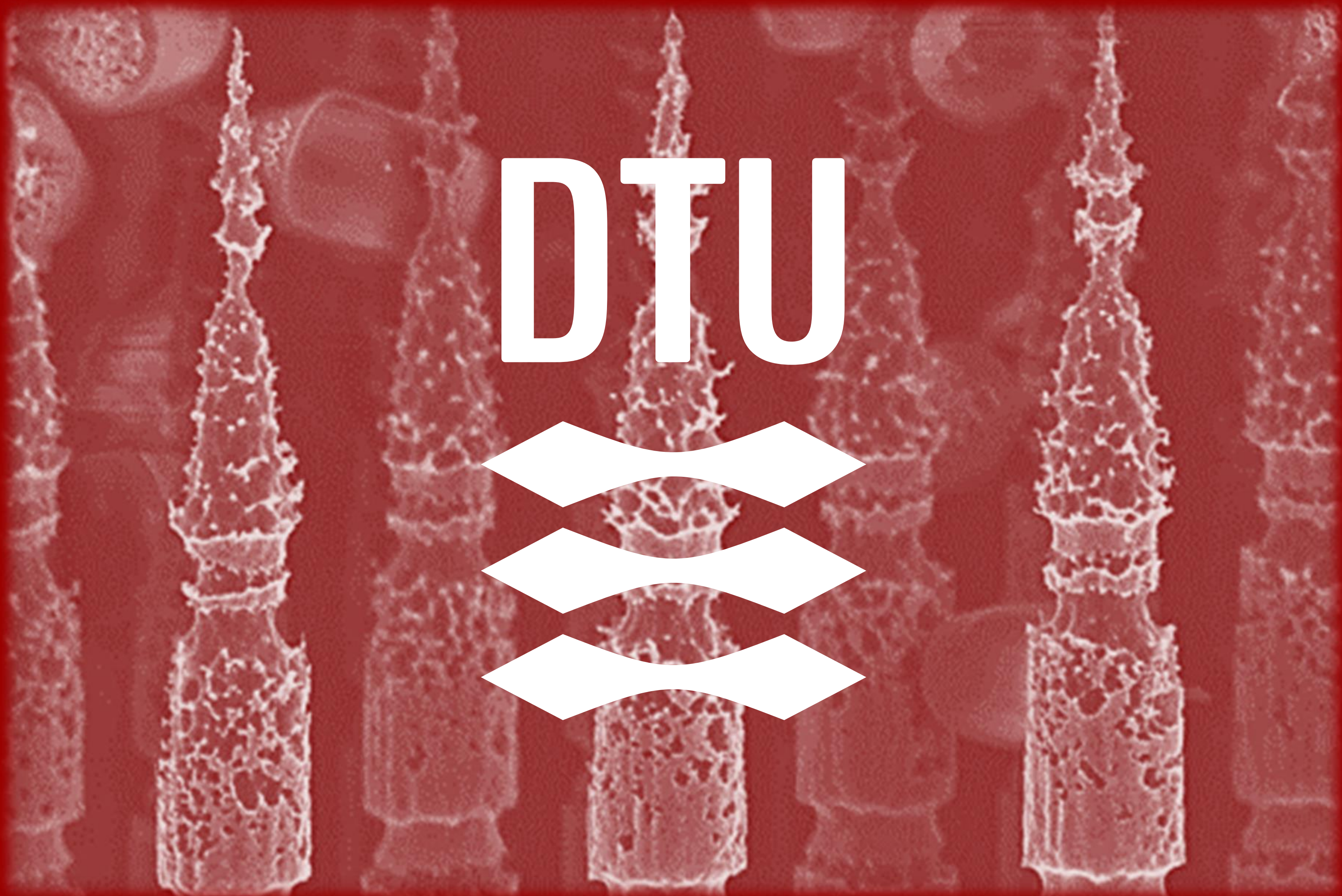

DTU

Generic build-up of silicon plasma etch processes: a practical guide to directional profiles

By:
Henri Jansen

Featuring:

Bingdong Chang

Jörg Hübner

Flemming Jensen

Roy Cork

Vy Thi Hoang Nguyen

Generic build-up of silicon plasma etch processes

- *What are plasmas*
- *Fundamental principles on plasmas*
- *What is plasma etching*
- *1-, 2-, and 3-steps procedures for profile control*
- *Mixed SF_6 plasma etch*
- *Switched SF_6 /FC plasma etch including DREM*
- *Beyond DREM: 4-steps DREAM and 3D silicon nano-sculpturing*
- *Switched SF_6 /O_2 plasma etch*

What are plasmas

Ordinarily, we hardly come into contact with plasma in our daily life.

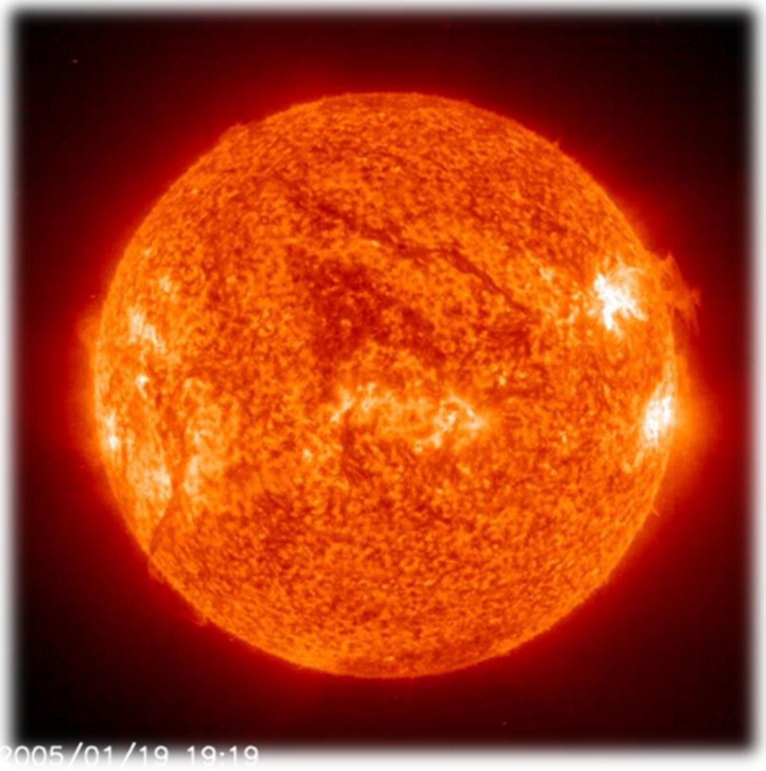
Matter, which is normally seen, exists in the solid, liquid, or gas phase.

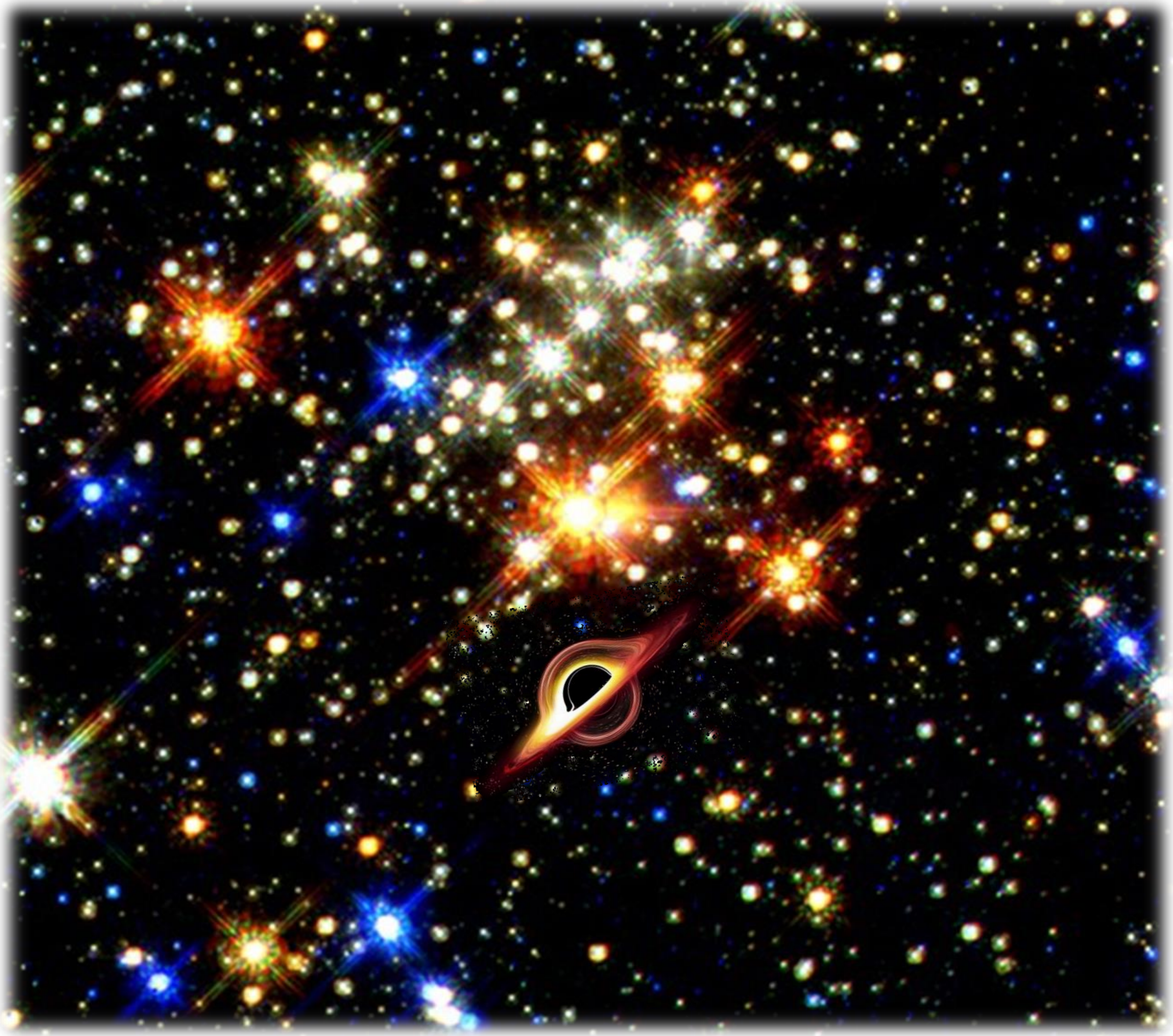
What are plasmas

But, lightning and auroras appearing in the polar regions are plasmas in nature and...

What are plasmas

… and all stars, including the sun, are masses of high-temperature plasmas.

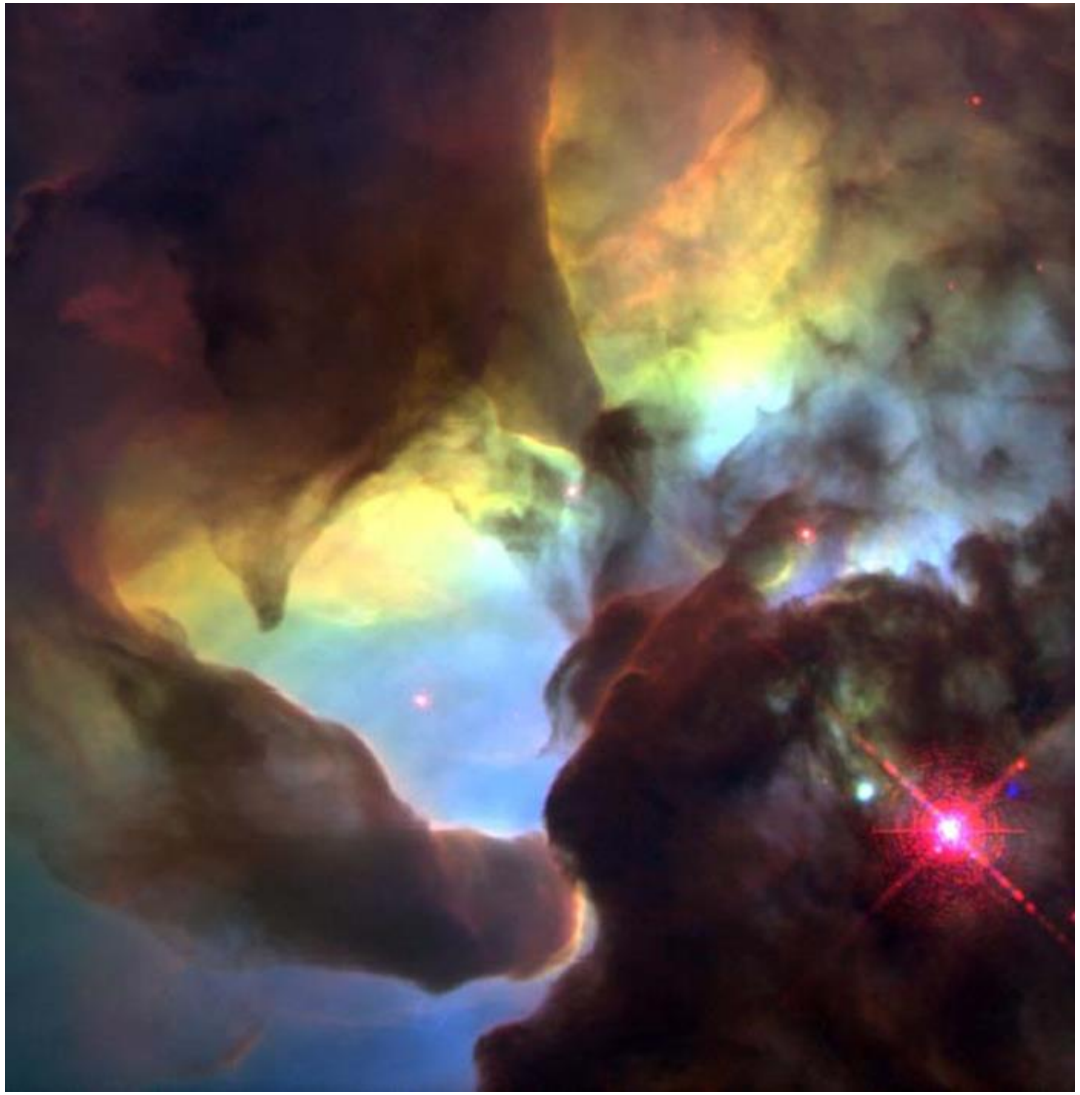




What are plasmas

Also the interstellar matter and nebulae are in the plasma state.

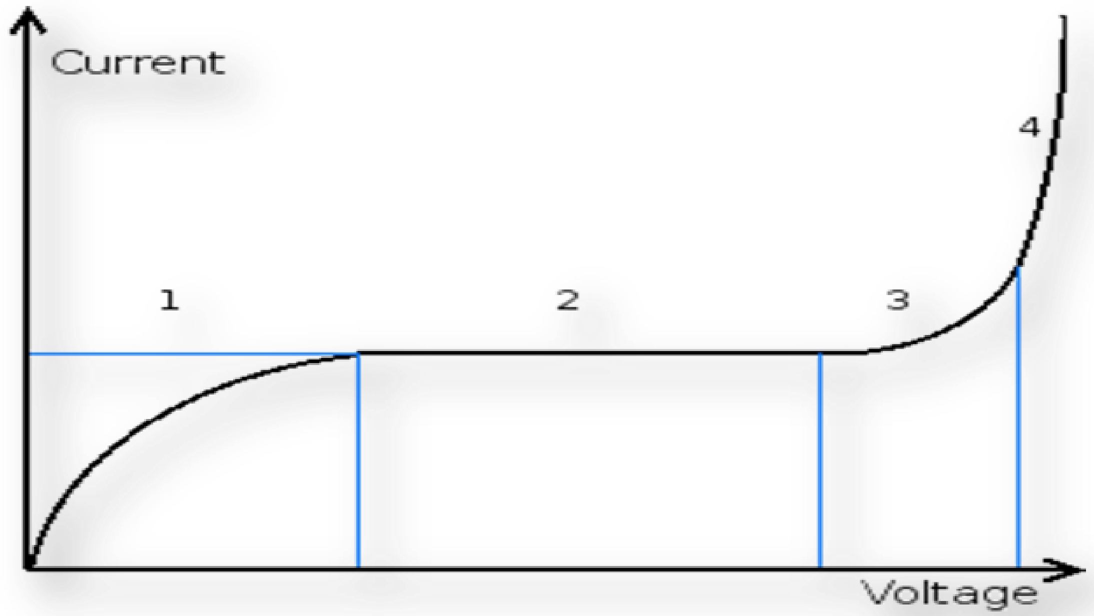
So, it has been said that the greater part of the universe is in the plasma state.

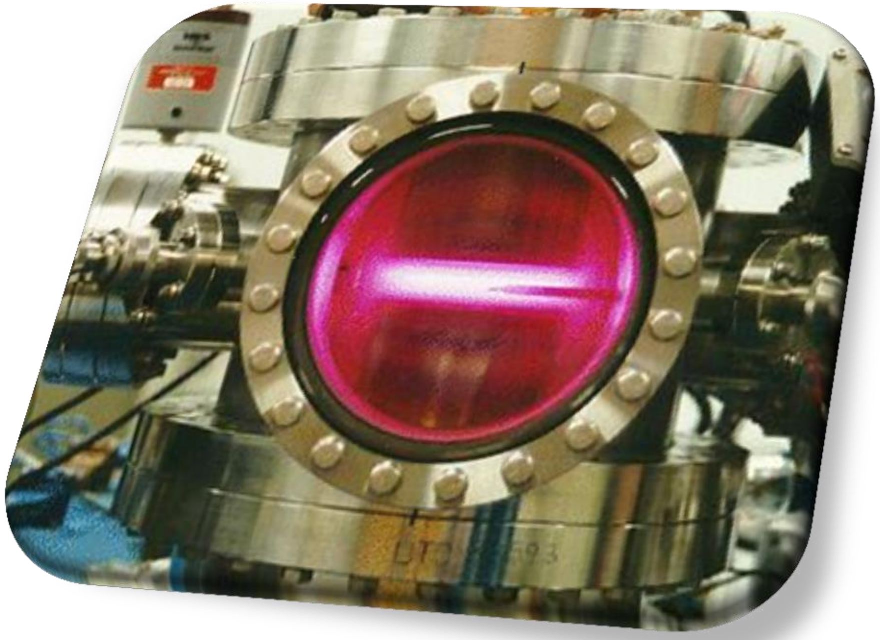


Electrical discharges: manmade plasmas

Manmade plasmas, or electrical discharges, are accomplished by using a glass tube with two metal electrodes installed, ***evacuating the tube*** *to a pressure between 0.1 to 1 mbar and* ***applying a high voltage*** *between the two electrodes.*

As the voltage gradually increases, only a small current flows. But when the voltage has reached a few hundred volts, current through the tube shows an abrupt increase, and the tube begins to emit visible light. A plasma is born.





