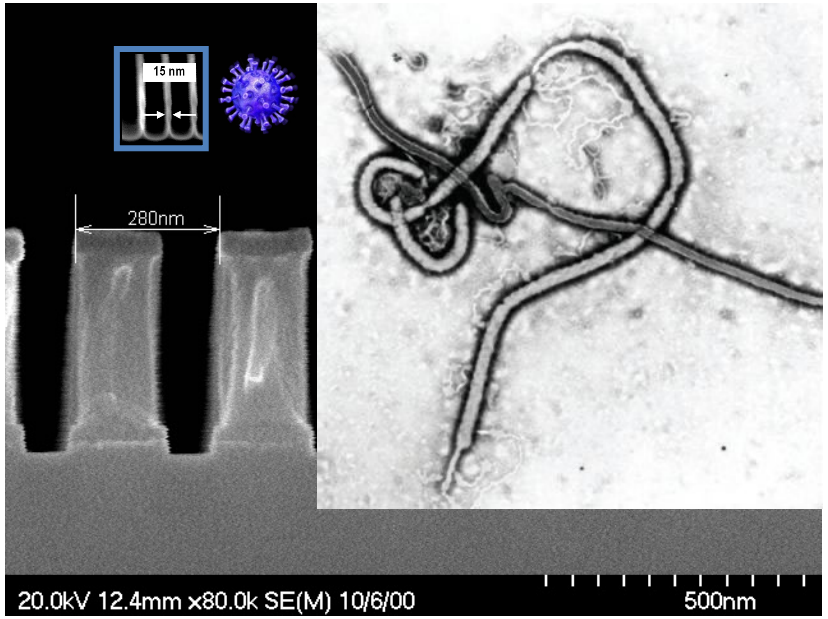
NC STATE UNIVERSITY

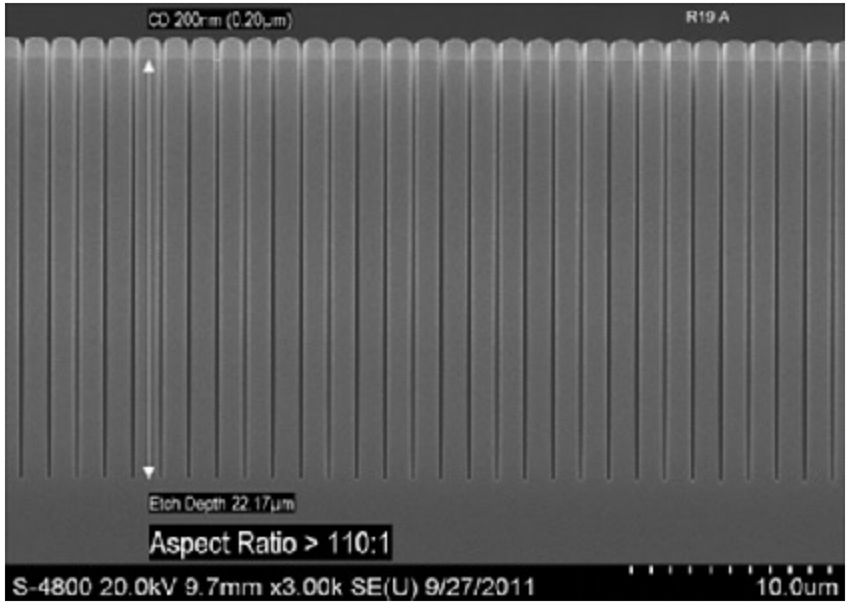
Department of
NUCLEAR ENGINEERING

Plasma Science: the unsung engine of the digital age

Steven Shannon

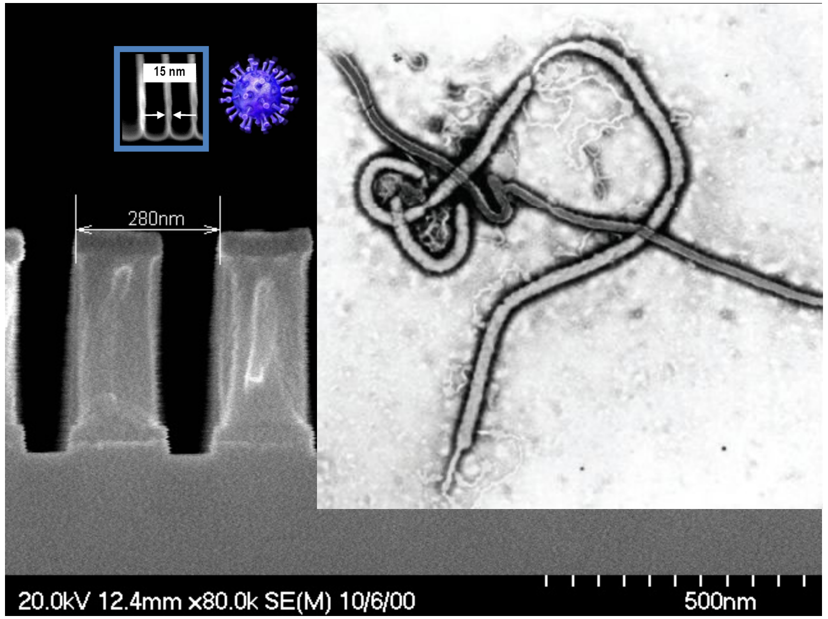
22 June 2022



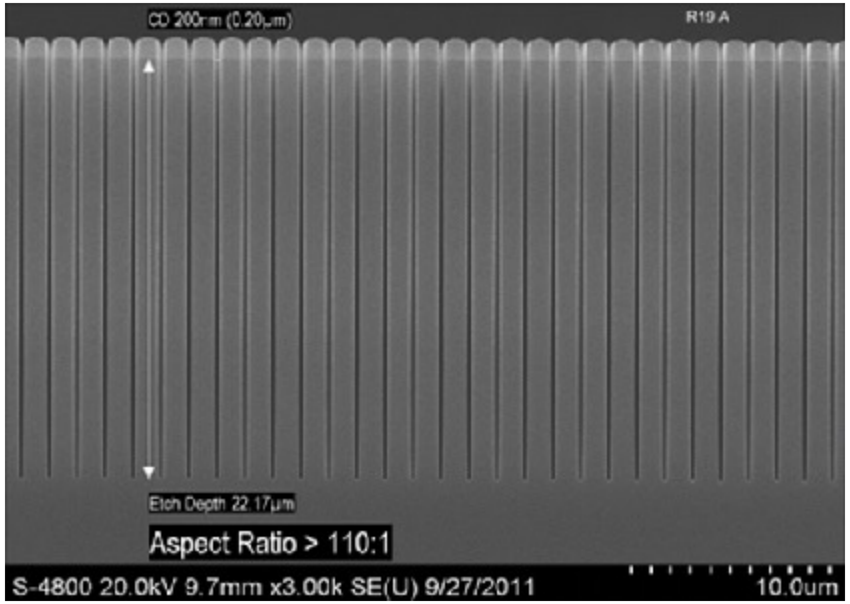


Peter Clarke, “Applied Materials readies DRIE machines for MEMS, *EETimes Magazine*, 22 March 2012

How do we make things so small?
Current SOA is 5nm!!!



How do we control the direction of a chemically driven process?



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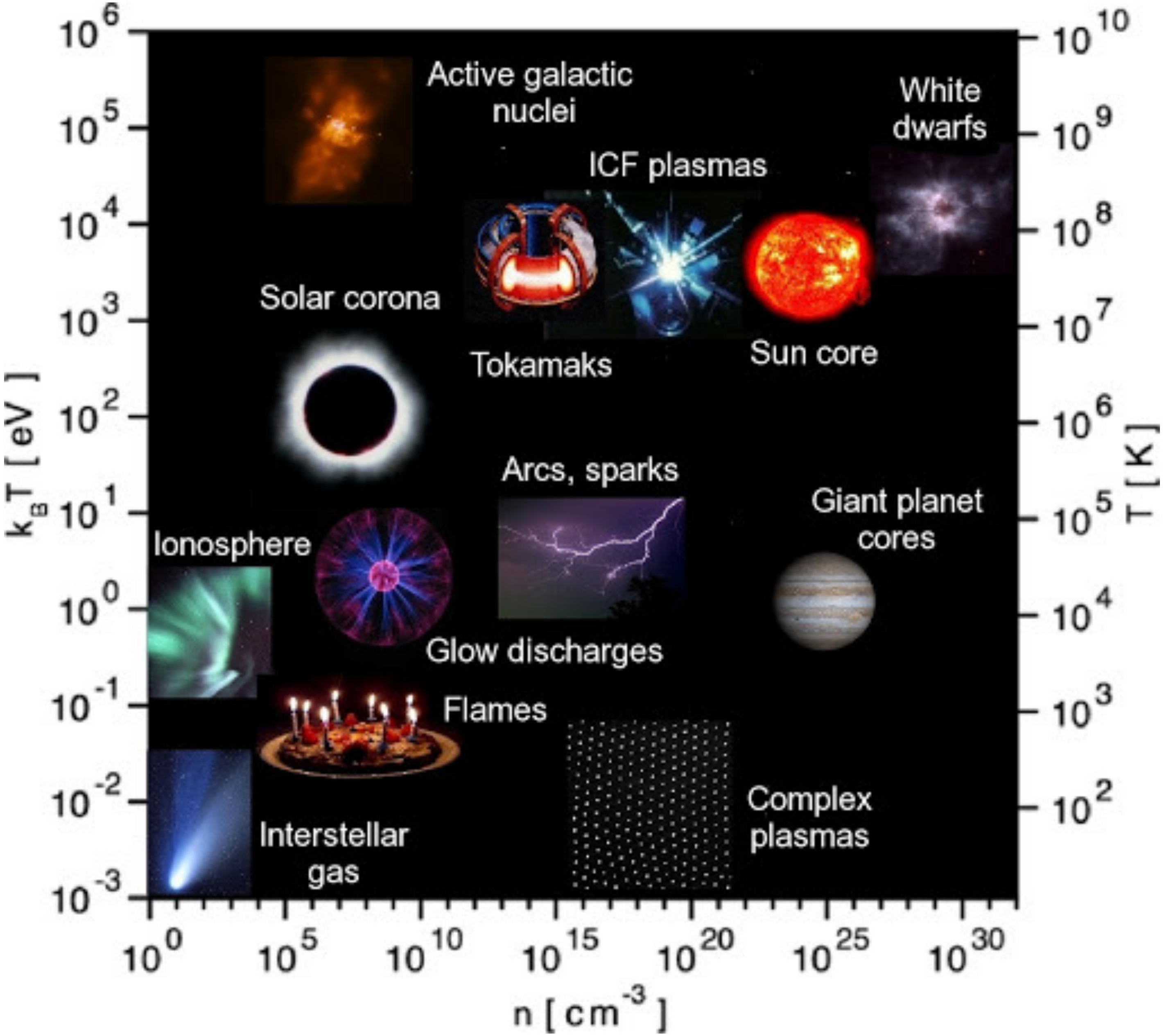
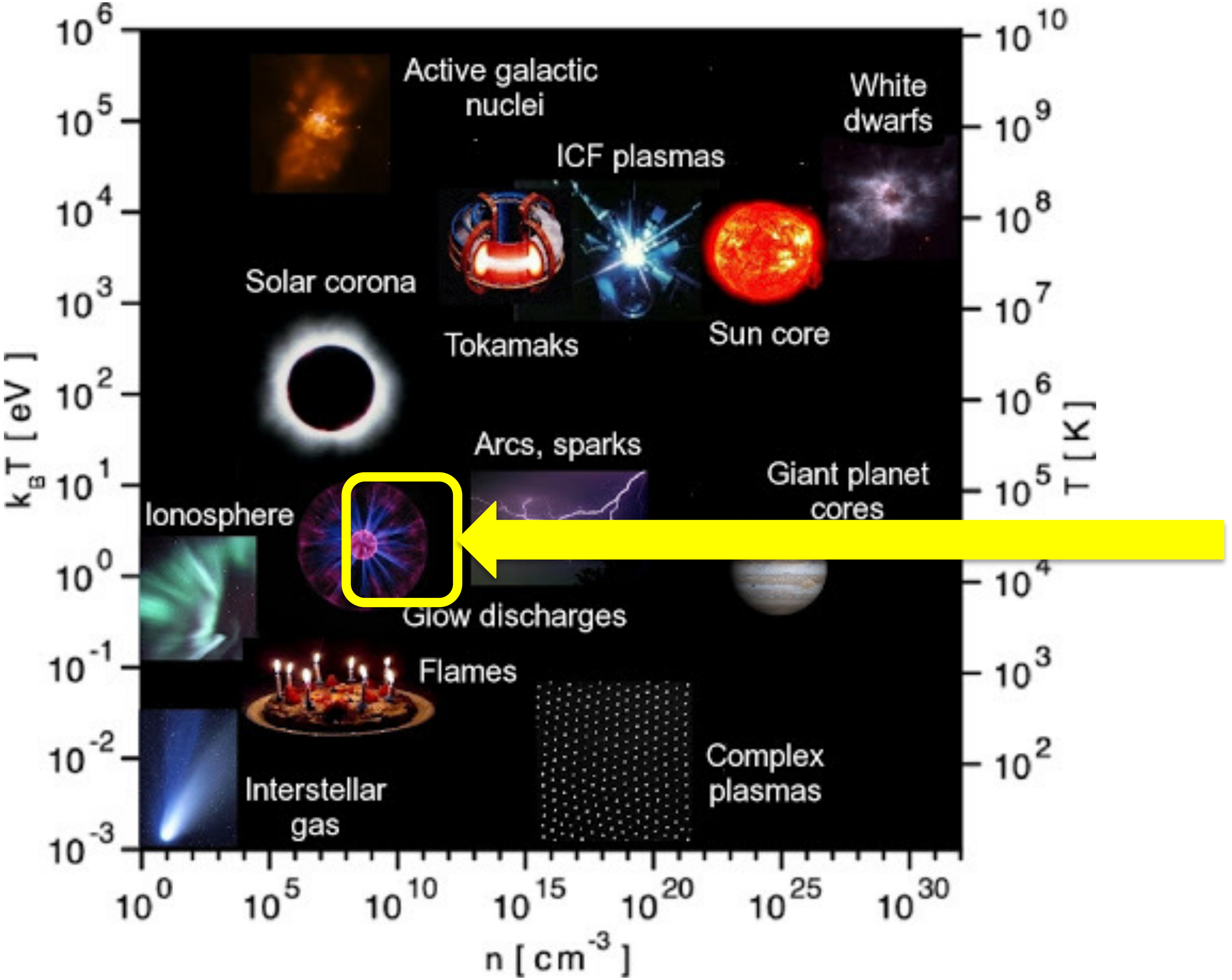

Active galactic nuclei
White dwarfs
ICF plasmas
Solar corona
Tokamaks
Sun core
Arcs, sparks
Giant planet cores
Ionosphere
Glow discharges
Flames
Complex plasmas
Interstellar gas
$k_B T$ [eV]
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
T [K]
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
n [cm^{-3}]
10^{0}
10^{5}
10^{10}
10^{15}
10^{20}
10^{25}
10^{30}



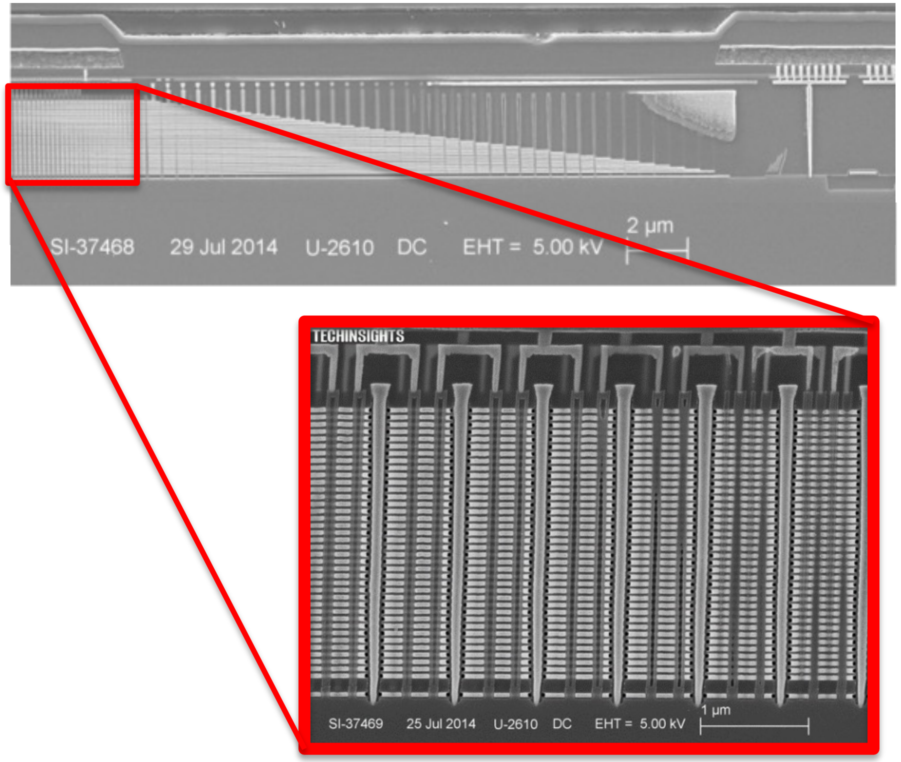
The majority of plasma processing resides in a pretty small window in "plasma space"

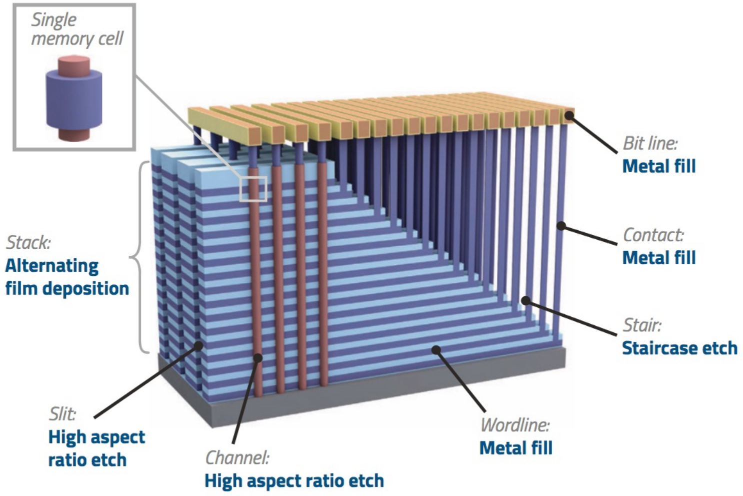
$10^8 cm^{-3} < n_e < 10^{12} cm^{-3}$
$0.5 eV < T_e < 10 eV$

Less than 1% of the gas is actually ionized

The background gas (and ions) stay roughly near room temperature

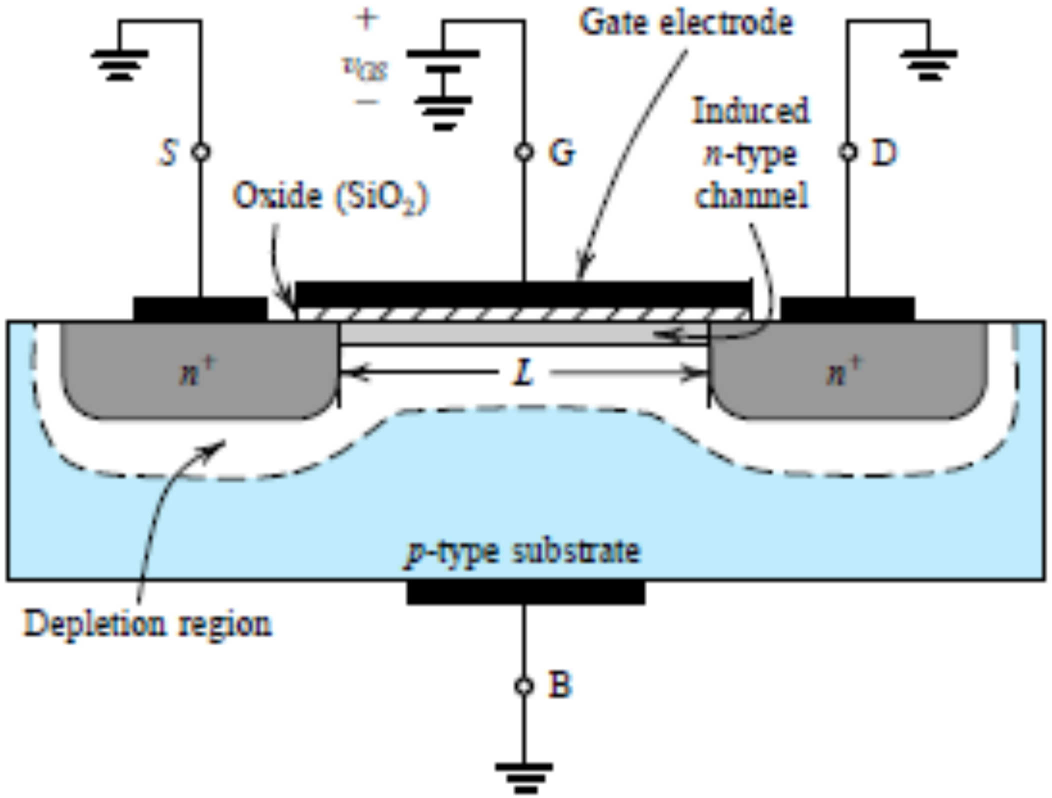
The basic challenge – fabrication of very complex features with dimensions ~10nm



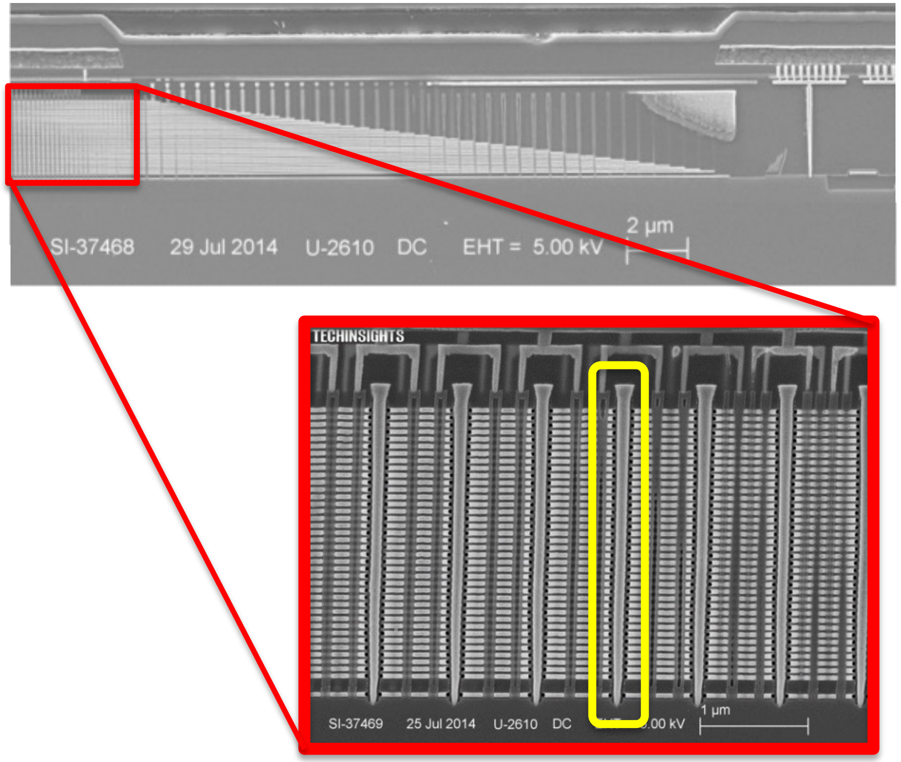


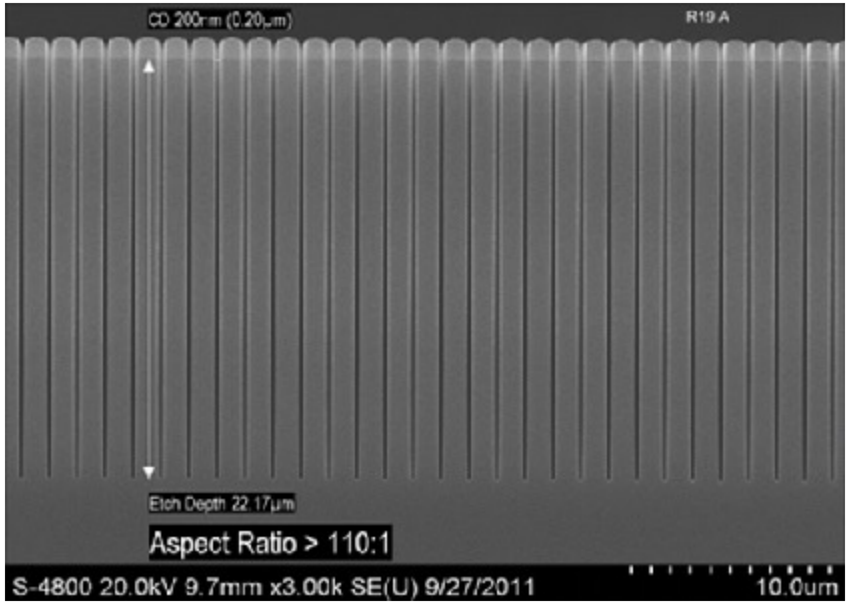
Harmeet Singh, “Overcoming challenges in 3D NAND volume manufacturing, *Solid State Technology Magazine*, July 2017
Dick James, “The Second Shoe Drops – Samsung V-NAND Flash”, www.chipworks.com, 5 August 2014

Why? Because the smaller the device, the faster it runs…



There are lots of challenges to make this device… we will focus on High Aspect Ratio etching in dielectric materials





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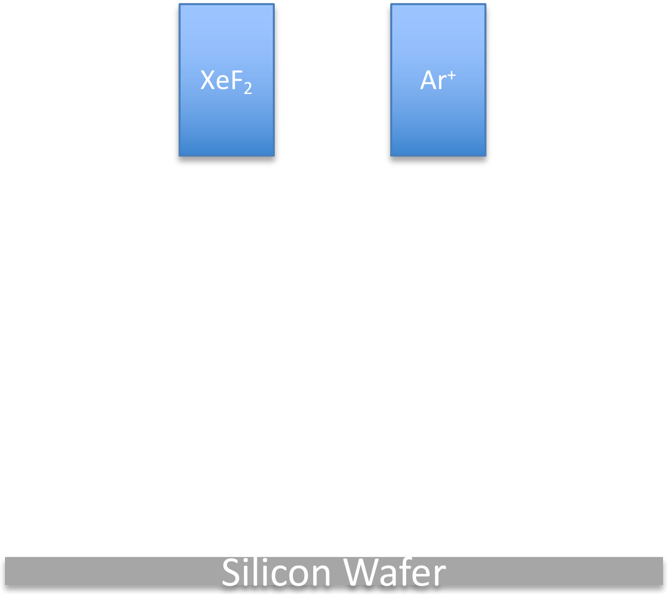
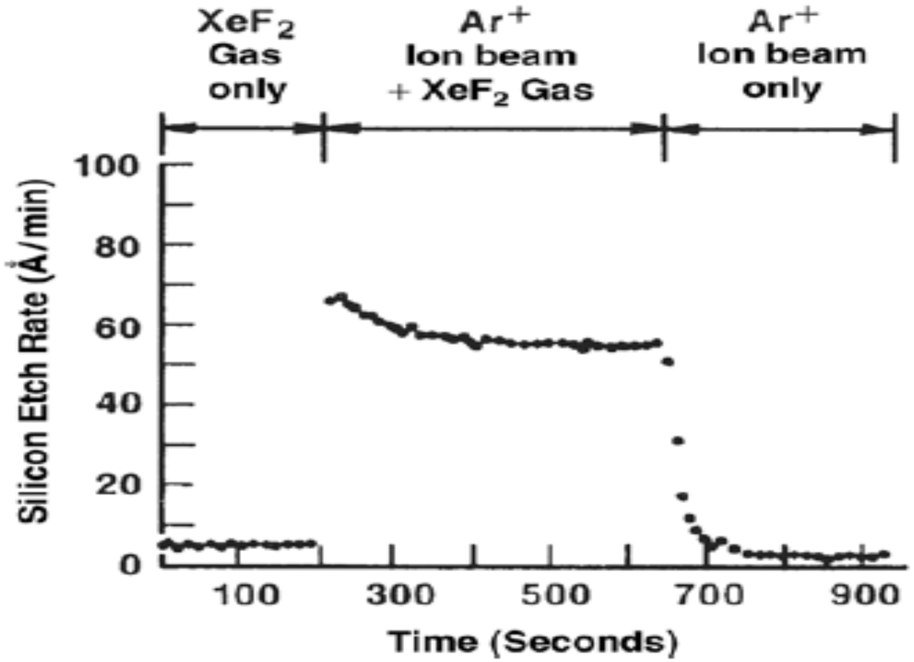
The “classic” experiment that drove plasma etch





