 10% CO_2 + 20% CF_4. The goal of this investigation was to show how to optimize the choice of high voltage for quick aging studies of modern gaseous detectors. In order to perform aging tests within a reasonable time period, the rate of accumulating charge must be at least 10 times higher than what is expected in a real experiment. This means a reasonably quick charge accumulation of about 0.1–0.2 C/cm per day (1–2.3 μA/cm). In order to be as close as possible to the real experimental conditions, the high voltage should be chosen so as to compensate for the space charge effect, which changes the gas gain in such quick aging tests. It is shown that the limited streamer mode becomes quite noticeable starting at a gas gain of 4.5×10^4.

Nuclear Instruments and Methods in Physics Research A 515 (2003) 283–287

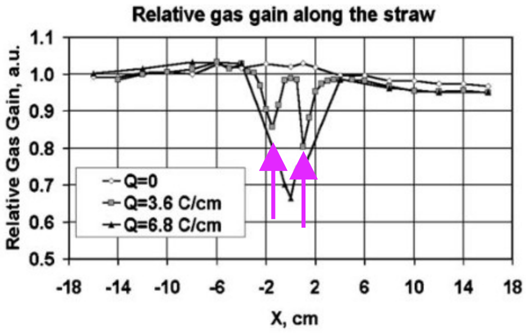

Fig. 5. Relative gas gain along the straw-tube for different accumulated doses.

45% of the space charge was compensated by HV

Is the result of such over-accelerated test reliable?

May be still useful for comparative studies?

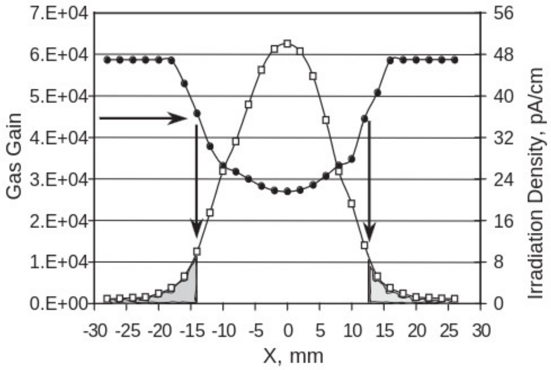

Fig. 6. The gas gain distribution across the beam profile. The beam profile was studied by measuring the irradiation current density for different straw position across the beam. Gray background labels two zones where the LSM can appear.

How scaling for longevity tests works?

- But even if we don't have the space charge, irradiate at the nominal gas gain and use a moderate acceleration factor… Still, can we scale?

- Primitively, just considering the reaction rate law:

  Reaction $aA+bB\rightarrow\ldots$
  rate = $k(T)\,[A]^n[B]^m$, but n and m depend on the reaction and has to be defined experimentally

- What about plasma conditions?..

- Probably comparative studies to choose the detector material and gas still can be performed with relatively large acceleration factors? **… but at least at the same conditions.**

- However, the final pre-production longevity test have to be performed **with the smallest reasonable acceleration factor**

What about the gas flow?

- We never can do accelerated aging test for the conditions identical to the operational. In this case we should choose the worst conditions

- “identical conditions” for volume scaling (small prototype studies) = the same replenishment rate (what about the local irradiation? :)
- Are there “identical conditions” for the accelerated irradiation?

- What we expect more from the gas flow?
  - To bring potentially dangerous outguessing/permeability products inside the gas volume?
    - Scaling the replenishment rate with the irradiation acceleration factor may be the solution
  - To remove dangerous products from the irradiation zone?
    - Keeping the same replenishment rate may be the solution

- Still should be some reasonable limits…
- If possible, several gas flow values can be tested

What about the gas flow?

Aging studies of CMS muon chamber prototypes

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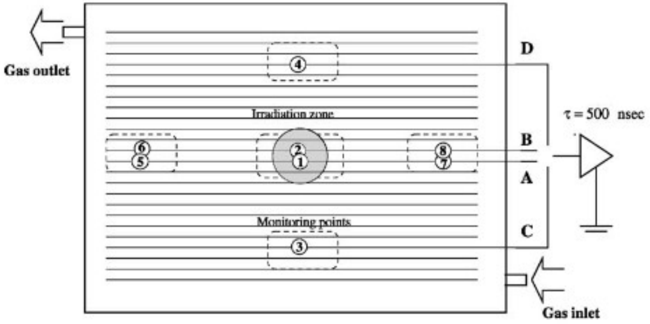
Received 21 March 2001; received in revised form 7 January 2002; accepted 7 January 2002

Nucl. Instrum. Methods Phys. Res., A 488 (2002) 240-257

Longevity tests with small CMS CSC prototype
Acceleration factor (source spot) – more than 1000!
Q expected ~0.1 C/cm



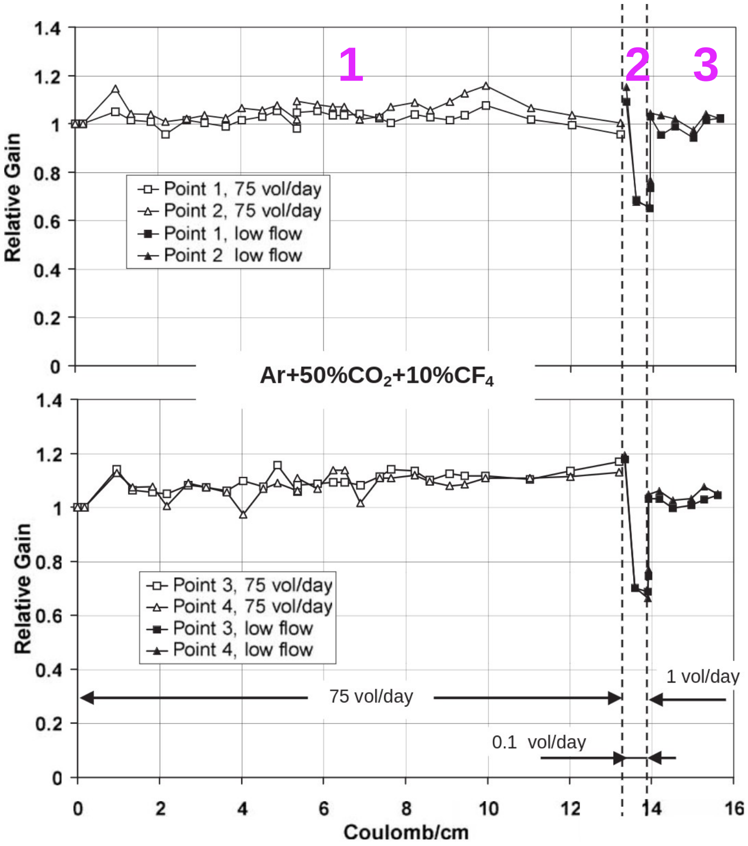


Fig. 16. Relative gas gain versus accumulated charge at points 1, 2 (top) and 3, 4 (bottom).