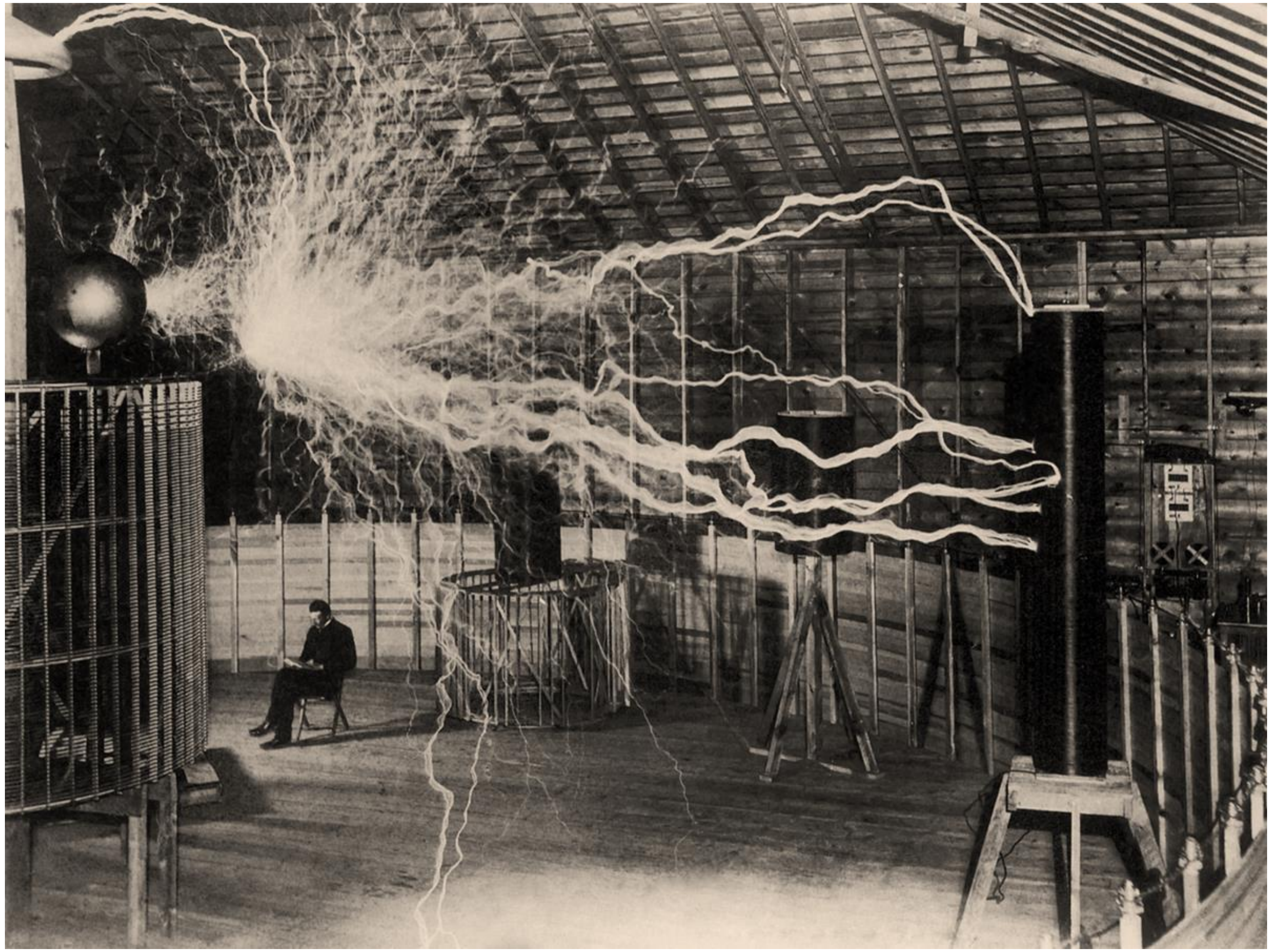
Electrical discharges

Vegas, city of fluorescent tubes and neon signs, is during the night in the plasma state.

Electrical discharges

*A plasma contains a high density of charged particles and is therefore **highly conductive**.*

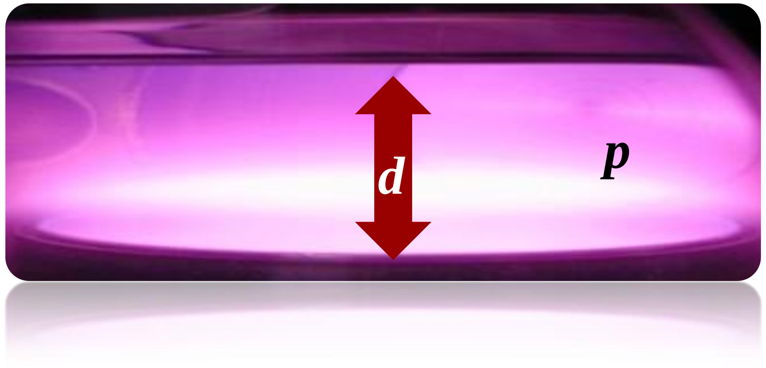
This conduction distinguishes the plasma from the normal gas and it is therefore called the forth state in which a material can exist.



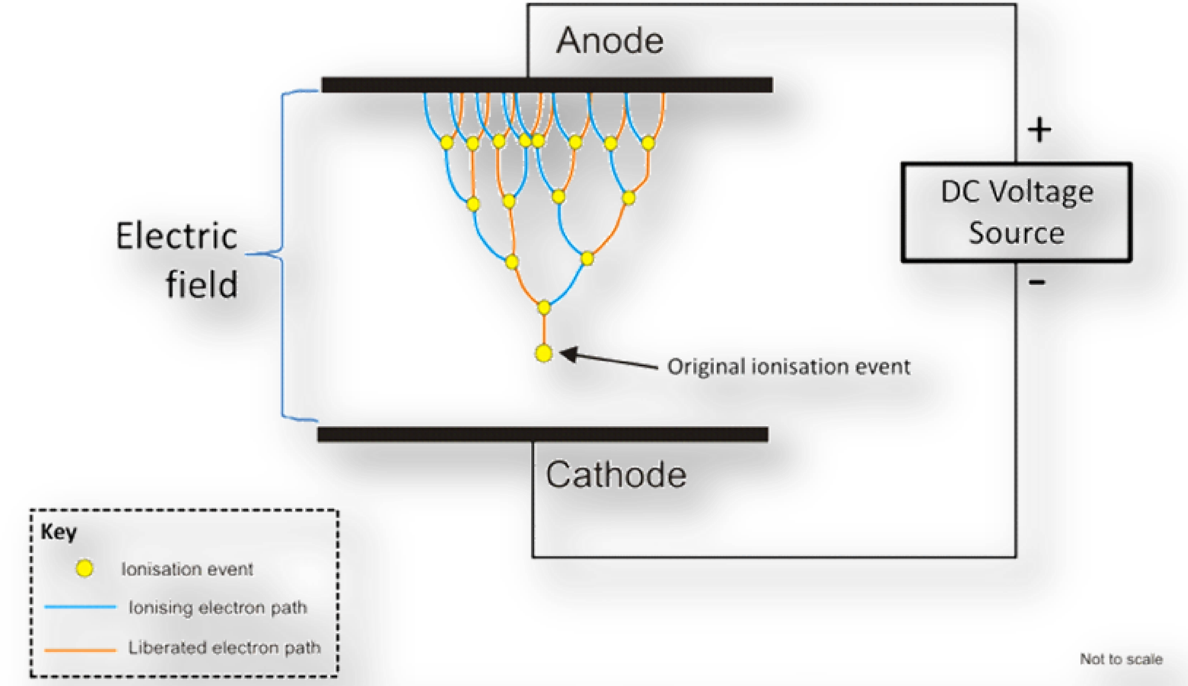
Nikola Tesla in his laboratory in 1899.

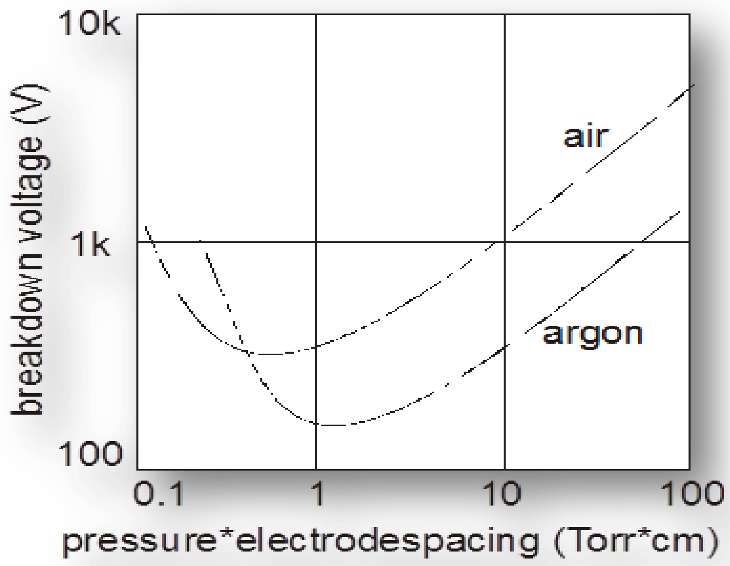
Electrical discharges

The simplest discharge uses a ***direct current (dc)*** *source. The high electrical field creates an ever-increasing number of free electrons - due to fatal collisions that liberate additional electrons - while passing towards the positively charged anode.*



An important discharge property is the Paschen curve. It shows the breakdown voltage of a gas between two electrodes separated by a distance ***d*** *at a pressure* ***p****.*

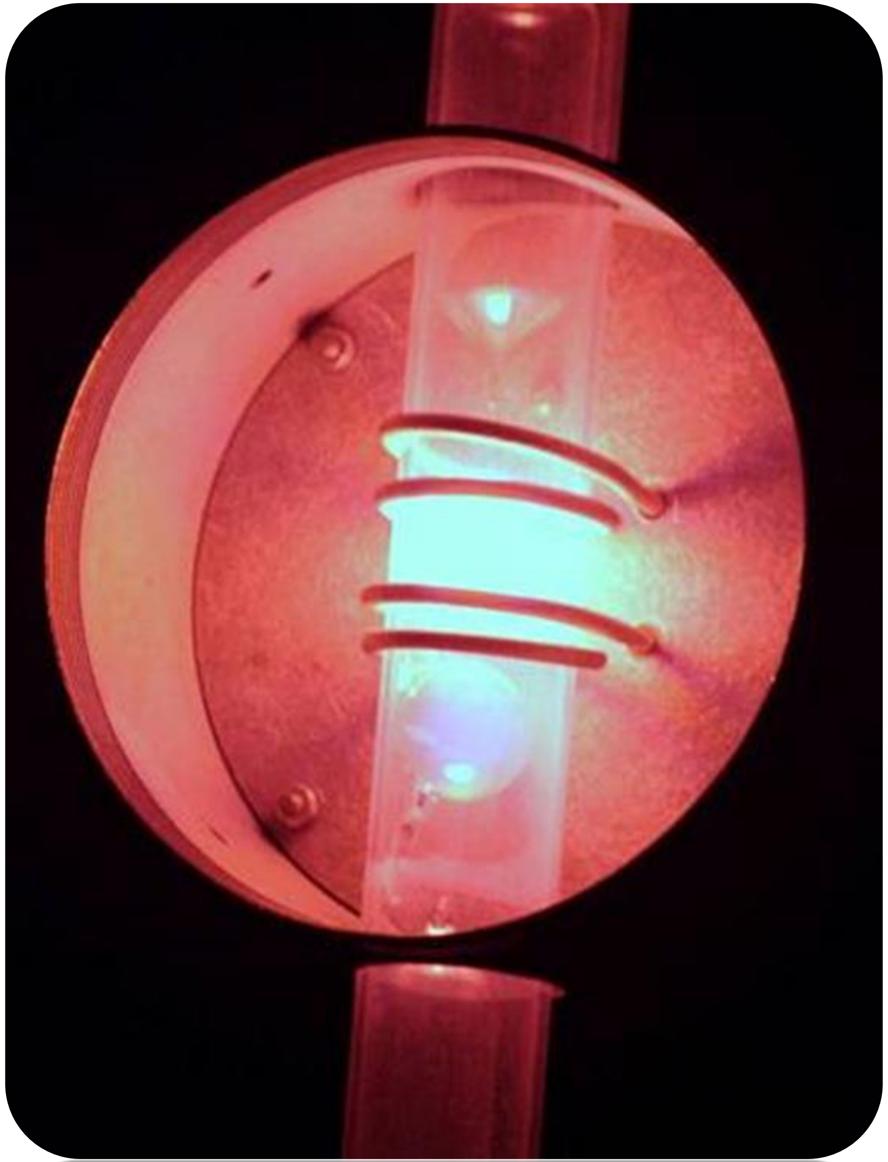




Electrical discharges

Plasma can also be generated using radio frequency (rf). This enables us to install electrodes with insulating surfaces. This type is called ***capacitively coupled plasma (CCP).***

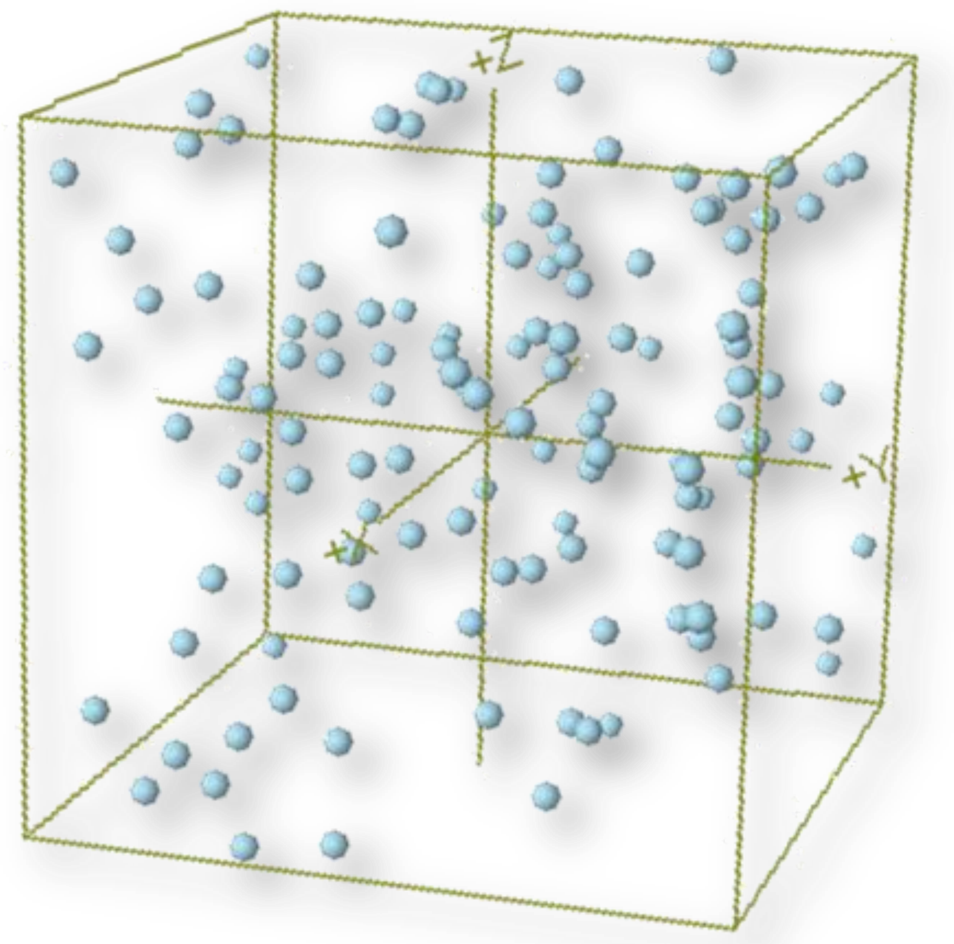
Another possibility is to use a coil rapped around a glass tube and excite the discharge electromagnetically. This type is called ***inductively coupled plasma (ICP)****.*



Fundamental principles

Physical model of the ideal gas

- *A gas consists of* ***molecules*** *of mass m and diameter d* ***in ceaseless random motion****.*
- ***The size of the molecules is negligible*** *(in the sense that their diameters are much smaller than the average distance travelled between collisions).*
- ***The molecules do not interact****, except that they make perfectly elastic collisions when the separation of their centres is equal to d.*



M–B speed distribution of the ideal gas

*The **Maxwell–Boltzmann (M-B) distribution** describes the probability **f(v)** of a particle's speed being near a given value as a function of the temperature **T** of the system, the mass **m** of the particle, and that speed value.*

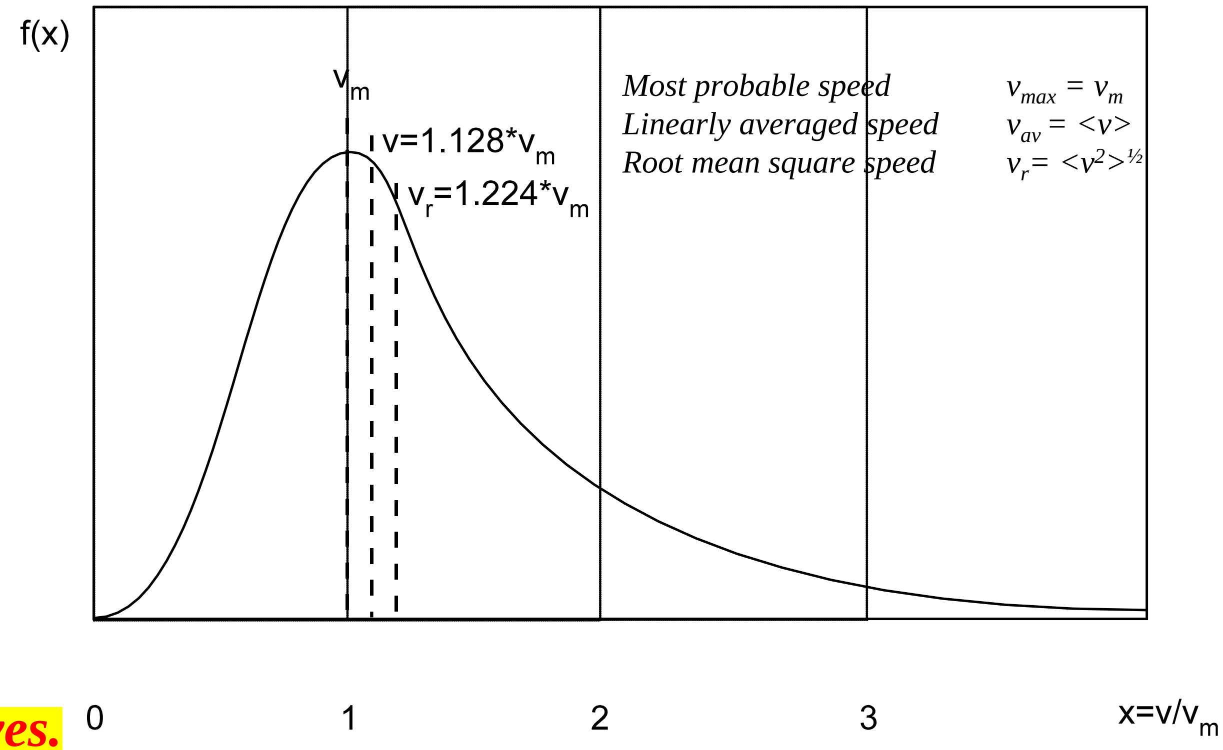
$$\frac{dN}{N} = f(v)dv = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right) dv$$

With this we find the most probable kinetic energy per molecule:

$$<E_{kin}> = \tfrac{1}{2} m v_{rms}^2 = 3kT/2$$

Where $v_{rms} = \left(\int_0^\infty v^2 \cdot f(v)dv\right)^{1/2} = \sqrt{\frac{3kT}{m}}$

So, the bigger the molecule, the slower it moves.