Coburn and Winters, J. Vac. Sci. Technol. **16**, 391

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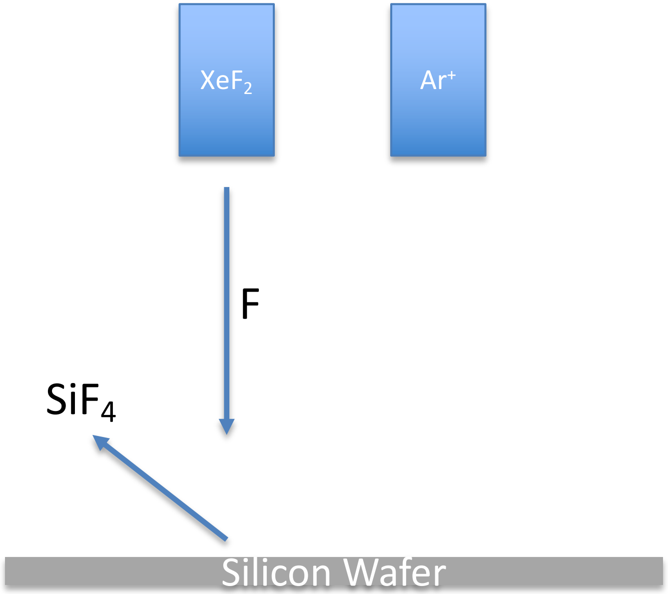

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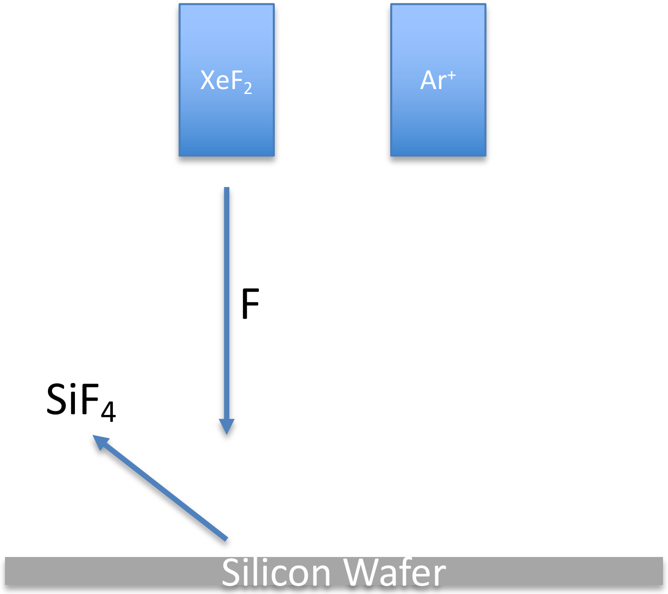

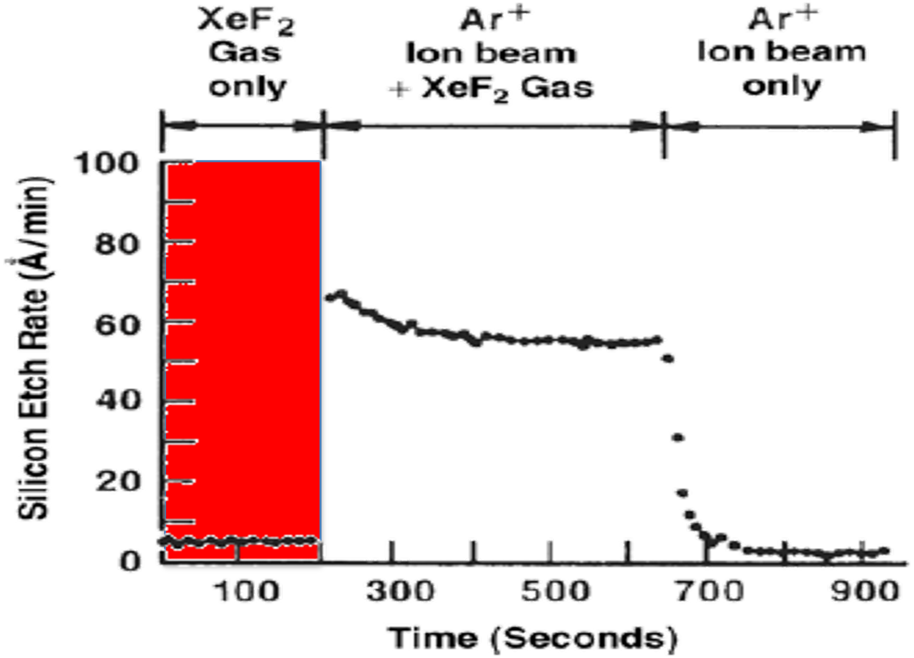

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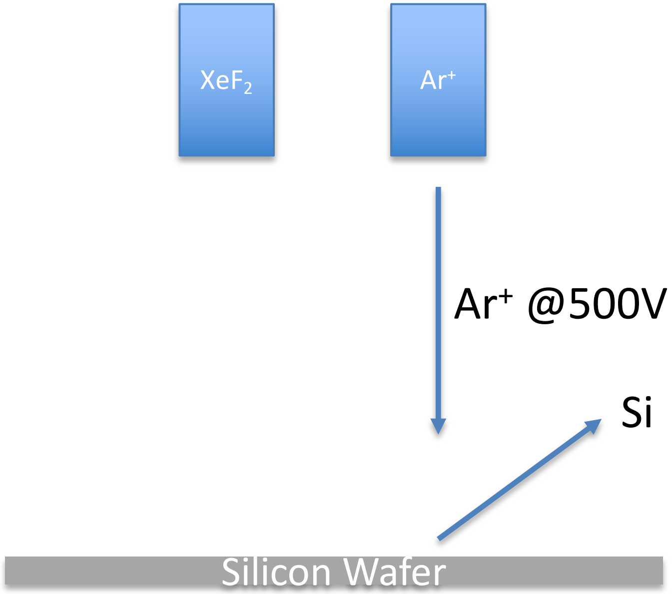

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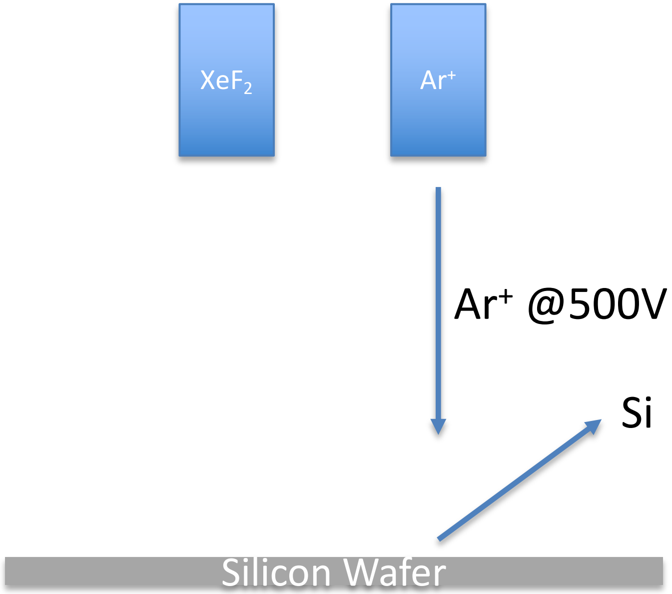

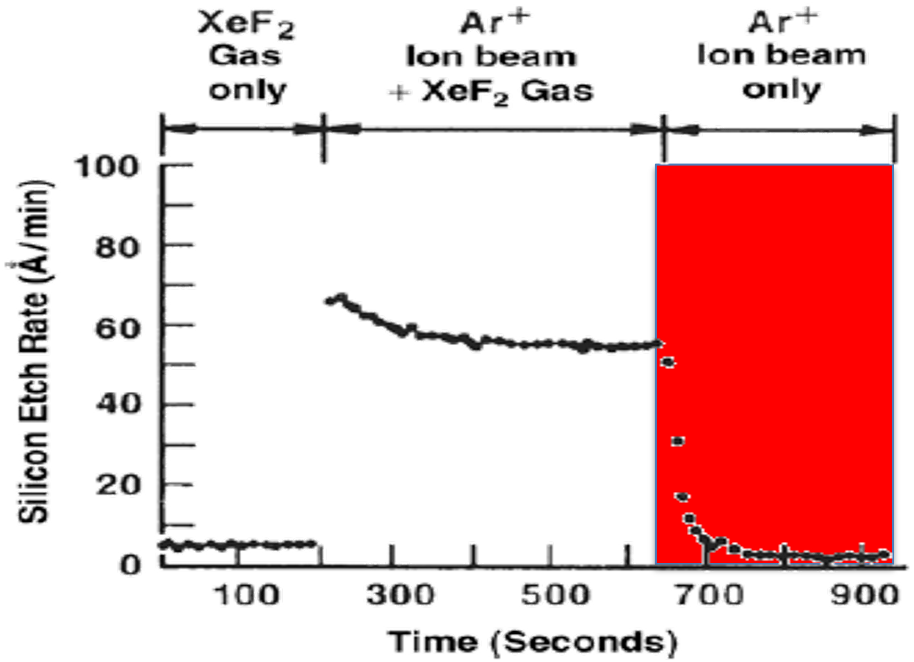

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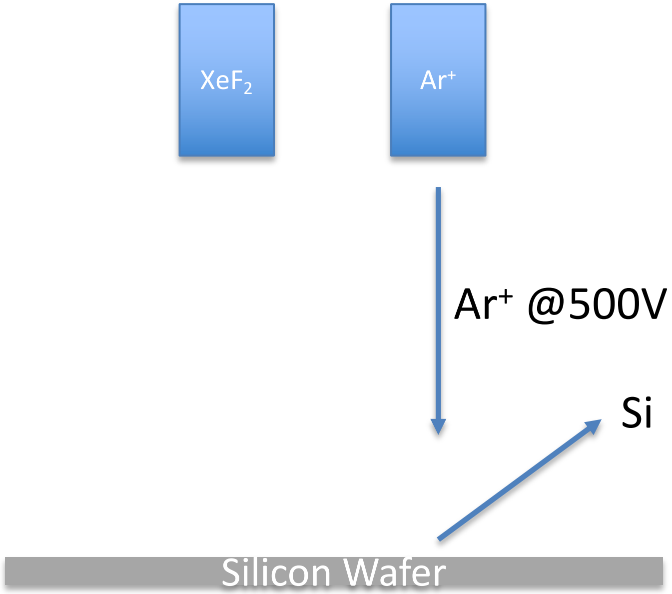
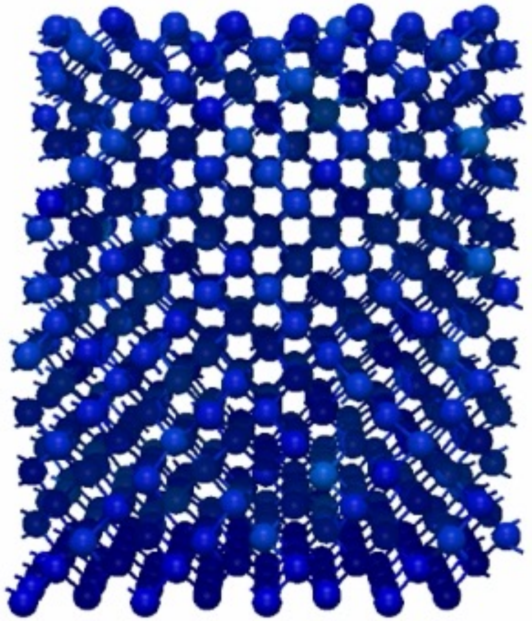
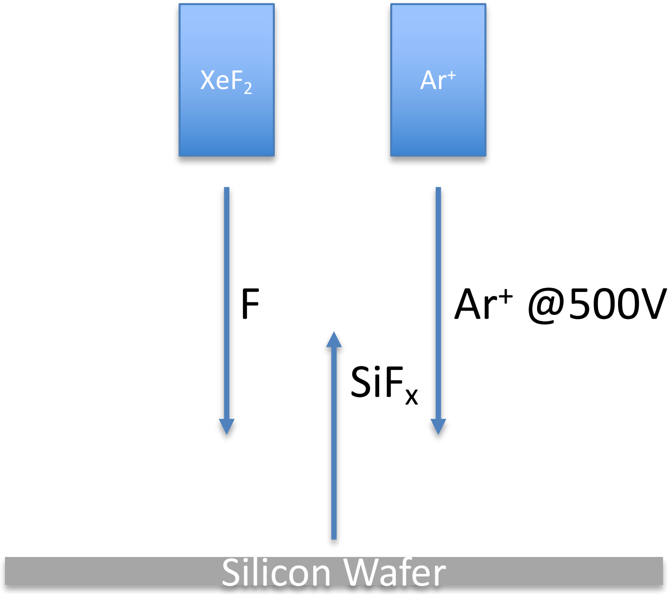


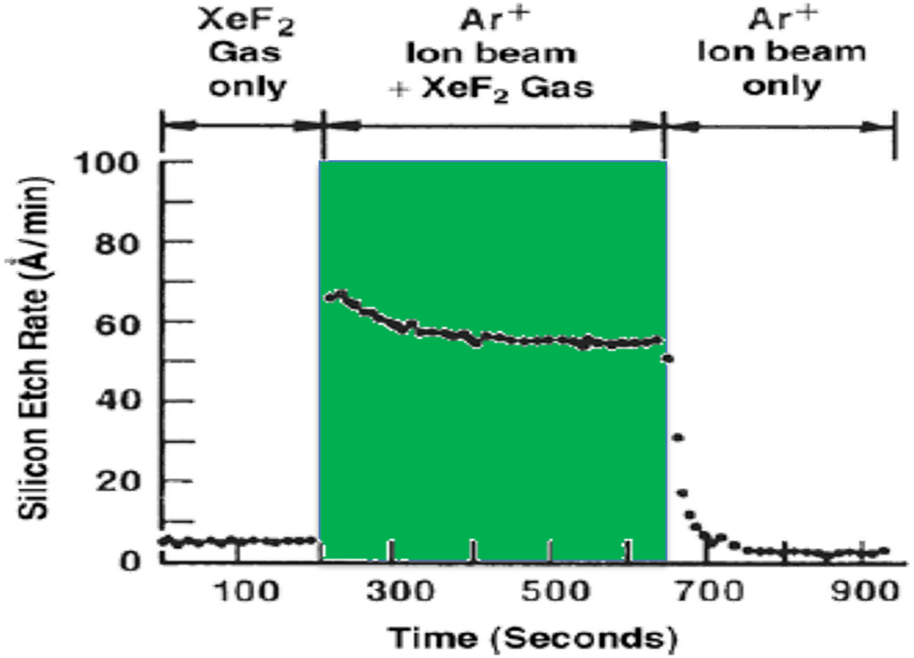
Initially Crystalline Si at 300 K



MD simulation by Graves group, UC Berkeley

The “classic” experiment that drove plasma etch





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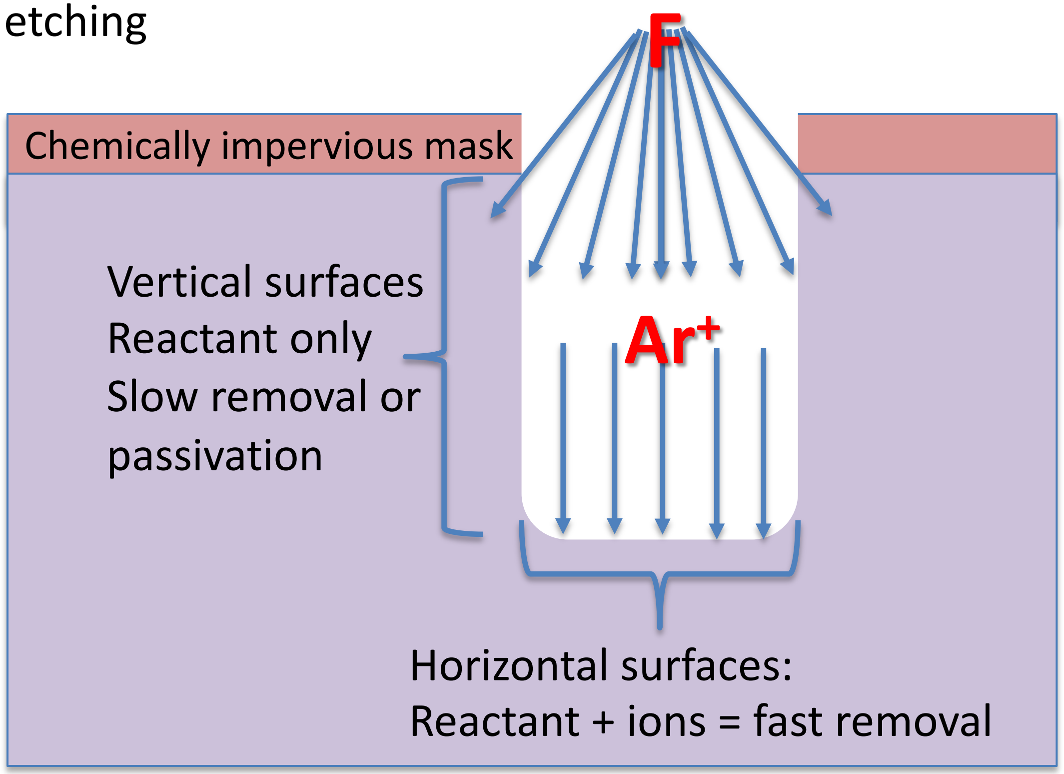
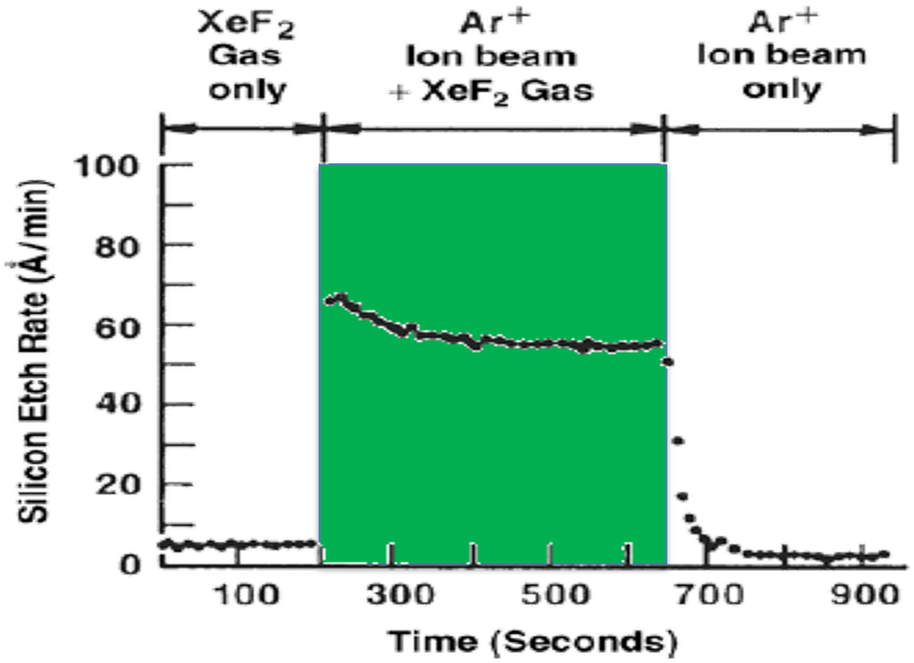
The “classic” experiment that drove plasma etch

What we learned: ion bombardment and reactive chemistries work in synergy to accelerate chemical reactions on the surface and accelerate processes like etching



Vertical surfaces
Reactant only
Slow removal or
passivation

Horizontal surfaces:
Reactant + ions = fast removal



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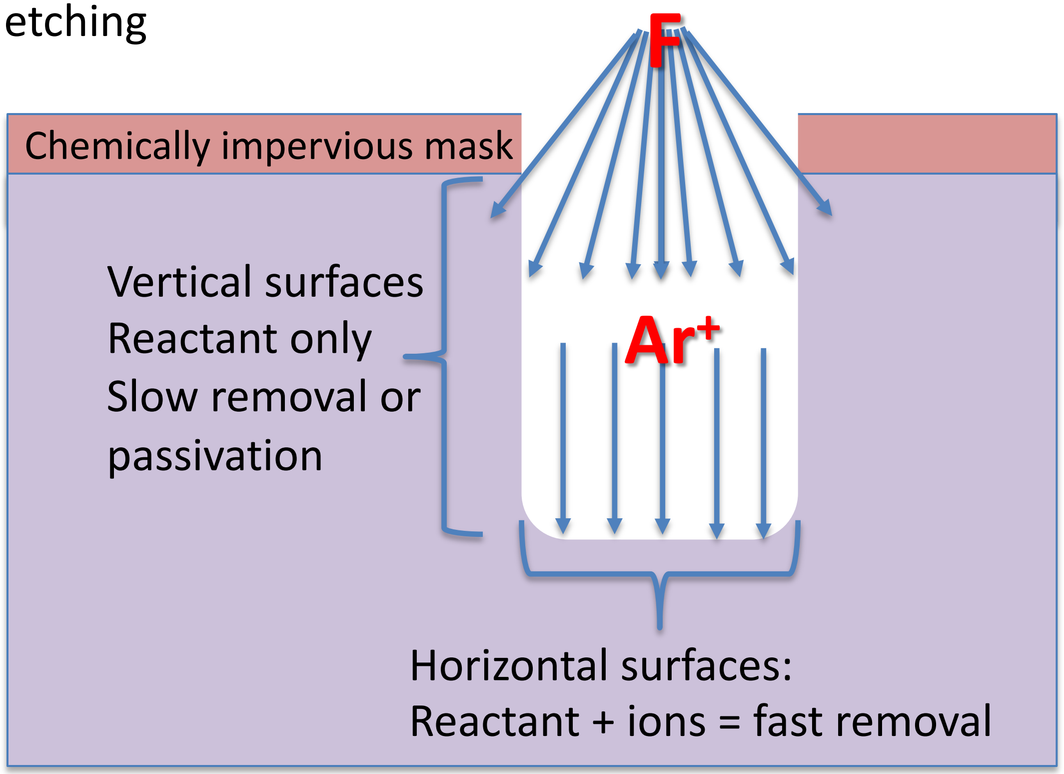

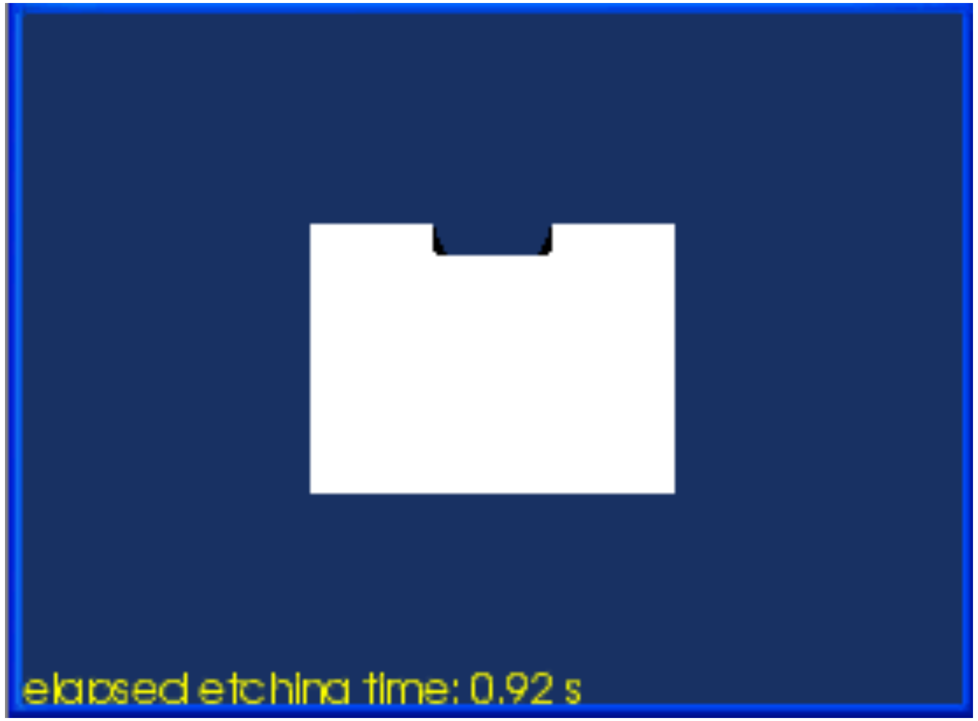

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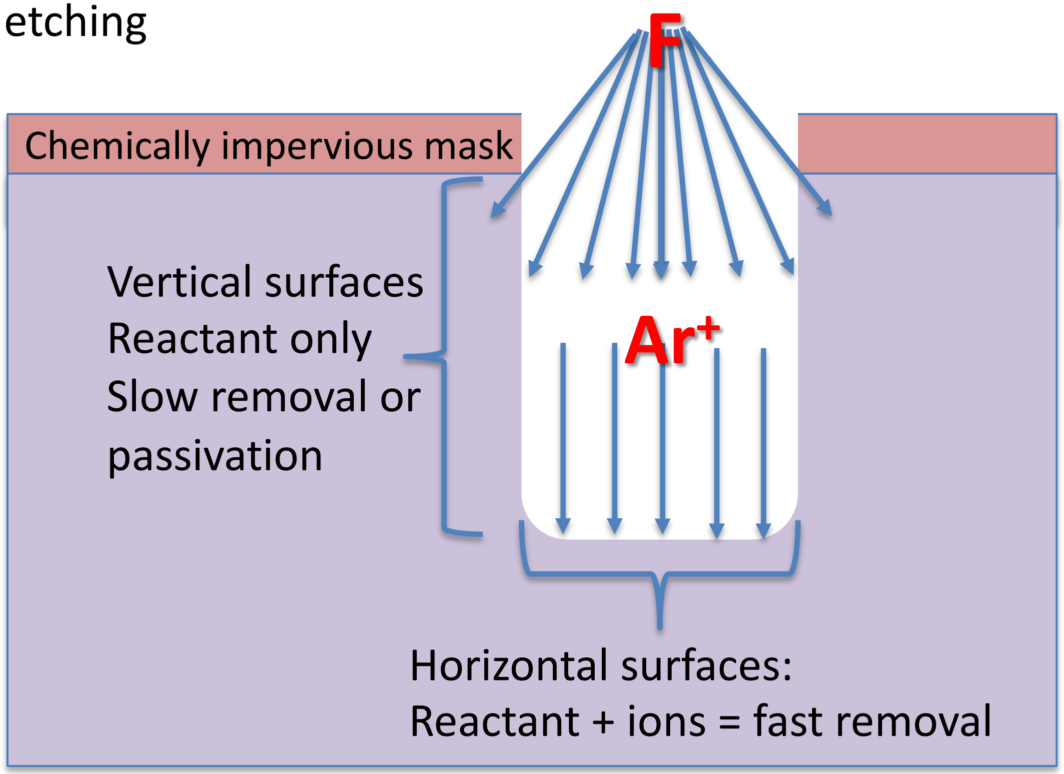
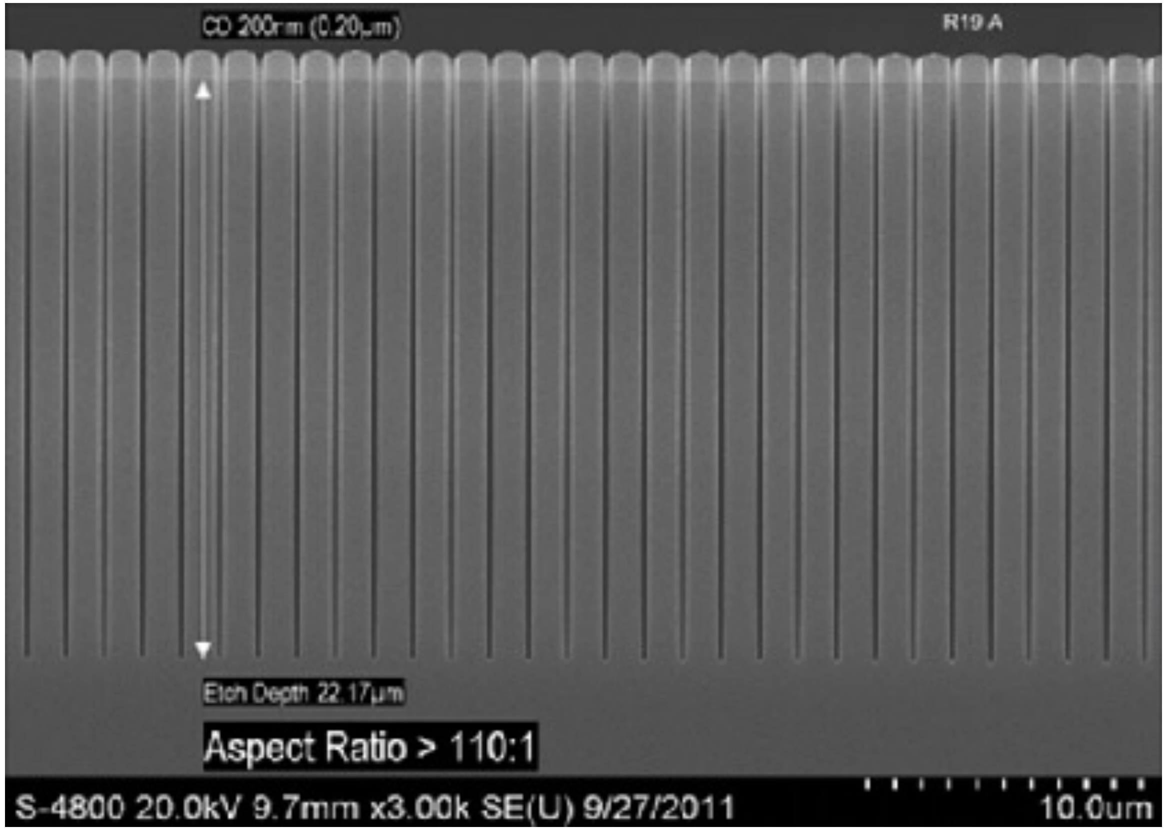