1 – flow not scaled (not too much informative)
2 – replenishment 40 times lower! Gas pollution
3 – replenishment rate comparable to expected - OK

Actual CMS CSC - 3(4) chambers per line, replenishment - 4V/day

Parameter monitoring during irradiation tests

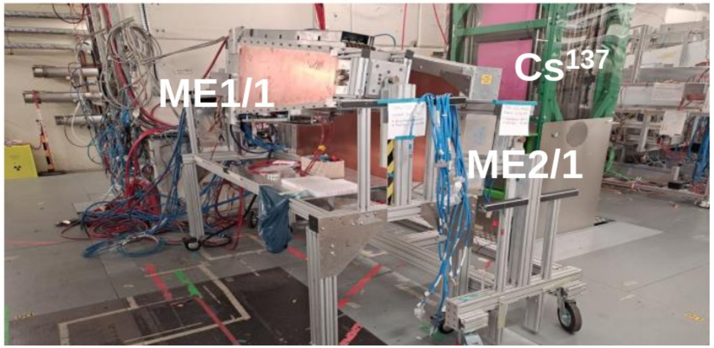
- Basic detector characteristics (both lab and pre-production tests)
  - Gas gain (absolute or relative)
    pressure/temperature dependent => relative wrt reference points/chamber/gaps
  - Dark current, dark rate
  - Current instabilities (Malter current) (lower intensity)
  - CSC: resistance between strips

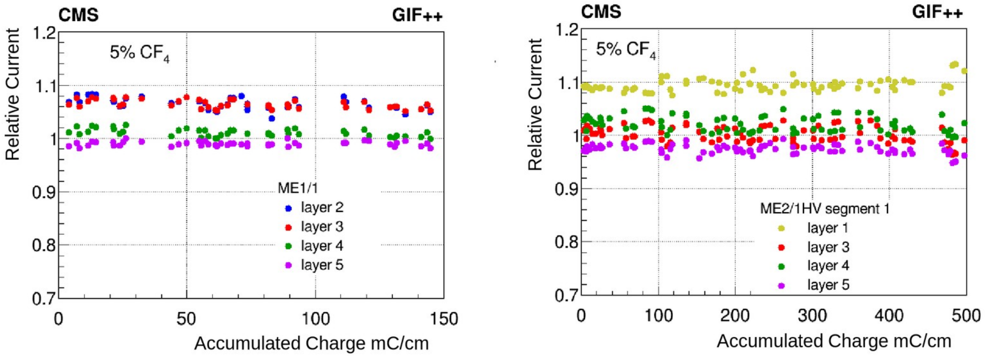
- Operation characteristics (pre-production tests, better if with the original electronics)
  - Efficiency
  - Spatial/time resolution

Gas gain monitoring during irradiation CMS-CSC example

CMS-CSC talk at ICPPA-2024

Full-scale chamber irradiation at GIF++ - detector current monitoring



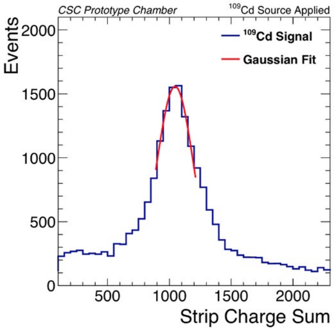


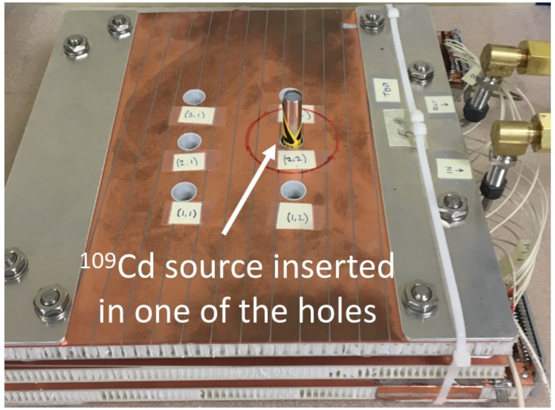
ME1/1 (left) and ME2/1 (right) plots of the relative currents in irradiated layers vs the accumulated charge. The relative current is a ratio of a value of the current in **irradiated** layer and an averaged current value of the two **reference** layers. During irradiation, the reference layers have HV=0. The closer the layer is to the Source, the higher current it has.

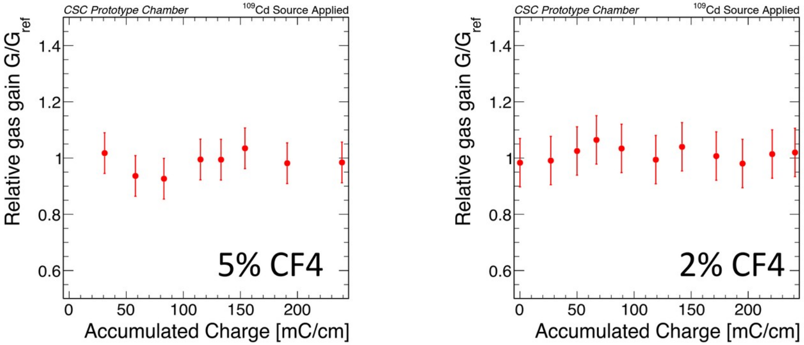
The data refers to the period of irradiation with 40%Ar+55%CO_2+5%CF_4 gas mixture. Each layer of the ME2/1 active area is divided into three independent high voltage zones – HV segments. Right plot is for ME2/1 segment 1.