Mean free path of the ideal gas

$$\lambda_g = \frac{v_{avg}}{f_{gg}} = \frac{1}{\sigma_g n_g 4\sqrt{2}} \quad [m]$$

$$\lambda_e = \frac{v_{ave}}{f_{eg}} = \frac{1}{\sigma_g n_g} = \frac{kT}{\sigma_g p_g} \quad [m]$$

So, the mean free path of the smaller electron is ca. 6 times larger than that of the gas molecule.

*For nitrogen, $\lambda_g * p_g \approx$ **50mm*mTorr***
and
$\lambda_e * p_g \approx$ 300mm*mTorr

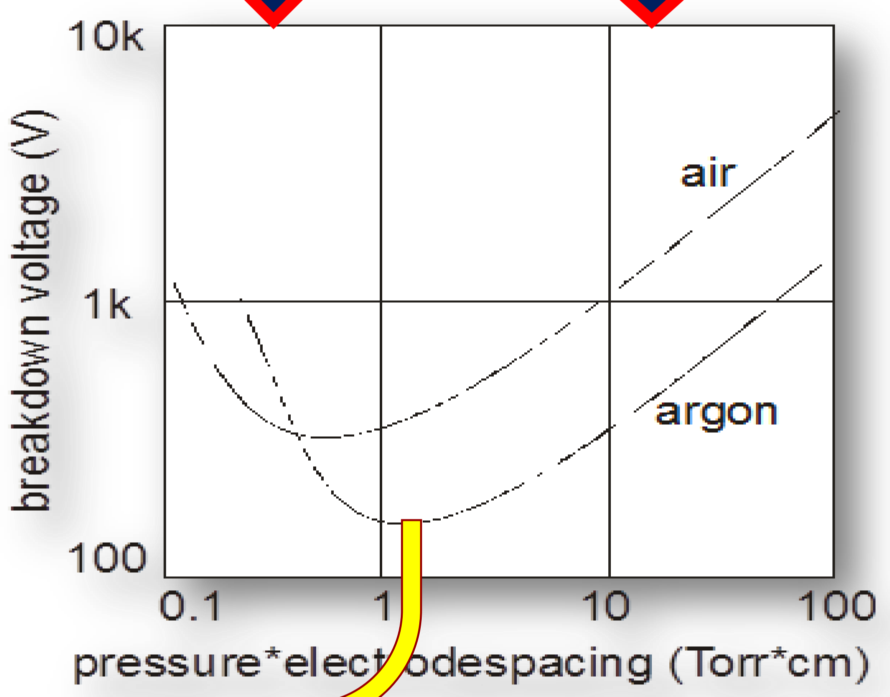
Only true for DC discharge

10.000/300 = 33 gap collisions
Avalance effect = $2^{33} \approx 10^{10}$ = 10billion per starting electron

10.000mm*mTorr = 10mm*Torr

Not enough energy to cause ionisation

Not enough collisions to cause avalance

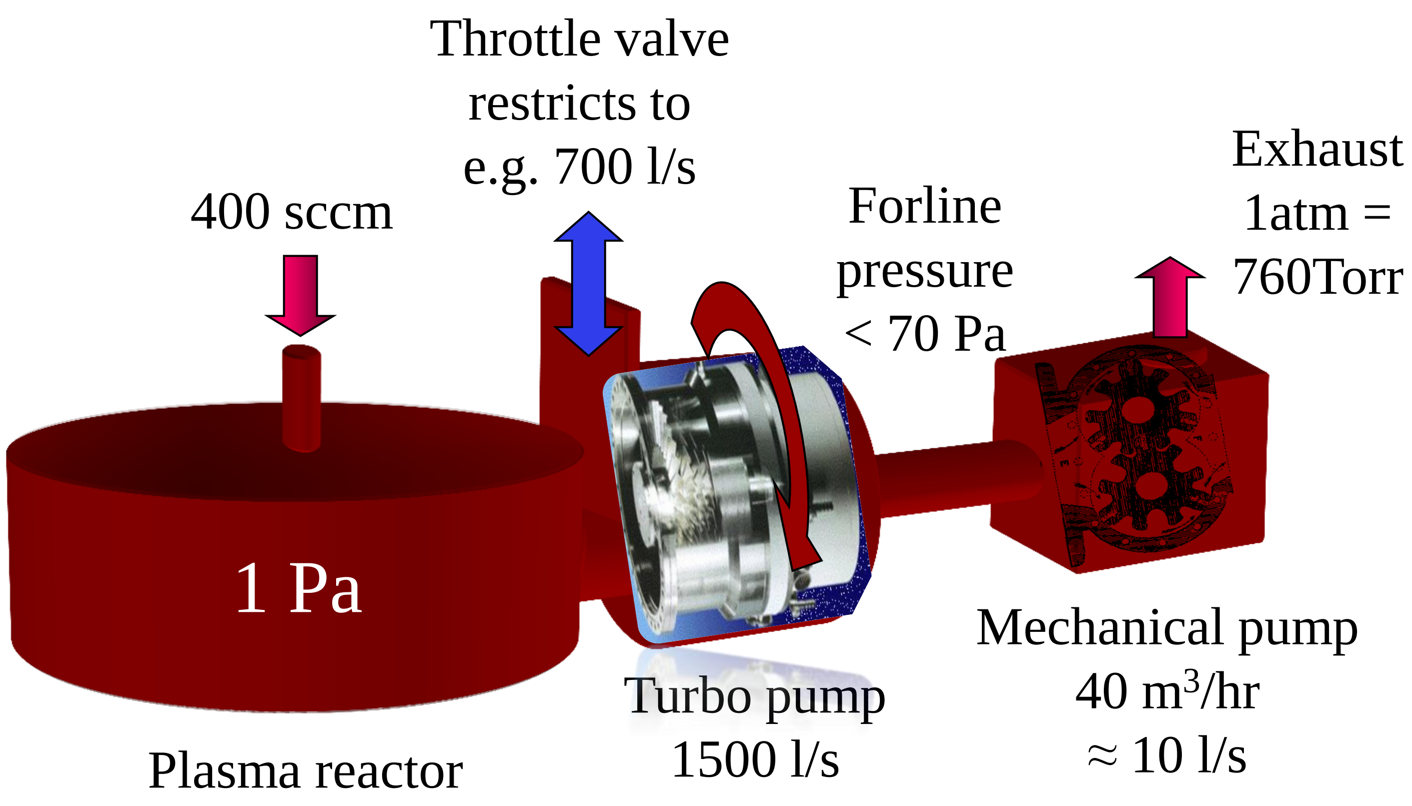


Pump system

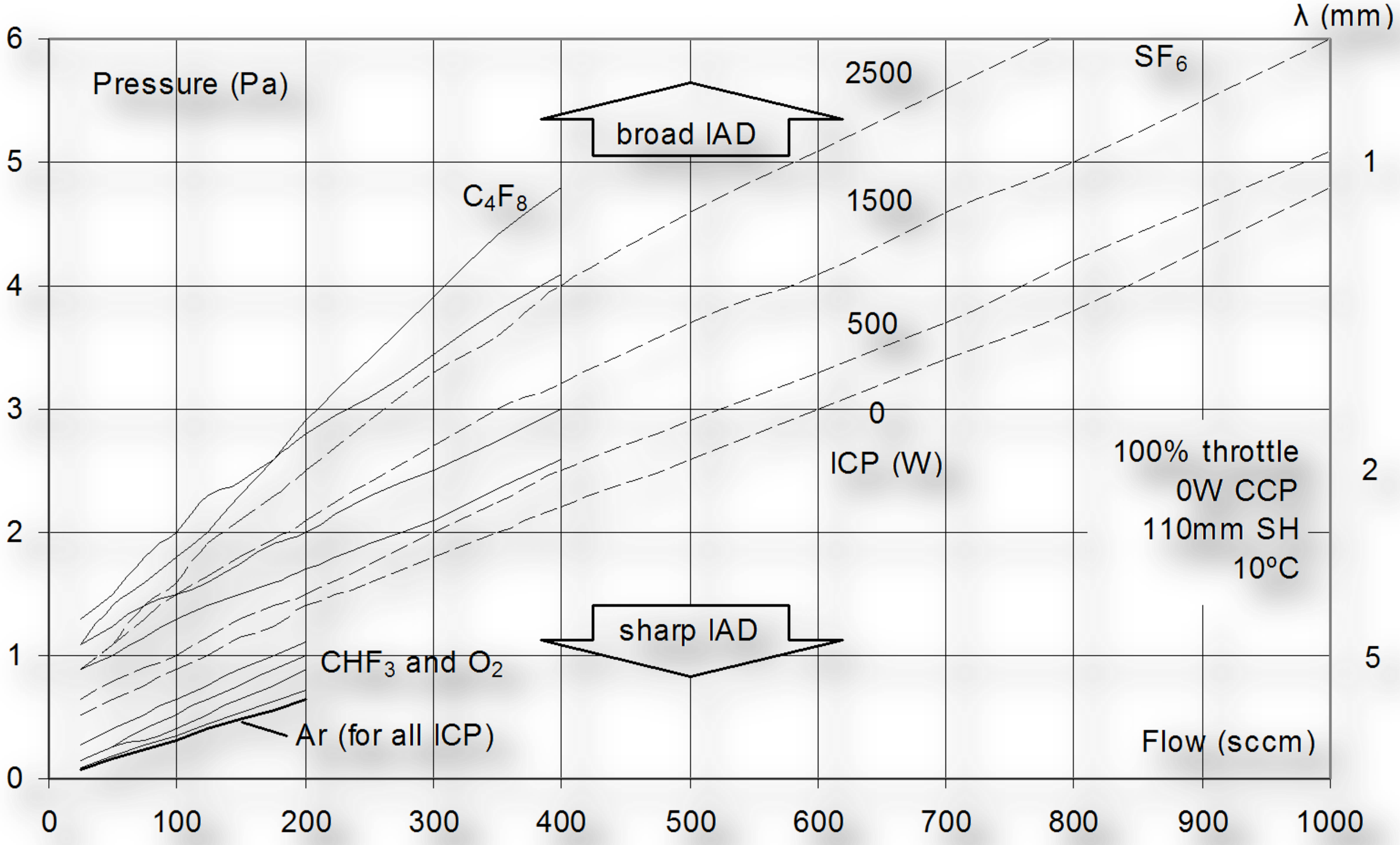
Mass Flow = 1 sccm

= 1 **s**tandard **c**ubic **c**m per **m**inute
= 1 cm^3/min at 1 atm and 0 ^oC (=STP)
= (1 ml/min)* 101 325 Pa
= 101 Pa l/min
= 1.69 Pa l/s

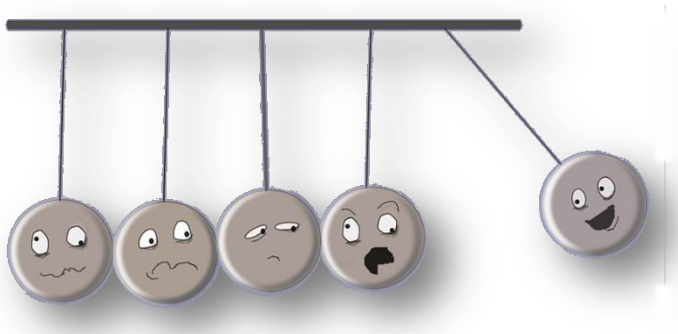
⇒ 400 sccm ~ 700 Pa l/s



Pump curves

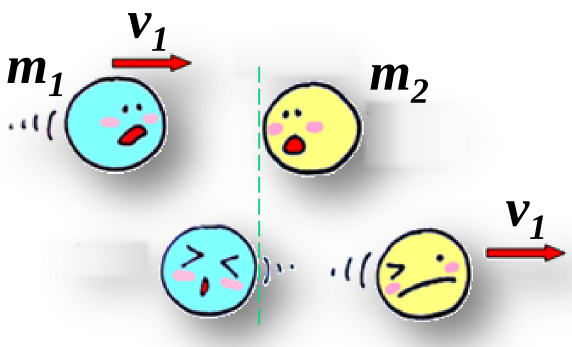

λ (mm)
Pressure (Pa)
broad IAD
2500
SF_6
C_4F_8
1500
500
0
ICP (W)
100% throttle
0W CCP
110mm SH
10°C
sharp IAD
CHF_3 and O_2
Ar (for all ICP)
Flow (sccm)
6
5
4
3
2
1
0
0
100
200
300
400
500
600
700
800
900
1000
1
2
5

Elastic collisions



***By conservation of linear momentum and energy** the fractional energy E transferred from mass m_1 to mass m_2 is:*

$$E_2/E_1 = \cos^2(\alpha)\, 4m_1 m_2/(m_1+m_2)^2 \quad [-]$$



When the collision is frontal and $m_1 = m_2$ this expression has its maximum of 1, i.e., the velocity of mass m_2 is v_1 and mass m_1 has lost all its kinetic energy. However, when an energetic electron strikes an SF_6 molecule, then the transfer function becomes just $4m_e/m_{SF6}$. So, the function has a value of about 10^{-5}, and very little energy can be transferred from the electron to the molecule.

Inelastic collisions

Now, it is allowed for the collision to be inelastic, *so that the molecule struck gains internal energy of ΔU. Then, using the same laws of conservation, we obtain:*

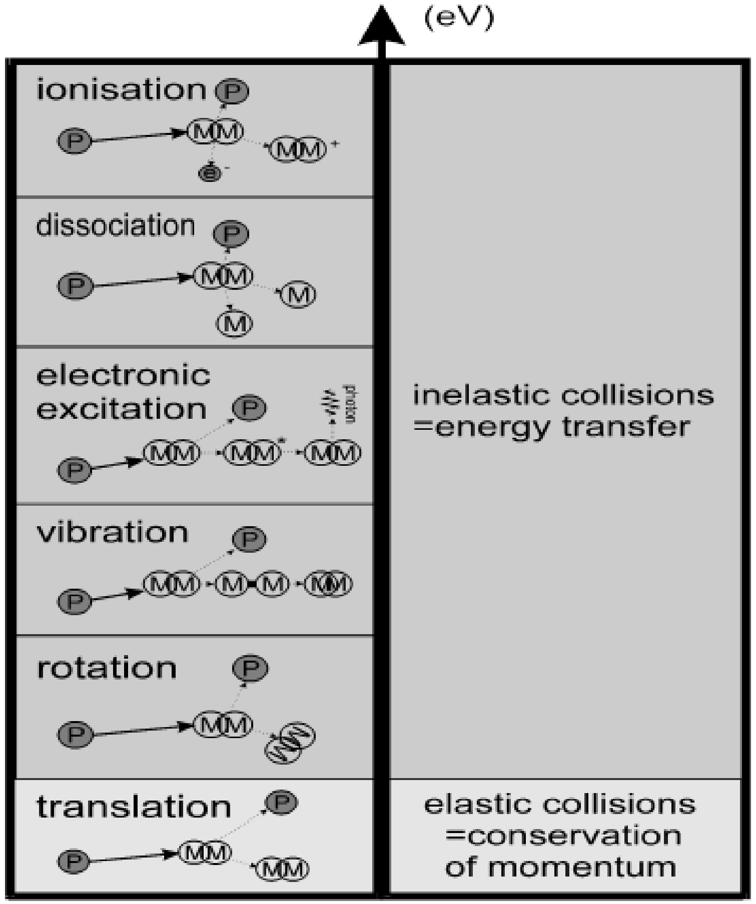
$$\Delta U/E_1 = \cos^2(\alpha)\, m_2/(m_1 + m_2) \quad [-]$$

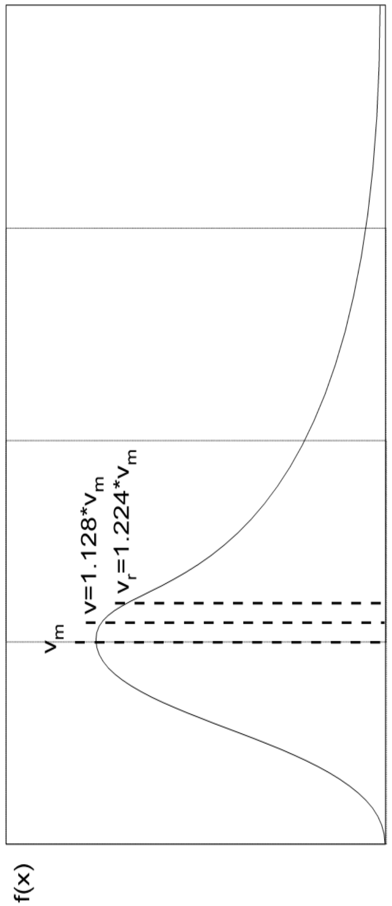
So, whereas the maximum elastic energy transfer from an electron to an SF_6 molecule was close to 0%, by inelastic means this may rise to near 100%.