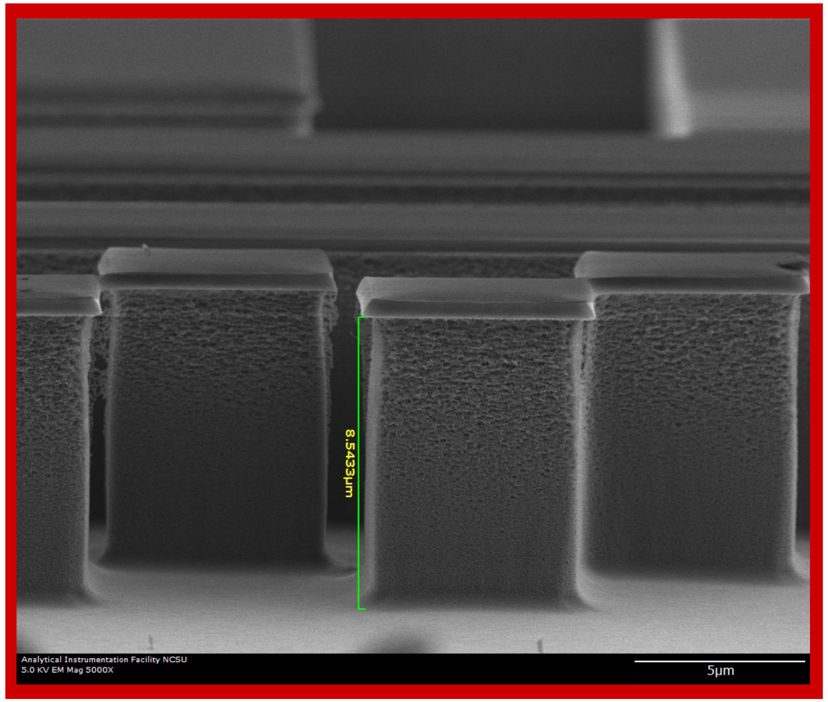
Chemically impervious mask

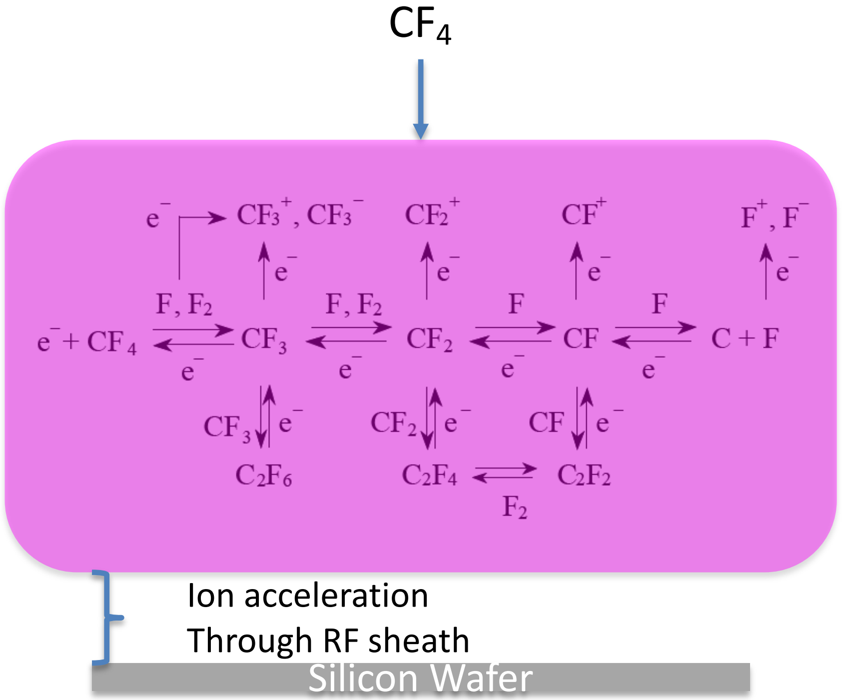
Vertical surfaces
Reactant only
Slow removal or
passivation

Horizontal surfaces:
Reactant + ions = fast removal



Fortunately this technology exists…





Applied Materials Advantage Etch System

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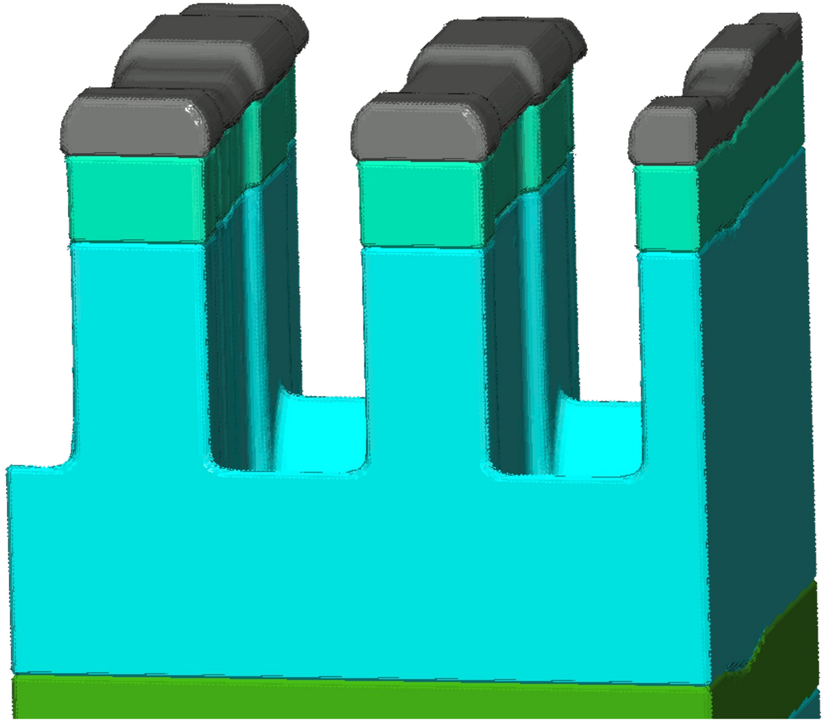
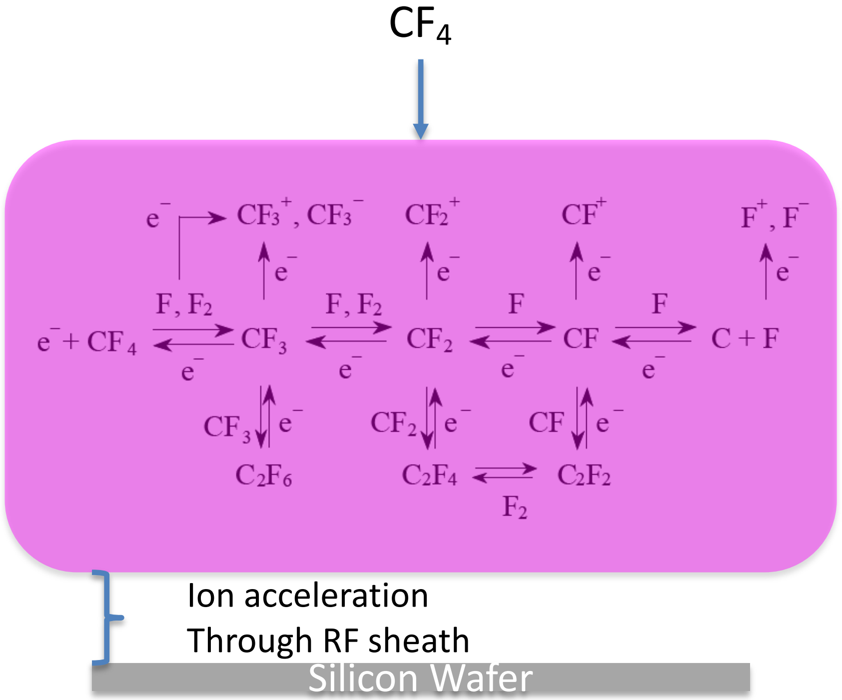




Ion acceleration
Through RF sheath

Silicon Wafer

Applied Materials Advantage Etch System

Fortunately this technology exists…

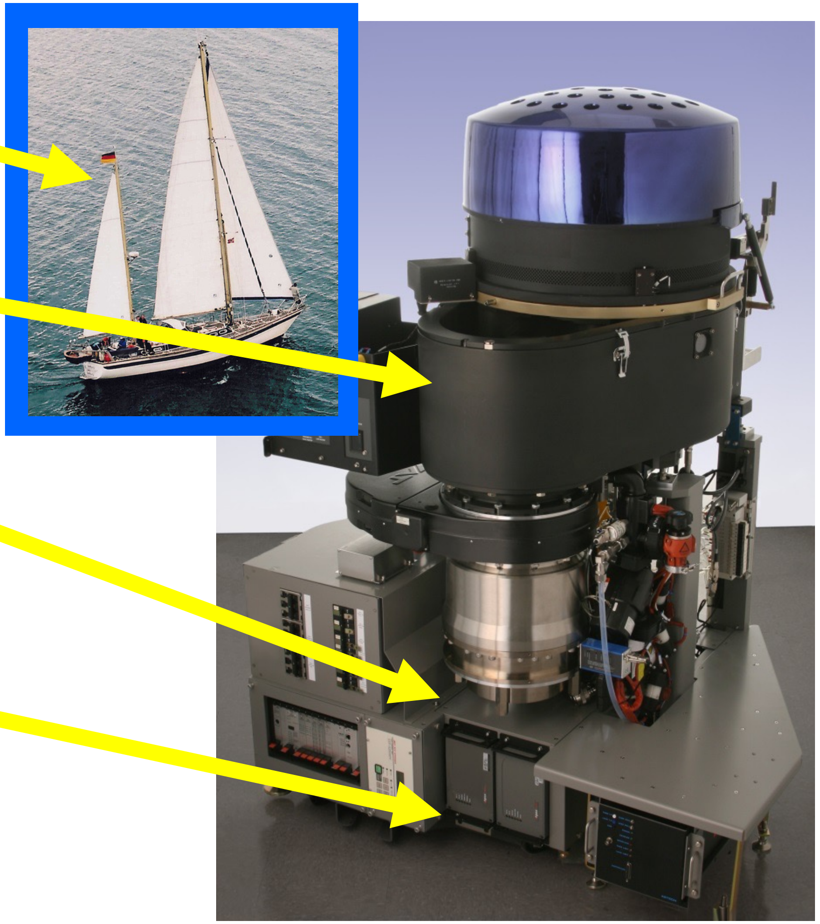
Costs more than a 53 foot yacht (~ $1,000,000)

Has a vacuum chamber that can provide the same conditions as outer space (base pressure < 1mTorr)

Turbo pump that spins faster than a jet engine (~25,000 RPM)

More RF power than a college radio station (~10,000 Watts)

Registered with the Federal Communications Commission



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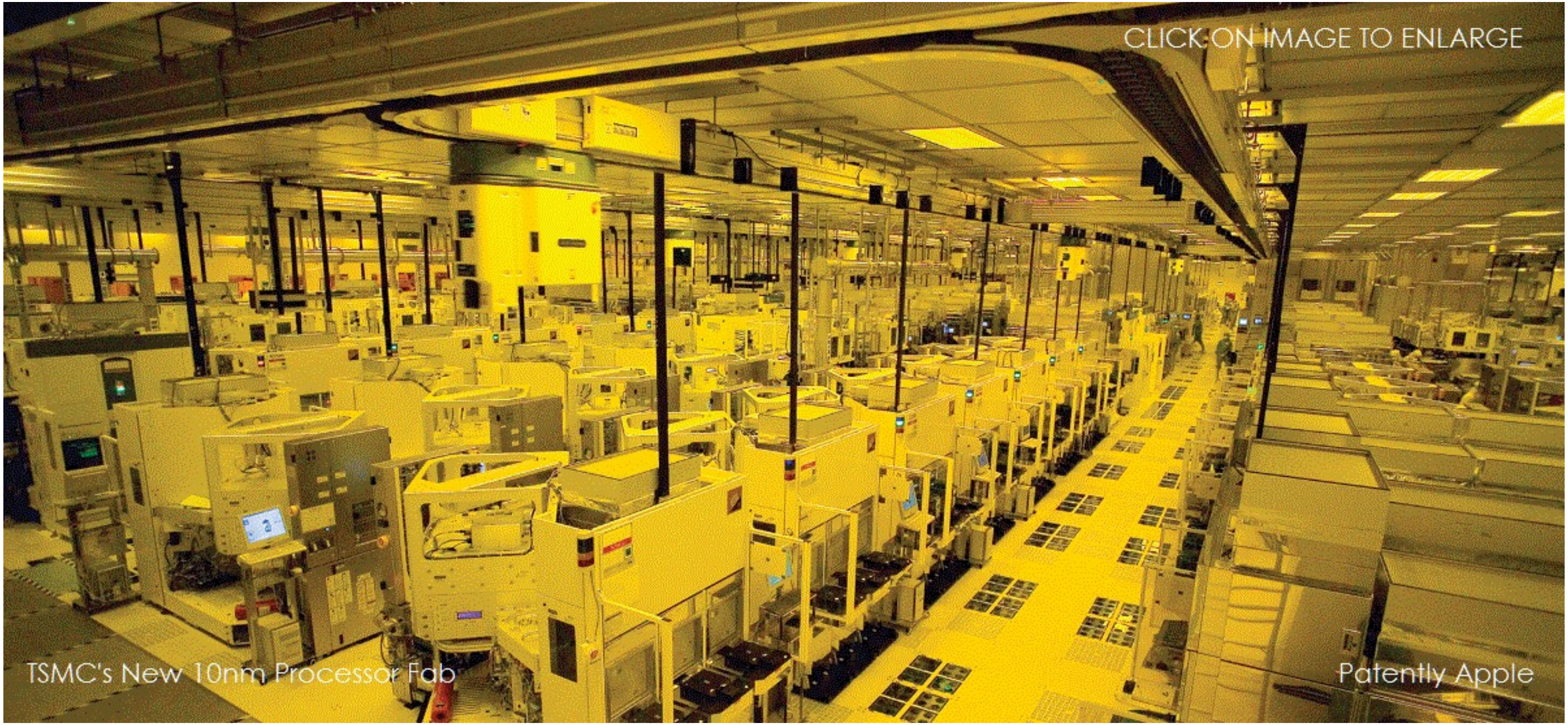
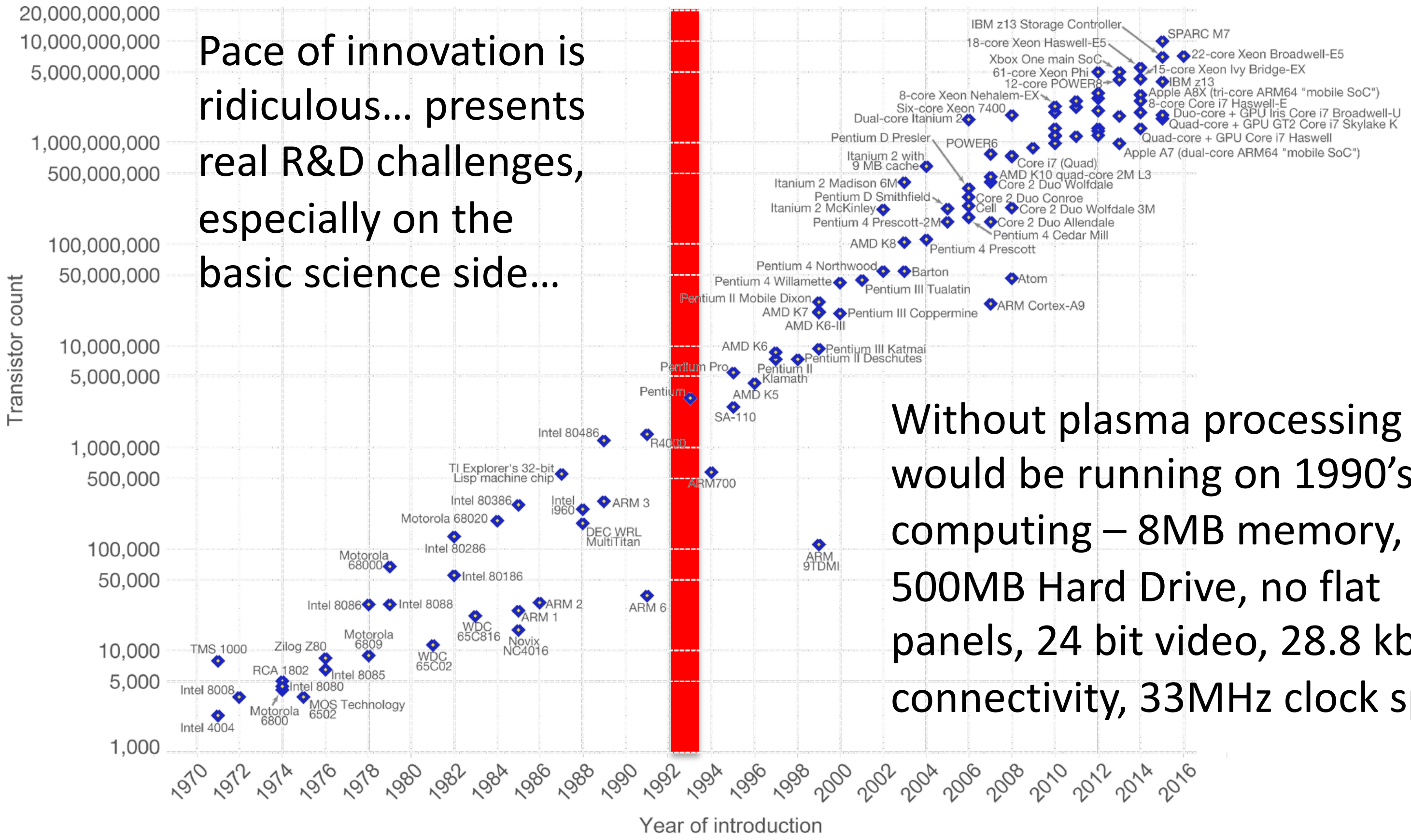


Seriously…. Fortunately this technology exists…



Moore's Law – The number of transistors on integrated circuit chips (1971-2016)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.

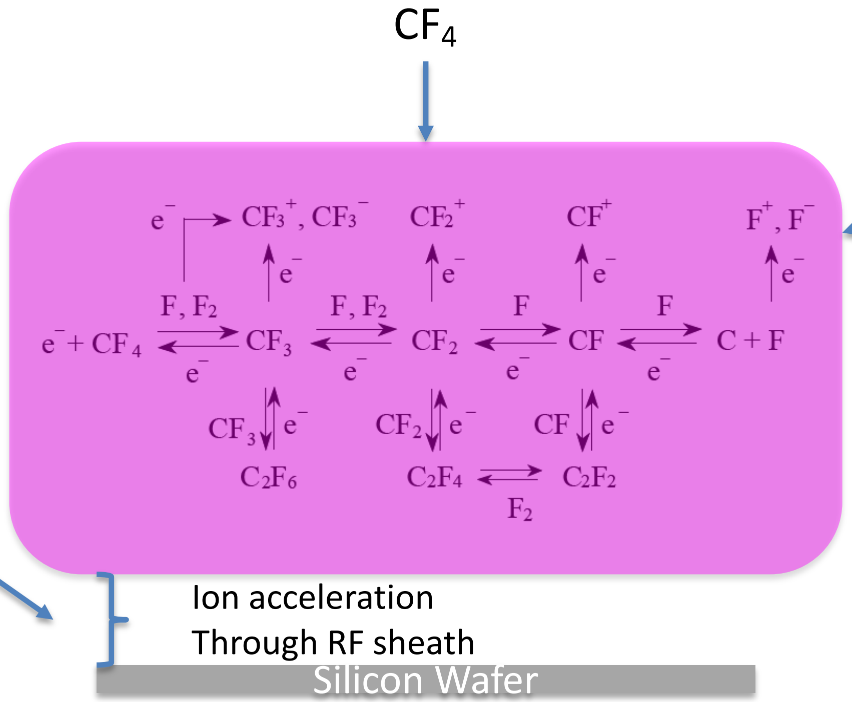
Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Pace of innovation is ridiculous… presents real R&D challenges, especially on the basic science side…

Without plasma processing we would be running on 1990's era computing – 8MB memory, 500MB Hard Drive, no flat panels, 24 bit video, 28.8 kbs connectivity, 33MHz clock speed

So… how does it work? We need two things…

Ion acceleration normal to the surface using naturally occurring electric fields at the plasma edge



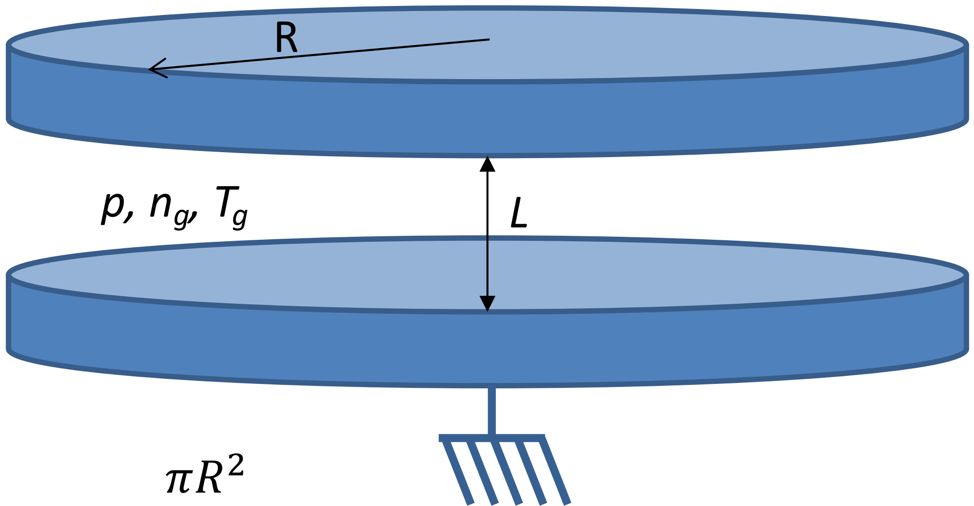
Electron driven “breaking” of molecules… don’t use thermal energy, use electron bombardment. This keeps the gas cool

If I can combine electron impact driven chemistry and controlled ion bombardment, I have an anisotropic reactor!

Plasmas can do both!

Building a simple plasma reactor, which in its simplest form is basically a high voltage gas filled capacitor

Will try to keep this as simple as possible, but unfortunately at some point things have to get a little ugly, but not super ugly…



$$C_{vac} = \varepsilon_0 \frac{\pi R^2}{L}$$

What happens if we fill this capacitor with a plasma?