CMS-CSC talk at DPF-2019

Small prototype local irradiation 109Cd peak position





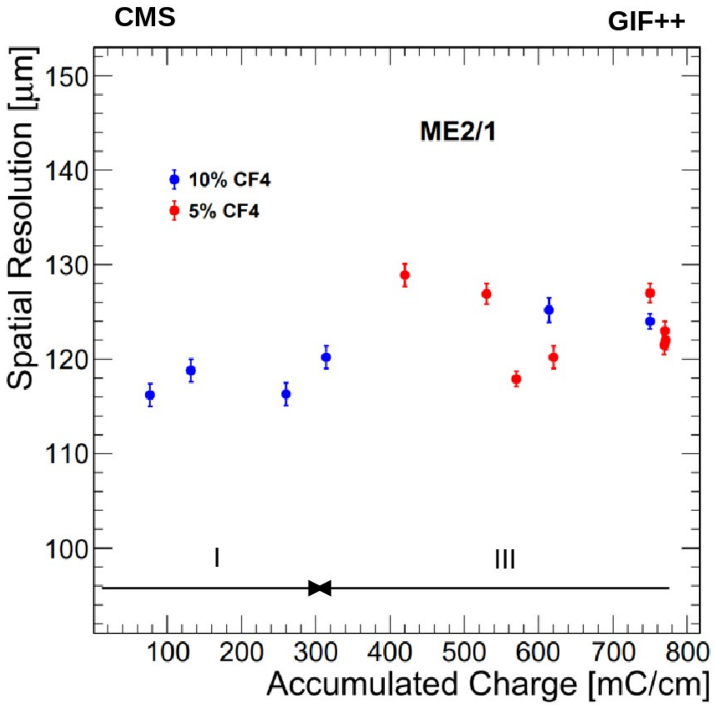


Performance monitoring at GIF++ test beam CMS-CSC examples

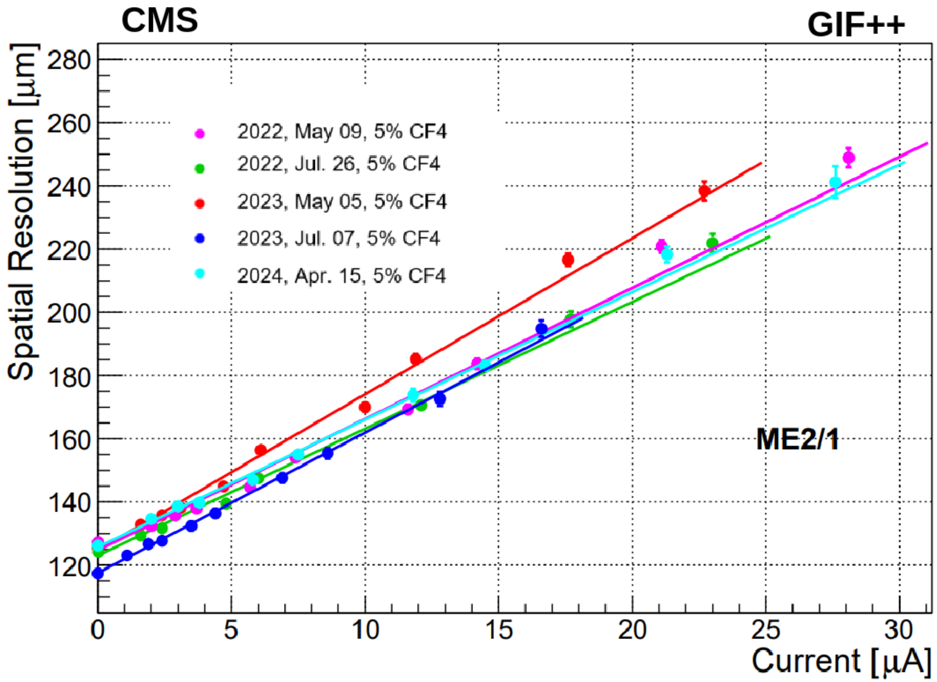
CMS-CSC talk at ICPPA-2024

Full-scale chamber irradiation at GIF++ - detector current monitoring

Muons only



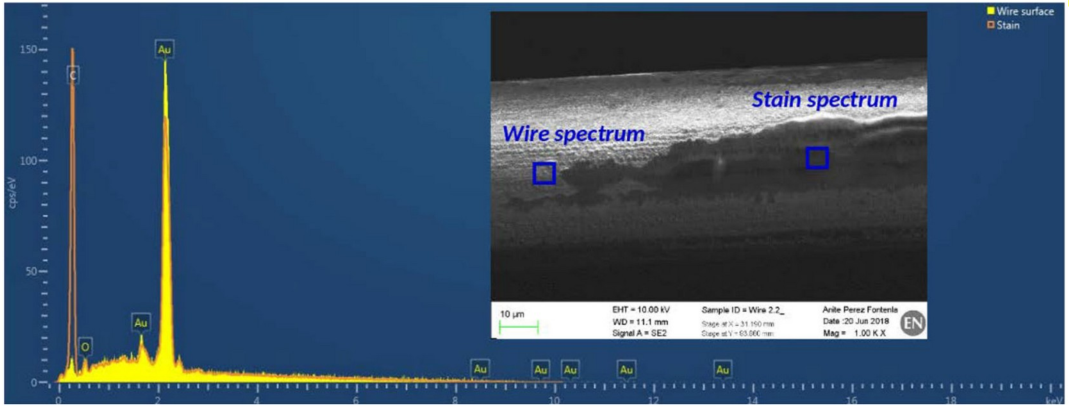
Muons + gamma background for different accumulated charges – performance in realistic conditions – unique for GIF++!