Consequently, electrons driven by the RF generator will loose their kinetic energy mostly by the inelastic collisions (e.g. ionisation) and will only slightly raise the gas temperature.

This is why they are frequently referred to as cold plasmas.

Excited state levels caused by particle collisions





Direct ionisation	$CF4+e^{-} \Rightarrow CF4^{+}+2e^{-}$	[15.5eV]
Dissociation	$CF4+e^{-} \Rightarrow CF3+F+e^{-}$	[12.5eV]
Excitation	$CF4+e^{-} \Rightarrow CF4^{*}+e^{-}$	[04.0eV]

Plasma-to-floating potential

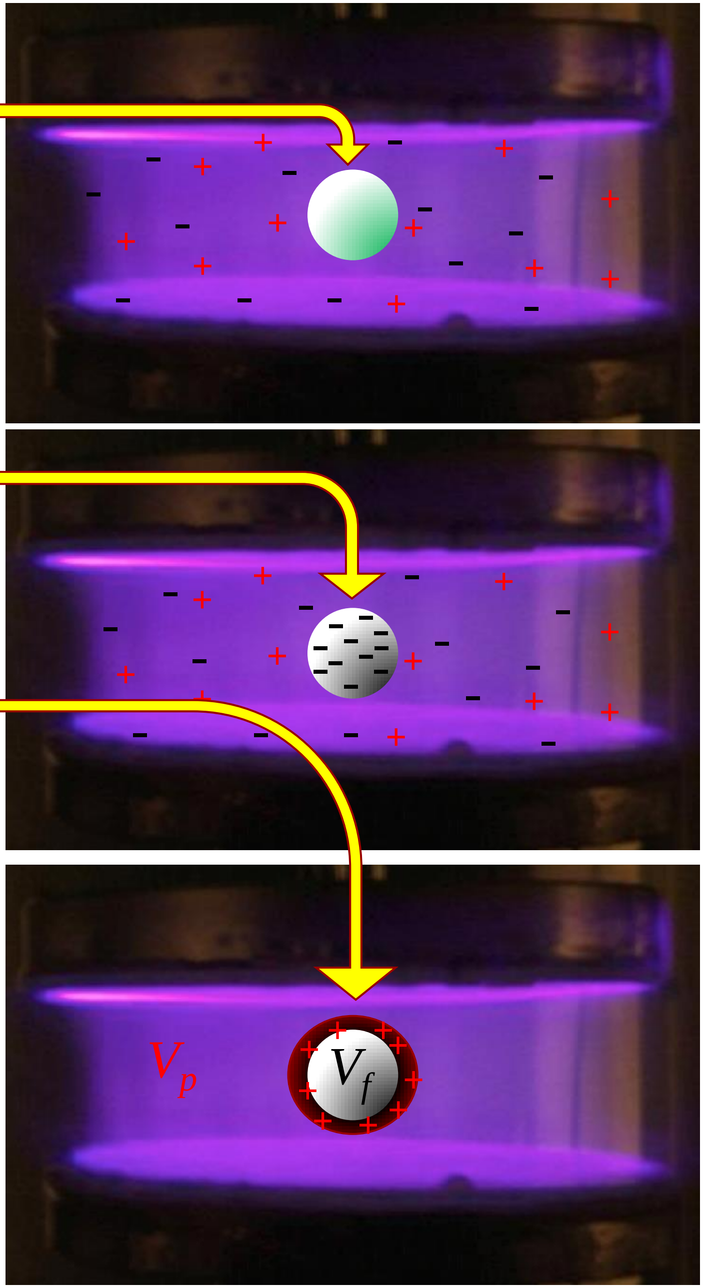
Consider an object that is emerged into a plasma. Initially much more electrons will flow into the object because electrons – driven by the RF source - move much faster than the heavier ions by at least a factor of $\sqrt{(m_i/m_e)}$*. The object will therefore be charged negative relative to the bulk plasma.*

Subsequently, positive ions will be forced to the negative object and surround it until it balances the negatively charged object: the so-called Debye shield.

Now, the plasma body is virtually electric field free (equipotential): the so-called plasma potential V_p*.*

Similarly, we can associate a floating potential V_f *with the isolated object which is always negative with respect to* V_p*.*

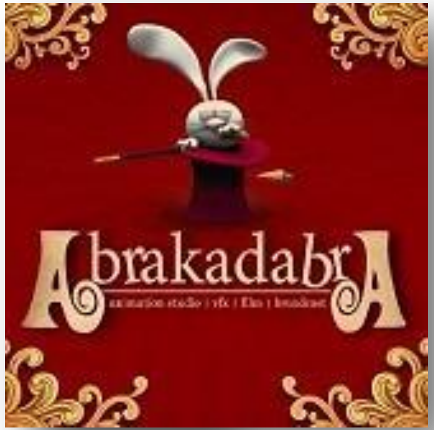
Since electrons are repelled by V_f*-*V_p*, the electron density is low in the sheath and therefore doesn't glow as much: the dark space.*



Plasma-to-floating potential: some algebracadabra

Let us now try to estimate the magnitude of V_f -V_p. To surmount this barrier, an electron needs q(V_f -V_p) of potential energy. Hence, only electrons that enter the sheath from the plasma with kinetic energies in excess of q(V_f -V_p) will reach the object. The M-B distribution function gives us the fraction that can do this:

$$V_\mathrm{f} - V_\mathrm{p} = \frac{kT_\mathrm{e}}{2q}\ln\left(\frac{m_\mathrm{e}T_\mathrm{i}}{m_\mathrm{i}T_\mathrm{e}}\right) \quad [\mathrm{V}]$$



*In case of an SF_5 ion, the ion mass M_i is 127*1836 times the electron mass M_e and we get:*

$$V_f - V_p \sim -5.2 * kT_e/q$$

Thus, the ions that reach the surface will have an energy equal to what they have in the plasma plus what they have gained in passing through the pre-sheath and sheath, (5.2+0.5)kT_e ~ 6kT_e.

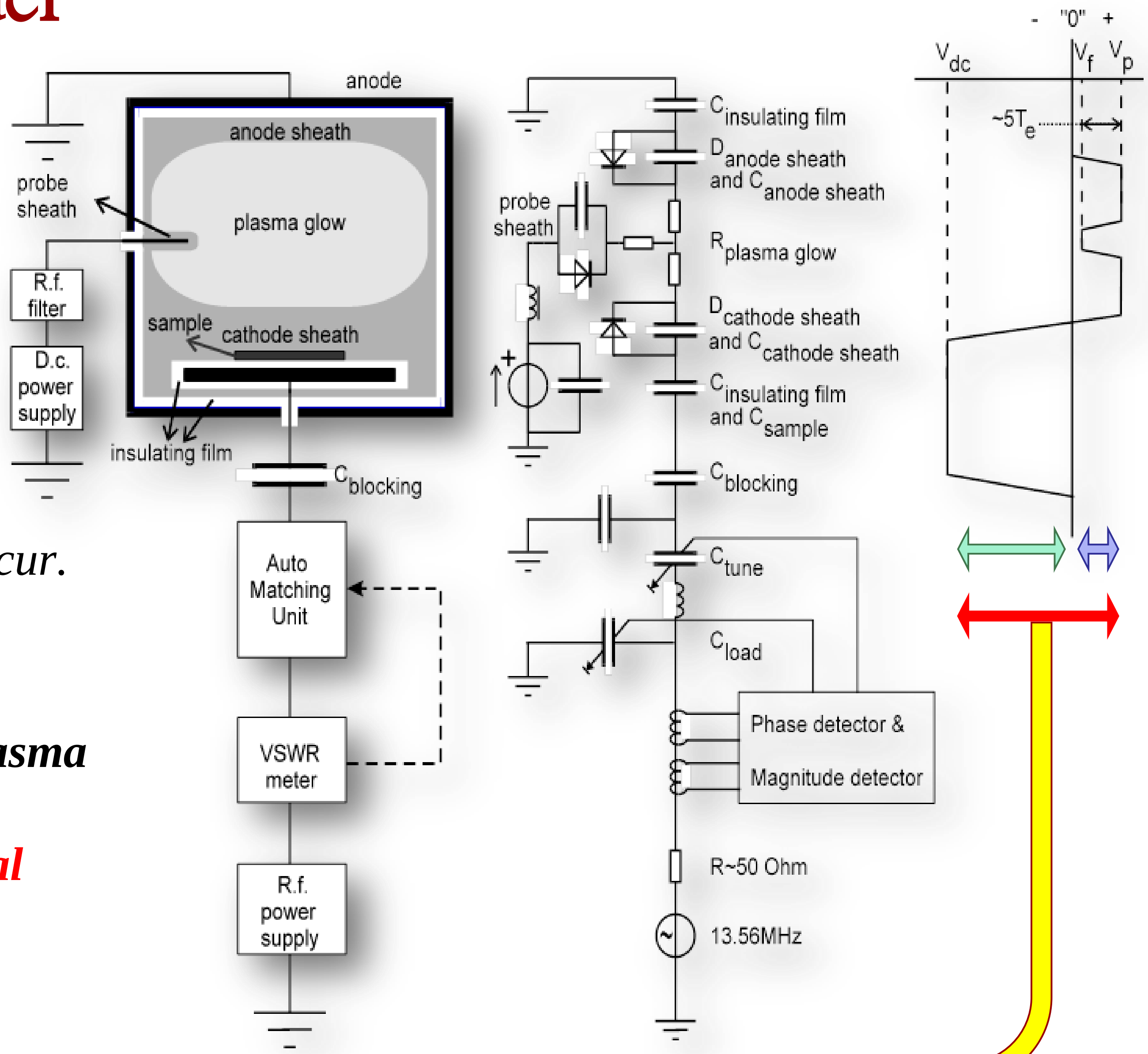
This means that ions will hit surfaces in a plasma environment severely - even when they are only floating - due to their acceleration in the plasma pre-sheath and sheath. In case of a typical electron temperature of kT_e~2eV, the ion energy is already 12eV, which is enough to break most chemical bonds.

Electrical circuit model

The V_{dc} is caused by the difference in capacitance between the anode-plasma and cathode-plasma dark spaces.

If these areas are the same, no V_{dc} will occur.

This does not mean that there is no ionic impact as we just found out that the plasma potential can still be large enough to enhance surface reactions. It is the total (V_{dc} + V_p) that depicts the impact!

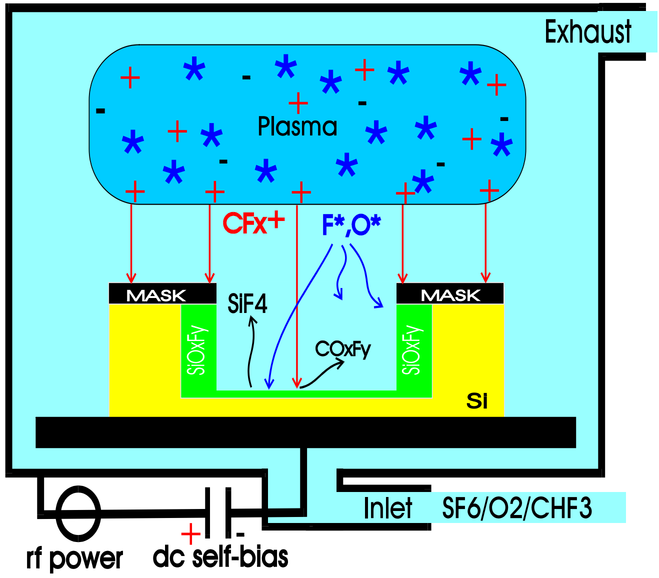


What is plasma etching

What is plasma etching

The basis of plasma-assisted etching is simple; ***use a gas glow discharge*** *to crack relatively stable molecules* ***forming chemically reactive and ionic species*** *and choose the chemistry such that these species* ***react with the solid to be etched to form volatile products****.*

<u>Generation</u>: *An rf power source is used to generate from a suitable feed gas (e.g. SF_6 for Si etching) by electron-impact dissociation/ionisation the gas phase etching environment which consists of neutrals, electrons, photons, radicals (F), and positive (SF_5^+) and negative (F^-) ions.*



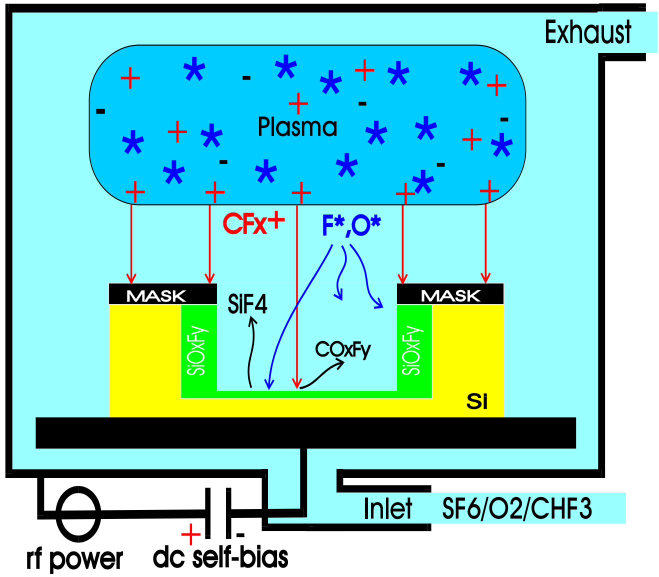
<u>Dc bias formation</u>: *The Si wafer is placed on an rf driven capacitatively coupled electrode. Since the electron mobility is much greater than the ion mobility, after ignition of the plasma the electrode acquires a negative charge i.e. the dc self-bias voltage V_{dc}.*

<u>Diffusion/forced convection</u>: *The transport of reactive intermediates from the bulk of the plasma to the Si surface occurs by diffusion. Positive ions from the glow region are forced to the substrate surface by way of the V_{dc} and will assist the etching. At higher pressure, the ion path is interrupted by many collisions causing non-directional etching.*

What is plasma etching

Adsorption: *Reactive radicals adsorb on the Si surface. This step can be strongly enhanced by concurrent ion bombardment which serves to produce "active sites" since it aids in the removal of e.g. an SiO_xF_y layer which otherwise passivates the Si surface.*

Reaction: *A reaction between the adsorbed species and the Si must take place. In the case of fluorine-based etching of Si, chemical reactions between the F-atoms and the surface produces -spontaneously- either volatile species, SiF_4, or their precursors, SiF_x ($x<4$).*



Desorption: *The desorption of the reaction product into the gas phase requires that the reaction product is volatile, thus it should have a high vapour pressure at the substrate temperature. Additionally, there should be no deposited blocking film at the surface. The removal of these films can be greatly accelerated by ion bombardment via sputtering. This mechanism is known as ion-inhibitor DRIE.*

Exhaust: *The desorbed species diffuse from the etching surface into the bulk of the plasma and should be pumped out, otherwise plasma induced dissociation of product molecules will occur and redeposition can take place.*

3 steps to find directional plasma etching recipes

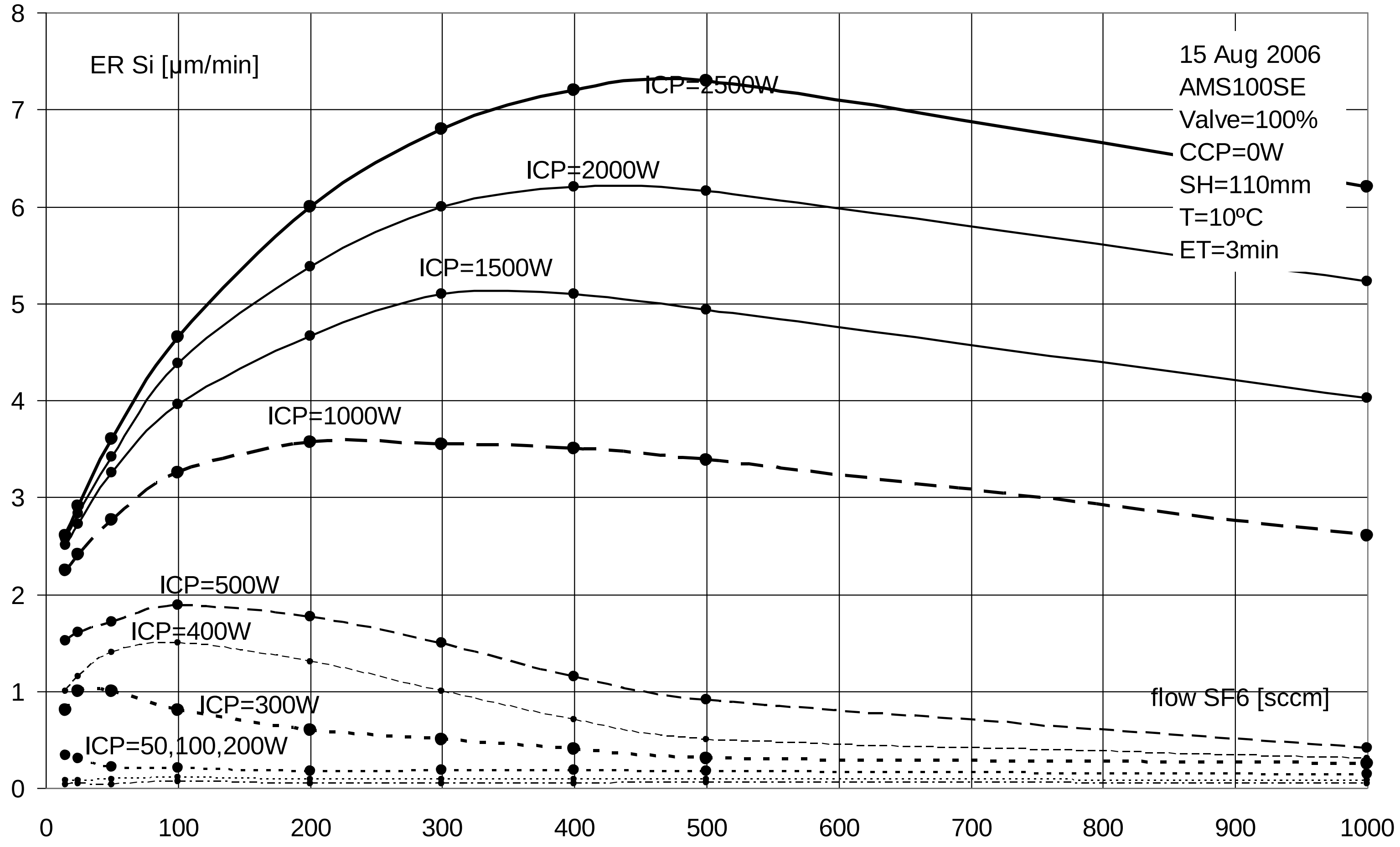
1. *The **spontaneous etch rate** of bare silicon wafers is determined for the whole spectrum of SF_6 flow and ICP power ("Spontaneous" means here the lack of any inhibiting layer which would slow down the etch rate).*

2. *Oxygen -or another inhibitor- is added to **inhibit etching** until practically no etching is observed (say less than 5% of the spontaneous etch rate).*

3. *The CCP power is increased to achieve ion-controlled **directional etching** until the requested etch rate is achieved.*

Finally, the wafer with the application specific resist pattern is etched with the arrived recipe and fine tuning starts.