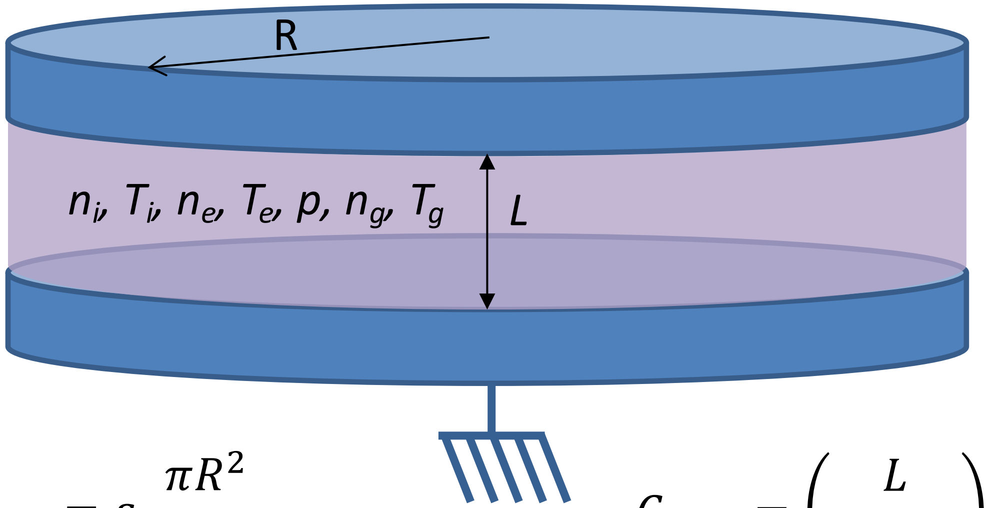
Note: most processing "plasmas" are still composed of around 99.9% neutral gas species

$$n_g = \frac{p}{kT_g} \approx 3\times10^{15}cm^{-3}@100mTorr\ 300K$$

$n_e = n_i \approx 10^8cm^{-3} - 10^{12}cm^{-3}$ typically

$T_e \approx 2eV - 10eV$ typically

$T_i \approx 0.03eV - 0.1eV$ typically



$$C_{vac} = \varepsilon_0 \frac{\pi R^2}{L}$$

$$C_{load} = \left(\frac{L}{\varepsilon_p \pi R^2}\right)^{-1}$$

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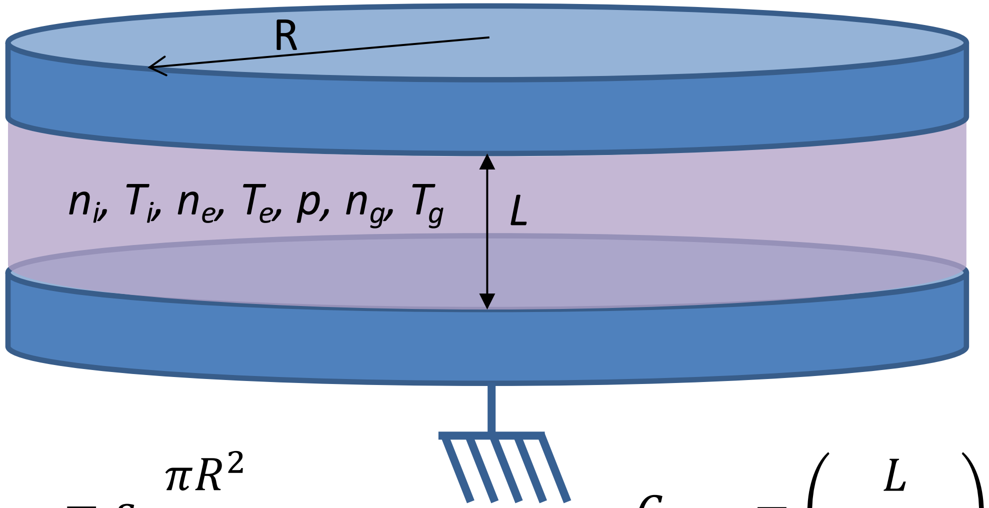

At time t = 0, the entire cylinder is filled with an equal distribution of electrons and ions

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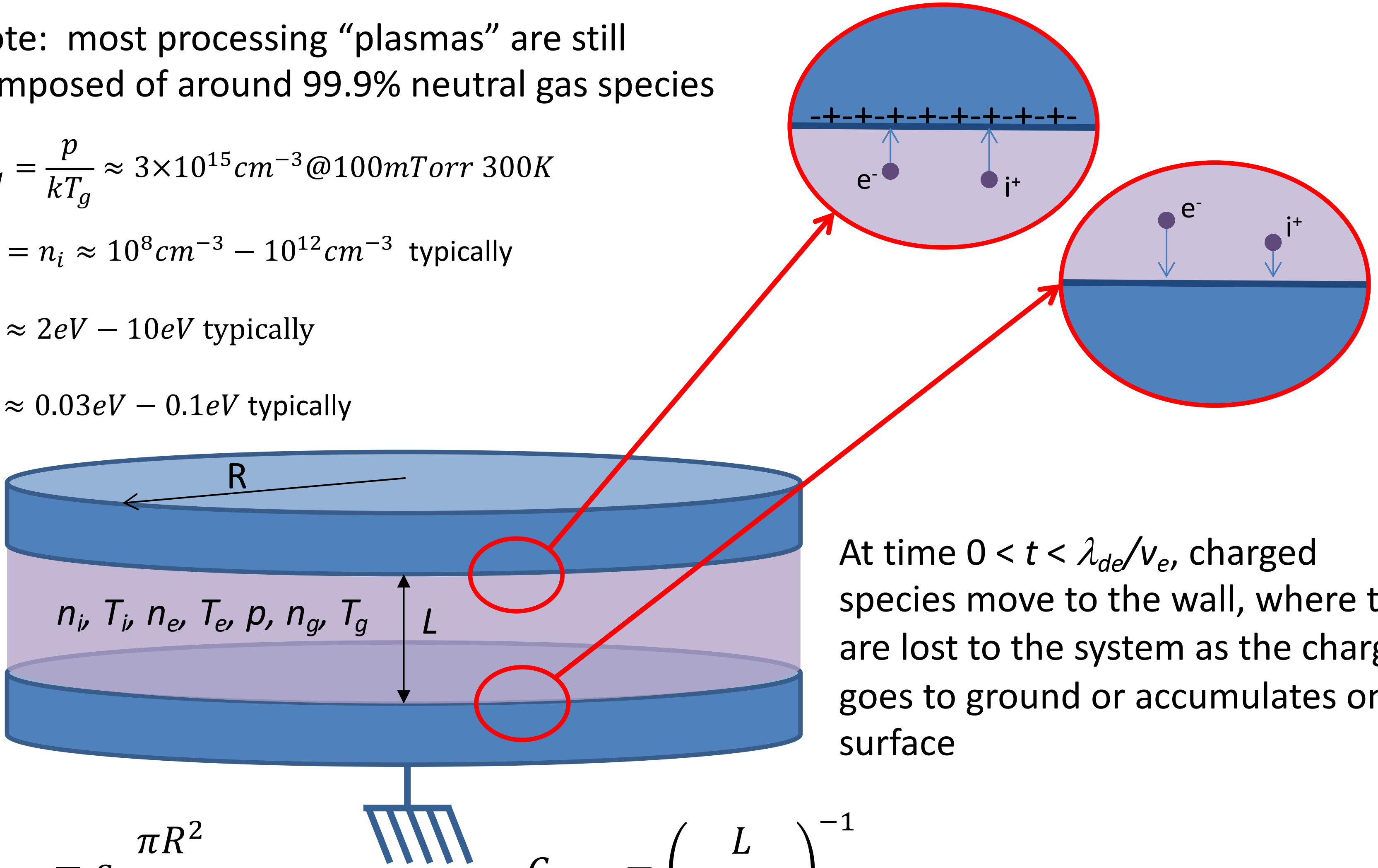

At time $0 < t < \lambda_{de}/v_e$, charged species move to the wall, where they are lost to the system as the charge goes to ground or accumulates on surface

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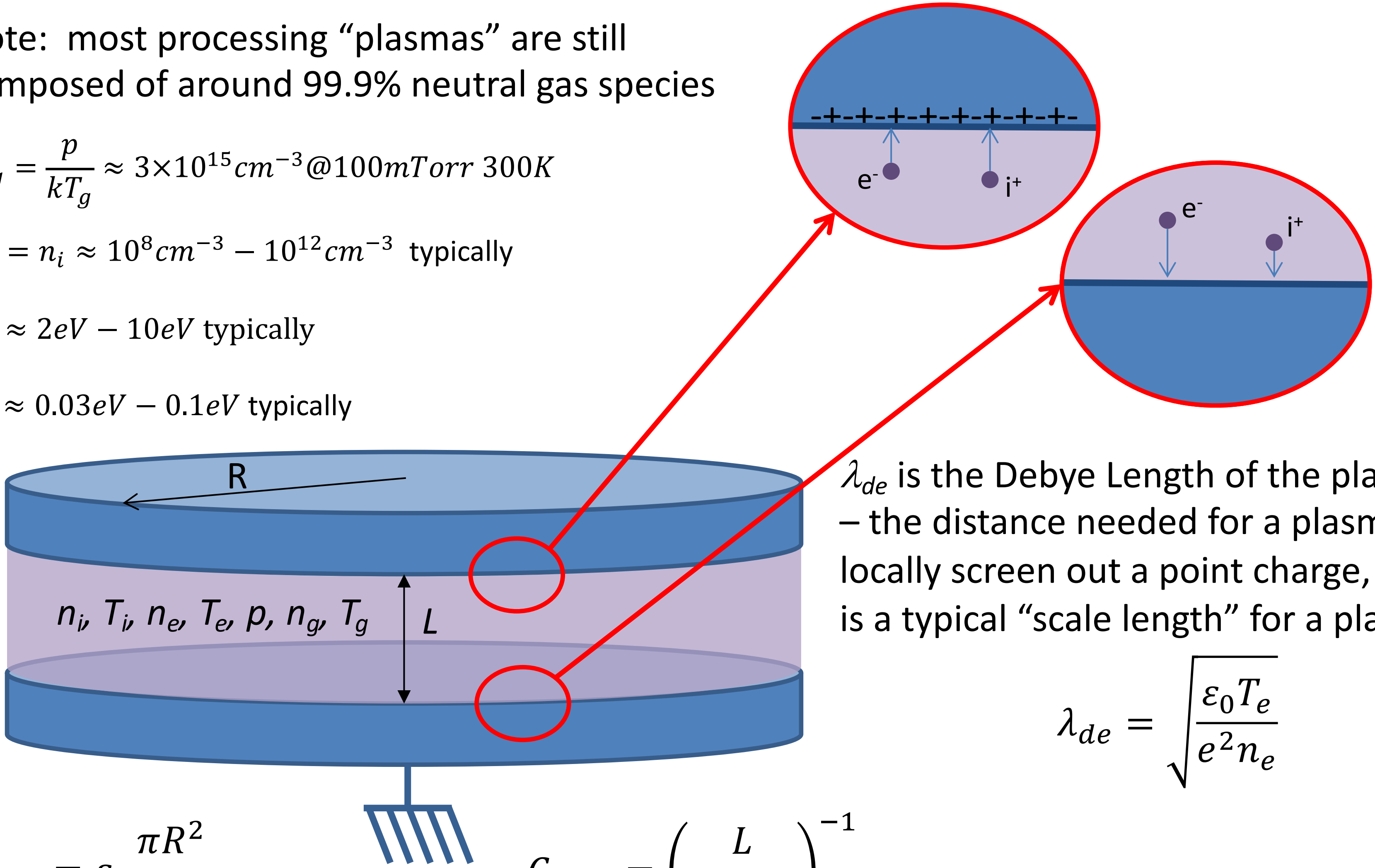

λ_{de} is the Debye Length of the plasma – the distance needed for a plasma to locally screen out a point charge, and is a typical "scale length" for a plasma

$$\lambda_{de} = \sqrt{\frac{\varepsilon_0 T_e}{e^2 n_e}}$$

$$C_{vac} = \varepsilon_0 \frac{\pi R^2}{L}$$

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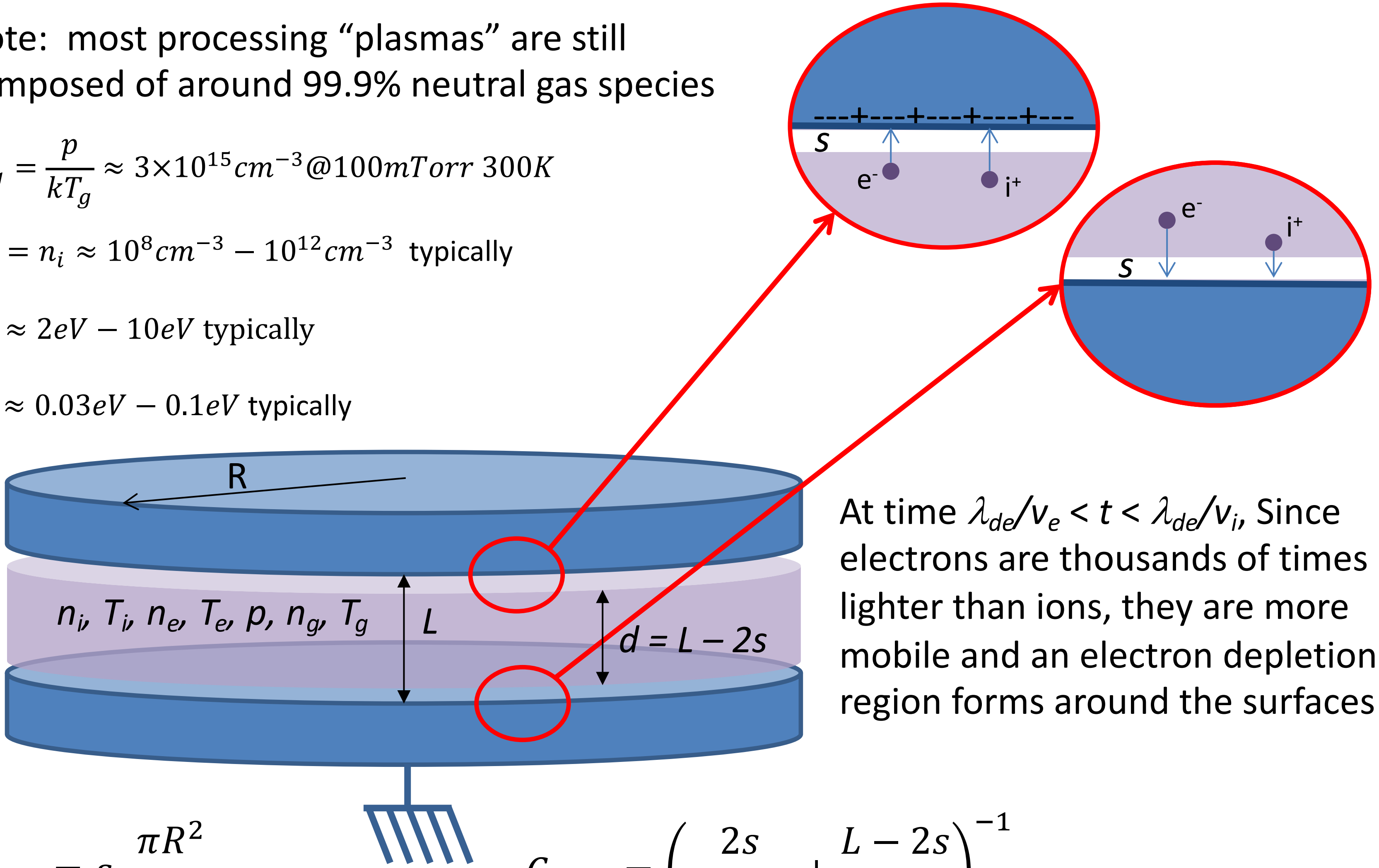

At time $\lambda_{de}/v_e < t < \lambda_{de}/v_i$, Since electrons are thousands of times lighter than ions, they are more mobile and an electron depletion region forms around the surfaces

$$C_{vac} = \varepsilon_0 \frac{\pi R^2}{L}$$

$$C_{load} = \left(\frac{2s}{\varepsilon_0 \pi R^2} + \frac{L-2s}{\varepsilon_p \pi R^2}\right)^{-1}$$

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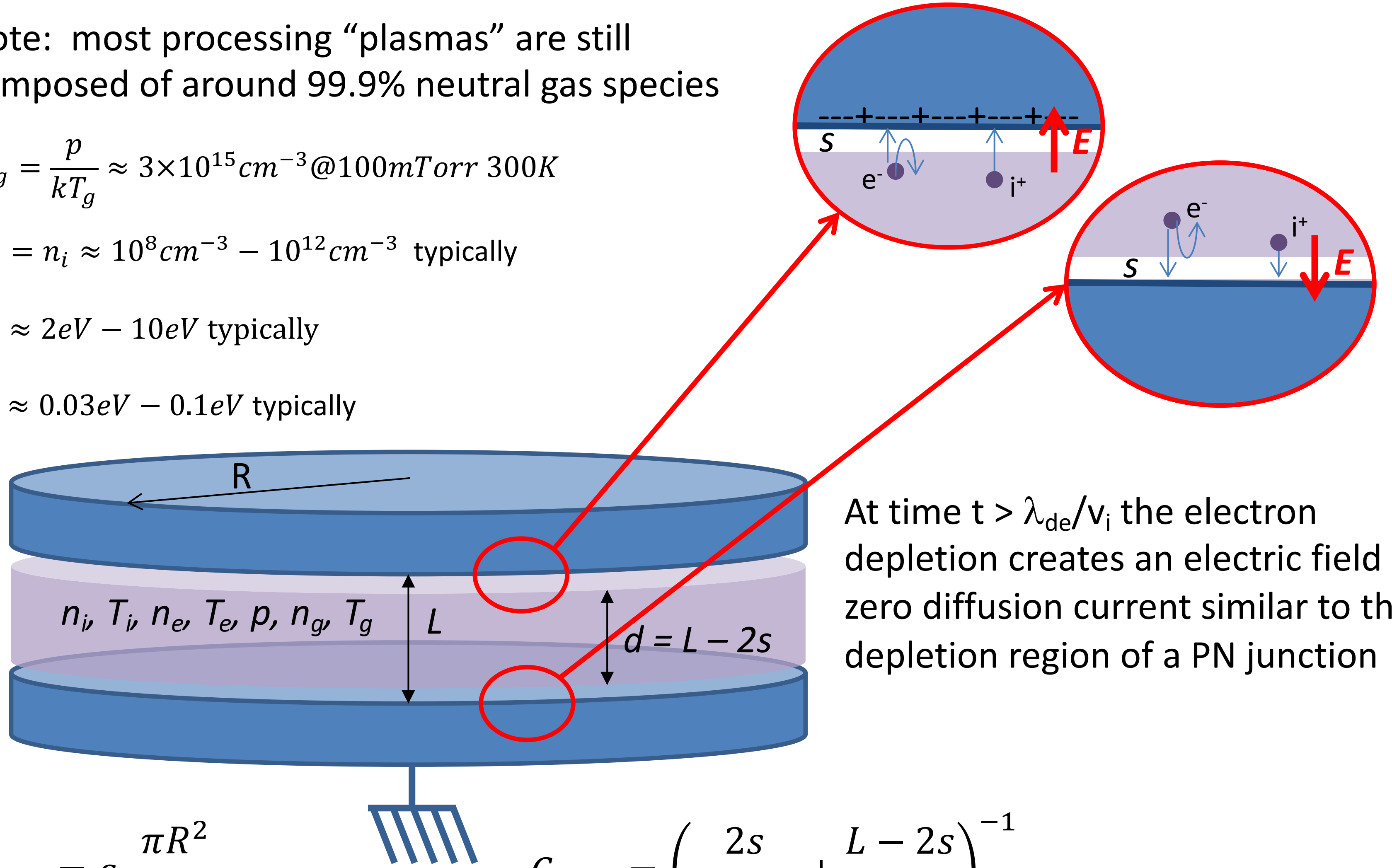

At time t > λ_{de}/v_i the electron depletion creates an electric field to zero diffusion current similar to the depletion region of a PN junction

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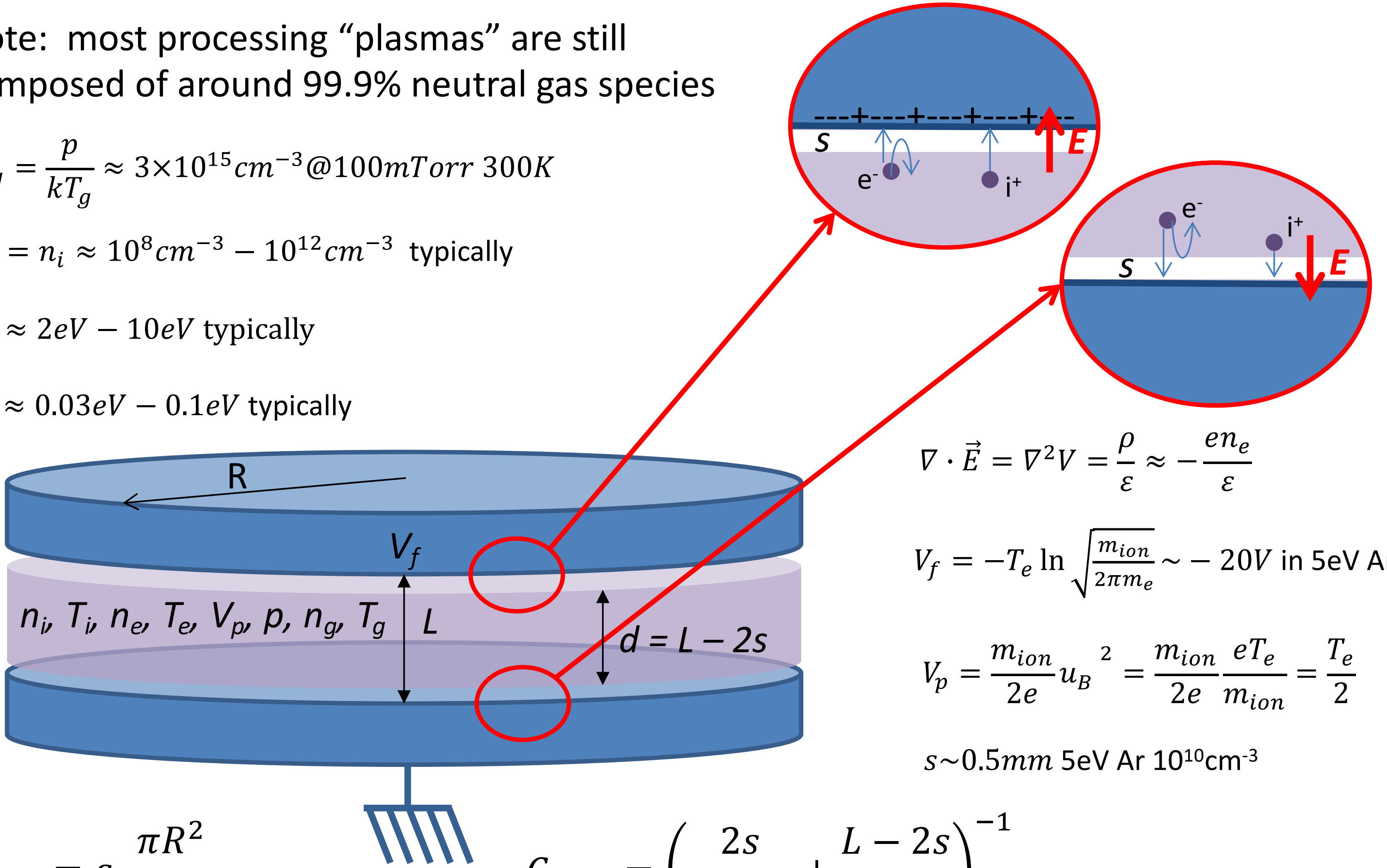

$$\nabla \cdot \vec{E} = \nabla^2 V = \frac{\rho}{\varepsilon} \approx -\frac{en_e}{\varepsilon}$$

$$V_f = -T_e \ln\sqrt{\frac{m_{ion}}{2\pi m_e}} \sim -20V$$ in 5eV Ar

$$V_p = \frac{m_{ion}}{2e} u_B{}^2 = \frac{m_{ion}}{2e}\frac{eT_e}{m_{ion}} = \frac{T_e}{2}$$

$s \sim 0.5mm$ 5eV Ar 10^{10}cm^{-3}

$$C_{vac} = \varepsilon_0 \frac{\pi R^2}{L}$$

$$C_{load} = \left(\frac{2s}{\varepsilon_0 \pi R^2} + \frac{L-2s}{\varepsilon_p \pi R^2}\right)^{-1}$$

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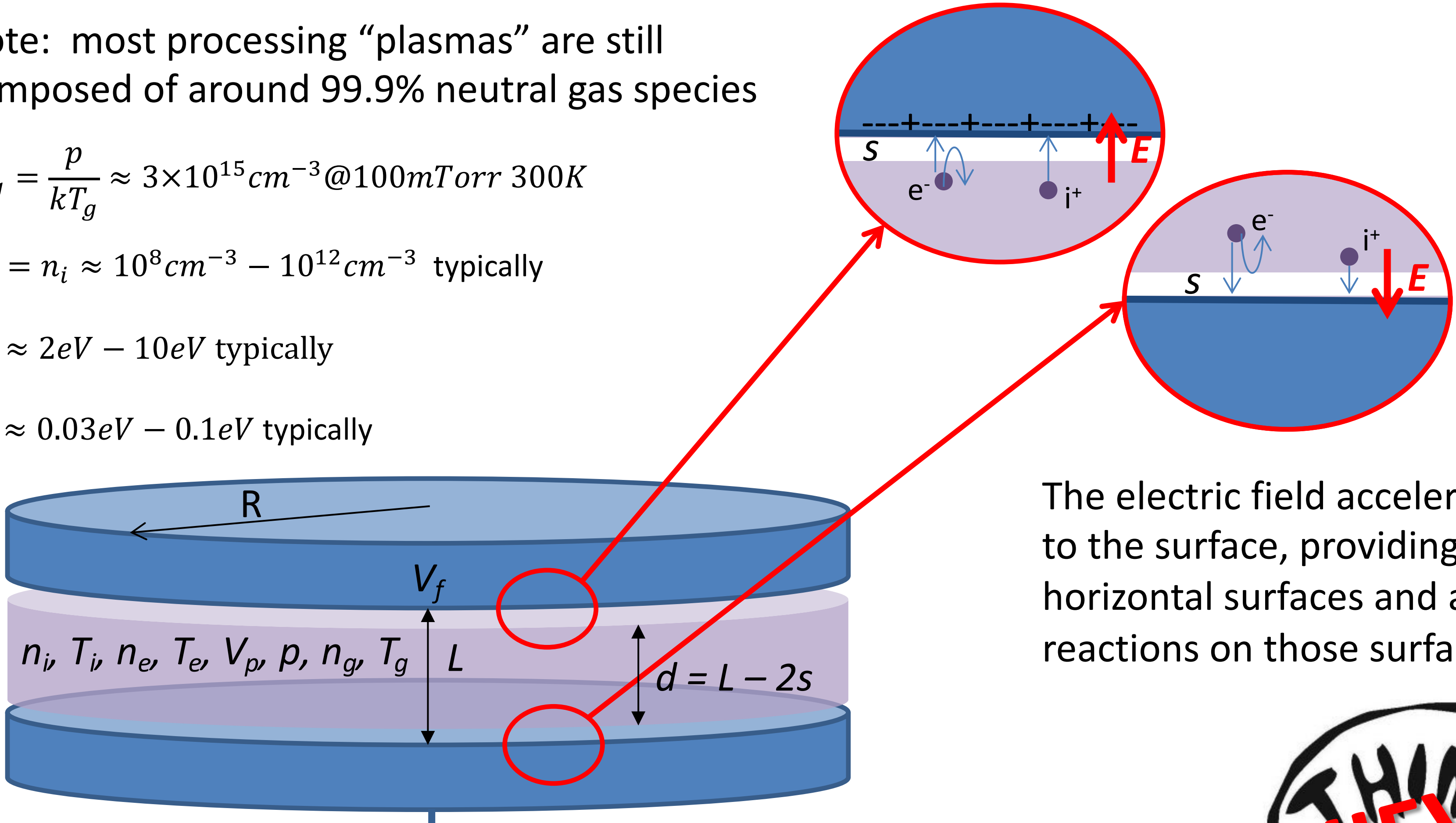

The electric field accelerates ions normal to the surface, providing ion flux to ONLY horizontal surfaces and accelerating reactions on those surfaces

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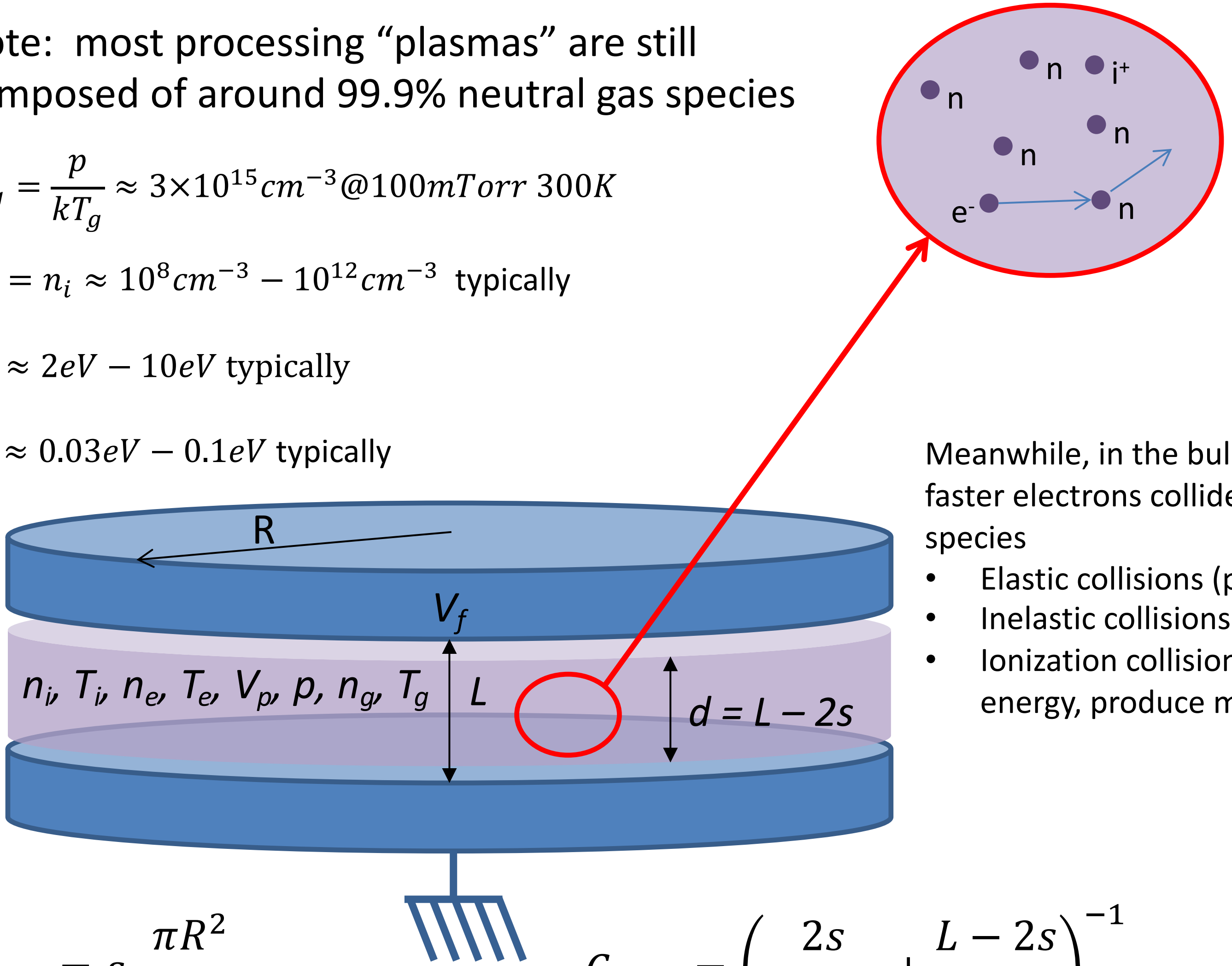