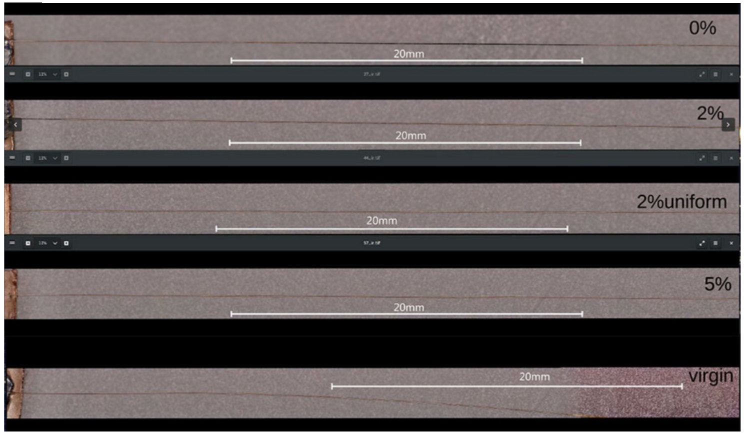


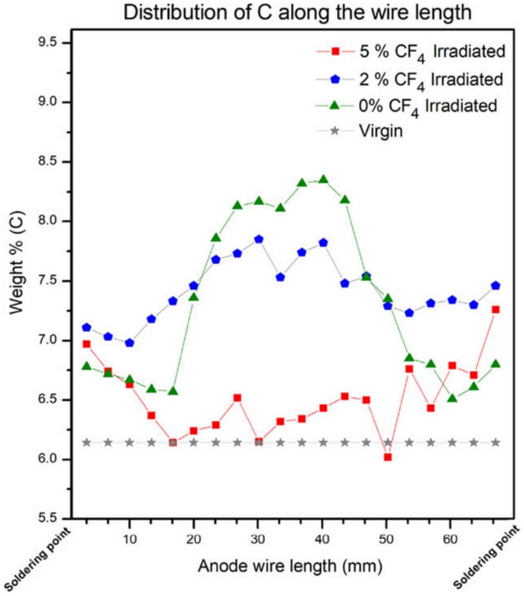
Material analysis after the irradiation
CMS-CSC examples

comparative studies with CSC prototypes

- Comparison of chamber material after irradiation tests with 0,2 and 5% CF4 - usual set of material analysis – visual inspection, SEM/EDS (CERN-MME-MM)
- But how to make them quantitative or at least comparable?
- 1. Irradiation runs are made in identical conditions up to the same accumulated charge
- 2. Averaging weight% measured in grid (not biased to any special features on the surface) – done by IGPC (Belgrade) :







summary

- Only reasonable methodology can provide adequate results – but still not a guarantee!! (usually a safety factor ~3 is considered to make the longevity prediction more reliable)
- There are quite a lot of studies and results, especially from the LHC experiment construction time, and quite a lot of new experience
- Close communication with chemists may be very useful not only in explaining the longevity test results but also for better organization of irradiation test
- Intensive experience exchange is very helpful!

DRD1 R&D Collaboration

Development of Gaseous Detectors Technologies

While we study aging on gas detectors …

PROCEEDINGS OF THE
WORKSHOP ON RADIATION DAMAGE TO WIRE CHAMBERS

Lawrence Berkeley Laboratory, Berkeley California

January 16-17, 1986

John Kadyk
Workshop Organizer

April 1986

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

This work was supported by the U.S. Department of Energy under contract DE-AC03-76SF00098.

MASTER

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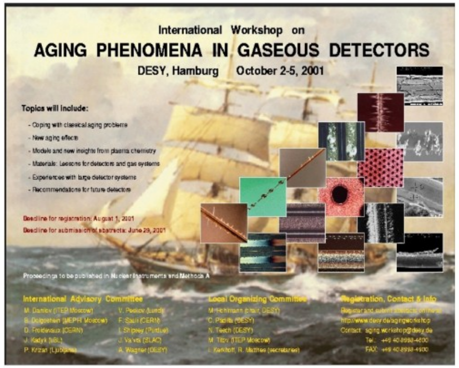
1986



International Workshop on
AGING PHENOMENA IN GASEOUS DETECTORS
DESY, Hamburg October 2-5, 2001

Topics will include:

- Coping with classical aging problems
- New aging effects
- Models and new insights from plasma chemistry
- Materials: Lessons for detectors and gas systems
- Experiences with large detector systems
- Recommendations for future detectors

Deadline for registration: August 1, 2001

Deadline for submission of abstracts: June 29, 2001

Proceedings to be published in Nuclear Instruments and Methods A

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Registration, Contact & Info
Register and submit abstracts on the web:
http://www.desy.de/agingworkshop
Contact: aging.workshop@desy.de
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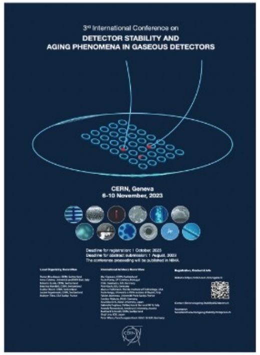
FAX: +49 40 8998-4600

2001

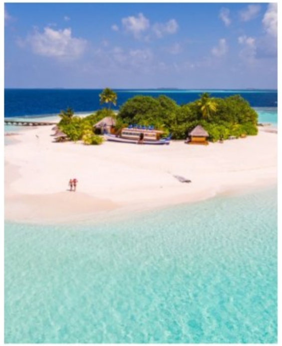


3rd International Conference on
DETECTOR STABILITY AND
AGING PHENOMENA IN GASEOUS DETECTORS

CERN, Geneva
6-10 November, 2023

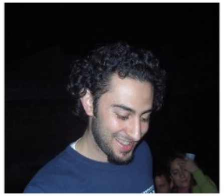
Deadline for registration: 1 October, 2023
Deadline for abstract submission: 1 August, 2023
The conference proceeding will be published in NIMA.

2023



When?