1. Find and choose spontaneous etch rate



Maximum etch rate for 500W/100sccm = 5W/sccm

1. Find and choose spontaneous etch rate

In plasma assume: $SF_6 \Rightarrow SF_5 + F$

At wafer surface: $Si + 4F \Rightarrow SiF_4$

Total: $4SF_6 + Si \Rightarrow 4SF_5 + SiF_4$

So, 4 SF_6 molecules will remove 1 Si atom

- STP: 1 mol SF_6 gas = 22 414 cm^3
- 100 sccm SF_6 = 100 cm^3 SF_6/min STP
- = (100/22414) mol SF_6/min = 4.46 mmol SF_6/min

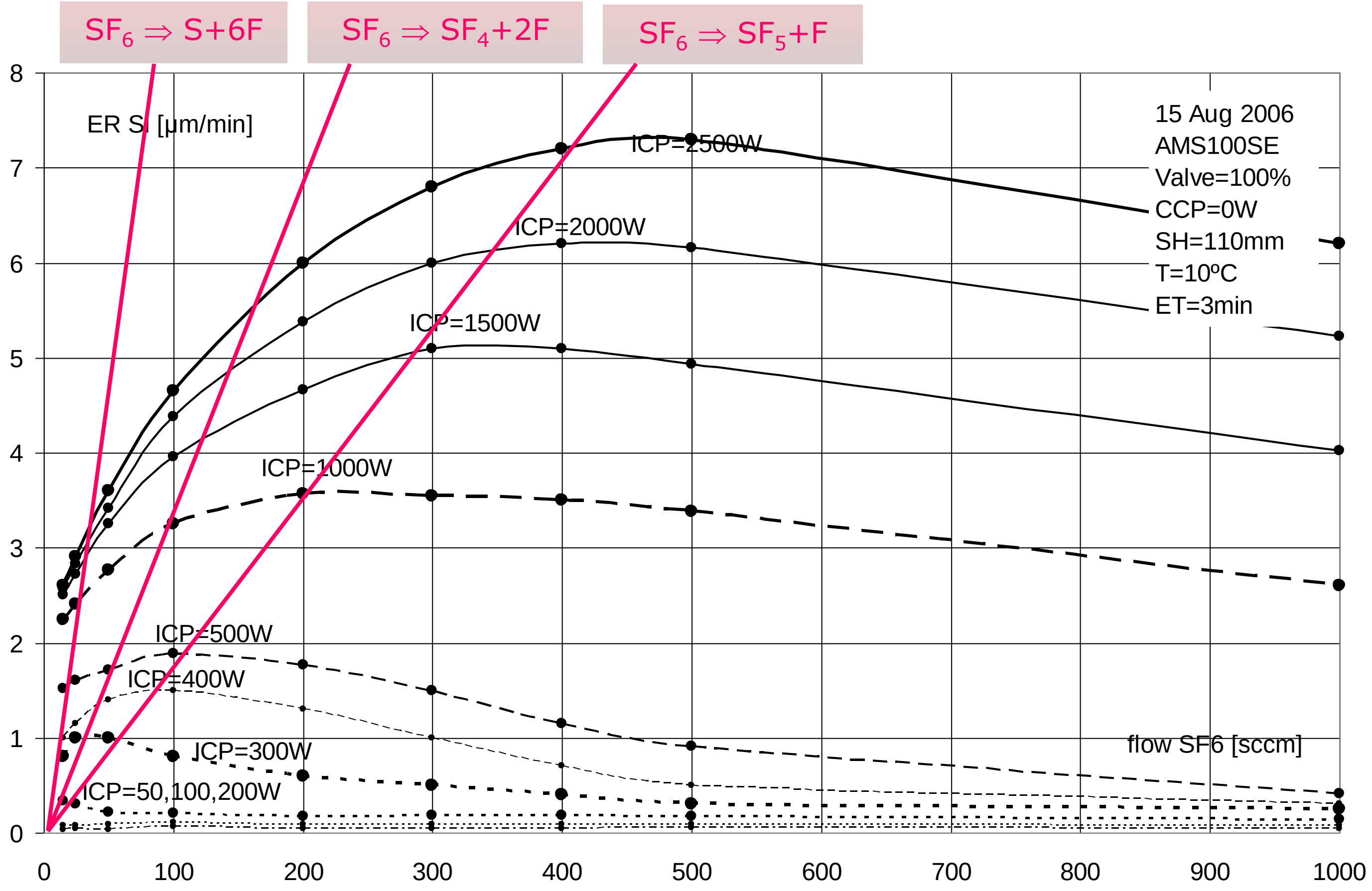
- 4 SF_6 molecules will remove 1 Si atom

- 100 sccm SF_6 etches ¼ *4.46 mmol Si/min
- = ¼ *4.46*28.1 mg Si/min = 31.36 mg Si/min
- 1 mg Si = 60nm Si (100mm wafer minus clampring)

1 mol Si = 28.1 gram

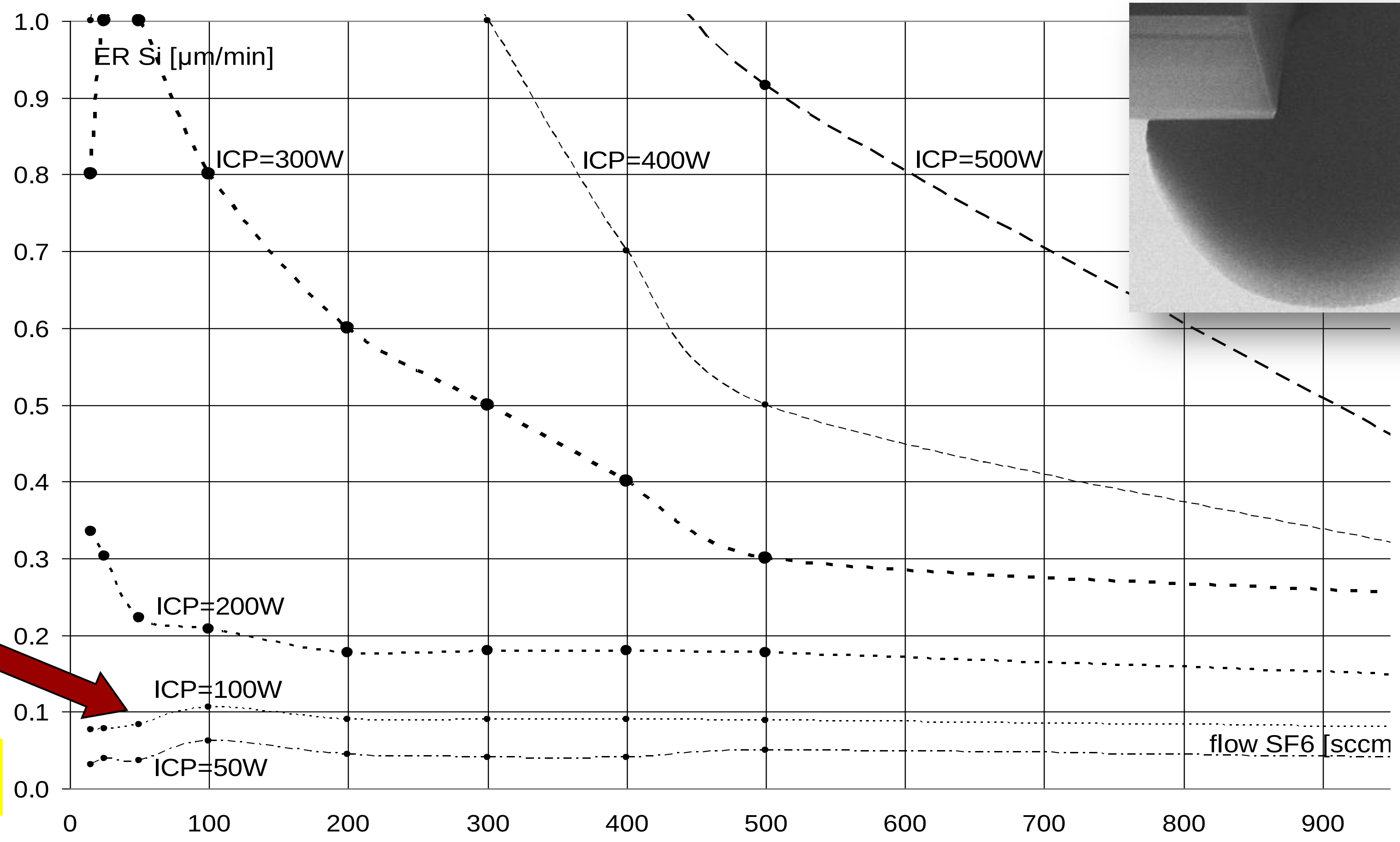
100 sccm SF_6 etches a full silicon wafer at 60*31.36 = 1882 ≈ 1900 nm/min

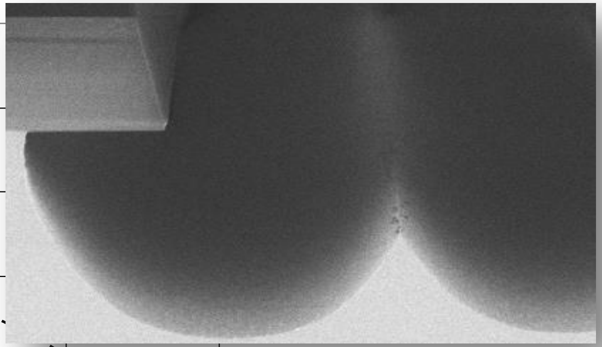
1. Find and choose spontaneous etch rate