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- Inelastic collisions – excitation, dissociation
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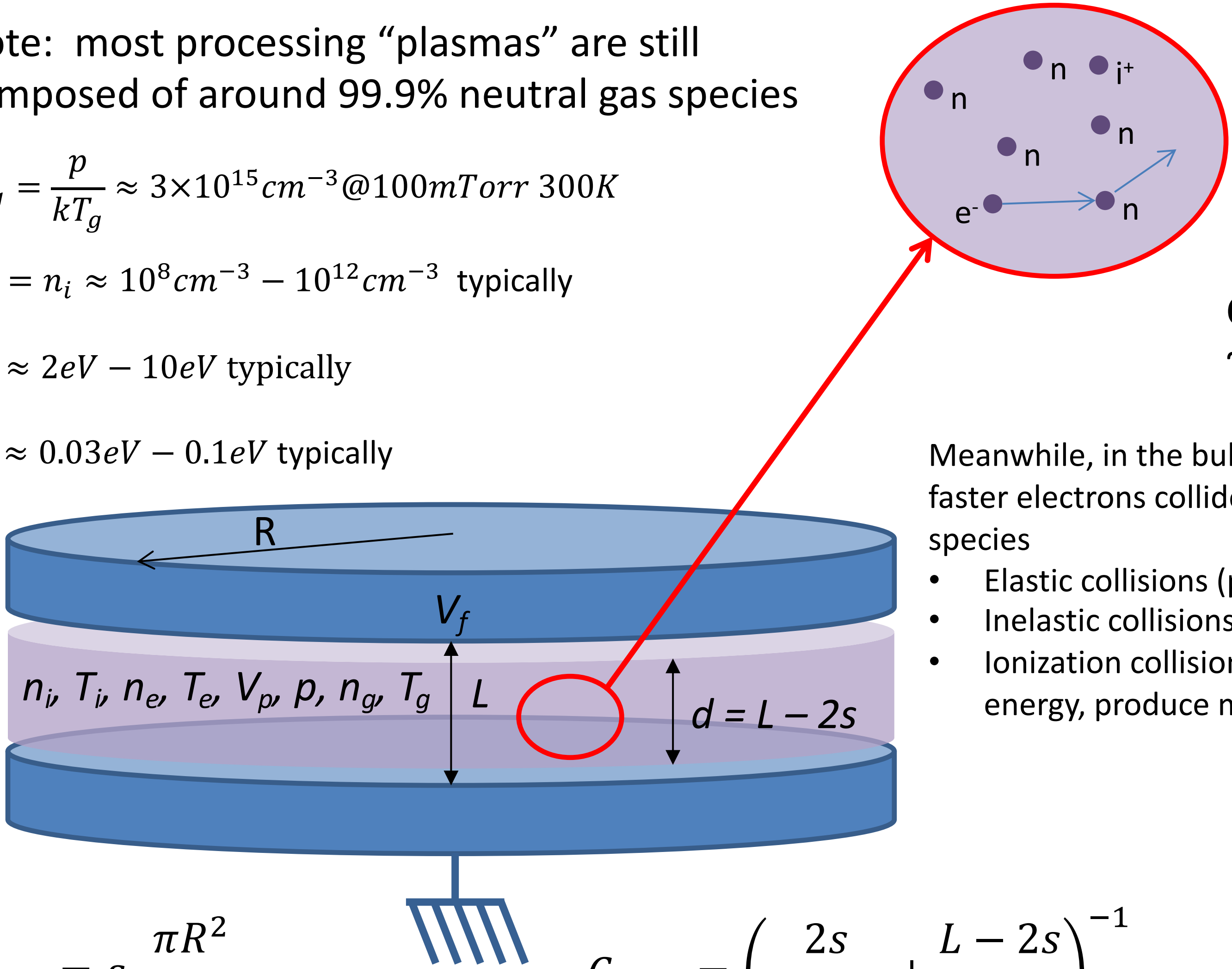

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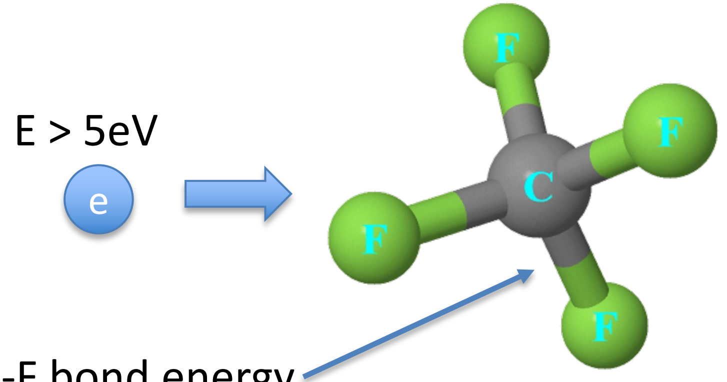

C-F bond energy ~5eV

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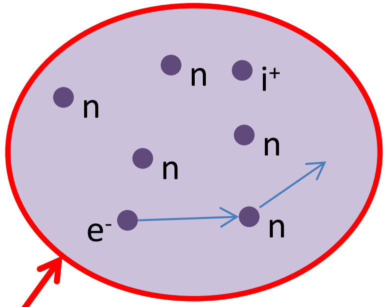

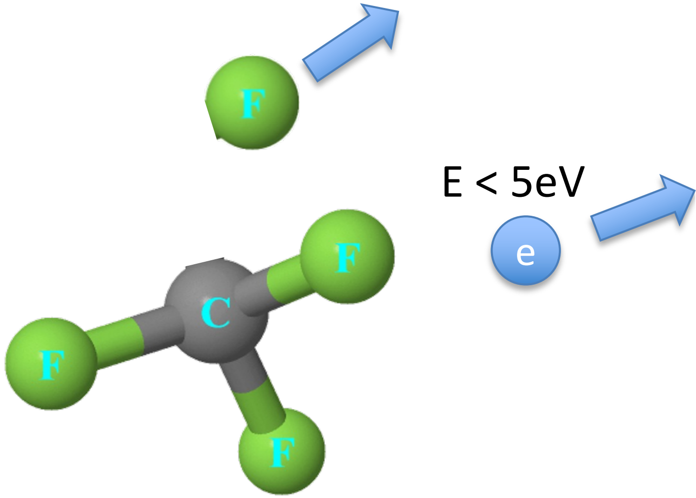

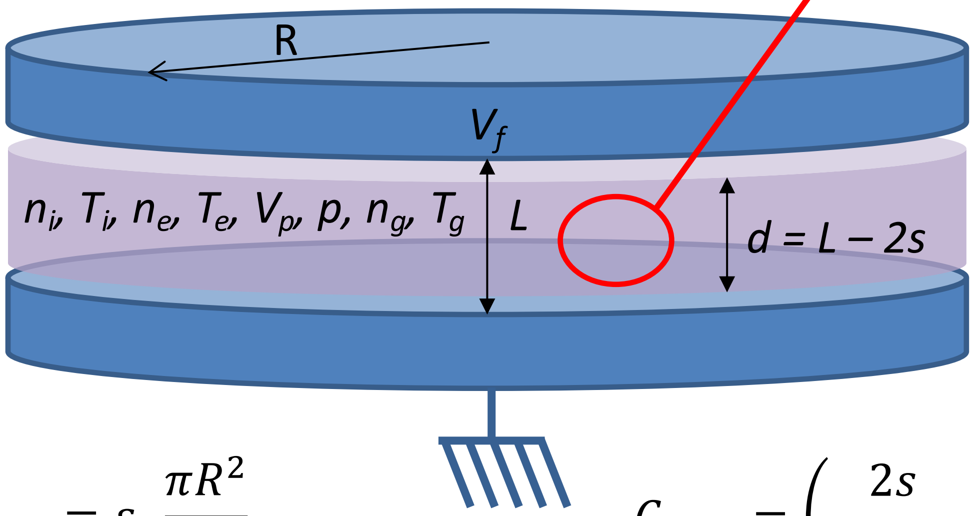

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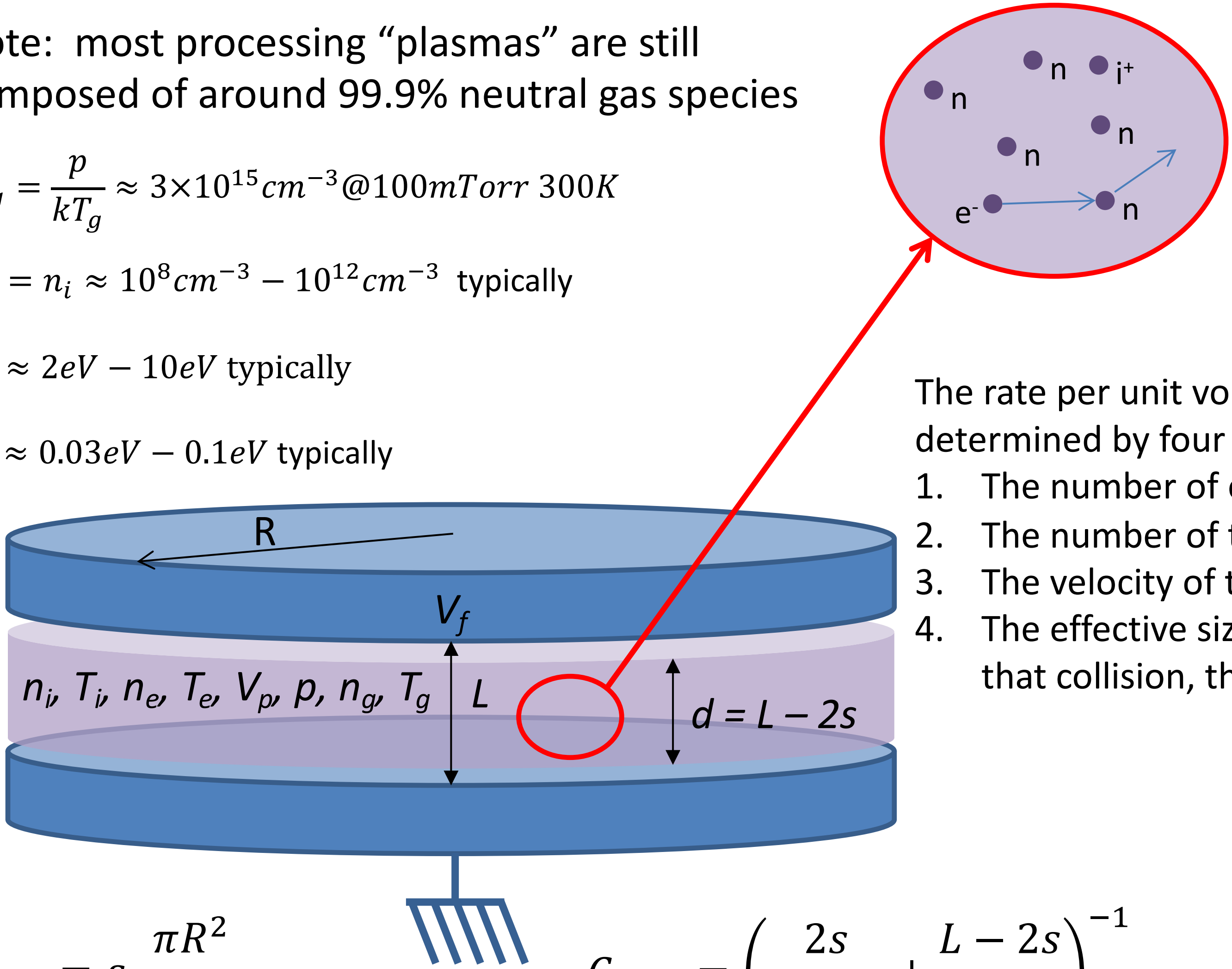

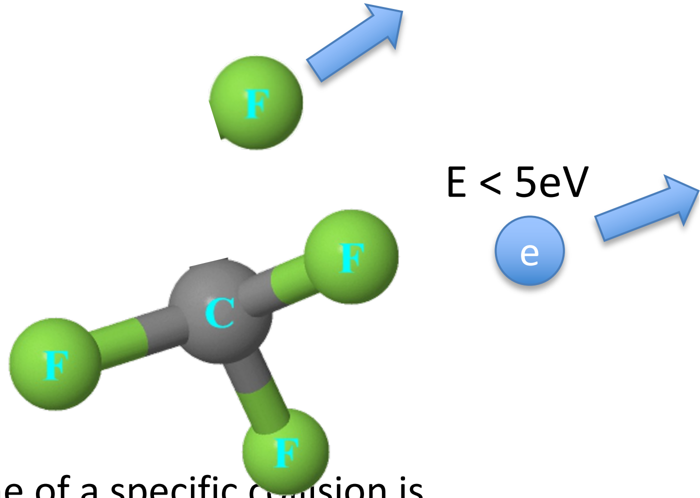

The rate per unit volume of a specific collision is determined by four factors:

1. The number of electrons n_e
2. The number of targets for the electron to hit n_{target}
3. The velocity of the electron $(2E_e/m_e)^{1/2}$
4. The effective size of the target atom or molecule for that collision, the cross section σ

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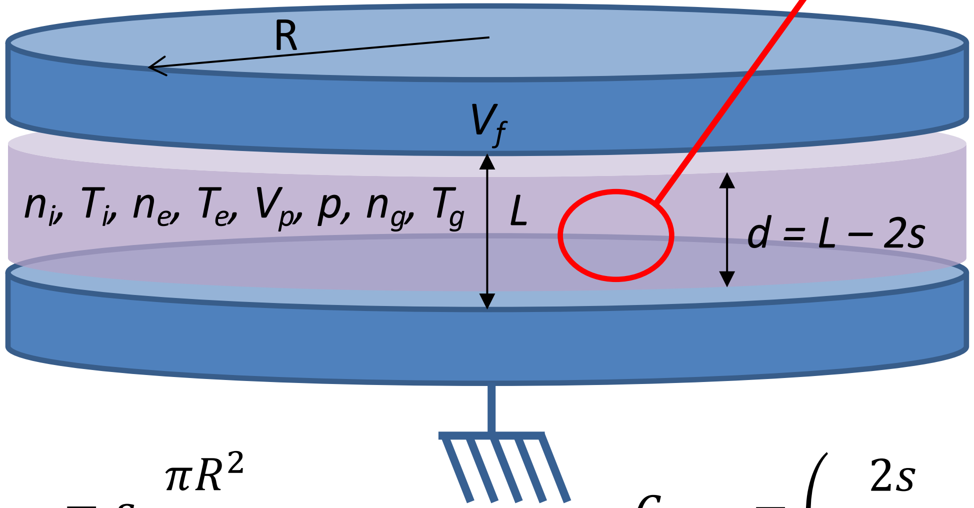

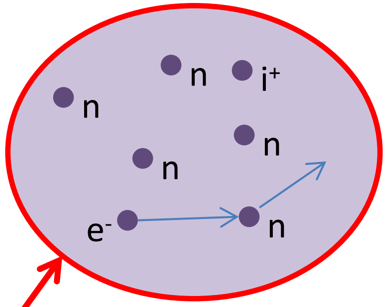

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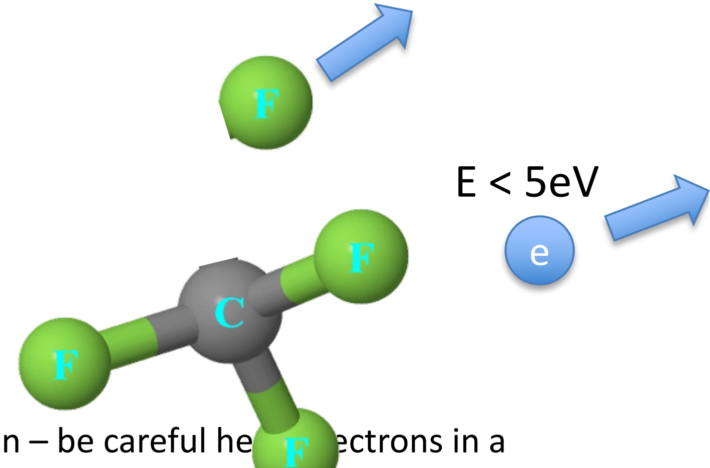

The velocity of the electron – be careful he ectrons in a plasma have a distribution of energies, not a ways Maxwellian

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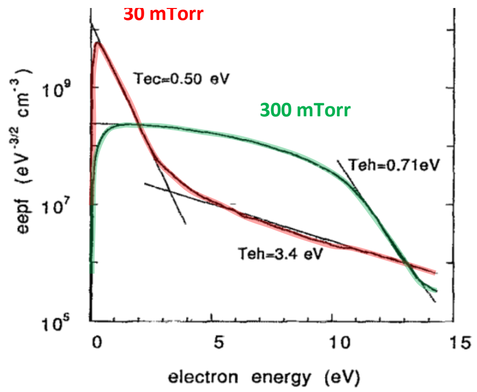

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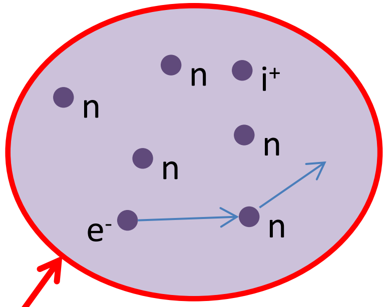
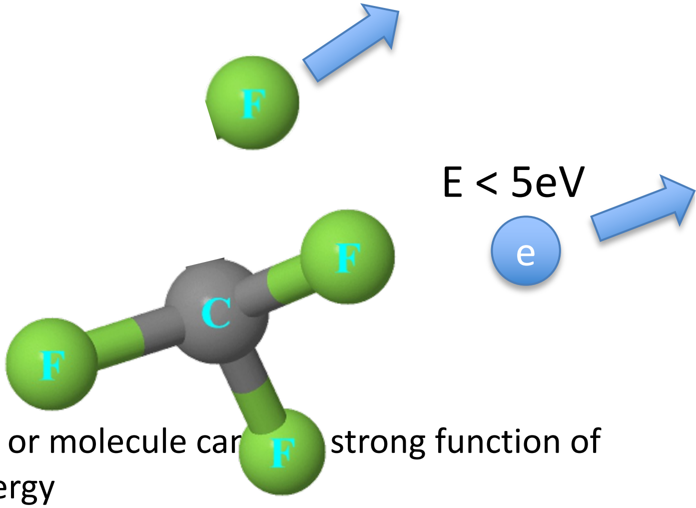
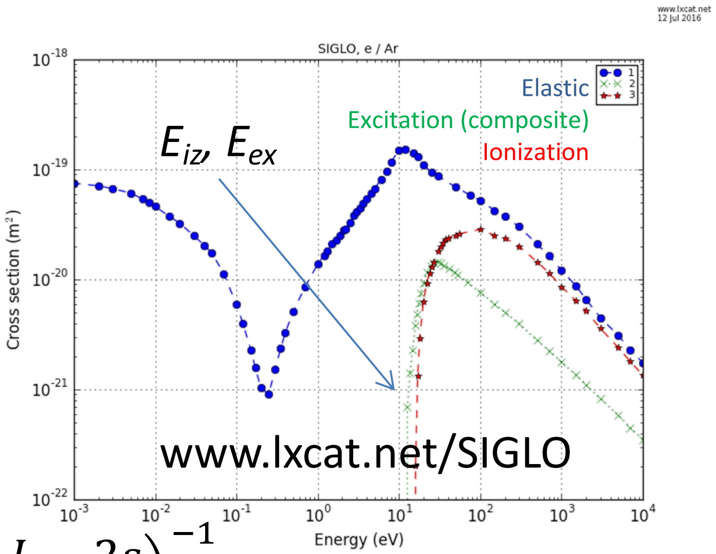
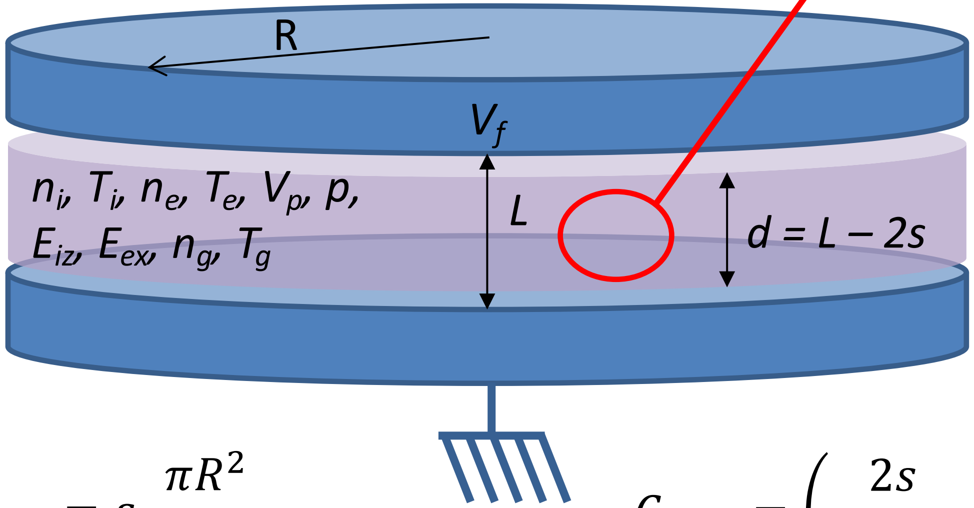




The target size of the atom or molecule car strong function of an individual electron’s energy





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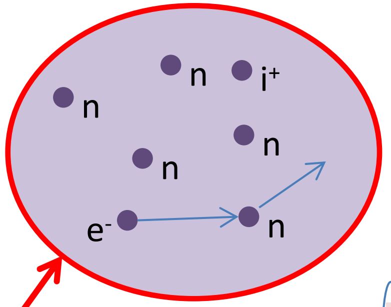
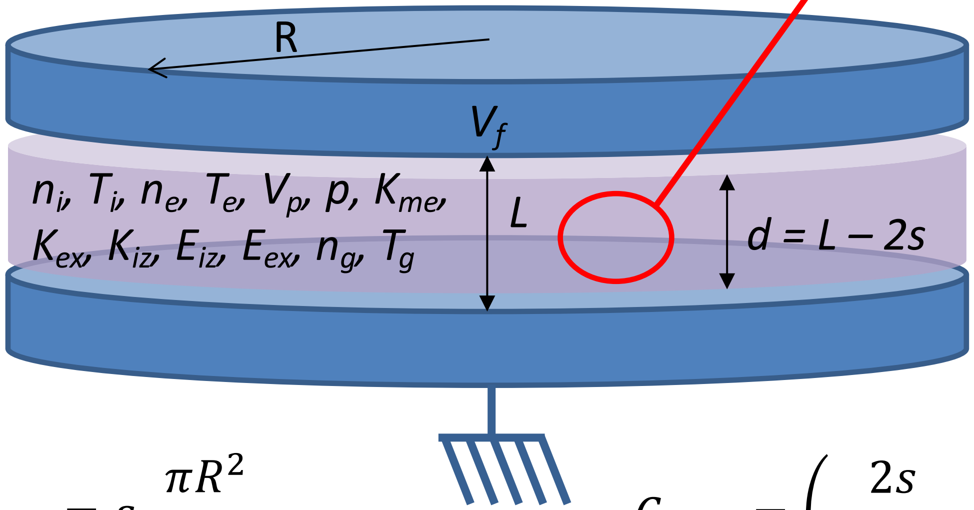
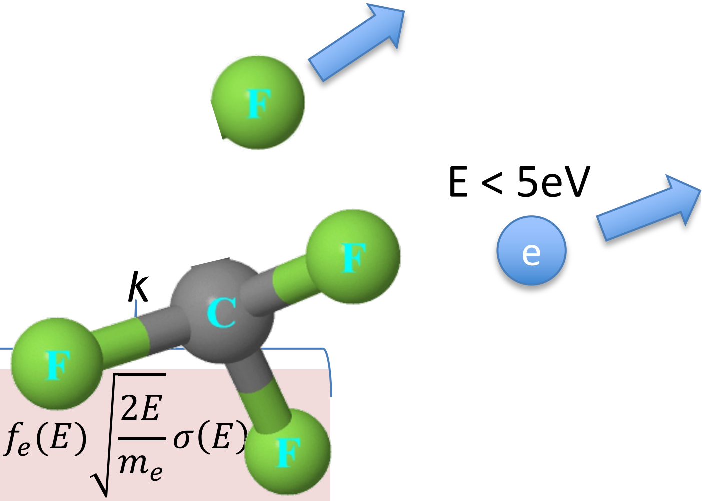
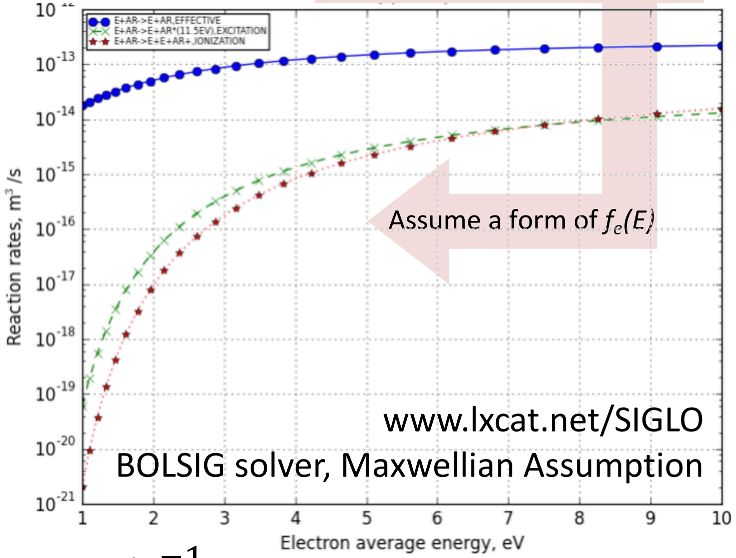






$$Rate\left(\frac{1}{m^3 s}\right) = n_g n_e \overbrace{\int_0^\infty f_e(E)\sqrt{\frac{2E}{m_e}}\sigma(E)}^{k}$$



Assume a form of $f_e(E)$

www.lxcat.net/SIGLO

BOLSIG solver, Maxwellian Assumption

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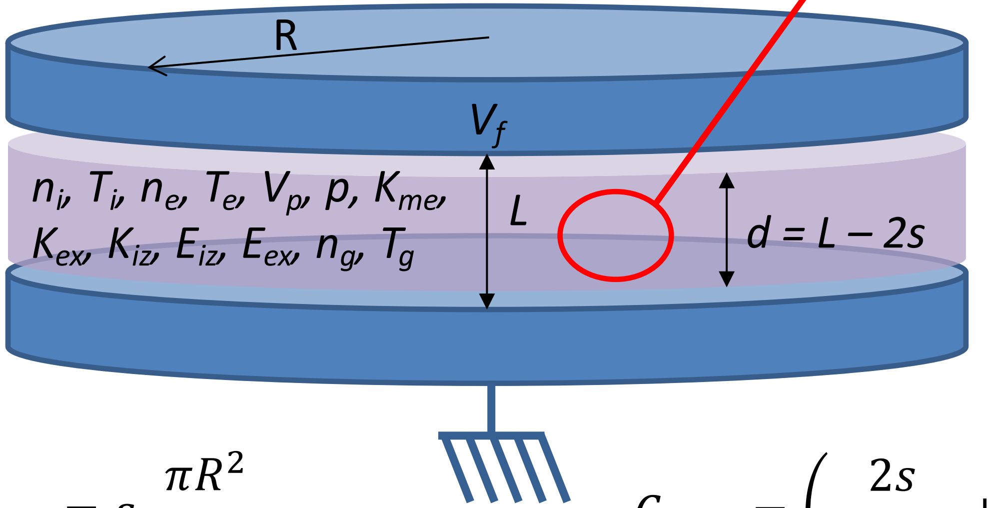
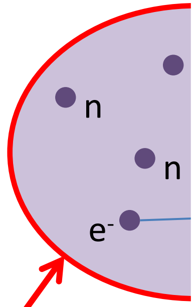
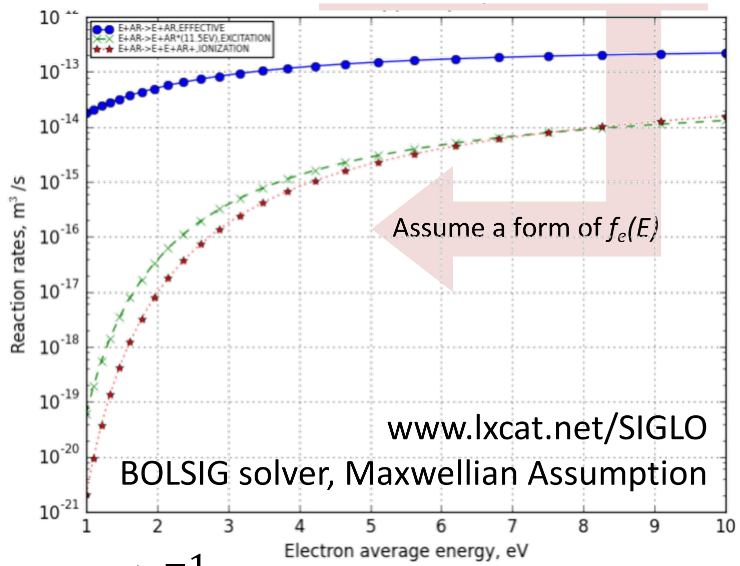