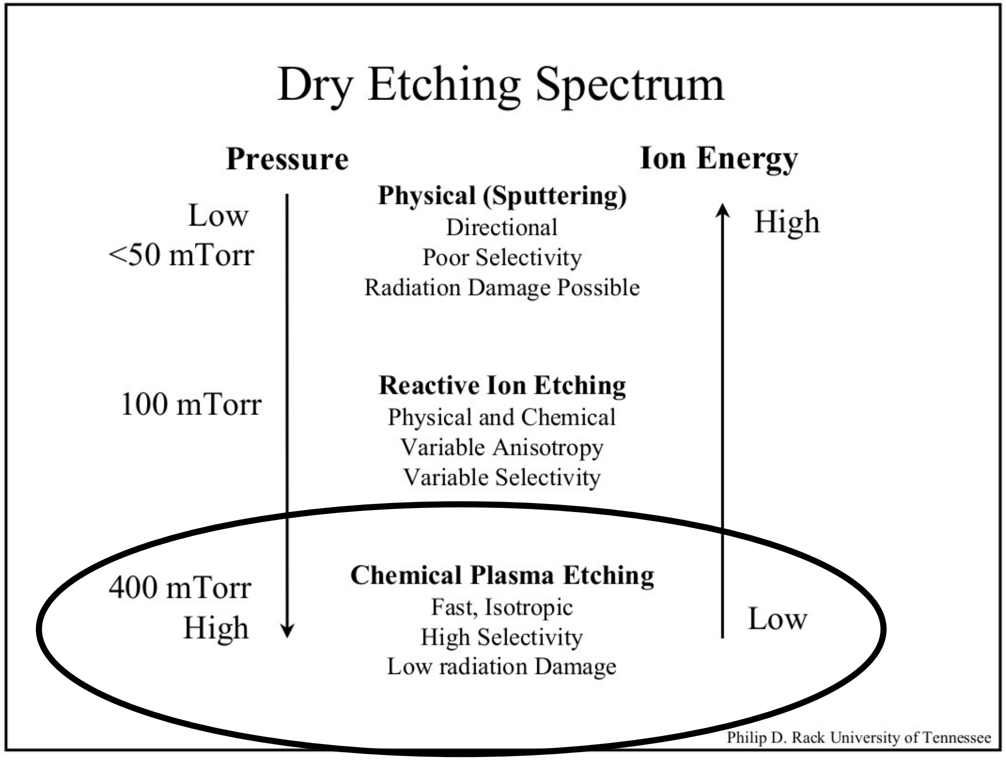
… its effects may also appear elsewhere



Don't wait too long!!!

BACKUP

CF4 and dry etching



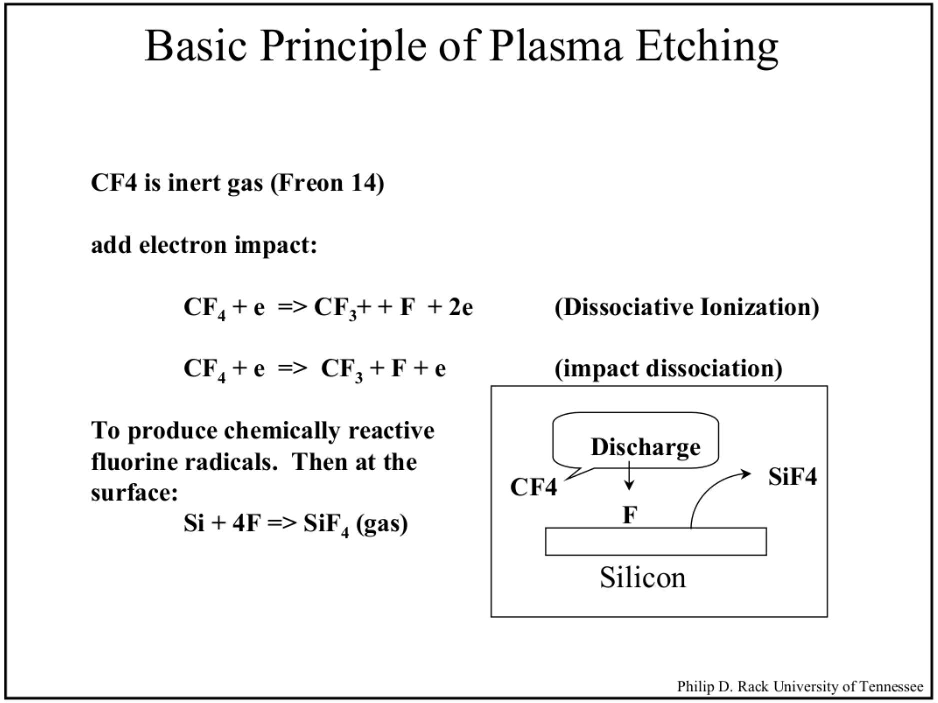
Dry Etching Spectrum

Physical (Sputtering)
Directional
Poor Selectivity
Radiation Damage Possible

Reactive Ion Etching
Physical and Chemical
Variable Anisotropy
Variable Selectivity

Chemical Plasma Etching
Fast, Isotropic
High Selectivity
Low radiation Damage

Philip D. Rack University of Tennessee



Basic Principle of Plasma Etching

CF4 is inert gas (Freon 14)

add electron impact:

$CF_4 + e => CF_3+ + F + 2e$ **(Dissociative Ionization)**

$CF_4 + e => CF_3 + F + e$ **(impact dissociation)**

To produce chemically reactive fluorine radicals. Then at the surface:

$Si + 4F => SiF_4$ **(gas)**

Philip D. Rack University of Tennessee

Not really the same
But can we learn something from them?

In a very naive consideration…

dry etching simulation

A combination of tools, approaches and models

- (1) description of the reactor and temperatures

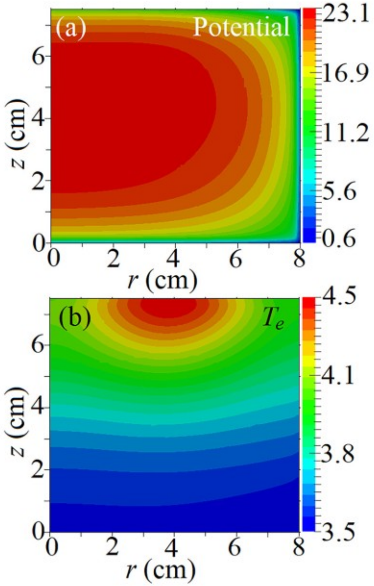
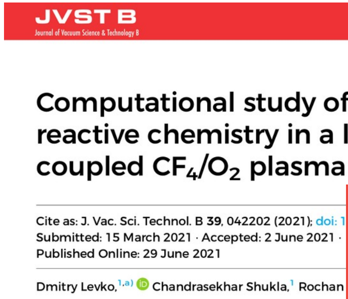


FIG. 2. (a) Electrostatic potential (in V) and (b) electron temperature (in eV) obtained for the gas pressure of 20 mTorr, discharge power of 100 W, $CF_4/O_2/Ar$ ratio of 70:5:25, and gas residence time of 0.01 s.