So indeed 100 sccm SF_6 etches silicon at 1900 nm/min

1. Find and choose spontaneous etch rate



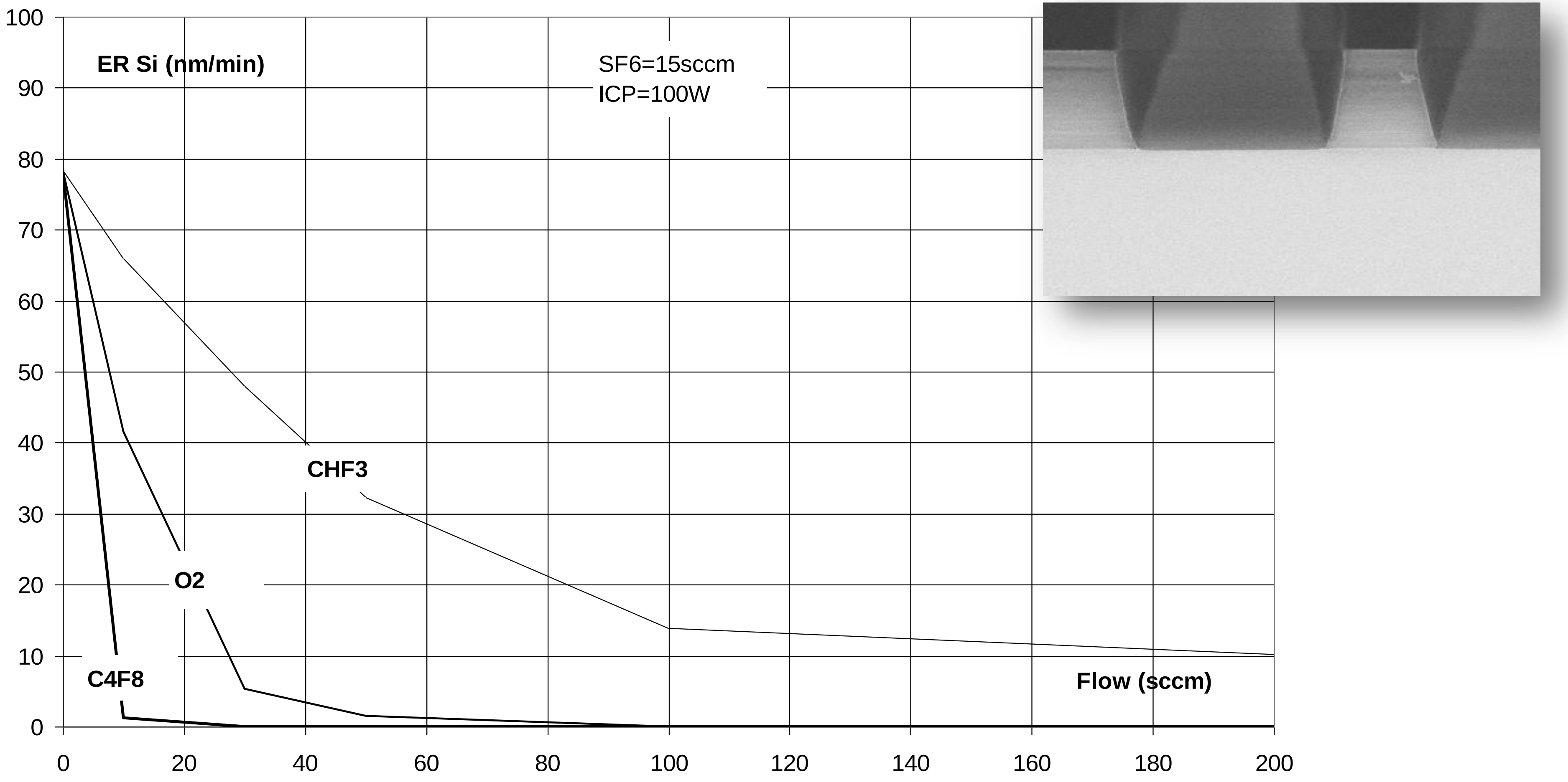


Nanoetch

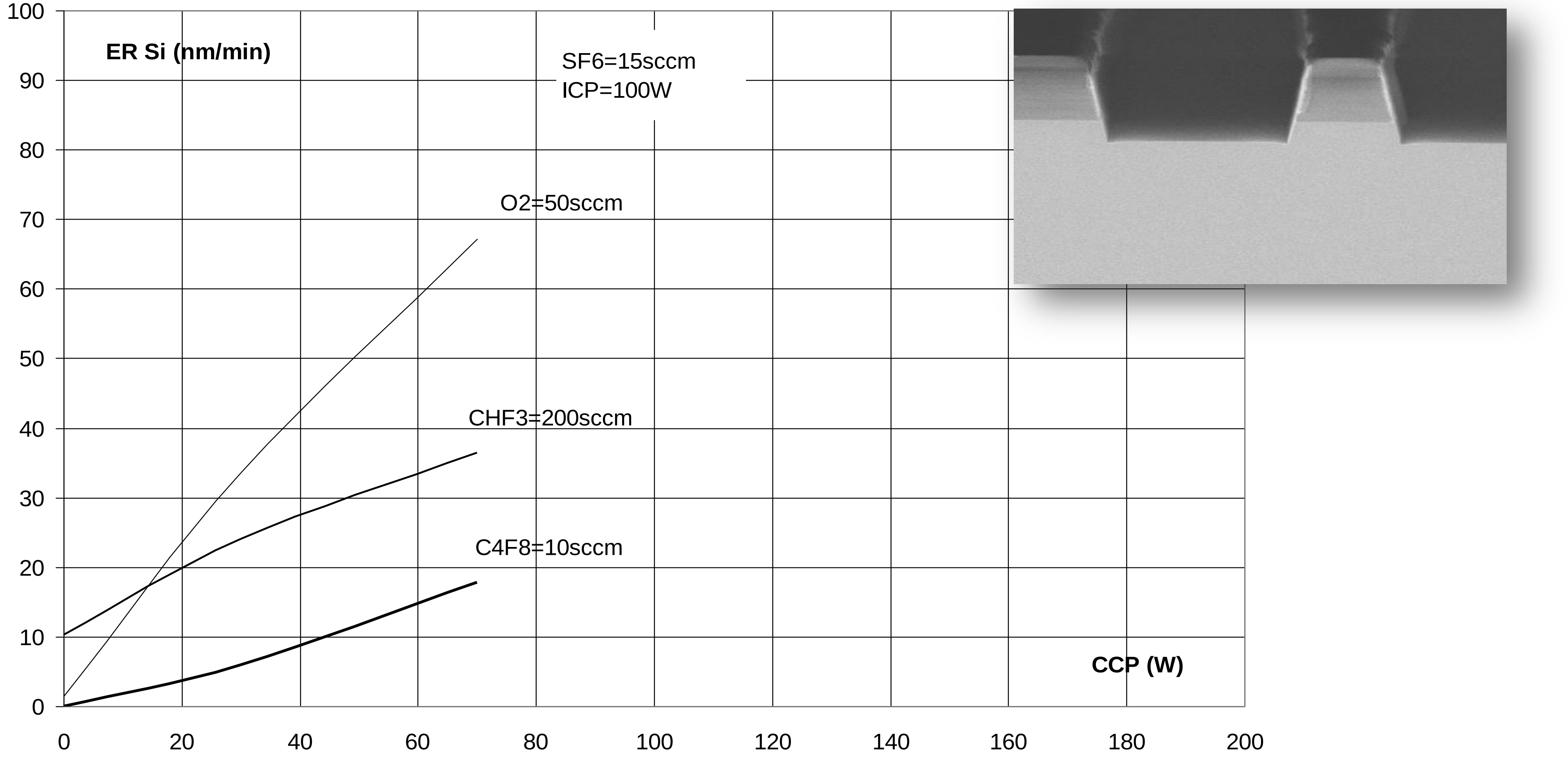
<100nm/min

5W/sccm

2. Inhibit the etch using O_2 or CF_x species

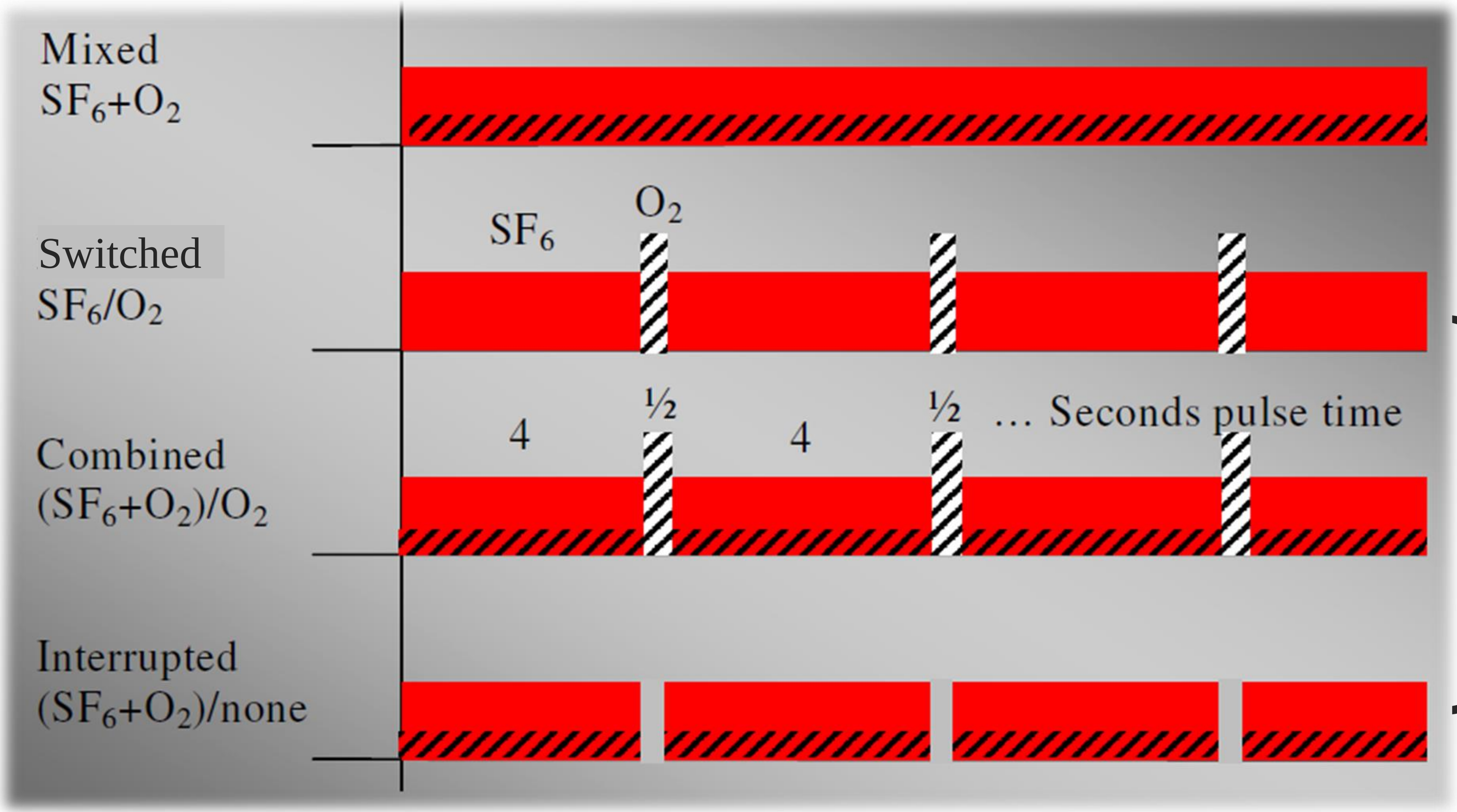


3. Increase bias for directional etch



1-, 2- and 3-steps procedures

Definition of (D)RIE modes



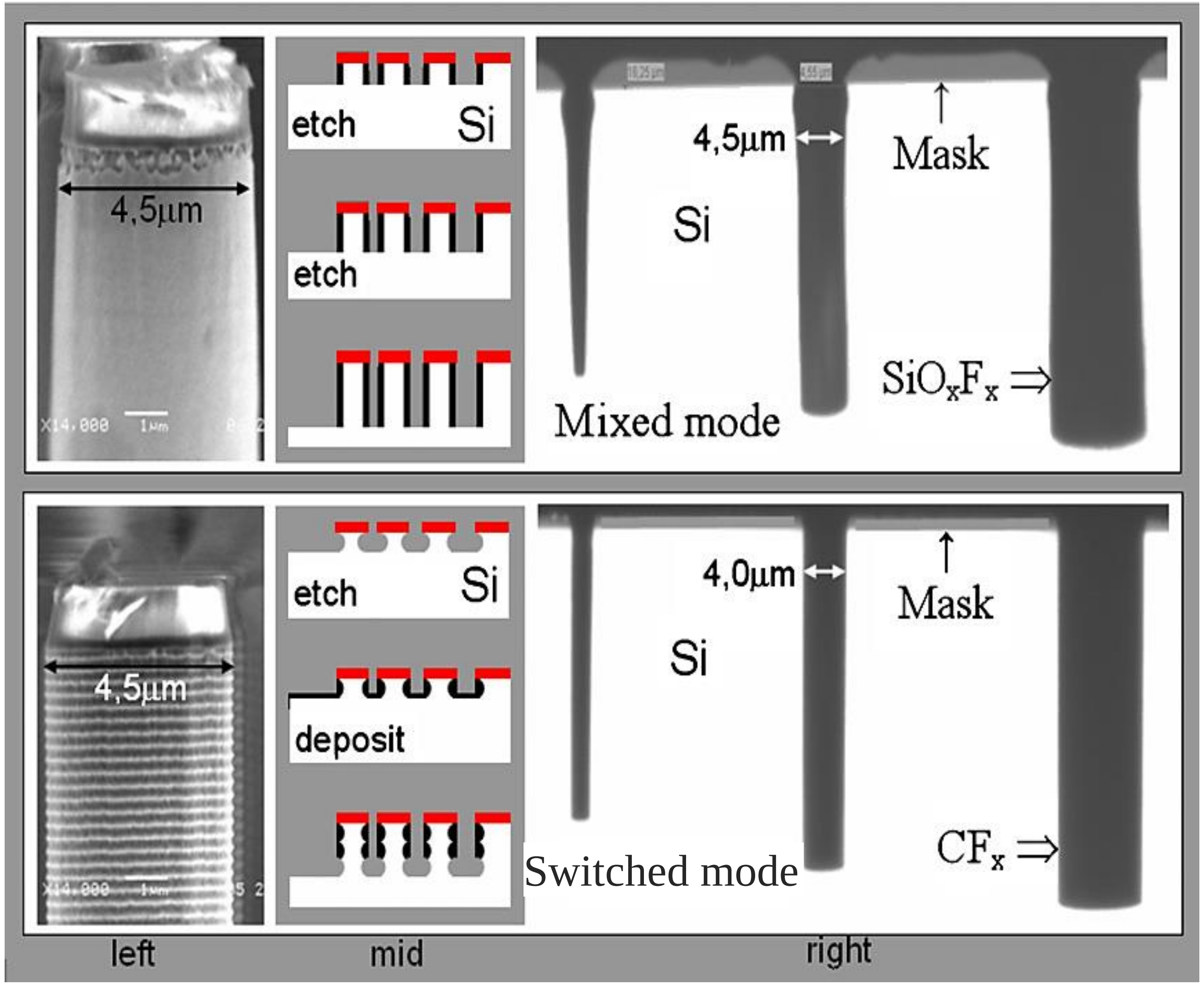
1 step

2 steps

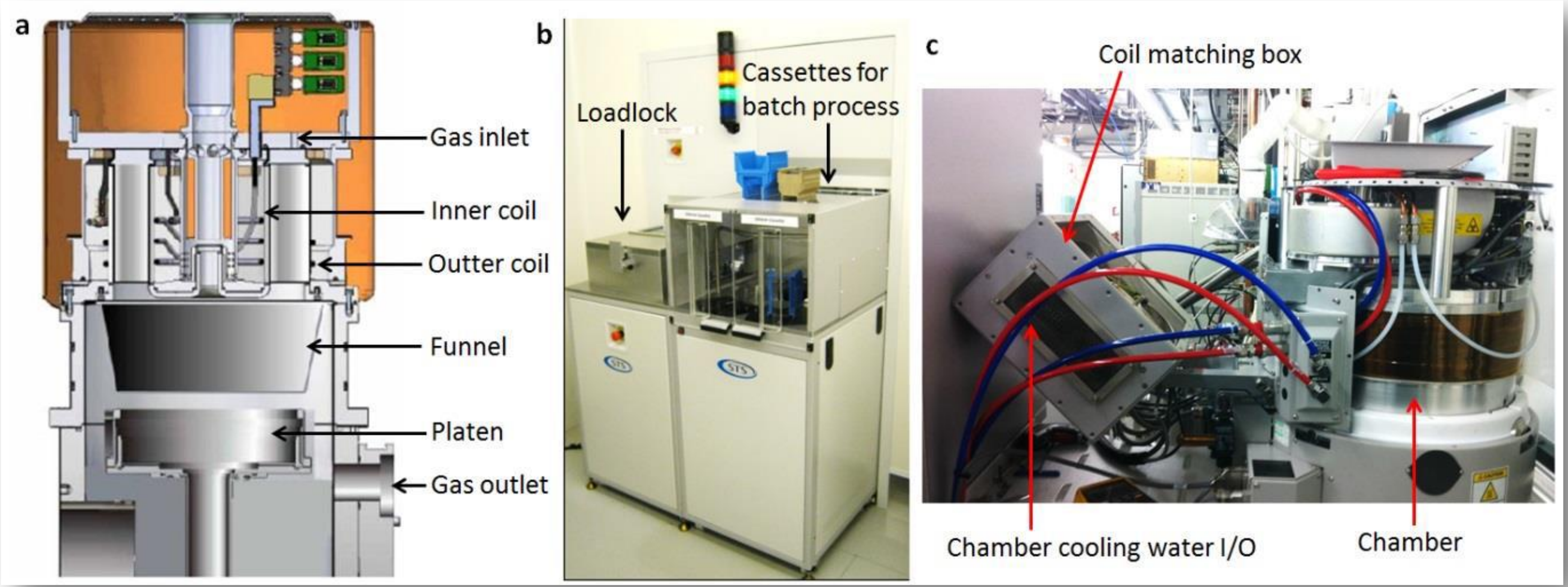
DRIE techniques for Si etch using SF_6–based plasma

	O-inhibitor	FC-inhibitor
Mixed	Cryogenic	Nano1.42
Switched	CORE	Bosch DREM

Either oxygen or fluorocarbon-based and either mixed or switched mode



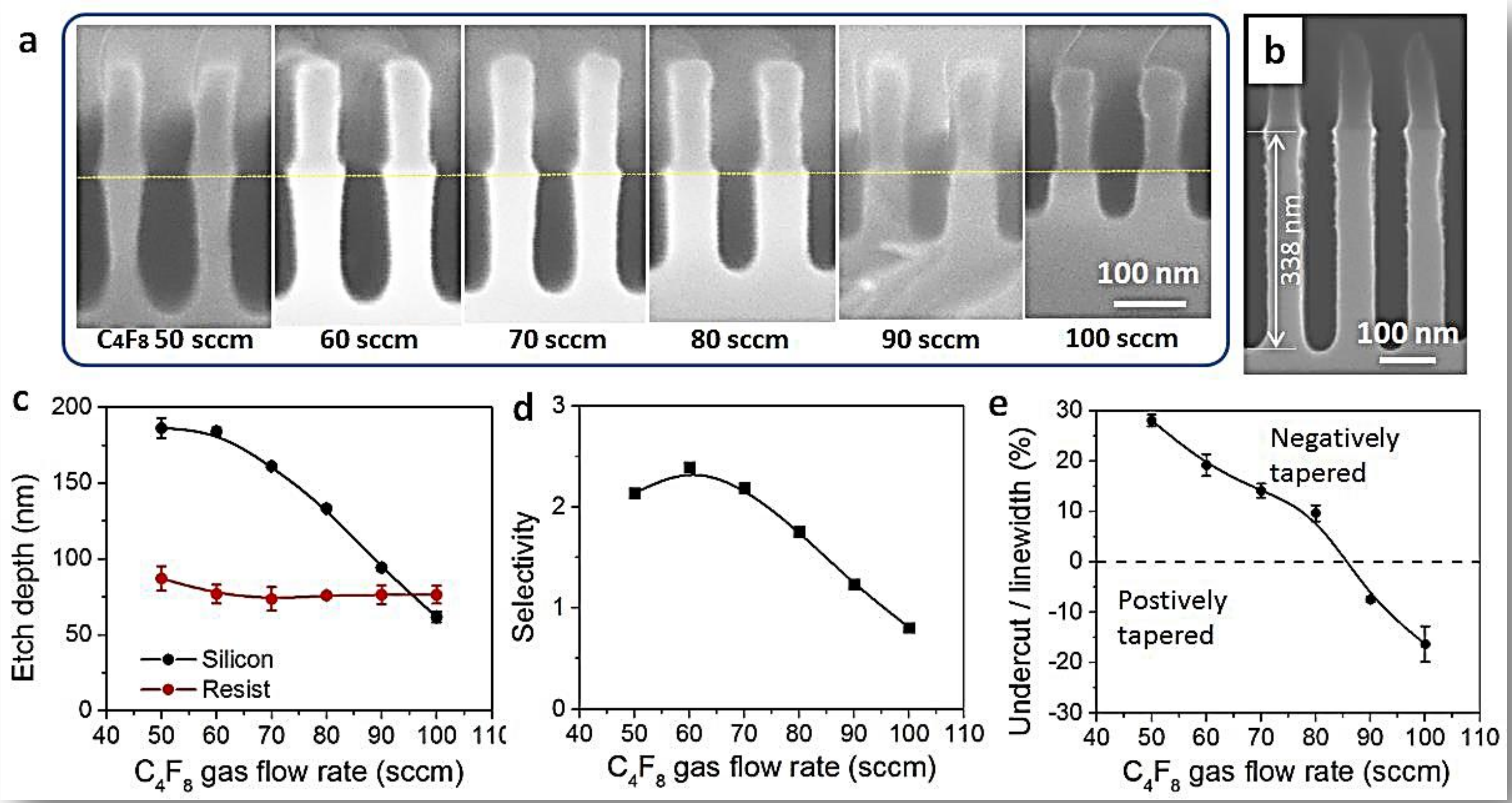
DRIE Tool: SPTS Pegasus



Mixed mode

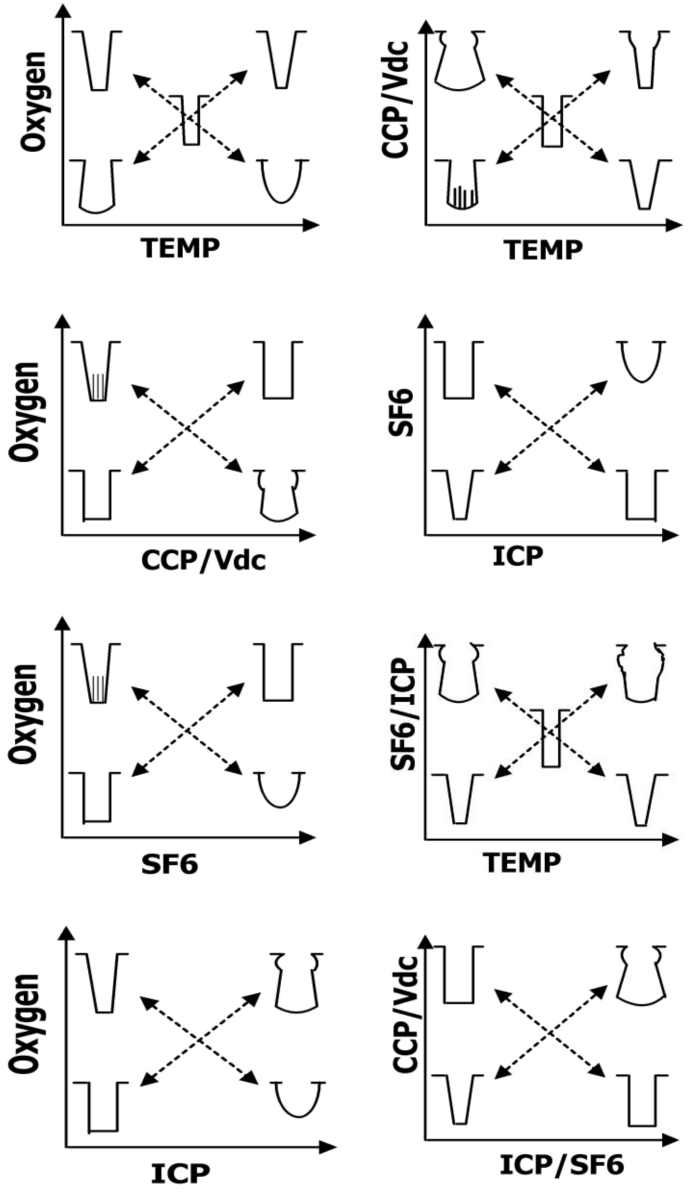
1 step

Mixed FC

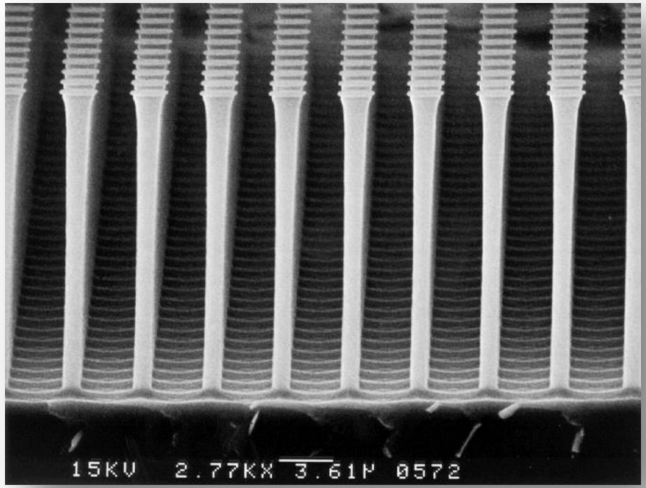

a
C4F8 50 sccm
60 sccm
70 sccm
80 sccm
90 sccm
100 sccm
100 nm
b
338 nm
100 nm
c
Etch depth (nm)
Silicon
Resist
C4F8 gas flow rate (sccm)
d
Selectivity
C4F8 gas flow rate (sccm)
e
Undercut / linewidth (%)
Negatively tapered
Postively tapered
C4F8 gas flow rate (sccm)