This gives us reaction rates (K), just like in chemistry, but they are a function of the electron's temperature, NOT the gas temperature

But – we do get reactive gas species without heating up the background gas much

$Rate\left(\frac{-}{n}\right.$



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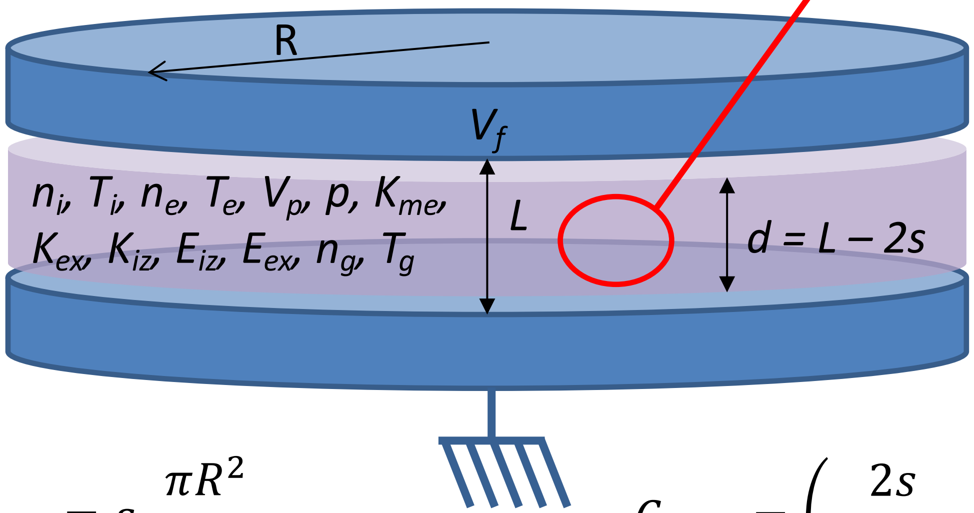

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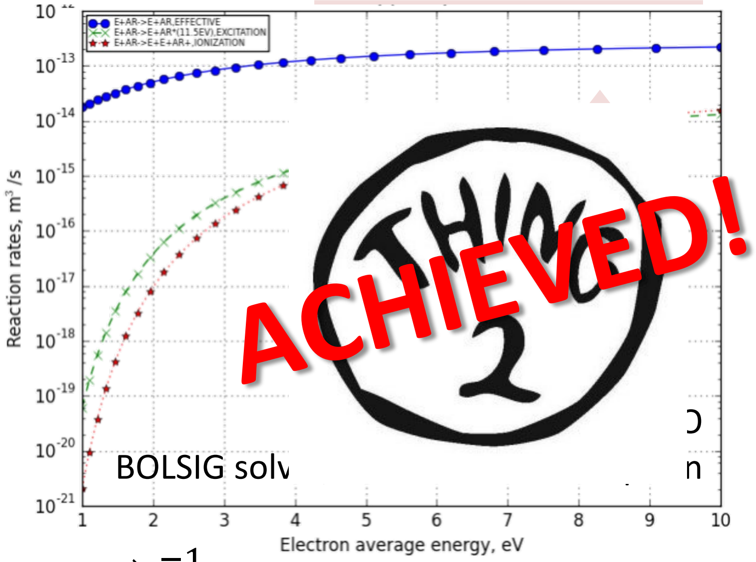
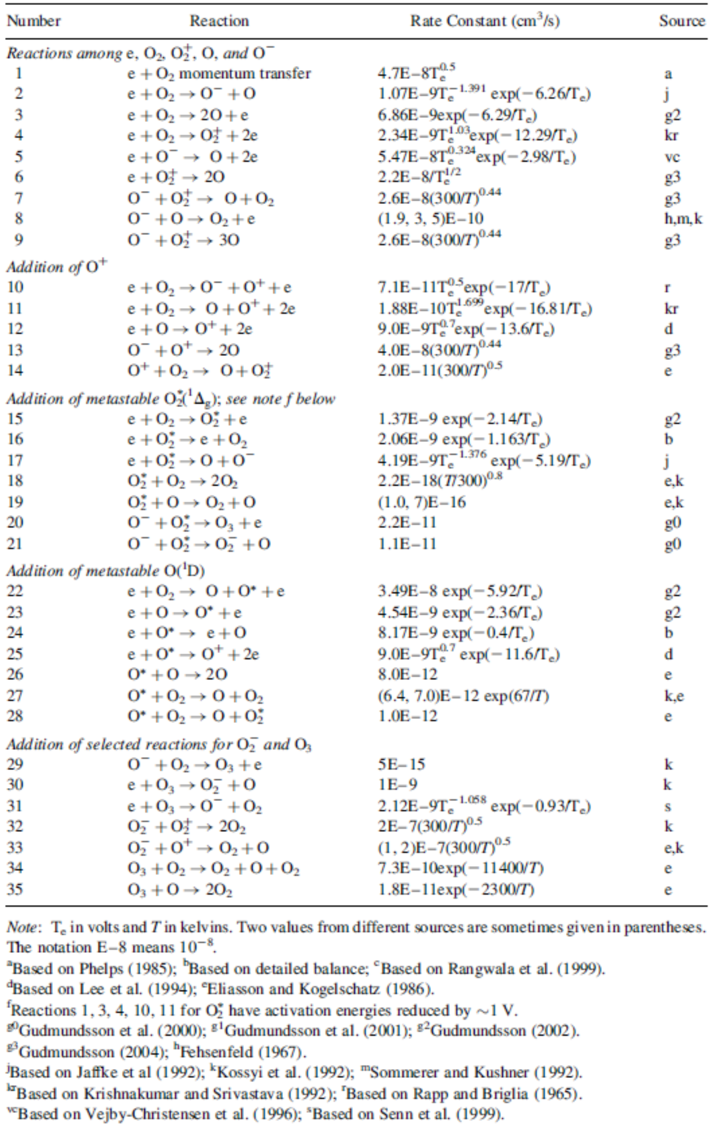


However - the list of reactions gets very long, and very difficult to set up and solve balance equations



Number	Reaction	Rate Constant (cm^3/s)	Source
Reactions among e, O_2, O_2^+, O, *and* O^-			
1	$e + O_2$ momentum transfer	$4.7E{-}8T_e^{0.5}$	a
2	$e + O_2 \rightarrow O^- + O$	$1.07E{-}9T_e^{-1.391}\exp(-6.26/T_e)$	j
3	$e + O_2 \rightarrow 2O + e$	$6.86E{-}9\exp(-6.29/T_e)$	g2
4	$e + O_2 \rightarrow O_2^+ + 2e$	$2.34E{-}9T_e^{1.03}\exp(-12.29/T_e)$	kr
5	$e + O^- \rightarrow O + 2e$	$5.47E{-}8T_e^{0.324}\exp(-2.98/T_e)$	vc
6	$e + O_2^+ \rightarrow 2O$	$2.2E{-}8/T_e^{1/2}$	g3
7	$O^- + O_2^+ \rightarrow O + O_2$	$2.6E{-}8(300/T)^{0.44}$	g3
8	$O^- + O \rightarrow O_2 + e$	$(1.9, 3, 5)E{-}10$	h,m,k
9	$O^- + O_2^+ \rightarrow 3O$	$2.6E{-}8(300/T)^{0.44}$	g3
Addition of O^+			
10	$e + O_2 \rightarrow O^- + O^+ + e$	$7.1E{-}11T_e^{0.5}\exp(-17/T_e)$	r
11	$e + O_2 \rightarrow O + O^+ + 2e$	$1.88E{-}10T_e^{1.699}\exp(-16.81/T_e)$	kr
12	$e + O \rightarrow O^+ + 2e$	$9.0E{-}9T_e^{0.7}\exp(-13.6/T_e)$	d
13	$O^- + O^+ \rightarrow 2O$	$4.0E{-}8(300/T)^{0.44}$	g3
14	$O^+ + O_2 \rightarrow O + O_2^+$	$2.0E{-}11(300/T)^{0.5}$	e
Addition of metastable $O_2^*(^1\Delta_g)$; *see note f below*			
15	$e + O_2 \rightarrow O_2^* + e$	$1.37E{-}9\exp(-2.14/T_e)$	g2
16	$e + O_2^* \rightarrow e + O_2$	$2.06E{-}9\exp(-1.163/T_e)$	b
17	$e + O_2^* \rightarrow O + O^-$	$4.19E{-}9T_e^{-1.376}\exp(-5.19/T_e)$	j
18	$O_2^* + O_2 \rightarrow 2O_2$	$2.2E{-}18(T/300)^{0.8}$	e,k
19	$O_2^* + O \rightarrow O_2 + O$	$(1.0, 7)E{-}16$	e,k
20	$O^- + O_2^* \rightarrow O_3 + e$	$2.2E{-}11$	g0
21	$O^- + O_2^* \rightarrow O_2^- + O$	$1.1E{-}11$	g0
Addition of metastable $O(^1D)$			
22	$e + O_2 \rightarrow O + O^* + e$	$3.49E{-}8\exp(-5.92/T_e)$	g2
23	$e + O \rightarrow O^* + e$	$4.54E{-}9\exp(-2.36/T_e)$	g2
24	$e + O^* \rightarrow e + O$	$8.17E{-}9\exp(-0.4/T_e)$	b
25	$e + O^* \rightarrow O^+ + 2e$	$9.0E{-}9T_e^{0.7}\exp(-11.6/T_e)$	d
26	$O^* + O \rightarrow 2O$	$8.0E{-}12$	e
27	$O^* + O_2 \rightarrow O + O_2$	$(6.4, 7.0)E{-}12\exp(67/T)$	k,e
28	$O^* + O_2 \rightarrow O + O_2^*$	$1.0E{-}12$	e
Addition of selected reactions for O_2^- *and* O_3			
29	$O^- + O_2 \rightarrow O_3 + e$	$5E{-}15$	k
30	$e + O_3 \rightarrow O_2^- + O$	$1E{-}9$	k
31	$e + O_3 \rightarrow O^- + O_2$	$2.12E{-}9T_e^{-1.058}\exp(-0.93/T_e)$	s
32	$O_2^- + O_2^+ \rightarrow 2O_2$	$2E{-}7(300/T)^{0.5}$	k
33	$O_2^- + O^+ \rightarrow O_2 + O$	$(1, 2)E{-}7(300/T)^{0.5}$	e,k
34	$O_3 + O_2 \rightarrow O_2 + O + O_2$	$7.3E{-}10\exp(-11400/T)$	e
35	$O_3 + O \rightarrow 2O_2$	$1.8E{-}11\exp(-2300/T)$	e

Note: T_e in volts and T in kelvins. Two values from different sources are sometimes given in parentheses. The notation E−8 means 10^{-8}.

[a] Based on Phelps (1985); [b] Based on detailed balance; [c] Based on Rangwala et al. (1999).

[d] Based on Lee et al. (1994); [e] Eliasson and Kogelschatz (1986).

[f] Reactions 1, 3, 4, 10, 11 for O_2^* have activation energies reduced by ~1 V.

[g0] Gudmundsson et al. (2000); [g1] Gudmundsson et al. (2001); [g2] Gudmundsson (2002).

[g3] Gudmundsson (2004); [h] Fehsenfeld (1967).

[j] Based on Jaffke et al (1992); [k] Kossyi et al. (1992); [m] Sommerer and Kushner (1992).

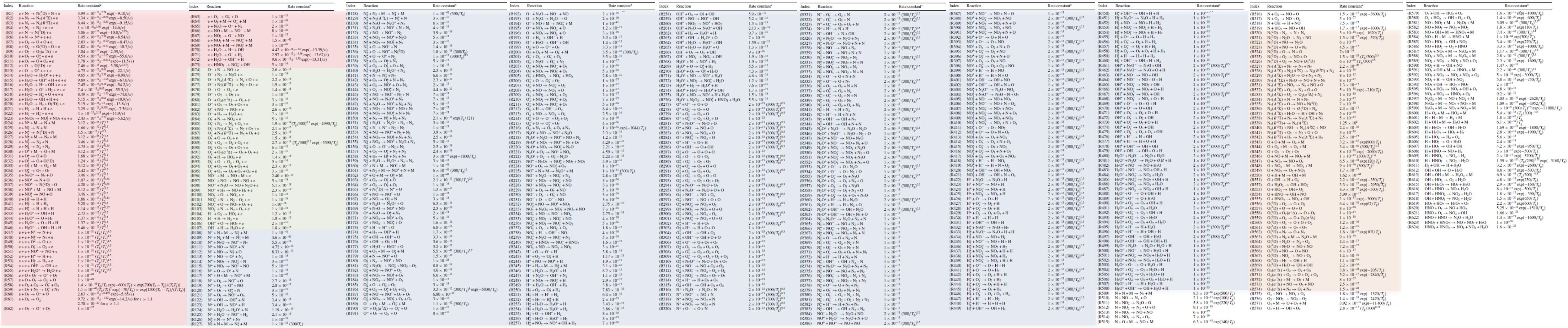
[kr] Based on Krishnakumar and Srivastava (1992); [r] Based on Rapp and Briglia (1965).

[vc] Based on Vejby-Christensen et al. (1996); [s] Based on Senn et al. (1999).

- Imagine the list of pertinent reactions for something like SF_6, CF_4, C_4F_8, or $Si(OC_2H_5)_4$ (TEOS)
- Even worse, realize that rarely is only one gas used for a process. Dielectric etch would run Ar, O_2, and C_4F_8 at the same time.
- And even if you could build a complete set of reactions, the cross sections and rate constants for many of these species are at best “qualitative”

And the list of reactions gets very long, and very difficult to set up and solve balance equations

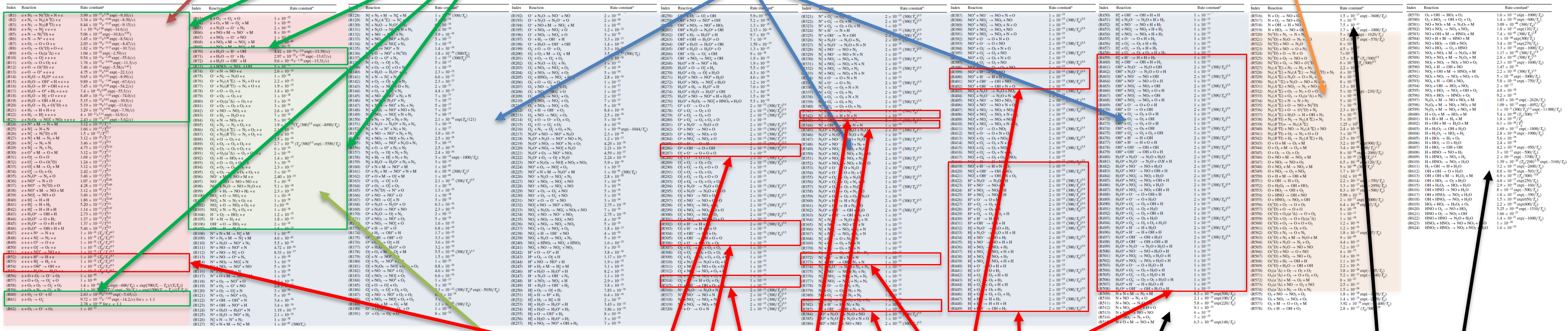
624 Reactions!