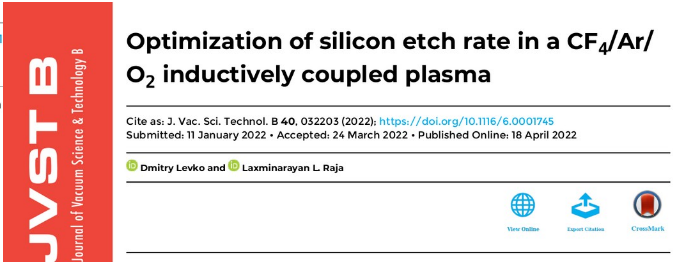


JVST B Journal of Vacuum Science & Technology B | ARTICLE | avs.scitation.org/journal/jvb

Computational study of plasma dynamics and reactive chemistry in a low-pressure inductively coupled CF_4/O_2 plasma

Cite as: J. Vac. Sci. Technol. B **39**, 042202 (2021); doi: 1
Submitted: 15 March 2021 · Accepted: 2 June 2021 ·
Published Online: 29 June 2021

Dmitry Levko,[1,a)] Chandrasekhar Shukla,[1] Rochan



JVST B Journal of Vacuum Science & Technology B

Optimization of silicon etch rate in a CF_4/Ar/O_2 inductively coupled plasma

Cite as: J. Vac. Sci. Technol. B **40**, 032203 (2022); https://doi.org/10.1116/6.0001745
Submitted: 11 January 2022 • Accepted: 24 March 2022 • Published Online: 18 April 2022

Dmitry Levko and Laxminarayan L. Raja

- (2) a process model and reaction rates

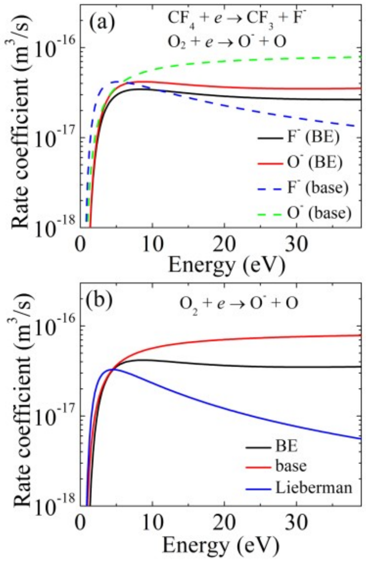


FIG. 2. (a) Rate coefficients of electron attachment reactions calculated using the Boltzmann equation solver and taken from Ref. 6 (base mechanism). (b) The rate coefficients of the reaction of electron attachment to O_2 obtained by solving the BE and taken from Ref. 2 (Lieberman) and Ref. 6 (base).

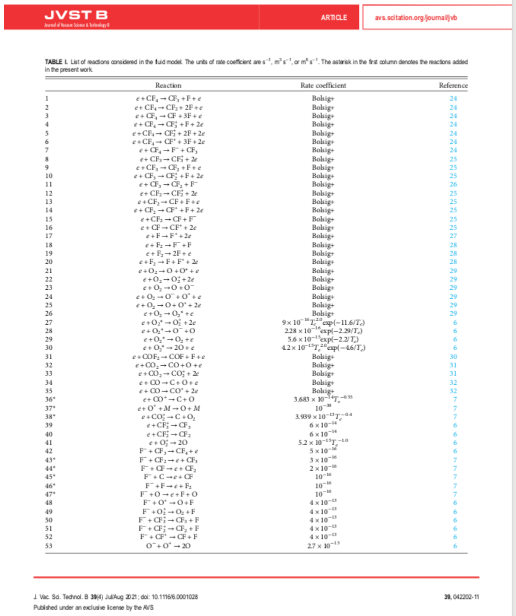


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TABLE I. List of reactions considered in the fluid model. The units of rate coefficient are s^{-1}, $m^3 s^{-1}$, or $m^6 s^{-1}$. The asterisk in the first column denotes the reactions added in the present work.

	Reaction	Rate coefficient	Reference
1	$e + CF_4 \to CF_3 + F + e$	Bolsig+	24
2	$e + CF_4 \to CF_2 + 2F + e$	Bolsig+	24
3	$e + CF_4 \to CF + 3F + e$	Bolsig+	24
4	$e + CF_4 \to CF_3^+ + F + 2e$	Bolsig+	24
5	$e + CF_4 \to CF_2^+ + 2F + 2e$	Bolsig+	24
6	$e + CF_4 \to CF^+ + 3F + 2e$	Bolsig+	24
7	$e + CF_4 \to F^- + CF_3$	Bolsig+	24
8	$e + CF_3 \to CF_3^+ + 2e$	Bolsig+	25
9	$e + CF_3 \to CF_2 + F + e$	Bolsig+	25
10	$e + CF_3 \to CF_2^+ + F + 2e$	Bolsig+	25
11	$e + CF_3 \to CF_2 + F^-$	Bolsig+	26
12	$e + CF_2 \to CF_2^+ + 2e$	Bolsig+	25
13	$e + CF_2 \to CF + F + e$	Bolsig+	25
14	$e + CF_2 \to CF^+ + F + 2e$	Bolsig+	25
15	$e + CF_2 \to CF + F^-$	Bolsig+	25
16	$e + CF \to CF^+ + 2e$	Bolsig+	25
17	$e + F \to F^+ + 2e$	Bolsig+	27
18	$e + F_2 \to F^- + F$	Bolsig+	28
19	$e + F_2 \to 2F + e$	Bolsig+	28
20	$e + F_2 \to F + F^+ + 2e$	Bolsig+	28
21	$e + O_2 \to O + O^* + e$	Bolsig+	29
22	$e + O_2 \to O_2^+ + 2e$	Bolsig+	29
23	$e + O_2 \to O + O^-$	Bolsig+	29
24	$e + O_2 \to O^- + O^+ + e$	Bolsig+	29
25	$e + O_2 \to O + O^+ + 2e$	Bolsig+	29
26	$e + O_2 \to O_2^* + e$	Bolsig+	29
27	$e + O_2^* \to O_2^+ + 2e$	$9 \times 10^{-16} T_e^{2.0} \exp(-11.6/T_e)$	6
28	$e + O_2^* \to O^- + O$	$2.28 \times 10^{-16} \exp(-2.29/T_e)$	6
29	$e + O_2^* \to O_2 + e$	$5.6 \times 10^{-15} \exp(-2.2/T_e)$	6
30	$e + O_2^* \to 2O + e$	$4.2 \times 10^{-15} T_e^{2.0} \exp(-4.6/T_e)$	6
31	$e + COF_2 \to COF + F + e$	Bolsig+	30
32	$e + CO_2 \to CO + O + e$	Bolsig+	31
33	$e + CO_2 \to CO_2^+ + 2e$	Bolsig+	31
34	$e + CO \to C + O + e$	Bolsig+	32
35	$e + CO \to CO^+ + 2e$	Bolsig+	32
36*	$e + CO^+ \to C + O$	$3.683 \times 10^{-14} T_e^{-0.55}$	7
37*	$e + O^+ + M \to O + M$	10^{-38}	7
38*	$e + CO_2^+ \to C + O_2$	$3.939 \times 10^{-13} T_e^{-0.4}$	7
39	$e + CF_3^+ \to CF_3$	6×10^{-14}	6
40	$e + CF_2^+ \to CF_2$	6×10^{-14}	6
41	$e + O_2^+ \to 2O$	$5.2 \times 10^{-15} T_e^{-1.0}$	6
42	$F^- + CF_3 \to CF_4 + e$	5×10^{-16}	6
43*	$F^- + CF_2 \to e + CF_3$	3×10^{-16}	7
44*	$F^- + CF \to e + CF_2$	2×10^{-16}	7
45*	$F^- + C \to e + CF$	10^{-16}	7
46*	$F^- + F \to e + F_2$	10^{-16}	7
47*	$F^- + O \to e + F + O$	10^{-16}	7
48	$F^- + O^+ \to O + F$	4×10^{-13}	6
49	$F^- + O_2^+ \to O_2 + F$	4×10^{-13}	6
50	$F^- + CF_3^+ \to CF_3 + F$	4×10^{-13}	6
51	$F^- + CF_2^+ \to CF_2 + F$	4×10^{-13}	6
52	$F^- + CF^+ \to CF + F$	4×10^{-13}	6
53	$O^- + O^+ \to 2O$	2.7×10^{-13}	6