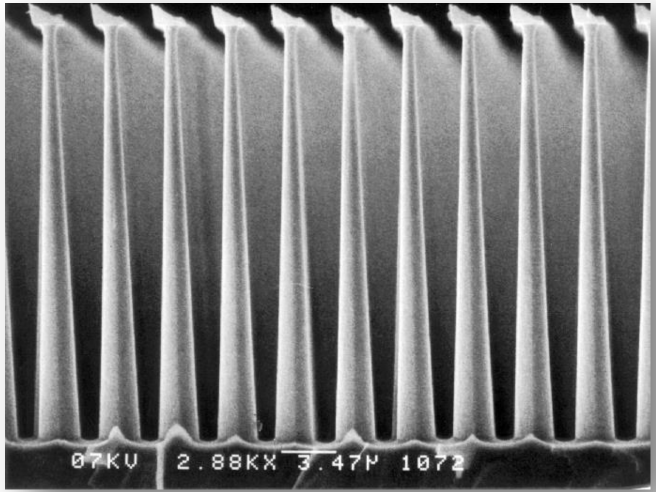
Mixed O_2:
Diagrams for Profile Control

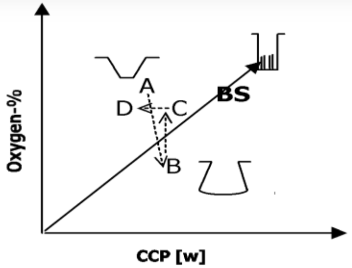
ofile/ Parameter range	isotropic	extr.neg	neg. bottling	neg. taper	neg. + BS	directional	pos. bottling	pos. taper	pos. +BS
O2[sccm] 0-12	0	2-4	5	6		8-10		11	12
CCP[Watts] 0-32	-	-	24-32	8-24	4	2		1	0
SF6[sccm] 50-150	-	-	-	150		100		125	50-75
Electr.[°C] -80-150	-	-	-	150-140		130-120	90-80	100-110	
ICP[Watts] 750– 2000	-	-	2000-1750	1750-1050		1050-750			
He[Torr] 1.5–9.8	-	-	-	10		6.0	1.5		
P[mTorr] 7,8,9	-	-	-	-		7-8	9		
Clamp.[Bar] 0.5 – 3.0	-	-	-	-	3	1.5-0.5			
Time[min] 5- 25	-	-	-	-	-	5-25	-	-	-

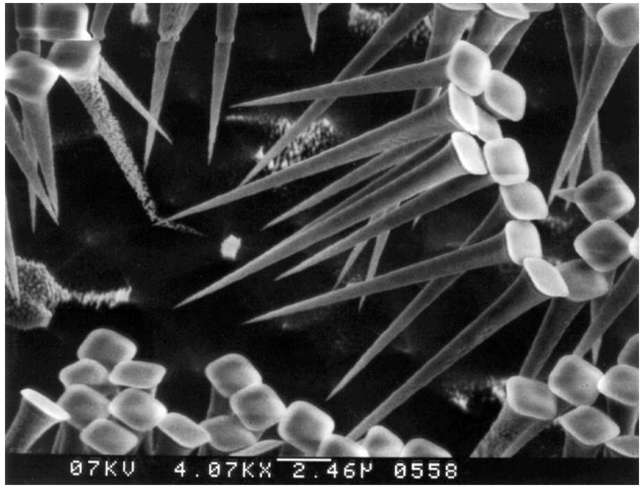


Mixed O_2: Needle etching



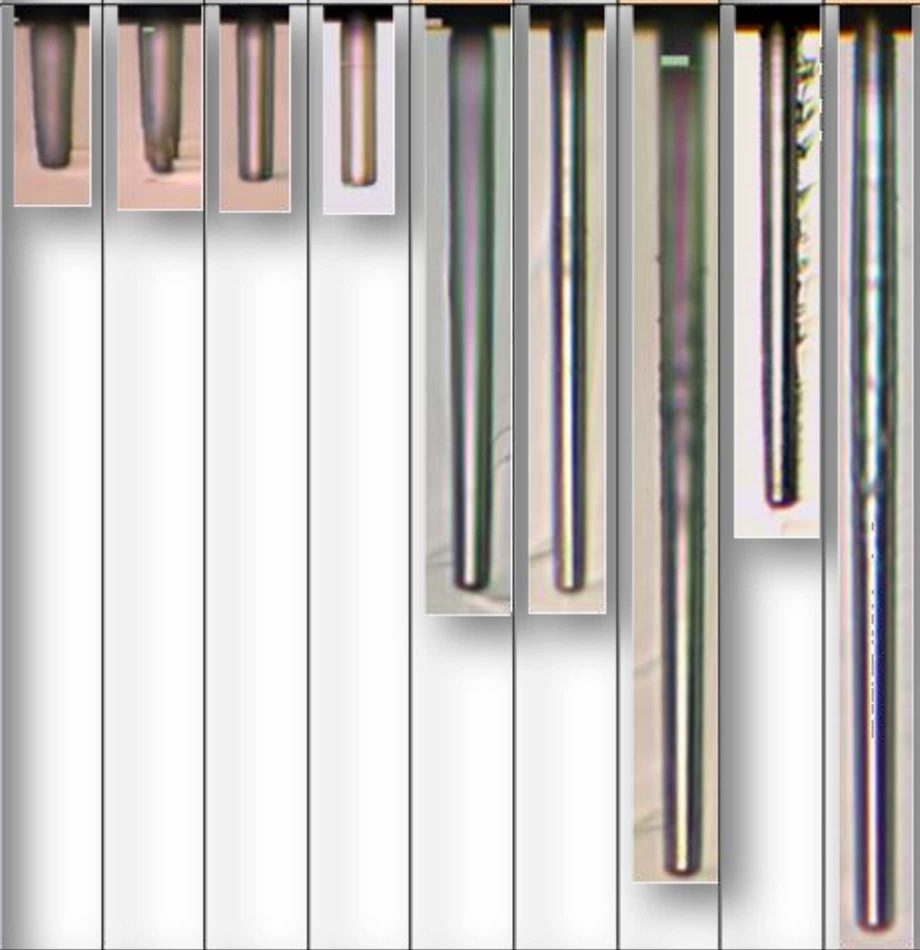






Parameters	Recipe A	Recipe B	Recipe C	Recipe D
Pressure (mTorr)	10	10	10	10
SF_6 (sccm)	90	90	90	90
O_2 (sccm)	10	3	7	7
ICP (Watts)	600	600	600	600
CCP (Watts)/Vdc (Volts)	2.5/-10	3/-14	3/-14	2.5/-10
Electrode temp. (°C)	-130	-130	-130	-130
Height (µm) /time (min)	2/10	20/10	29/15	25/15
Profile sidewall	positive	negative	positive	positive

Mixed O_2: Hole etching

Exp. #	1	2	3	4	5	6	7	8	9
T [ºC]	0	0	0	-40	-40	-80	-80	-120	-120
CCP LF [W]	20	20	20	20	20	20	20	20	20
CCP On-Off [ms]	10-90	10-90	20-80	20-80	20-80	20-80	20-80	20-80	20-80
CHF_3 time [sec]	½	1	1	1	1	1	1	1	½
Etch Time [min]	3	3	3	3	15	15	20	20	15
Etch profile of a micro hole									
Etch Depth [um]	21	22	24	26	74	76	90	58	95

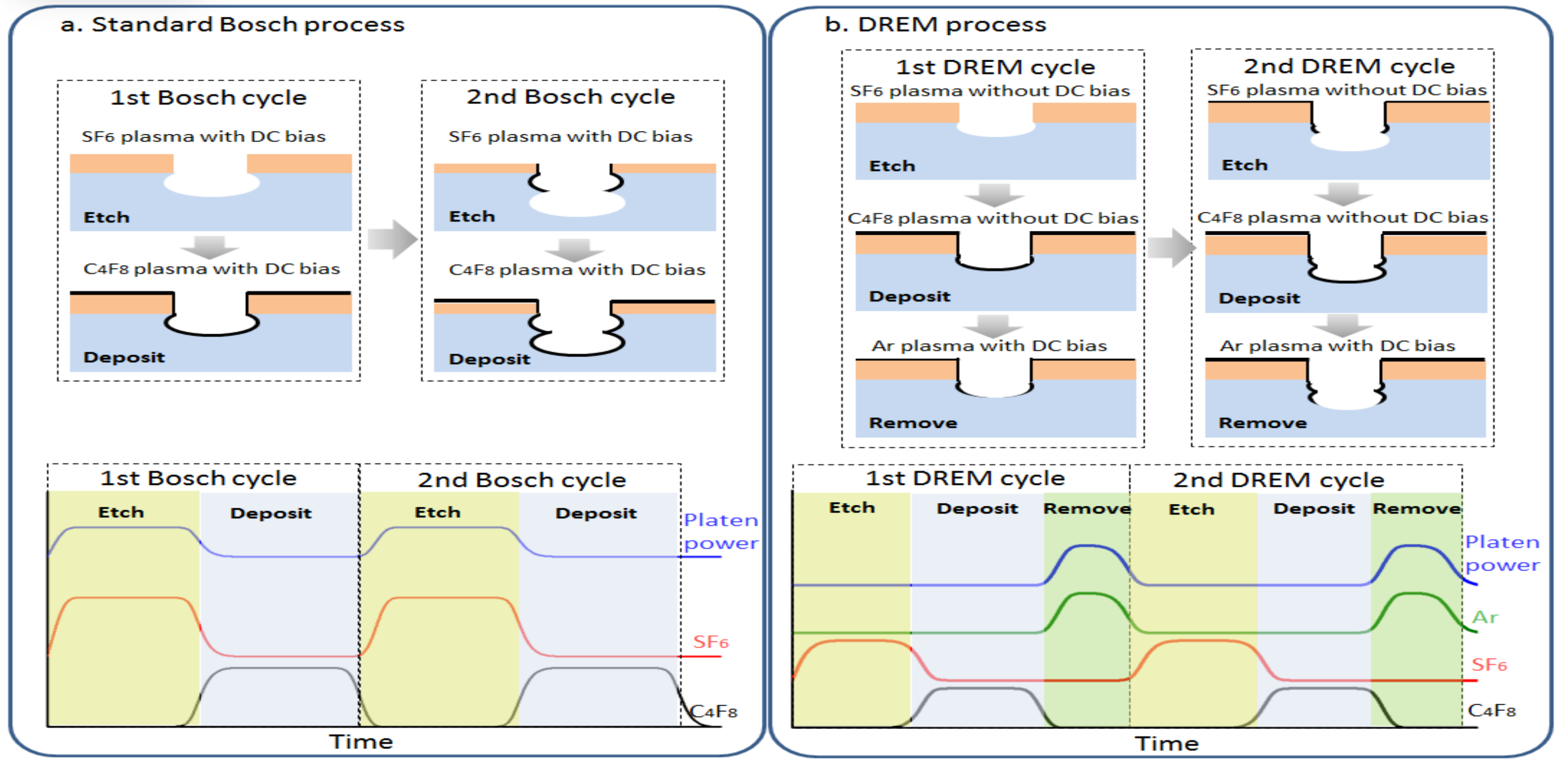
Switched FC mode
2- and 3-steps

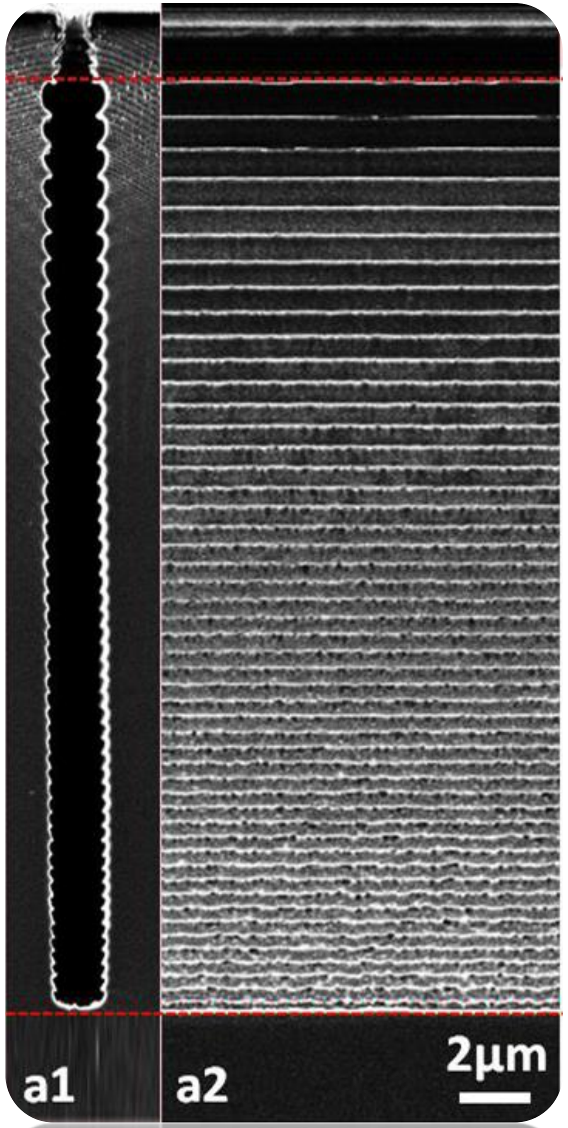
Switched FC: 2-steps versus 3-steps

DREM process (Deposit, Remove, Etch, Multistep)

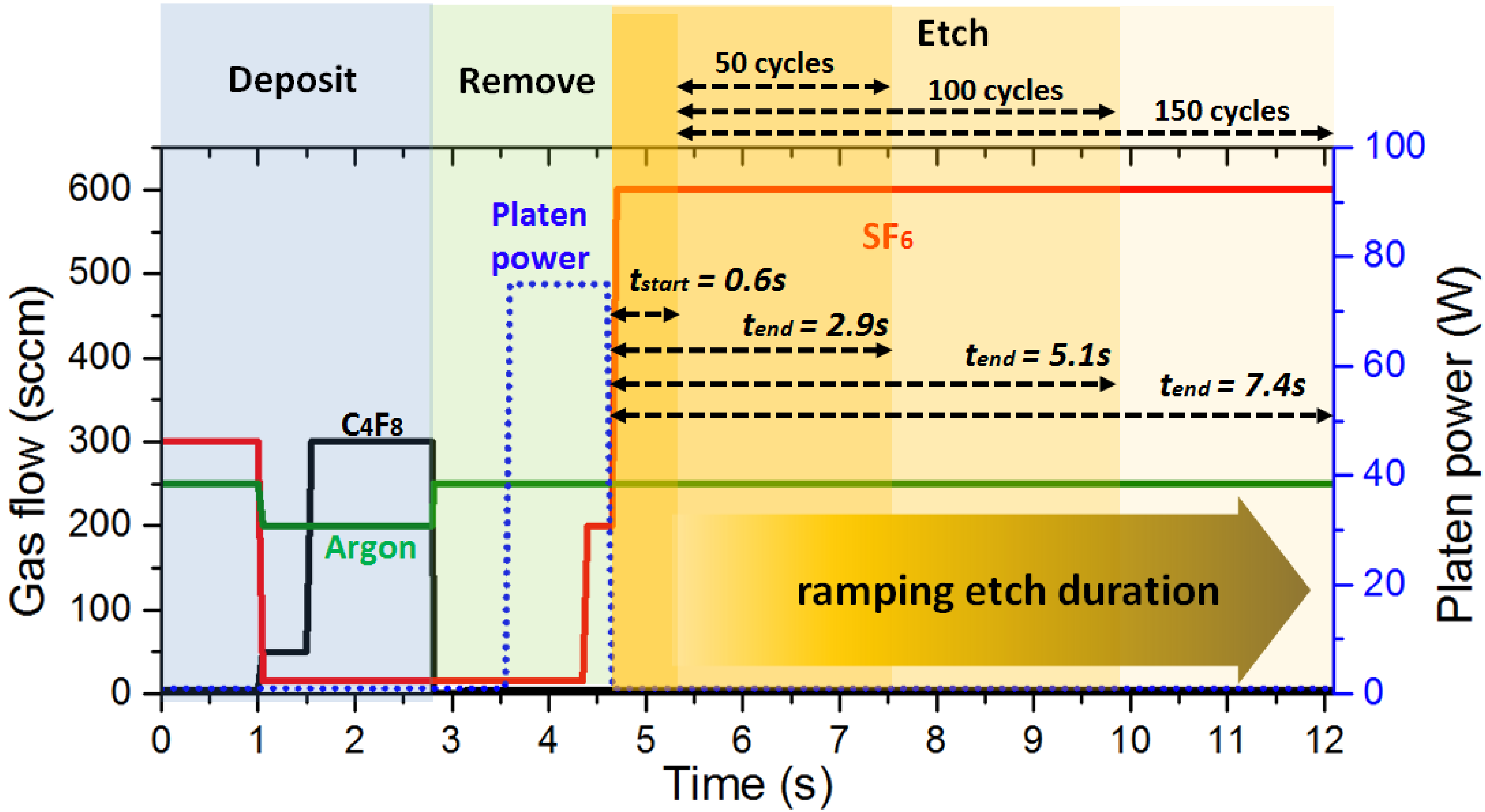
To improve process controllability and mask selectivity.

The latter due to shorter time applied platen power.