Index	Reaction	Rate constant^a
(R1)	$e + N_2 \to N(^2D) + N + e$	$3.99 \times 10^{-17} \varepsilon^{2.24} \exp(-9.10/\varepsilon)$
(R2)	$e + N_2 \to N_2(A\,^3\Sigma) + e$	$3.34 \times 10^{-16} \varepsilon^{-0.06} \exp(-8.50/\varepsilon)$
(R3)	$e + N_2 \to N_2(B\,^3\Pi) + e$	$8.44 \times 10^{-15} \varepsilon^{-0.33} \exp(-9.15/\varepsilon)$
(R4)	$e + N_2 \to N_2^+ + e + e$	$1 \times 10^{-16} \varepsilon^{1.90} \exp(-14.6/\varepsilon)$
(R5)	$e + N \to N(^2D) + e$	$5.06 \times 10^{-15} \exp(-10.8/\varepsilon^{3.95})$
(R6)	$e + N \to N^+ + e + e$	$1.45 \times 10^{-17} \varepsilon^{2.58} \exp(-8.54/\varepsilon)$
(R7)	$e + O_2 \to O + O + e$	$2.03 \times 10^{-14} \varepsilon^{-0.10} \exp(-8.47/\varepsilon)$
(R8)	$e + O_2 \to O(^1D) + O + e$	$1.82 \times 10^{-14} \varepsilon^{-0.13} \exp(-10.7/\varepsilon)$
(R9)	$e + O_2 \to O_2(a\,^1\Delta) + e$	$1.04 \times 10^{-15} \exp(-2.59/\varepsilon)$
(R10)	$e + O_2 \to O_2^+ + e + e$	$9.54 \times 10^{-12} \varepsilon^{-1.05} \exp(-55.6/\varepsilon)$
(R11)	$e + O_3 \to O + O_2 + e$	$1.78 \times 10^{-12} \varepsilon^{-0.614} \exp(-11.5/\varepsilon)$
(R12)	$e + O \to O(^1D) + e$	$7.46 \times 10^{-15} \exp(-5.58/\varepsilon^{1.47})$
(R13)	$e + O \to O^+ + e + e$	$4.75 \times 10^{-15} \varepsilon^{0.61} \exp(-22.1/\varepsilon)$
(R14)	$e + H_2O \to H_2O^+ + e + e$	$9.65 \times 10^{-18} \varepsilon^{2.53} \exp(-8.99/\varepsilon)$
(R15)	$e + H_2O \to OH^+ + H + e + e$	$9.89 \times 10^{-12} \varepsilon^{-1.64} \exp(-67.6/\varepsilon)$
(R16)	$e + H_2O \to H^+ + OH + e + e$	$7.45 \times 10^{-15} \varepsilon^{0.34} \exp(-54.2/\varepsilon)$
(R17)	$e + H_2O \to O^+ + H_2 + e + e$	$7.4 \times 10^{-16} \varepsilon^{0.45} \exp(-55.5/\varepsilon)$
(R18)	$e + H_2O \to H_2^+ + O + e + e$	$8.49 \times 10^{-15} \varepsilon^{-1.23} \exp(-74.0/\varepsilon)$
(R19)	$e + H_2O \to OH + H + e$	$5.15 \times 10^{-15} \varepsilon^{0.62} \exp(-10.9/\varepsilon)$
(R20)	$e + H_2O \to H_2 + O(^1D) + e$	$5.19 \times 10^{-18} \varepsilon^{1.2} \exp(-13.8/\varepsilon)$
(R21)	$e + H_2 \to H + H + e$	$3.29 \times 10^{-15} \varepsilon^{0.578} \exp(-7.56/\varepsilon)$
(R22)	$e + H_2 \to H_2^+ + e + e$	$4 \times 10^{-17} \varepsilon^{2.13} \exp(-14.9/\varepsilon)$
(R23)	$e + N_2O_5 \to NO_2^+ + NO_3 + e + e$	$2.43 \times 10^{-17} \varepsilon^{2.77} \exp(-5.62/\varepsilon)$
(R24)	$e + N^+ + M \to N + M$	$3.12 \times 10^{-35}/T_e^{1.5}$
(R25)	$e + N_2^+ \to N + N$	$1.66 \times 10^{-12}/T_e^{0.7}$
(R26)	$e + N_2^+ \to N(^2D) + N$	$1.5 \times 10^{-12}/T_e^{0.7}$
(R27)	$e + N_2^+ + M \to N_2 + M$	$3.12 \times 10^{-35}/T_e^{1.5}$
(R28)	$e + N_3^+ \to N_2 + N$	$3.46 \times 10^{-12}/T_e^{0.5}$
(R29)	$e + N_4^+ \to N_2 + N_2$	$4.73 \times 10^{-11}/T_e^{0.53}$
(R30)	$e + O^+ + M \to O + M$	$3.12 \times 10^{-35}/T_e^{1.5}$
(R31)	$e + O_2^+ \to O + O$	$1.68 \times 10^{-11}/T_e^{0.7}$
(R32)	$e + O_2^+ \to O + O(^1D)$	$1.24 \times 10^{-11}/T_e^{0.7}$
(R33)	$e + O_2^+ + M \to O_2 + M$	$3.12 \times 10^{-35}/T_e^{1.5}$
(R34)	$e + O_4^+ \to O_2 + O_2$	$2.42 \times 10^{-11}/T_e^{0.5}$
(R35)	$e + N_2O^+ \to N_2 + O$	$3.46 \times 10^{-12}/T_e^{0.5}$
(R36)	$e + NO^+ \to N + O$	$1.07 \times 10^{-11}/T_e^{0.85}$
(R37)	$e + NO^+ \to N(^2D) + O$	$4.28 \times 10^{-11}/T_e^{0.85}$
(R38)	$e + NO^+ + M \to NO + M$	$3.12 \times 10^{-35}/T_e^{1.5}$
(R39)	$e + NO_2^+ \to NO + O$	$3.46 \times 10^{-12}/T_e^{0.5}$
(R40)	$e + H_2^+ \to H + H$	$1.86 \times 10^{-13}/T_e^{0.43}$
(R41)	$e + H_3^+ \to H + H_2$	$5.20 \times 10^{-11}/T_e^{0.5}$
(R42)	$e + H_3^+ \to H + H + H$	$1.14 \times 10^{-11}/T_e^{0.97}$
(R43)	$e + H_2O^+ \to OH + H$	$2.73 \times 10^{-12}/T_e^{0.5}$
(R44)	$e + H_2O^+ \to O + H_2$	$1.37 \times 10^{-12}/T_e^{0.5}$
(R45)	$e + H_2O^+ \to O + H + H$	$1.37 \times 10^{-12}/T_e^{0.5}$
(R46)	$e + H_3O^+ \to OH + H + H$	$5.46 \times 10^{-12}/T_e^{0.5}$
(R47)	$e + e + N^+ \to N + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R48)	$e + e + N_2^+ \to N_2 + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R49)	$e + e + O^+ \to O + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R50)	$e + e + O_2^+ \to O_2 + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R51)	$e + e + NO^+ \to NO + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R52)	$e + e + H^+ \to H + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R53)	$e + e + H_2^+ \to H_2 + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R54)	$e + e + OH^+ \to OH + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R55)	$e + e + H_2O^+ \to H_2O + e$	$1 \times 10^{-31} (T_g/T_e)^{4.5}$
(R56)	$e + O + O_2 \to O^- + O_2$	1×10^{-43}
(R57)	$e + O + O_2 \to O_2^- + O$	1×10^{-43}
(R58)	$e + O_2 + O_2 \to O_2^- + O_2$	$1.4 \times 10^{-41} T_g/T_e \exp(-600/T_g) \times \exp[700(T_e - T_g)/(T_e T_g)]$
(R59)	$e + O_2 + N_2 \to O_2^- + N_2$	$1.1 \times 10^{-43} (T_g/T_e)^2 \exp(-70/T_g) \times \exp[1500(T_e - T_g)/(T_e T_g)]$
(R60)	$e + O_2 \to O^- + O$	$2.63 \times 10^{-16} \varepsilon^{-0.495} \exp(-5.65/\varepsilon)$
(R61)	$e + O_2 \to O_2^-$	$9.72 \times 10^{-15} \varepsilon^{-1.62} \exp(-14.2/\varepsilon)$ for $\varepsilon > 1.1$ 2.78×10^{-20} for $\varepsilon < 1.1$
(R62)	$e + O_3 \to O^- + O_2$	1×10^{-17}
(R63)	$e + O_3 \to O_2^- + O$	1×10^{-15}
(R64)	$e + O_3 + M \to O_3^- + M$	1×10^{-43}
(R65)	$e + N_2O \to O^- + N_2$	2×10^{-16}
(R66)	$e + NO + M \to NO^- + M$	8×10^{-43}
(R67)	$e + NO_2 \to O^- + NO$	1×10^{-17}
(R68)	$e + NO_2 + M \to NO_2^- + M$	1.5×10^{-42}
(R69)	$e + NO_3 + M \to NO_3^- + M$	1×10^{-42}
(R70)	$e + H_2O \to H^- + OH$	$4.42 \times 10^{-14} \varepsilon^{-2.0} \exp(-13.39/\varepsilon)$
(R71)	$e + H_2O \to O^- + H_2$	$2.97 \times 10^{-15} \varepsilon^{-1.56} \exp(-13.67/\varepsilon)$
(R72)	$e + H_2O \to OH^- + H$	$9.6 \times 10^{-16} \varepsilon^{-1.70} \exp(-13.31/\varepsilon)$
(R73)	$e + HNO_3 \to NO_2^- + OH$	5×10^{-14}
(R74)	$O^- + N \to NO + e$	2.6×10^{-16}
(R75)	$O^- + N_2 \to N_2O + e$	1×10^{-18}
(R76)	$O^- + N_2(A\,^3\Sigma) \to N_2 + O + e$	2.2×10^{-15}
(R77)	$O^- + N_2(B\,^3\Pi) \to N_2 + O + e$	1.9×10^{-15}
(R78)	$O^- + O \to O_2 + e$	1.4×10^{-16}
(R79)	$O^- + O_2 \to O_3 + e$	1×10^{-18}
(R80)	$O^- + O_2(a\,^1\Delta) \to O_3 + e$	3×10^{-16}
(R81)	$O^- + O_3 \to O_2 + O_2 + e$	3×10^{-16}
(R82)	$O^- + NO \to NO_2 + e$	2.6×10^{-16}
(R83)	$O^- + H_2 \to H_2O + e$	7×10^{-16}
(R84)	$O_2^- + N \to NO_2 + e$	5×10^{-16}
(R85)	$O_2^- + N_2 \to N_2 + O_2 + e$	$1.9 \times 10^{-18} (T_g/300)^{0.5} \exp(-4990/T_g)$
(R86)	$O_2^- + N_2(A\,^3\Sigma) \to N_2 + O_2 + e$	2.1×10^{-15}
(R87)	$O_2^- + N_2(B\,^3\Pi) \to N_2 + O_2 + e$	2.5×10^{-15}
(R88)	$O_2^- + O \to O_3 + e$	1.5×10^{-16}
(R89)	$O_2^- + O_2 \to O_2 + O_2 + e$	$2.7 \times 10^{-16} (T_g/300)^{0.5} \exp(-5590/T_g)$
(R90)	$O_2^- + O_3 \to O_3 + O_2 + e$	6×10^{-16}
(R91)	$O_2^- + O_2(a\,^1\Delta) \to O_2 + O_2 + e$	2×10^{-16}
(R92)	$O_2^- + H \to HO_2 + e$	1.4×10^{-15}
(R93)	$O_3^- + O \to O_2 + O_2 + e$	3×10^{-16}
(R94)	$O_3^- + O_2 \to O_3 + O_2 + e$	2.3×10^{-17}
(R95)	$O_3^- + O_3 \to O_2 + O_2 + O_2 + e$	3×10^{-16}
(R96)	$NO^- + M \to NO + M + e$	2.40×10^{-19}
(R97)	$NO^- + NO \to NO + NO + e$	5×10^{-18}
(R98)	$NO^- + N_2O \to NO + N_2O + e$	5.1×10^{-18}
(R99)	$NO^- + H_2 \to NO + H_2 + e$	2.3×10^{-19}
(R100)	$NO_2^- + O \to NO_3 + e$	1×10^{-18}
(R10)1	$NO_2^- + N \to N_2 + O_2 + e$	1×10^{-18}
(R102)	$NO_3^- + O \to NO_2 + O_2 + e$	1×10^{-18}
(R103)	$NO_3^- + N \to N_2 + O_3 + e$	1×10^{-18}
(R104)	$H^- + O_2 \to HO_2 + e$	1.2×10^{-15}
(R105)	$H^- + H \to H_2 + e$	1.8×10^{-15}
(R106)	$OH^- + O \to HO_2 + e$	2×10^{-16}
(R107)	$OH^- + H \to H_2O + e$	1.8×10^{-15}
(R108)	$N^+ + N + M \to N_2^+ + M$	1×10^{-41}
(R109)	$N^+ + N_2 + M \to N_3^+ + M$	4.6×10^{-41}
(R110)	$N^+ + N_2O \to NO^+ + N_2$	5.5×10^{-16}
(R111)	$N^+ + NO \to NO^+ + N$	4.72×10^{-16}
(R112)	$N^+ + NO \to N_2^+ + O$	8.33×10^{-17}
(R113)	$N^+ + NO \to O^+ + N_2$	1×10^{-18}
(R114)	$N^+ + NO_2 \to NO_2^+ + N$	3×10^{-16}
(R115)	$N^+ + NO_2 \to NO^+ + NO$	5×10^{-16}
(R116)	$N^+ + O \to O^+ + N$	1×10^{-18}
(R117)	$N^+ + O + M \to NO^+ + M$	1×10^{-41}
(R118)	$N^+ + O_2 \to NO^+ + O$	2.7×10^{-16}
(R119)	$N^+ + O_2 \to O^+ + NO$	2.8×10^{-17}
(R120)	$N^+ + O_2 \to O_2^+ + N$	3×10^{-16}
(R121)	$N^+ + O_3 \to NO^+ + O_2$	5×10^{-16}
(R122)	$N^+ + OH \to OH^+ + N$	3.4×10^{-16}
(R123)	$N^+ + OH \to NO^+ + H$	3.4×10^{-16}
(R124)	$N^+ + H_2O \to H_2O^+ + N$	1.19×10^{-15}
(R125)	$N^+ + H_2O \to NO^+ + H_2$	2.1×10^{-16}
(R126)	$N_2^+ + N \to N^+ + N_2$	1×10^{-18}
(R127)	$N_2^+ + N + M \to N_3^+ + M$	$1 \times 10^{-41} (300/T_g)$
(R128)	$N_2^+ + N_2 + M \to N_4^+ + M$	$1 \times 10^{-41} (300/T_g)$
(R129)	$N_2^+ + N_2(A\,^3\Sigma) \to N_3^+ + N$	3×10^{-16}
(R130)	$N_2^+ + N_2O \to N_2O^+ + N_2$	6×10^{-16}
(R131)	$N_2^+ + N_2O \to NO^+ + N + N_2$	4×10^{-16}
(R132)	$N_2^+ + NO \to NO^+ + N_2$	3.9×10^{-16}
(R133)	$N_2^+ + NO_2 \to NO^+ + N_2O$	5×10^{-17}
(R134)	$N_2^+ + NO_2 \to NO_2^+ + N_2$	3×10^{-16}
(R135)	$N_2^+ + O \to NO^+ + N$	1.4×10^{-16}
(R136)	$N_2^+ + O \to NO^+ + N(^2D)$	$1.8 \times 10^{-16} (300/T_g)$
(R137)	$N_2^+ + O \to O^+ + N_2$	$1 \times 10^{-17} (300/T_g)^{0.5}$
(R138)	$N_2^+ + O_2 \to O_2^+ + N_2$	5×10^{-17}
(R139)	$N_2^+ + O_3 \to O_2^+ + O + N_2$	1×10^{-16}
(R140)	$N_2^+ + H_2O \to H_2O^+ + N_2$	2.3×10^{-15}
(R141)	$N_3^+ + N \to N_2^+ + N_2$	6.6×10^{-17}
(R142)	$N_3^+ + O_2 \to O_2^+ + N + N_2$	2.3×10^{-17}
(R143)	$N_3^+ + O_2 \to NO^+ + O + N_2$	2×10^{-17}
(R144)	$N_3^+ + O_2 \to NO_2^+ + N_2$	4.4×10^{-17}
(R145)	$N_3^+ + NO \to NO^+ + N_2 + N$	7×10^{-17}
(R146)	$N_3^+ + NO \to N_2O^+ + N_2$	7×10^{-17}
(R147)	$N_3^+ + N_2O \to NO^+ + N_2 + N_2$	5×10^{-17}
(R148)	$N_3^+ + NO_2 \to NO^+ + NO + N_2$	7×10^{-17}
(R149)	$N_3^+ + NO_2 \to NO_2^+ + N + N_2$	7×10^{-17}
(R150)	$N_4^+ + N_2 \to N_2^+ + N_2 + N_2$	$2.1 \times 10^{-16} \exp(T_g/121)$
(R151)	$N_4^+ + N_2O \to N_2O^+ + N_2 + N_2$	3×10^{-16}
(R152)	$N_4^+ + N \to N^+ + N_2 + N_2$	1×10^{-17}
(R153)	$N_4^+ + NO \to NO^+ + N_2 + N_2$	3.9×10^{-16}
(R154)	$N_4^+ + NO_2 \to NO_2^+ + N_2 + N_2$	2.5×10^{-16}
(R155)	$N_4^+ + NO_2 \to NO^+ + N_2O + N_2$	5×10^{-17}
(R156)	$N_4^+ + O \to O^+ + N_2 + N_2$	2.5×10^{-16}
(R157)	$N_4^+ + O_2 \to O_2^+ + N_2 + N_2$	2.4×10^{-16}
(R158)	$N_4^+ + H_2 \to H_2^+ + N_2 + N_2$	$3 \times 10^{-16} \exp(-1800/T_g)$
(R159)	$N_4^+ + H_2O \to H_2O^+ + N_2 + N_2$	3×10^{-15}
(R160)	$O^+ + N + M \to NO^+ + M$	1×10^{-41}
(R161)	$O^+ + N_2 + M \to NO^+ + N + M$	$6 \times 10^{-41} (300/T_g)^2$
(R162)	$O^+ + O + M \to O_2^+ + M$	1×10^{-41}
(R163)	$O^+ + O_2 \to O_2^+ + O$	$2.1 \times 10^{-17} (300/T_g)^{0.5}$
(R164)	$O^+ + O_3 \to O_2^+ + O_2$	1×10^{-16}
(R165)	$O^+ + N(^2D) \to N^+ + O$	1.3×10^{-16}
(R166)	$O^+ + NO \to NO^+ + O$	1×10^{-18}
(R167)	$O^+ + NO \to O_2^+ + N$	3×10^{-18}
(R168)	$O^+ + N_2O \to N_2O^+ + O$	6.3×10^{-16}
(R169)	$O^+ + N_2O \to NO^+ + NO$	2.3×10^{-16}
(R170)	$O^+ + N_2O \to O_2^+ + N_2$	2×10^{-17}
(R171)	$O^+ + NO_2 \to NO^+ + O_2$	5×10^{-16}
(R172)	$O^+ + NO_2 \to NO_2^+ + O$	1.6×10^{-15}
(R173)	$O^+ + H \to H^+ + O$	6.8×10^{-16}
(R174)	$O^+ + H_2 \to OH^+ + H$	1.7×10^{-15}
(R175)	$O^+ + OH \to OH^+ + O$	3.3×10^{-16}
(R176)	$O^+ + OH \to O_2^+ + H$	3.6×10^{-16}
(R177)	$O^+ + H_2O \to H_2O^+ + O$	3.2×10^{-15}
(R178)	$O_2^+ + O_2 + M \to O_4^+ + M$	$5.5 \times 10^{-43} (300/T_g)^{2.7}$
(R179)	$O_2^+ + N \to NO^+ + O$	1.5×10^{-16}
(R180)	$O_2^+ + N_2 \to NO^+ + NO$	1×10^{-23}
(R181)	$O_2^+ + N_2O_5 \to NO_2^+ + NO_3 + O_2$	8.8×10^{-16}
(R182)	$O_2^+ + NO \to NO^+ + O_2$	4.6×10^{-16}
(R183)	$O_2^+ + NO_2 \to NO_2^+ + O_2$	6.6×10^{-16}
(R184)	$O_2^+ + NO_2 \to NO^+ + O_3$	1×10^{-17}
(R185)	$O_4^+ + O \to O_2^+ + O_3$	3×10^{-16}
(R186)	$O_4^+ + O_2 \to O_2^+ + O_2 + O_2$	$3.3 \times 10^{-12} (300/T_g)^4 \exp(-5030/T_g)$
(R187)	$O_4^+ + NO \to NO^+ + O_2 + O_2$	6.80×10^{-16}
(R188)	$O_4^+ + NO_2 \to NO_2^+ + O_2 + O_2$	3×10^{-16}
(R189)	$O^- + O_2 + M \to O_3^- + M$	$1.1 \times 10^{-42} (300/T_g)$
(R190)	$O^- + O_2(a\,^1\Delta) \to O_2^- + O$	1×10^{-16}
(R191)	$O^- + O_3 \to O_3^- + O$	8×10^{-16}
(R192)	$O^- + N_2O \to NO^- + NO$	2×10^{-16}
(R193)	$O^- + N_2O \to N_2O^- + O$	2×10^{-18}
(R194)	$O^- + NO + M \to NO_2^- + M$	1×10^{-41}
(R195)	$O^- + NO_2 \to NO_2^- + O$	1.2×10^{-15}
(R196)	$O^- + NO_3 \to NO_3^- + O$	3×10^{-16}
(R197)	$O^- + H_2 \to OH^- + H$	3.3×10^{-17}
(R198)	$O^- + H_2O \to OH^- + OH$	1.4×10^{-15}
(R199)	$O_2^- + O \to O^- + O_2$	3.3×10^{-16}
(R200)	$O_2^- + O_2 + M \to O_4^- + M$	$3.5 \times 10^{-43} (300/T_g)$
(R201)	$O_2^- + O_3 \to O_3^- + O_2$	3.5×10^{-16}
(R202)	$O_2^- + N_2O \to O_3^- + N_2$	1×10^{-17}
(R203)	$O_2^- + NO_2 \to NO_2^- + O_2$	7×10^{-16}
(R204)	$O_2^- + NO_3 \to NO_3^- + O_2$	5×10^{-16}
(R205)	$O_2^- + HNO_3 \to NO_3^- + HO_2$	2.8×10^{-16}
(R206)	$O_3^- + O \to O_2^- + O_2$	1×10^{-17}
(R207)	$O_3^- + NO \to NO_2^- + O_2$	1×10^{-17}
(R208)	$O_3^- + NO \to NO_3^- + O$	1×10^{-17}
(R209)	$O_3^- + NO_2 \to NO_3^- + O_2$	2×10^{-17}
(R210)	$O_3^- + NO_2 \to NO_2^- + O_3$	7×10^{-17}
(R211)	$O_3^- + NO_3 \to NO_3^- + O_3$	5×10^{-16}
(R212)	$O_3^- + H \to OH^- + O_2$	8.4×10^{-16}
(R213)	$O_4^- + NO \to NO_3^- + O_2$	2.5×10^{-16}
(R214)	$O_4^- + O \to O^- + O_2 + O_2$	3×10^{-16}
(R215)	$O_4^- + O \to O_3^- + O_2$	4×10^{-16}
(R216)	$O_4^- + N_2 \to O_2^- + O_2 + N_2$	$1 \times 10^{-16} \exp(-1044/T_g)$
(R217)	$N_2O^+ + NO \to NO^+ + N_2O$	2.3×10^{-16}
(R218)	$N_2O^+ + N_2O \to NO^+ + NO + N_2$	1.2×10^{-17}
(R219)	$N_2O^+ + NO_2 \to NO^+ + N_2 + O_2$	4.29×10^{-16}
(R220)	$N_2O^+ + NO_2 \to NO_2^+ + N_2O$	2.21×10^{-16}
(R221)	$N_2O^+ + O_2 \to NO^+ + NO_2$	4.59×10^{-17}
(R222)	$N_2O^+ + O_2 \to O_2^+ + N_2O$	2.24×10^{-16}
(R223)	$NO^+ + N_2O_5 \to NO_2^+ + NO_2 + NO_2$	5.9×10^{-16}
(R224)	$NO^+ + O_3 \to NO_2^+ + O_2$	1×10^{-21}
(R225)	$NO^+ + N + M \to N_2O^+ + M$	$1 \times 10^{-41} (300/T_g)$
(R226)	$NO^- + N_2O \to NO_2^- + N_2$	2.8×10^{-20}
(R227)	$NO^- + NO_2 \to NO_2^- + NO$	3×10^{-16}
(R228)	$NO^- + NO_3 \to NO_3^- + NO$	3×10^{-16}
(R229)	$NO^- + O_2 \to O_2^- + NO$	5×10^{-16}
(R230)	$NO^- + O_3 \to O_3^- + NO$	3×10^{-16}
(R231)	$NO^- + O \to O^- + NO$	3×10^{-16}
(R232)	$NO_2^+ + NO \to NO^+ + NO_2$	2.75×10^{-16}
(R233)	$NO_2^- + N_2O_5 \to NO_3^- + NO_3 + NO$	7×10^{-16}
(R234)	$NO_2^- + NO \to NO^- + NO_2$	2.75×10^{-16}
(R235)	$NO_2^- + NO_2 \to NO_3^- + NO$	4×10^{-18}
(R236)	$NO_2^- + NO_3 \to NO_3^- + NO_2$	5×10^{-16}
(R237)	$NO_2^- + O_3 \to NO_3^- + O_2$	1.8×10^{-17}
(R238)	$NO_2^- + H \to OH^- + NO$	4×10^{-16}
(R239)	$NO_2^- + N_2O \to NO_3^- + N_2$	5×10^{-19}
(R240)	$NO_2^- + HNO_3 \to NO_3^- + HNO_2$	1.6×10^{-15}
(R241)	$NO_3^- + NO \to NO_2^- + NO_2$	3×10^{-21}
(R242)	$H^+ + O \to O^+ + H$	3.8×10^{-16}
(R243)	$H^+ + O_2 \to O_2^+ + H$	1.17×10^{-15}
(R244)	$H^+ + NO \to NO^+ + H$	1.9×10^{-15}
(R245)	$H^+ + H_2 + M \to H_3^+ + M$	3.1×10^{-41}
(R246)	$H^+ + H_2O \to H_2O^+ + H$	8.2×10^{-15}
(R247)	$H^- + N_2O \to OH^- + N_2$	1.1×10^{-15}
(R248)	$H^- + NO_2 \to NO_2^- + H$	2.9×10^{-15}
(R249)	$H^- + H_2O \to OH^- + H_2$	3.8×10^{-15}
(R250)	$H_2^+ + O_2 \to O_2^+ + H_2$	7.83×10^{-16}
(R251)	$H_2^+ + H \to H^+ + H_2$	6.4×10^{-16}
(R252)	$H_2^+ + H_2 \to H_3^+ + H$	2×10^{-15}
(R253)	$H_2^+ + H_2O \to H_3O^+ + H$	3.43×10^{-15}
(R254)	$H_2^+ + H_2O \to H_2O^+ + H_2$	3.86×10^{-15}
(R255)	$H_3^+ + O \to OH^+ + H_2$	8×10^{-16}
(R256)	$H_3^+ + H_2O \to H_3O^+ + H_2$	3×10^{-15}
(R257)	$H_3^+ + NO_2 \to NO^+ + OH + H_2$	7×10^{-16}
(R258)	$OH^+ + O_2 \to O_2^+ + OH$	5.9×10^{-16}
(R259)	$OH^+ + NO \to NO^+ + OH$	5.2×10^{-16}
(R260)	$OH^+ + NO_2 \to NO^+ + HO_2$	1.3×10^{-15}
(R261)	$OH^+ + N_2O \to N_2O^+ + OH$	2.13×10^{-16}
(R262)	$OH^+ + H_2 \to H_2O^+ + H$	9.7×10^{-16}
(R263)	$OH^+ + OH \to H_2O^+ + O$	7×10^{-16}
(R264)	$OH^+ + H_2O \to H_2O^+ + OH$	1.59×10^{-15}
(R265)	$OH^+ + H_2O \to H_3O^+ + O$	1.3×10^{-15}
(R266)	$OH^- + O_3 \to O_3^- + OH$	9×10^{-16}
(R267)	$OH^- + NO_2 \to NO_2^- + OH$	1.9×10^{-15}
(R268)	$H_2O^+ + N \to NO^+ + H_2$	1.9×10^{-16}
(R269)	$H_2O^+ + O \to O_2^+ + H_2$	5.5×10^{-17}
(R270)	$H_2O^+ + O_2 \to O_2^+ + H_2O$	4.3×10^{-16}
(R271)	$H_2O^+ + NO \to NO^+ + H_2O$	4.6×10^{-16}
(R272)	$H_2O^+ + NO_2 \to NO_2^+ + H_2O$	1.2×10^{-15}
(R273)	$H_2O^+ + H_2 \to H_3O^+ + H$	7.6×10^{-16}
(R274)	$H_2O^+ + H_2O \to H_3O^+ + OH$	1.7×10^{-15}
(R275)	$H_3O^+ + NO \to NO^+ + H + H_2O$	1.5×10^{-18}
(R276)	$H_3O^+ + N_2O_5 \to NO_2^+ + HNO_3 + H_2O$	5.5×10^{-16}
(R277)	$O^+ + O^- \to O + O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R278)	$O^+ + O_2^- \to O_2 + O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R279)	$O^+ + O_3^- \to O_3 + O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R280)	$O^+ + O_4^- \to O_2 + O_2 + O$	1×10^{-13}
(R281)	$O^+ + N_2O^- \to N_2O + O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R282)	$O^+ + NO^- \to NO + O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R283)	$O^+ + NO_2^- \to NO_2 + O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R284)	$O^+ + NO_3^- \to NO_3 + O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R285)	$O^+ + H^- \to O + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R286)	$O^+ + OH^- \to O + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R287)	$O_2^+ + O^- \to O + O + O$	1×10^{-13}
(R288)	$O_2^+ + O^- \to O + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R289)	$O_2^+ + O_2^- \to O_2 + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R290)	$O_2^+ + O_2^- \to O_2 + O + O$	1×10^{-13}
(R291)	$O_2^+ + O_3^- \to O_3 + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R292)	$O_2^+ + O_3^- \to O_3 + O + O$	1×10^{-13}
(R293)	$O_2^+ + O_4^- \to O_2 + O_2 + O_2$	1×10^{-13}
(R294)	$O_2^+ + N_2O^- \to N_2O + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R295)	$O_2^+ + N_2O^- \to N_2O + O + O$	1×10^{-13}
(R296)	$O_2^+ + NO^- \to NO + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R297)	$O_2^+ + NO^- \to NO + O + O$	1×10^{-13}
(R298)	$O_2^+ + NO_2^- \to NO_2 + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R299)	$O_2^+ + NO_2^- \to NO_2 + O + O$	1×10^{-13}
(R300)	$O_2^+ + NO_3^- \to NO_3 + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R301)	$O_2^+ + NO_3^- \to NO_3 + O + O$	1×10^{-13}
(R302)	$O_2^+ + H^- \to H + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R303)	$O_2^+ + H^- \to H + O + O$	1×10^{-13}
(R304)	$O_2^+ + OH^- \to OH + O_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R305)	$O_2^+ + OH^- \to OH + O + O$	1×10^{-13}
(R306)	$O_4^+ + O^- \to O + O_2 + O_2$	1×10^{-13}
(R307)	$O_4^+ + O_2^- \to O_2 + O_2 + O_2$	1×10^{-13}
(R308)	$O_4^+ + O_3^- \to O_3 + O_2 + O_2$	1×10^{-13}
(R309)	$O_4^+ + O_4^- \to O_2 + O_2 + O_2 + O_2$	1×10^{-13}
(R310)	$O_4^+ + N_2O^- \to N_2O + O_2 + O_2$	1×10^{-13}
(R311)	$O_4^+ + NO^- \to NO + O_2 + O_2$	1×10^{-13}
(R312)	$O_4^+ + NO_2^- \to NO_2 + O_2 + O_2$	1×10^{-13}
(R313)	$O_4^+ + NO_3^- \to NO_3 + O_2 + O_2$	1×10^{-13}
(R314)	$O_4^+ + H^- \to H + O_2 + O_2$	1×10^{-13}
(R315)	$O_4^+ + OH^- \to OH + O_2 + O_2$	1×10^{-13}
(R316)	$N^+ + N_2O^- \to N_2O + N$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R317)	$N^+ + NO^- \to NO + N$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R318)	$N^+ + NO_2^- \to NO_2 + N$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R319)	$N^+ + NO_3^- \to NO_3 + N$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R320)	$N^+ + O^- \to O + N$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R321)	$N^+ + O_2^- \to O_2 + N$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R322)	$N^+ + O_3^- \to O_3 + N$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R323)	$N^+ + O_4^- \to O_2 + O_2 + N$	1×10^{-13}
(R324)	$N^+ + H^- \to N + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R325)	$N^+ + OH^- \to N + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R326)	$N_2^+ + N_2O^- \to N_2O + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R327)	$N_2^+ + N_2O^- \to N_2O + N + N$	1×10^{-13}
(R328)	$N_2^+ + NO^- \to NO + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R329)	$N_2^+ + NO^- \to NO + N + N$	1×10^{-13}
(R330)	$N_2^+ + NO_2^- \to NO_2 + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R331)	$N_2^+ + NO_2^- \to NO_2 + N + N$	1×10^{-13}
(R332)	$N_2^+ + NO_3^- \to NO_3 + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R333)	$N_2^+ + NO_3^- \to NO_3 + N + N$	1×10^{-13}
(R334)	$N_2^+ + O^- \to O + N + N$	1×10^{-13}
(R335)	$N_2^+ + O^- \to O + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R336)	$N_2^+ + O_2^- \to O_2 + N + N$	1×10^{-13}
(R337)	$N_2^+ + O_2^- \to O_2 + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R338)	$N_2^+ + O_3^- \to O_3 + N + N$	1×10^{-13}
(R339)	$N_2^+ + O_3^- \to O_3 + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R340)	$N_2^+ + O_4^- \to O_2 + O_2 + N_2$	1×10^{-13}
(R341)	$N_2^+ + H^- \to H + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R342)	$N_2^+ + H^- \to H + N + N$	1×10^{-13}
(R343)	$N_2^+ + OH^- \to OH + N_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R344)	$N_2^+ + OH^- \to OH + N + N$	1×10^{-13}
(R345)	$N_2O^+ + N_2O^- \to N_2O + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R346)	$N_2O^+ + N_2O^- \to N_2O + N_2 + O$	1×10^{-13}
(R347)	$N_2O^+ + NO^- \to NO + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R348)	$N_2O^+ + NO^- \to NO + N_2 + O$	1×10^{-13}
(R349)	$N_2O^+ + NO_2^- \to NO_2 + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R350)	$N_2O^+ + NO_2^- \to NO_2 + N_2 + O$	1×10^{-13}
(R351)	$N_2O^+ + NO_3^- \to NO_3 + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R352)	$N_2O^+ + NO_3^- \to NO_3 + N_2 + O$	1×10^{-13}
(R353)	$N_2O^+ + O^- \to O + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R354)	$N_2O^+ + O^- \to O + N_2 + O$	1×10^{-13}
(R355)	$N_2O^+ + O_2^- \to O_2 + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R356)	$N_2O^+ + O_2^- \to O_2 + N_2 + O$	1×10^{-13}
(R357)	$N_2O^+ + O_3^- \to O_3 + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R358)	$N_2O^+ + O_3^- \to O_3 + N_2 + O$	1×10^{-13}
(R359)	$N_2O^+ + O_4^- \to O_2 + O_2 + N_2O$	1×10^{-13}
(R360)	$N_2O^+ + H^- \to H + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R361)	$N_2O^+ + H^- \to H + N_2 + O$	1×10^{-13}
(R362)	$N_2O^+ + OH^- \to OH + N_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R363)	$N_2O^+ + OH^- \to OH + N_2 + O$	1×10^{-13}
(R364)	$N_3^+ + N_2O^- \to N_2O + N_2 + N$	1×10^{-13}
(R365)	$N_3^+ + NO^- \to NO + N_2 + N$	1×10^{-13}
(R366)	$N_3^+ + NO_2^- \to NO_2 + N_2 + N$	1×10^{-13}
(R367)	$N_3^+ + NO_3^- \to NO_3 + N_2 + N$	1×10^{-13}
(R368)	$N_3^+ + O^- \to O + N_2 + N$	1×10^{-13}
(R369)	$N_3^+ + O_2^- \to O_2 + N_2 + N$	1×10^{-13}
(R370)	$N_3^+ + O_3^- \to O_3 + N_2 + N$	1×10^{-13}
(R371)	$N_3^+ + O_4^- \to O_2 + O_2 + N + N_2$	1×10^{-13}
(R372)	$N_3^+ + H^- \to H + N_2 + N$	1×10^{-13}
(R373)	$N_3^+ + OH^- \to OH + N_2 + N$	1×10^{-13}
(R374)	$N_4^+ + N_2O^- \to N_2O + N_2 + N_2$	1×10^{-13}
(R375)	$N_4^+ + NO^- \to NO + N_2 + N_2$	1×10^{-13}
(R376)	$N_4^+ + NO_2^- \to NO_2 + N_2 + N_2$	1×10^{-13}
(R377)	$N_4^+ + NO_3^- \to NO_3 + N_2 + N_2$	1×10^{-13}
(R378)	$N_4^+ + O^- \to O + N_2 + N_2$	1×10^{-13}
(R379)	$N_4^+ + O_2^- \to O_2 + N_2 + N_2$	1×10^{-13}
(R380)	$N_4^+ + O_3^- \to O_3 + N_2 + N_2$	1×10^{-13}
(R381)	$N_4^+ + O_4^- \to O_2 + O_2 + N_2 + N_2$	1×10^{-13}
(R382)	$N_4^+ + H^- \to H + N_2 + N_2$	1×10^{-13}
(R383)	$N_4^+ + OH^- \to OH + N_2 + N_2$	1×10^{-13}
(R384)	$NO^+ + N_2O^- \to N_2O + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R385)	$NO^+ + N_2O^- \to N_2O + N + O$	1×10^{-13}
(R386)	$NO^+ + NO^- \to NO + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R387)	$NO^+ + NO^- \to NO + N + O$	1×10^{-13}
(R388)	$NO^+ + NO_2^- \to NO_2 + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R389)	$NO^+ + NO_2^- \to NO_2 + N + O$	1×10^{-13}
(R390)	$NO^+ + NO_3^- \to NO_3 + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R391)	$NO^+ + NO_3^- \to NO_3 + N + O$	1×10^{-13}
(R392)	$NO^+ + O^- \to O + N + O$	1×10^{-13}
(R393)	$NO^+ + O^- \to O + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R394)	$NO^+ + O_2^- \to O_2 + N + O$	1×10^{-13}
(R395)	$NO^+ + O_2^- \to O_2 + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R396)	$NO^+ + O_3^- \to O_3 + N + O$	1×10^{-13}
(R397)	$NO^+ + O_3^- \to O_3 + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R398)	$NO^+ + O_4^- \to O_2 + O_2 + NO$	1×10^{-13}
(R399)	$NO^+ + H^- \to H + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R400)	$NO^+ + H^- \to H + N + O$	1×10^{-13}
(R401)	$NO^+ + OH^- \to OH + NO$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R402)	$NO^+ + OH^- \to OH + N + O$	1×10^{-13}
(R403)	$NO_2^+ + N_2O^- \to N_2O + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R404)	$NO_2^+ + N_2O^- \to N_2O + N + O_2$	1×10^{-13}
(R405)	$NO_2^+ + NO^- \to NO + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R406)	$NO_2^+ + NO^- \to NO + N + O_2$	1×10^{-13}
(R407)	$NO_2^+ + NO_2^- \to NO_2 + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R408)	$NO_2^+ + NO_2^- \to NO_2 + N + O_2$	1×10^{-13}
(R409)	$NO_2^+ + NO_3^- \to NO_3 + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R410)	$NO_2^+ + NO_3^- \to NO_3 + N + O_2$	1×10^{-13}
(R411)	$NO_2^+ + O^- \to O + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R412)	$NO_2^+ + O^- \to O + N + O_2$	1×10^{-13}
(R413)	$NO_2^+ + O_2^- \to O_2 + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R414)	$NO_2^+ + O_2^- \to O_2 + N + O_2$	1×10^{-13}
(R415)	$NO_2^+ + O_3^- \to O_3 + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R416)	$NO_2^+ + O_3^- \to O_3 + N + O_2$	1×10^{-13}
(R417)	$NO_2^+ + O_4^- \to O_2 + O_2 + NO_2$	1×10^{-13}
(R418)	$NO_2^+ + H^- \to H + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R419)	$NO_2^+ + H^- \to H + N + O_2$	1×10^{-13}
(R420)	$NO_2^+ + OH^- \to OH + NO_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R421)	$NO_2^+ + OH^- \to OH + N + O_2$	1×10^{-13}
(R422)	$H^+ + N_2O^- \to N_2O + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R423)	$H^+ + NO^- \to NO + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R424)	$H^+ + NO_2^- \to NO_2 + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R425)	$H^+ + NO_3^- \to NO_3 + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R426)	$H^+ + O^- \to O + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R427)	$H^+ + O_2^- \to O_2 + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R428)	$H^+ + O_3^- \to O_3 + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R429)	$H^+ + O_4^- \to O_2 + O_2 + H$	1×10^{-13}
(R430)	$H^+ + H^- \to H + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R431)	$H^+ + OH^- \to OH + H$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R432)	$H_2^+ + N_2O^- \to N_2O + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R433)	$H_2^+ + N_2O^- \to N_2O + H + H$	1×10^{-13}
(R434)	$H_2^+ + NO^- \to NO + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R435)	$H_2^+ + NO^- \to NO + H + H$	1×10^{-13}
(R436)	$H_2^+ + NO_2^- \to NO_2 + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R437)	$H_2^+ + NO_2^- \to NO_2 + H + H$	1×10^{-13}
(R438)	$H_2^+ + NO_3^- \to NO_3 + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R439)	$H_2^+ + NO_3^- \to NO_3 + H + H$	1×10^{-13}
(R440)	$H_2^+ + O^- \to O + H + H$	1×10^{-13}
(R441)	$H_2^+ + O^- \to O + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R442)	$H_2^+ + O_2^- \to O_2 + H + H$	1×10^{-13}
(R443)	$H_2^+ + O_2^- \to O_2 + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R444)	$H_2^+ + O_3^- \to O_3 + H + H$	1×10^{-13}
(R445)	$H_2^+ + O_3^- \to O_3 + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R446)	$H_2^+ + O_4^- \to O_2 + O_2 + H_2$	1×10^{-13}
(R447)	$H_2^+ + H^- \to H + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R448)	$H_2^+ + H^- \to H + H + H$	1×10^{-13}
(R449)	$H_2^+ + OH^- \to OH + H_2$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R450)	$H_2^+ + OH^- \to OH + H + H$	1×10^{-13}
(R451)	$H_3^+ + N_2O^- \to N_2O + H + H_2$	1×10^{-13}
(R452)	$H_3^+ + NO^- \to NO + H + H_2$	1×10^{-13}
(R453)	$H_3^+ + NO_2^- \to NO_2 + H + H_2$	1×10^{-13}
(R454)	$H_3^+ + NO_3^- \to NO_3 + H + H_2$	1×10^{-13}
(R455)	$H_3^+ + O^- \to O + H + H_2$	1×10^{-13}
(R456)	$H_3^+ + O_2^- \to O_2 + H + H_2$	1×10^{-13}
(R457)	$H_3^+ + O_3^- \to O_3 + H + H_2$	1×10^{-13}
(R458)	$H_3^+ + O_4^- \to O_2 + O_2 + H + H_2$	1×10^{-13}
(R459)	$H_3^+ + H^- \to H + H + H_2$	1×10^{-13}
(R460)	$H_3^+ + OH^- \to OH + H + H_2$	1×10^{-13}
(R461)	$OH^+ + N_2O^- \to N_2O + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R462)	$OH^+ + N_2O^- \to N_2O + O + H$	1×10^{-13}
(R463)	$OH^+ + NO^- \to NO + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R464)	$OH^+ + NO^- \to NO + O + H$	1×10^{-13}
(R465)	$OH^+ + NO_2^- \to NO_2 + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R466)	$OH^+ + NO_2^- \to NO_2 + O + H$	1×10^{-13}
(R467)	$OH^+ + NO_3^- \to NO_3 + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R468)	$OH^+ + NO_3^- \to NO_3 + O + H$	1×10^{-13}
(R469)	$OH^+ + O^- \to O + O + H$	1×10^{-13}
(R470)	$OH^+ + O^- \to O + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R471)	$OH^+ + O_2^- \to O_2 + O + H$	1×10^{-13}
(R472)	$OH^+ + O_2^- \to O_2 + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R473)	$OH^+ + O_3^- \to O_3 + O + H$	1×10^{-13}
(R474)	$OH^+ + O_3^- \to O_3 + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R475)	$OH^+ + O_4^- \to O_2 + O_2 + OH$	1×10^{-13}
(R476)	$OH^+ + H^- \to H + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R477)	$OH^+ + H^- \to H + O + H$	1×10^{-13}
(R478)	$OH^+ + OH^- \to OH + OH$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R479)	$OH^+ + OH^- \to OH + O + H$	1×10^{-13}
(R480)	$H_2O^+ + N_2O^- \to N_2O + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R481)	$H_2O^+ + N_2O^- \to N_2O + OH + H$	1×10^{-13}
(R482)	$H_2O^+ + NO^- \to NO + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R483)	$H_2O^+ + NO^- \to NO + OH + H$	1×10^{-13}
(R484)	$H_2O^+ + NO_2^- \to NO_2 + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R485)	$H_2O^+ + NO_2^- \to NO_2 + OH + H$	1×10^{-13}
(R486)	$H_2O^+ + NO_3^- \to NO_3 + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R487)	$H_2O^+ + NO_3^- \to NO_3 + OH + H$	1×10^{-13}
(R488)	$H_2O^+ + O^- \to O + OH + H$	1×10^{-13}
(R489)	$H_2O^+ + O^- \to O + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R490)	$H_2O^+ + O_2^- \to O_2 + OH + H$	1×10^{-13}
(R491)	$H_2O^+ + O_2^- \to O_2 + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R492)	$H_2O^+ + O_3^- \to O_3 + OH + H$	1×10^{-13}
(R493)	$H_2O^+ + O_3^- \to O_3 + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R494)	$H_2O^+ + O_4^- \to O_2 + O_2 + H_2O$	1×10^{-13}
(R495)	$H_2O^+ + H^- \to H + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R496)	$H_2O^+ + H^- \to H + OH + H$	1×10^{-13}
(R497)	$H_2O^+ + OH^- \to OH + H_2O$	$2 \times 10^{-13} (300/T_g)^{0.5}$
(R498)	$H_2O^+ + OH^- \to OH + OH + H$	1×10^{-13}
(R499)	$H_3O^+ + N_2O^- \to N_2O + H_2O + H$	1×10^{-13}
(R500)	$H_3O^+ + NO^- \to NO + H_2O + H$	1×10^{-13}
(R501)	$H_3O^+ + NO_2^- \to NO_2 + H_2O + H$	1×10^{-13}
(R502)	$H_3O^+ + NO_3^- \to NO_3 + H_2O + H$	1×10^{-13}
(R503)	$H_3O^+ + O^- \to O + H_2O + H$	1×10^{-13}
(R504)	$H_3O^+ + O_2^- \to O_2 + H_2O + H$	1×10^{-13}
(R505)	$H_3O^+ + O_3^- \to O_3 + H_2O + H$	1×10^{-13}
(R506)	$H_3O^+ + O_4^- \to O_2 + O_2 + H_2O + H$	1×10^{-13}
(R507)	$H_3O^+ + H^- \to H + H_2O + H$	1×10^{-13}
(R508)	$H_3O^+ + OH^- \to OH + H_2O + H$	1×10^{-13}
(R509)	$N + N + M \to N_2 + M$	$8.3 \times 10^{-46} \exp(500/T_g)$
(R510)	$N + NO \to N_2 + O$	$2.1 \times 10^{-17} \exp(100/T_g)$
(R511)	$N + NO_2 \to N_2O + O$	$5.8 \times 10^{-18} \exp(220/T_g)$
(R512)	$N + NO_2 \to N_2 + O + O$	9.1×10^{-19}
(R513)	$N + NO_2 \to NO + NO$	6×10^{-19}
(R514)	$N + NO_2 \to N_2 + O_2$	7×10^{-19}
(R515)	$N + O + M \to NO + M$	$6.3 \times 10^{-45} \exp(140/T_g)$
(R516)	$N + O_2 \to NO + O$	$1.5 \times 10^{-17} \exp(-3600/T_g)$
(R517)	$N + O_3 \to NO + O_2$	5×10^{-22}
(R518)	$N + OH \to H + NO$	7.5×10^{-17}
(R519)	$N + HO_2 \to NO + OH$	$1.7 \times 10^{-17} \exp(-1000/T_g)$
(R520)	$N(^2D) + N_2 \to N + N_2$	$5 \times 10^{-18} \exp(-1620/T_g)$
(R521)	$N(^2D) + N_2O \to N_2 + NO$	$1.5 \times 10^{-17} \exp(-570/T_g)$
(R522)	$N(^2D) + NO \to N_2O$	6×10^{-17}
(R523)	$N(^2D) + NO \to O + N_2$	4.5×10^{-17}
(R524)	$N(^2D) + O \to N + O$	7×10^{-19}
(R525)	$N(^2D) + O_2 \to NO + O$	$1.5 \times 10^{-18} (T_g/300)^{0.5}$
(R526)	$N(^2D) + O_2 \to NO + O(^1D)$	$6 \times 10^{-18} (T_g/300)^{0.5}$
(R527)	$N_2(A\,^3\Sigma) + N_2 \to N_2 + N_2$	2.2×10^{-20}
(R528)	$N_2(A\,^3\Sigma) + N_2(A\,^3\Sigma) \to N_2(B\,^3\Pi) + N_2$	4×10^{-16}
(R529)	$N_2(A\,^3\Sigma) + N_2O \to O + N_2 + N_2$	8×10^{-17}
(R530)	$N_2(A\,^3!\Sigma) + N_2O \to NO + N + N_2$	8×10^{-17}
(R531)	$N_2(A\,^3\Sigma) + NO_2 \to N_2 + NO + O$	1.3×10^{-17}
(R532)	$N_2(A\,^3\Sigma) + O_2 \to N_2 + O + O$	$5 \times 10^{-18} \exp(-210/T_g)$
(R533)	$N_2(A\,^3\Sigma) + O_2 \to O_2(a\,^1\Delta) + N_2$	1×10^{-18}
(R534)	$N_2(A\,^3\Sigma) + N \to N + N_2$	5×10^{-17}
(R535)	$N_2(A\,^3\Sigma) + O \to NO + N(^2D)$	7×10^{-18}
(R536)	$N_2(A\,^3\Sigma) + O \to O(^1D) + N_2$	2.3×10^{-17}
(R537)	$N_2(A\,^3\Sigma) + H_2O \to H + OH + N_2$	5×10^{-20}
(R538)	$N_2(B\,^3\Pi) + N_2 \to N_2(A\,^3\Sigma) + N_2$	5×10^{-17}
(R539)	$N_2(B\,^3\Pi) + \to N_2(A\,^3\Sigma)$	1.25×10^{5}
(R540)	$N_2(B\,^3\Pi) + NO \to N_2(A\,^3\Sigma) + NO$	2.4×10^{-16}
(R541)	$N_2(B\,^3\Pi) + O_2 \to N_2 + O + O$	3×10^{-16}
(R542)	$N_2(B\,^3\Pi) + H_2 \to N_2(A\,^3\Sigma) + H_2$	2.5×10^{-17}
(R543)	$O + O + M \to O_2 + M$	$3.2 \times 10^{-47} \exp(900/T_g)$
(R544)	$O + O_2 + M \to O_3 + M$	$3.4 \times 10^{-46} (300/T_g)^{1.2}$
(R545)	$O + O_3 \to O_2 + O_2$	$8 \times 10^{-18} \exp(-2060/T_g)$
(R546)	$O + NO + M \to NO_2 + M$	$1 \times 10^{-43} (300/T_g)^{1.6}$
(R547)	$O + NO_2 \to NO + O_2$	$6.5 \times 10^{-18} \exp(120/T_g)$
(R548)	$O + NO_2 + M \to NO_3 + M$	$9 \times 10^{-44} (300/T_g)^2$
(R549)	$O + NO_3 \to O_2 + NO_2$	1.7×10^{-17}
(R550)	$O + H + M \to OH + M$	1.62×10^{-44}
(R551)	$O + OH \to H + O_2$	$2.2 \times 10^{-17} \exp(-350/T_g)$
(R552)	$O + H_2O_2 \to OH + HO_2$	$3.3 \times 10^{-17} \exp(-2950/T_g)$
(R553)	$O + HO_2 \to OH + O_2$	$8.3 \times 10^{-17} \exp(-500/T_g)$
(R554)	$O + HNO \to OH + NO$	5.99×10^{-17}
(R555)	$O + HNO_2 \to NO_2 + OH$	$2 \times 10^{-17} \exp(-3000/T_g)$
(R556)	$O(^1D) + O_2 \to O + O_2$	$6.4 \times 10^{-18} \exp(67/T_g)$
(R557)	$O(^1D) + O \to O + O$	8×10^{-18}
(R558)	$O(^1D) + O_2(a\,^1\Delta) \to O + O_2$	1×10^{-17}
(R559)	$O(^1D) + O_2 \to O + O_2(a\,^1\Delta)$	1×10^{-18}
(R560)	$O(^1D) + O_3 \to O + O + O_2$	1.2×10^{-16}
(R561)	$O(^1D) + O_3 \to O_2 + O_2$	1.2×10^{-16}
(R562)	$O(^1D) + N_2 \to O + N_2$	$1.8 \times 10^{-17} \exp(107/T_g)$
(R563)	$O(^1D) + N_2 + M \to N_2O + M$	9×10^{-49}
(R564)	$O(^1D) + N_2O \to N_2 + O_2$	4.4×10^{-17}
(R565)	$O(^1D) + N_2O \to NO + NO$	7.2×10^{-17}
(R566)	$O(^1D) + NO \to O + NO$	4×10^{-17}
(R567)	$O(^1D) + NO_2 \to NO + O_2$	1.4×10^{-16}
(R568)	$O(^1D) + H_2 \to OH + H$	1.1×10^{-16}
(R569)	$O(^1D) + H_2O \to OH + OH$	2.2×10^{-16}
(R570)	$O_2(a\,^1\Delta) + O_2 \to O_2 + O_2$	$3.8 \times 10^{-24} \exp(-205/T_g)$
(R571)	$O_2(a\,^1\Delta) + O_3 \to O + O_2 + O_2$	$5.2 \times 10^{-17} \exp(-2840/T_g)$
(R572)	$O_2(a\,^1\Delta) + M \to O_2 + M$	8×10^{-27}
(R573)	$O_2(a\,^1\Delta) + NO \to O_2 + NO$	2.5×10^{-17}
(R574)	$O_2(a\,^1\Delta) + N_2 \to O_2 + N_2$	1.5×10^{-24}
(R575)	$O_3 + NO \to NO_2 + O_2$	$1.8 \times 10^{-18} \exp(-1370/T_g)$
(R576)	$O_3 + NO_2 \to NO_3 + O_2$	$1.4 \times 10^{-19} \exp(-2470/T_g)$
(R577)	$O_3 + M \to O + O_2 + M$	$3.92 \times 10^{-16} \exp(-11\,400/T_g)$
(R578)	$O_3 + H \to OH + O_2$	$2.8 \times 10^{-17} (T_g/300)^{0.75}$
(R579)	$O_3 + OH \to HO_2 + O_2$	$1.6 \times 10^{-18} \exp(-1000/T_g)$
(R580)	$O_3 + HO_2 \to OH + O_2 + O_2$	$1.4 \times 10^{-20} \exp(-600/T_g)$
(R581)	$NO + NO_2 + M \to N_2O_3 + M$	$3.09 \times 10^{-46} (300/T_g)^{7.7}$
(R582)	$NO + NO_3 \to NO_2 + NO_2$	$1.8 \times 10^{-17} \exp(110/T_g)$
(R583)	$NO + OH + M \to HNO_2 + M$	$7.4 \times 10^{-43} (300/T_g)^{2.4}$
(R584)	$NO + H + M \to HNO + M$	$1 \times 10^{-44} \exp(300/T_g)$
(R585)	$NO + HO_2 \to OH + NO_2$	$3.4 \times 10^{-18} \exp(270/T_g)$
(R586)	$NO + HO_2 \to O_2 + HNO$	$3.3 \times 10^{-19} \exp(-1000/T_g)$
(R587)	$NO_2 + NO_2 + M \to N_2O_4 + M$	$1.17 \times 10^{-45} (300/T_g)^{3.8}$
(R588)	$NO_2 + NO_3 + M \to N_2O_5 + M$	$2.8 \times 10^{-42} (300/T_g)^{3.5}$
(R589)	$NO_2 + NO_3 \to NO_2 + NO + O_2$	$2.3 \times 10^{-19} \exp(-1600/T_g)$
(R590)	$NO_2 + H \to OH + NO$	1.47×10^{-16}
(R591)	$NO_2 + OH + M \to HNO_3 + M$	$2.2 \times 10^{-42} (300/T_g)^{2.9}$
(R592)	$NO_3 + NO_3 \to NO_2 + NO_2 + O_2$	$5 \times 10^{-18} \exp(-3000/T_g)$
(R593)	$NO_3 + H \to OH + NO_2$	$5.8 \times 10^{-16} \exp(-750/T_g)$
(R594)	$NO_3 + OH \to HO_2 + NO_2$	2×10^{-17}
(R595)	$NO_3 + HO_2 \to NO_2 + OH + O_2$	4.8×10^{-18}
(R596)	$NO_3 + HO_2 \to HNO_3 + O_2$	9.2×10^{-19}
(R597)	$N_2O_3 + M \to NO + NO_2 + M$	$1.03 \times 10^{-16} \exp(-2628/T_g)$
(R598)	$N_2O_4 + M \to NO_2 + NO_2 + M$	$1.09 \times 10^{-13} \exp(-4952/T_g)$
(R599)	$N_2O_5 + M \to NO_2 + NO_3 + M$	$1 \times 10^{-9} (300/T_g)^{3.5} \exp(-11\,000/T_g)$
(R600)	$H + O_2 + M \to HO_2 + M$	$5.4 \times 10^{-44} (T_g/300)^{-1.8}$
(R601)	$H + H + M \to H_2 + M$	$1.8 \times 10^{-42}/T_g$
(R602)	$H + OH + M \to H_2O + M$	$6.1 \times 10^{-38}/T_g^2$
(R603)	$H + H_2O_2 \to OH + H_2O$	$1.69 \times 10^{-17} \exp(-1800/T_g)$
(R604)	$H + H_2O_2 \to HO_2 + H_2$	$2.8 \times 10^{-18} \exp(-1900/T_g)$
(R605)	$H + HO_2 \to H_2 + O_2$	5.6×10^{-18}
(R606)	$H + HO_2 \to O + H_2O$	2.4×10^{-18}
(R607)	$H + HO_2 \to OH + OH$	$4.2 \times 10^{-16} \exp(-950/T_g)$
(R608)	$H + HNO \to NO + H_2$	$3 \times 10^{-17} \exp(-500/T_g)$
(R609)	$H + HNO_2 \to NO_2 + H_2$	$2 \times 10^{-17} \exp(-3700/T_g)$
(R610)	$H + HNO_3 \to NO_2 + H_2O$	$1.39 \times 10^{-20} (T_g/298)^{3.29} \exp(-3160/T_g)$
(R611)	$H_2 + OH \to H + H_2O$	$3.2 \times 10^{-17} \exp(-2600/T_g)$
(R612)	$OH + OH \to O + H_2O$	$8.8 \times 10^{-18} \exp(-503/T_g)$
(R613)	$OH + OH + M \to H_2O_2 + M$	$6.9 \times 10^{-43} (T_g/300)^{-0.8}$
(R614)	$OH + HO_2 \to O_2 + H_2O$	$4.8 \times 10^{-17} \exp(250/T_g)$
(R615)	$OH + H_2O_2 \to HO_2 + H_2O$	$2.9 \times 10^{-18} \exp(-160/T_g)$
(R616)	$OH + HNO \to NO + H_2O$	$8 \times 10^{-17} \exp(-500/T_g)$
(R617)	$OH + HNO_2 \to NO_2 + H_2O$	$1.8 \times 10^{-17} \exp(-390/T_g)$
(R618)	$OH + HNO_3 \to NO_3 + H_2O$	$1.5 \times 10^{-20} \exp(650/T_g)$
(R619)	$HO_2 + HO_2 \to H_2O_2 + O_2$	$2.2 \times 10^{-19} \exp(600/T_g)$
(R620)	$HNO + O_2 \to NO + HO_2$	$5.25 \times 10^{-18} \exp(-1510/T_g)$
(R621)	$HNO + O_2 \to NO_2 + OH$	1.66×10^{-21}
(R622)	$HNO + HNO \to N_2O + H_2O$	$1.4 \times 10^{-21} \exp(-1600/T_g)$
(R623)	$HNO_2 + HNO_2 \to NO + NO_2 + H_2O$	1×10^{-26}
(R624)	$HNO_2 + HNO_3 \to NO_2 + NO_2 + H_2O$	1.6×10^{-23}