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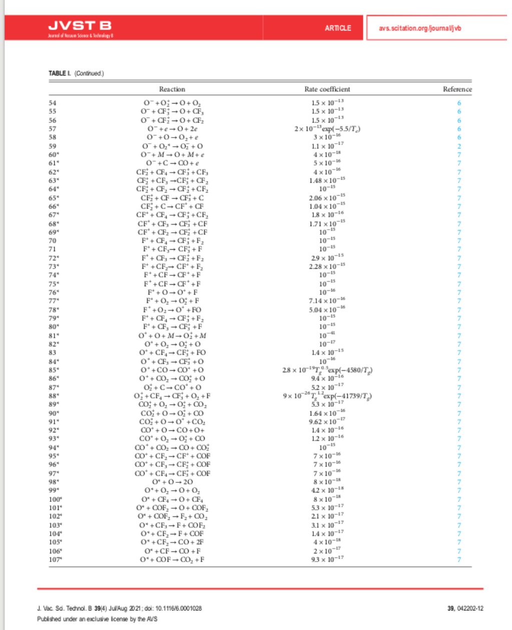

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TABLE I. *(Continued.)*

	Reaction	Rate coefficient	Reference
54	$O^- + O_2^+ \to O + O_2$	1.5×10^{-13}	6
55	$O^- + CF_3^+ \to O + CF_3$	1.5×10^{-13}	6
56	$O^- + CF_2^+ \to O + CF_2$	1.5×10^{-13}	6
57	$O^- + e \to O + 2e$	$2 \times 10^{-13} \exp(-5.5/T_e)$	6
58	$O^- + O \to O_2 + e$	3×10^{-16}	6
59	$O^- + O_2^* \to O_2^- + O$	1.1×10^{-17}	2
60*	$O^- + M \to O + M + e$	4×10^{-18}	7
61*	$O^- + C \to CO + e$	5×10^{-16}	7
62*	$CF_2^+ + CF_4 \to CF_3^+ + CF_3$	4×10^{-16}	7
63*	$CF_2^+ + CF_3 \to CF_3^+ + CF_2$	1.48×10^{-15}	7
64*	$CF_2^+ + CF_2 \to CF_2^+ + CF_2$	10^{-15}	7
65*	$CF_2^+ + CF \to CF_3^+ + C$	2.06×10^{-15}	7
66*	$CF_2^+ + C \to CF^+ + CF$	1.04×10^{-15}	7
67*	$CF^+ + CF_4 \to CF_3^+ + CF_2$	1.8×10^{-16}	7
68*	$CF^+ + CF_3 \to CF_3^+ + CF$	1.71×10^{-15}	7
69*	$CF^+ + CF_2 \to CF_2^+ + CF$	10^{-15}	7
70	$F^+ + CF_4 \to CF_3^+ + F_2$	10^{-15}	7
71	$F^+ + CF_3 \to CF_3^+ + F$	10^{-15}	7
72*	$F^+ + CF_3 \to CF_2^+ + F_2$	2.9×10^{-15}	7
73*	$F^+ + CF_2 \to CF^+ + F_2$	2.28×10^{-15}	7
74*	$F^+ + CF \to CF^+ + F$	10^{-15}	7
75*	$F^+ + CF \to CF^+ + F$	10^{-15}	7
76*	$F^+ + O \to O^+ + F$	10^{-16}	7
77*	$F^+ + O_2 \to O_2^+ + F$	7.14×10^{-16}	7
78*	$F^+ + O_2 \to O^+ + FO$	5.04×10^{-16}	7
79*	$F^+ + CF_4 \to CF_3^+ + F_2$	10^{-15}	7
80*	$F^+ + CF_3 \to CF_3^+ + F$	10^{-15}	7
81*	$O^+ + O + M \to O_2^+ + M$	10^{-41}	7
82*	$O^+ + O_2 \to O_2^+ + O$	10^{-17}	7
83	$O^+ + CF_4 \to CF_3^+ + FO$	1.4×10^{-15}	7
84*	$O^+ + CF_3 \to CF_3^+ + O$	10^{-16}	7
85*	$O^+ + CO \to CO^+ + O$	$2.8 \times 10^{-19} T_g^{0.5} \exp(-4580/T_g)$	7
86*	$O^+ + CO_2 \to CO_2^+ + O$	9.4×10^{-16}	7
87*	$O_2^+ + C \to CO^+ + O$	5.2×10^{-17}	7
88*	$O_2^+ + CF_4 \to CF_3^+ + O_2 + F$	$9 \times 10^{-26} T_g^{1.2} \exp(-41739/T_g)$	7
89*	$CO_2^+ + O_2 \to O_2^+ + CO_2$	5.3×10^{-17}	7
90*	$CO_2^+ + O \to O_2^+ + CO$	1.64×10^{-16}	7
91*	$CO_2^+ + O \to O^+ + CO_2$	9.62×10^{-17}	7
92*	$CO^+ + O \to CO + O+$	1.4×10^{-16}	7
93*	$CO^+ + O_2 \to O_2^+ + CO$	1.2×10^{-16}	7
94*	$CO^+ + CO_2 \to CO + CO_2^+$	10^{-15}	7
95*	$CO^+ + CF_2 \to CF^+ + COF$	7×10^{-16}	7
96*	$CO^+ + CF_3 \to CF_2^+ + COF$	7×10^{-16}	7
97*	$CO^+ + CF_4 \to CF_3^+ + COF$	7×10^{-16}	7
98*	$O^* + O \to 2O$	8×10^{-18}	7
99*	$O^* + O_2 \to O + O_2$	4.2×10^{-18}	7
100*	$O^* + CF_4 \to O + CF_4$	8×10^{-18}	7
101*	$O^* + COF_2 \to O + COF_2$	5.3×10^{-17}	7
102*	$O^* + COF_2 \to F_2 + CO_2$	2.1×10^{-17}	7
103*	$O^* + CF_3 \to F + COF_2$	3.1×10^{-17}	7
104*	$O^* + CF_2 \to F + COF$	1.4×10^{-17}	7
105*	$O^* + CF_2 \to CO + 2F$	4×10^{-18}	7
106*	$O^* + CF \to CO + F$	2×10^{-17}	7
107*	$O^* + COF \to CO_2 + F$	9.3×10^{-17}	7

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dry etching simulation

- (3) densities and fluxes
  - Electron drift + diffusion
  - Ion drift

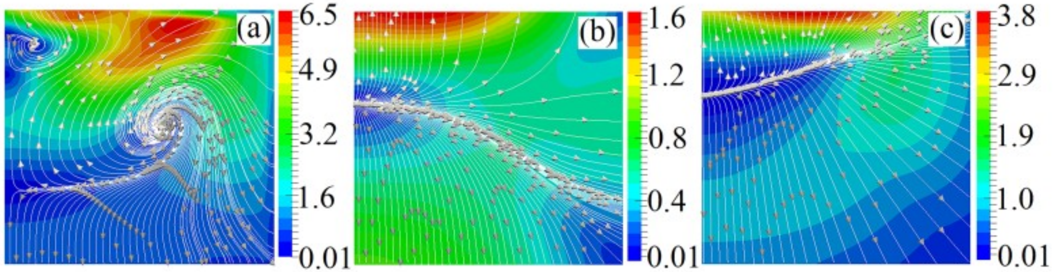
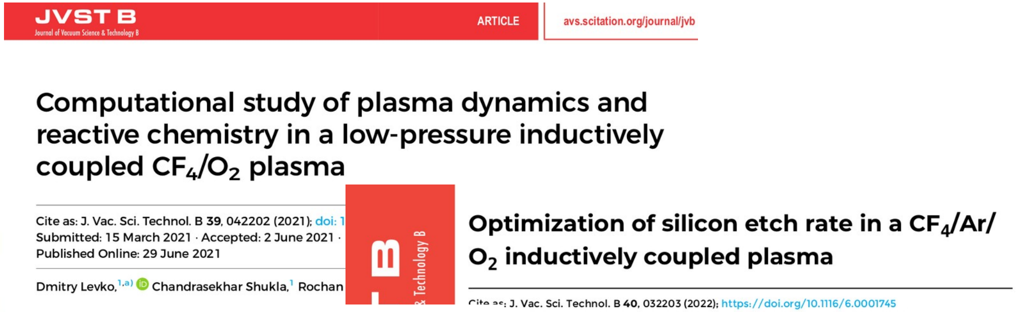


FIG. 6. Number fluxes of (a) electrons, (b) ions CF_3^+, and (c) ions O^+ in m^{-2} s^{-1}. All the fluxes shown in the figure should be multiplied by the factor of 10^{20} m^{-3}.

- (4) predictions
  vs
  measurements



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Computational study of plasma dynamics and reactive chemistry in a low-pressure inductively coupled CF_4/O_2 plasma

Cite as: J. Vac. Sci. Technol. B **39**, 042202 (2021); doi: 1
Submitted: 15 March 2021 · Accepted: 2 June 2021 ·
Published Online: 29 June 2021

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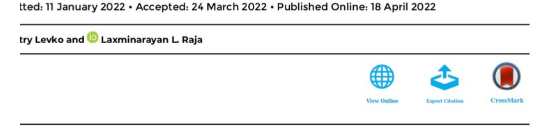
Optimization of silicon etch rate in a CF_4/Ar/ O_2 inductively coupled plasma



Cite as: J. Vac. Sci. Technol. B **40**, 032203 (2022); https://doi.org/10.1116/6.0001745
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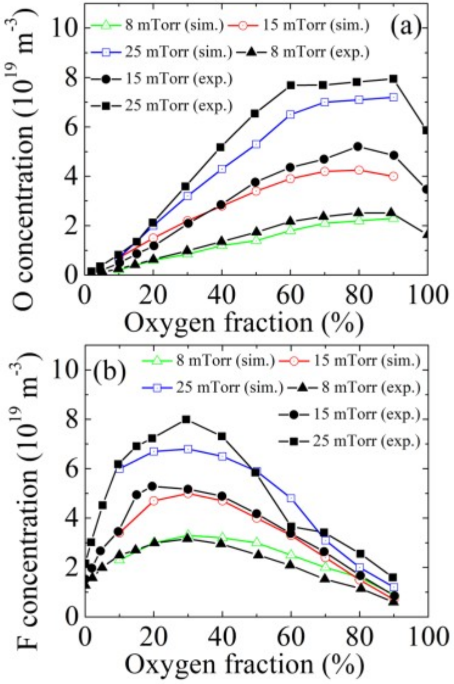

FIG. 8. Comparison between the simulation and experimental results (Ref. 6) for the atomic (a) oxygen and (b) fluorine concentrations obtained at various total gas pressures. The experimental data were reproduced from Ref. 6.