And the list of reactions gets very long, and very difficult to set up and solve balance equations

624 Reactions!



Electron Impact Driven

Boltzmann Reactions

Positive (and negative) Ion Driven Reactions

Excited Atomic and Molecular Specie Driven

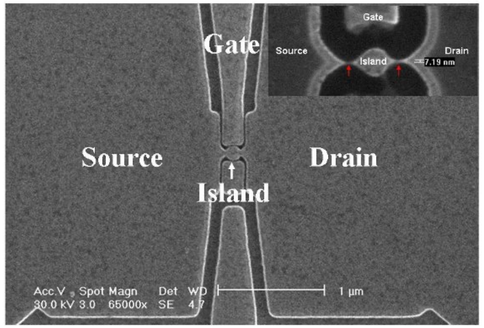
Reactions where we have to “guess”

Charge Exchange Free Electron Forming

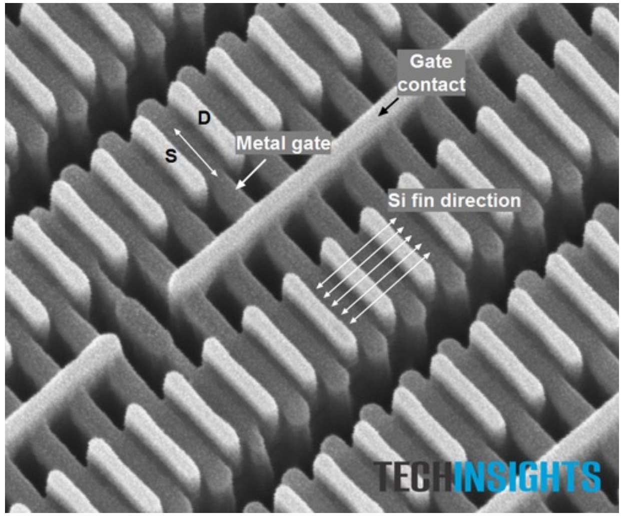
“Boring” Gas Phase Ground State Stuff

Plasma technology has had (and still still does) need to keep pace

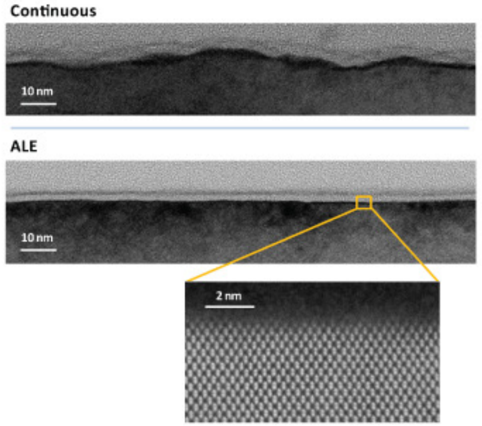
- 1990’s – etch rate, etch selectivity, dual damescene
- 2000’s – profile shape, aspect ratio, 300mm
- 2010’s – aspect ratio, complex material stacks, residual material damage
- 2020’s – (one person’s opinion at least) – new pathways for anisotropy + advanced chemistry control to maintain anisotropy with minimal device damage down to the atomic scale



Silicon Quantum Dot
Single electron transistor
Michael Wang, *Lithography,*
Intech Press (2010)



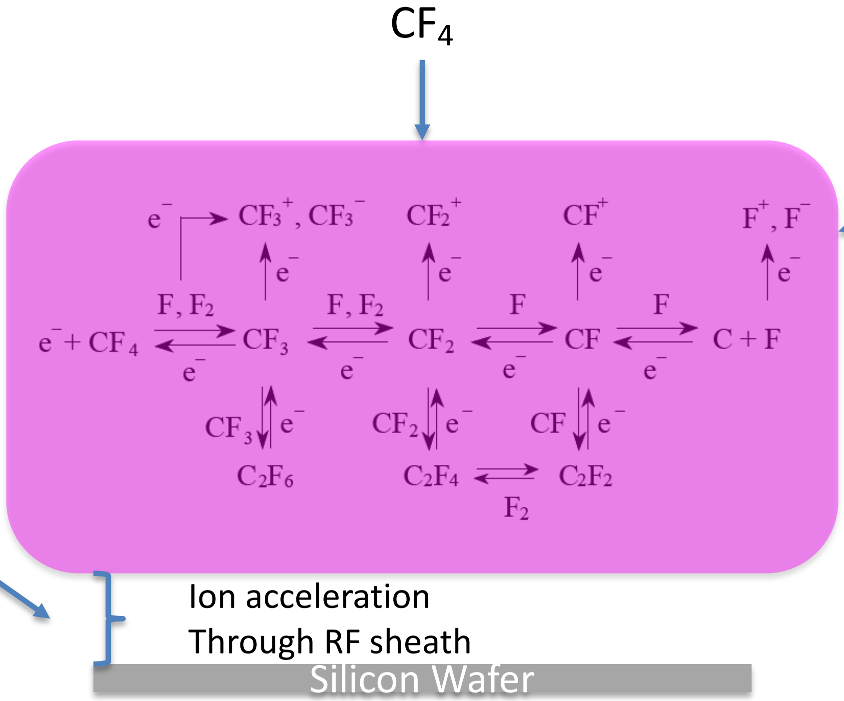
Kevin Gibb, “Samsung’s 14 nm LPE FinFET Transistors”, *EETimes*, 2016



Keren Kanarik et. al., “Moving atomic layer etch from lab to fab”, *Solid State Technology Magazine*, January 2014

Summary – we need two things to drive device fabrication – ions and reactive low temperature chemistry. Plasmas give us both.

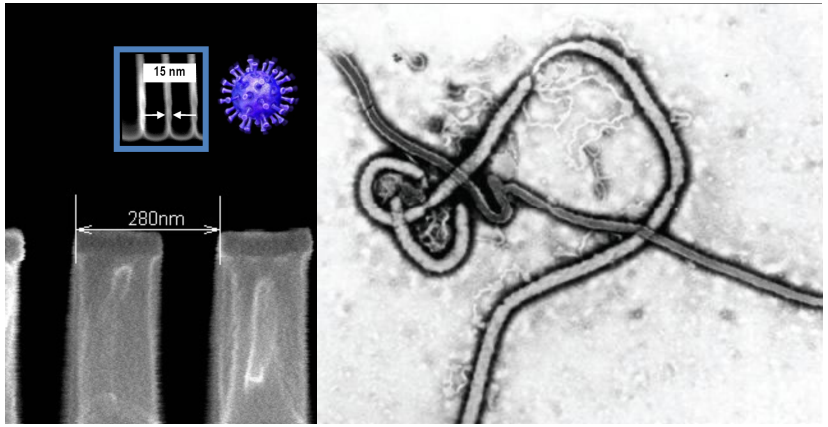
Ion acceleration normal to the surface using naturally occurring electric fields at the plasma edge

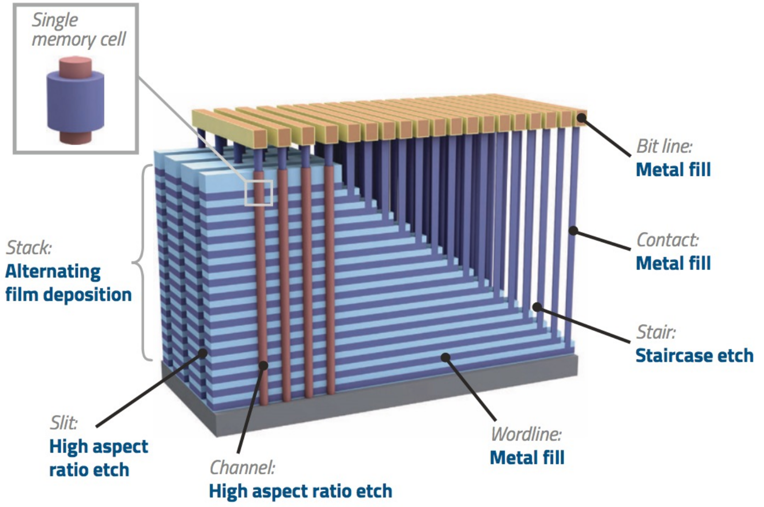


Electron driven “breaking” of molecules… don’t use thermal energy, use electron bombardment. This keeps the gas cool

Summary – using plasma technology allows us to combine Thing 1 + Thing 2 to produce the nano-scale devices in electronic equipment today

Ion acceleration normal to the surface using naturally occurring electric fields at the plasma edge





Electron driven “breaking” of molecules… don’t use thermal energy, use electron bombardment. This keeps the gas cool

Acknowledgements

- Countless students, engineers, scientists, and collaborators over the last 25+ years

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