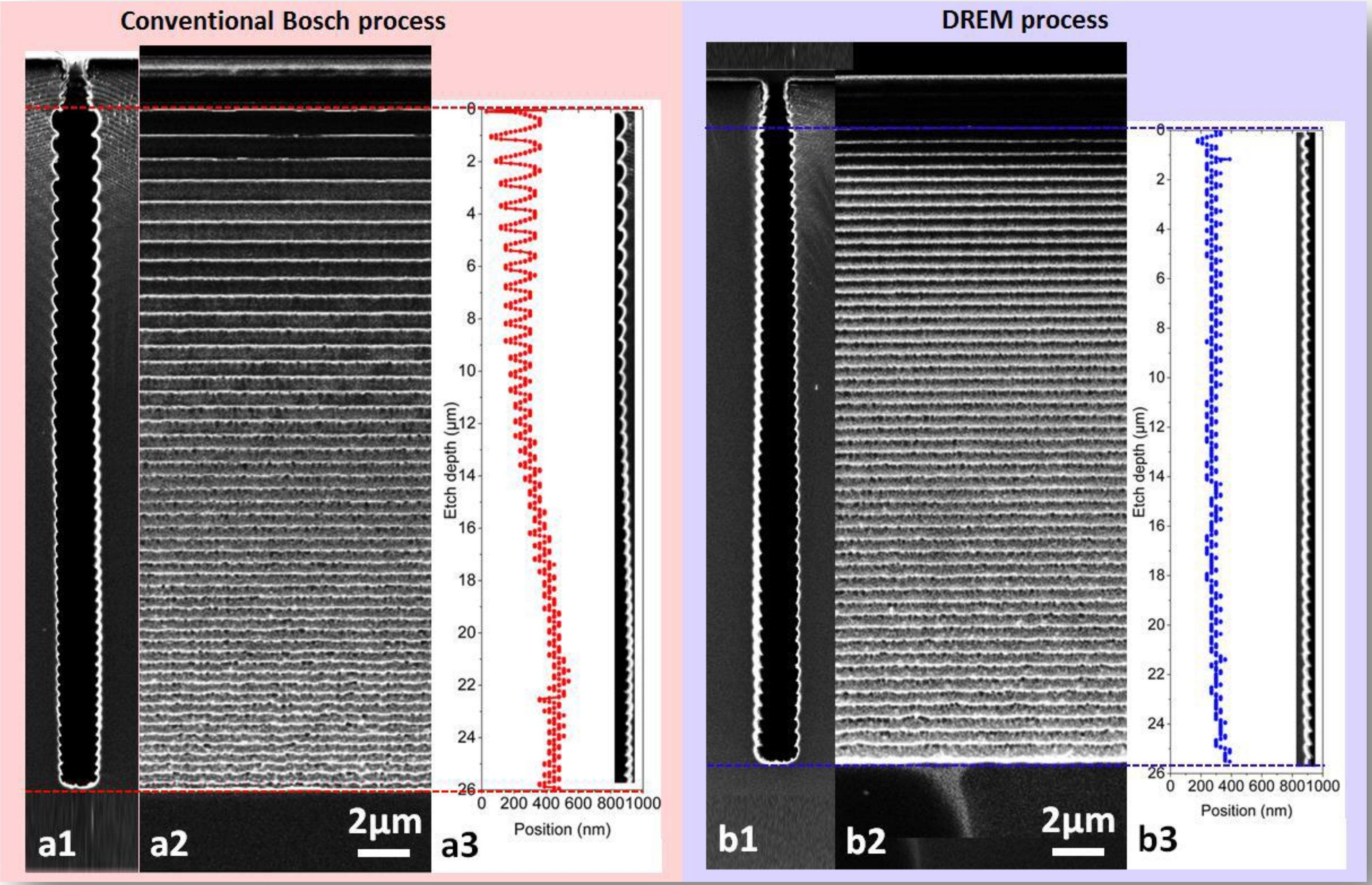


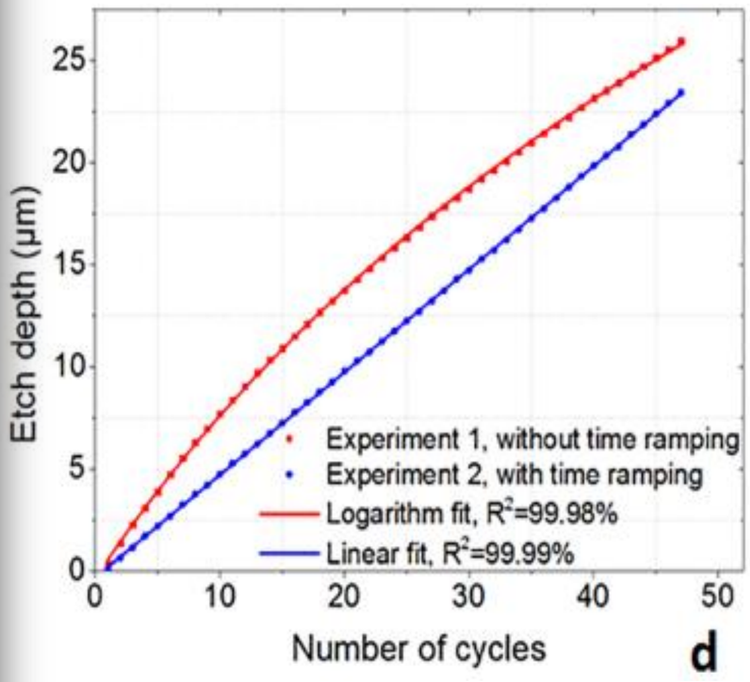


Switched FC: DREM with SF_6 etch time ramping

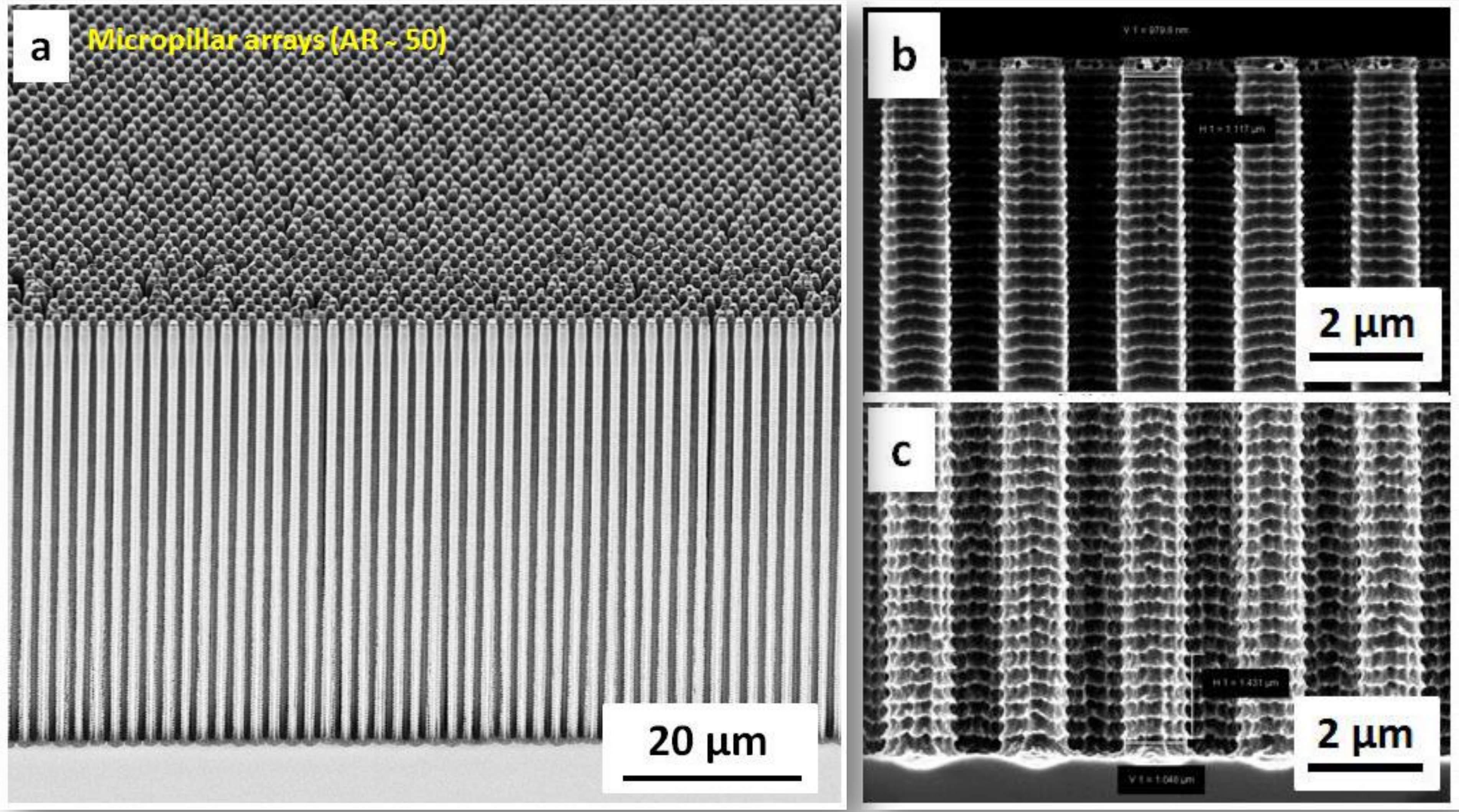


Switched FC: DREM with SF_6 etch time ramping





Switched FC DREM: AR=50 micropillars



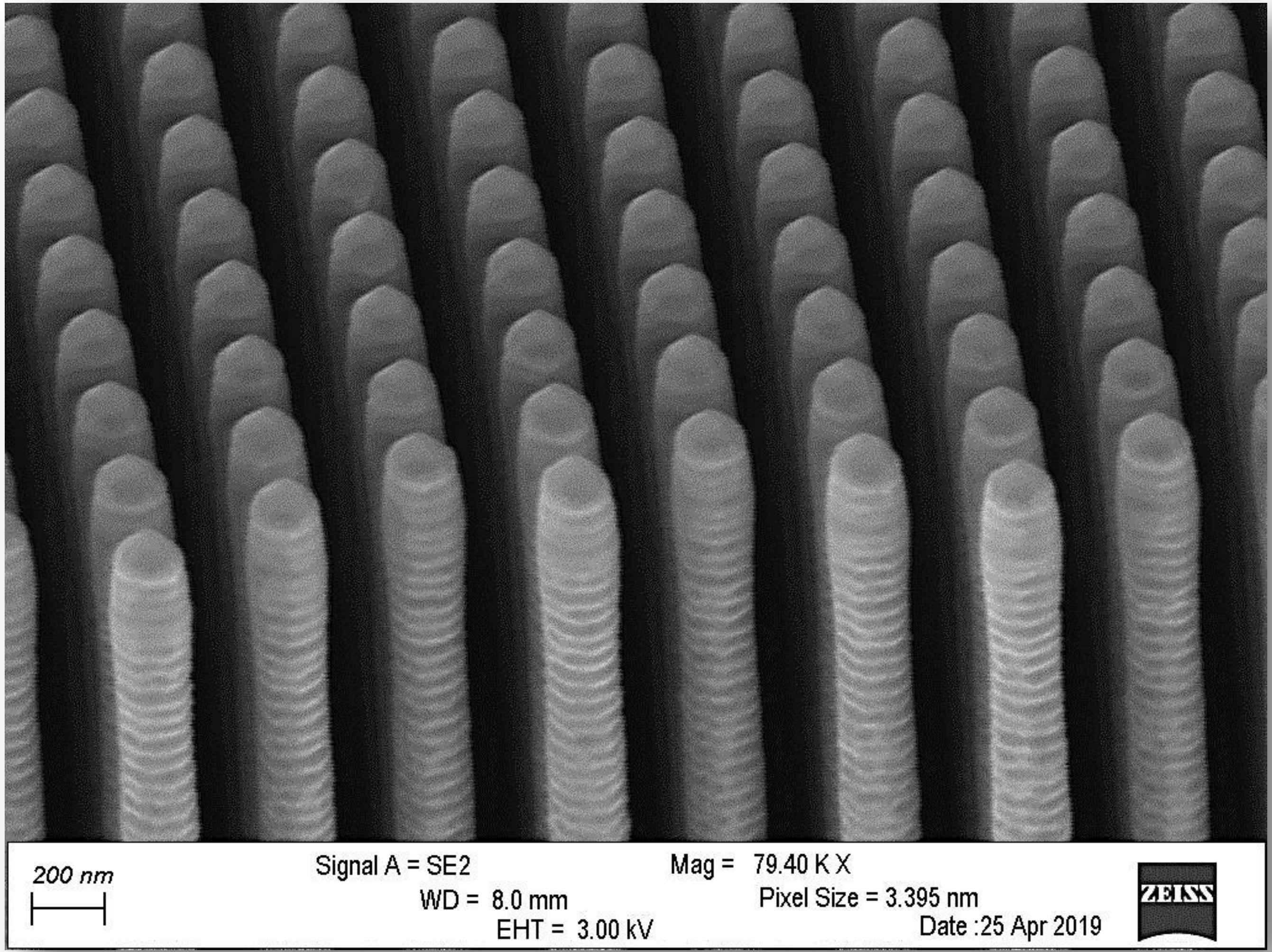
Top

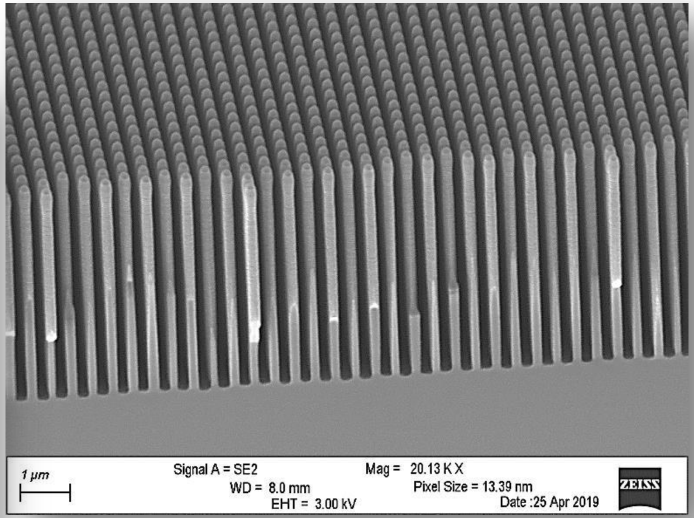
of the pillars

Bottom

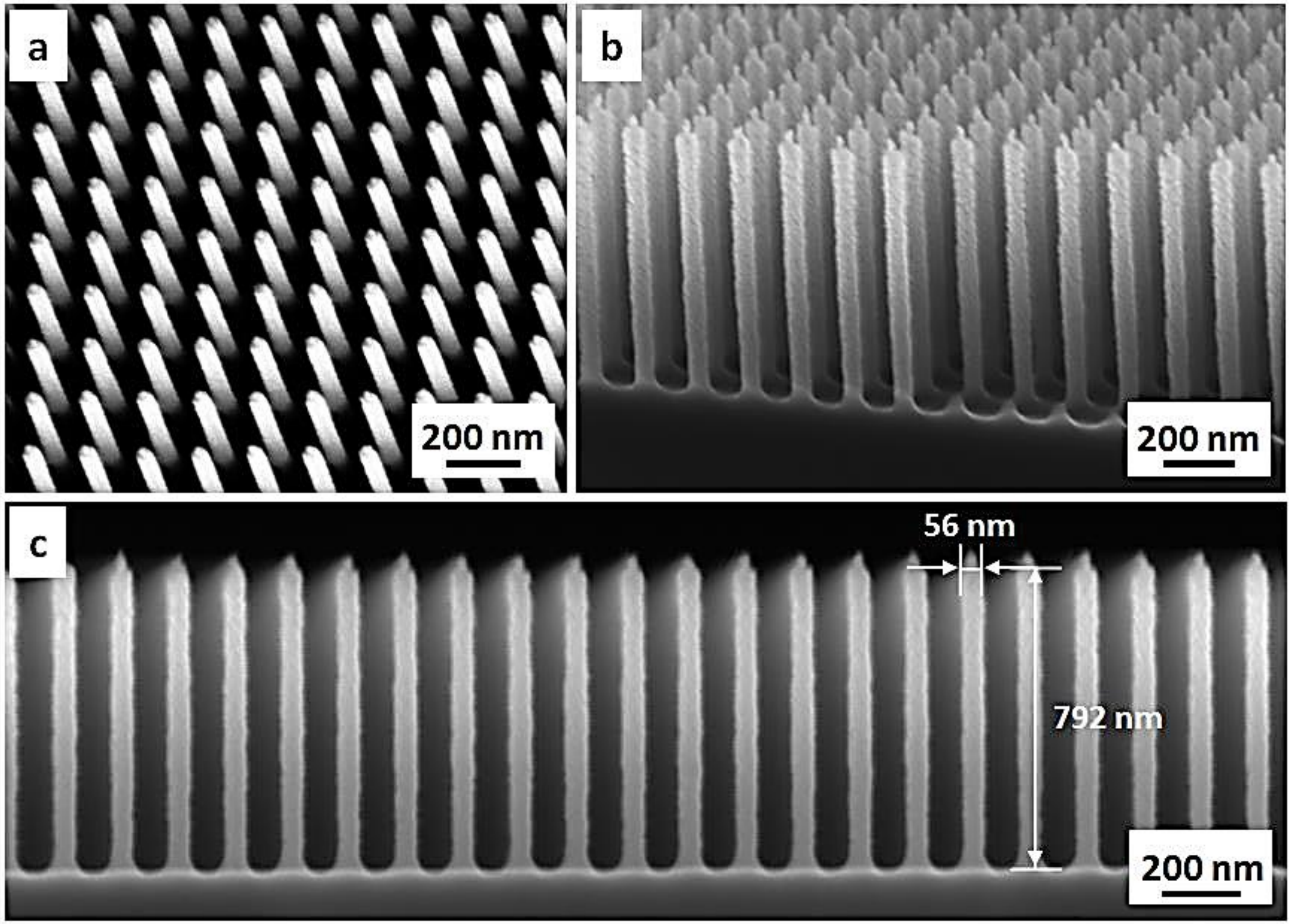
of the pillars

Switched FC DREM: AR=25 submicron pillars

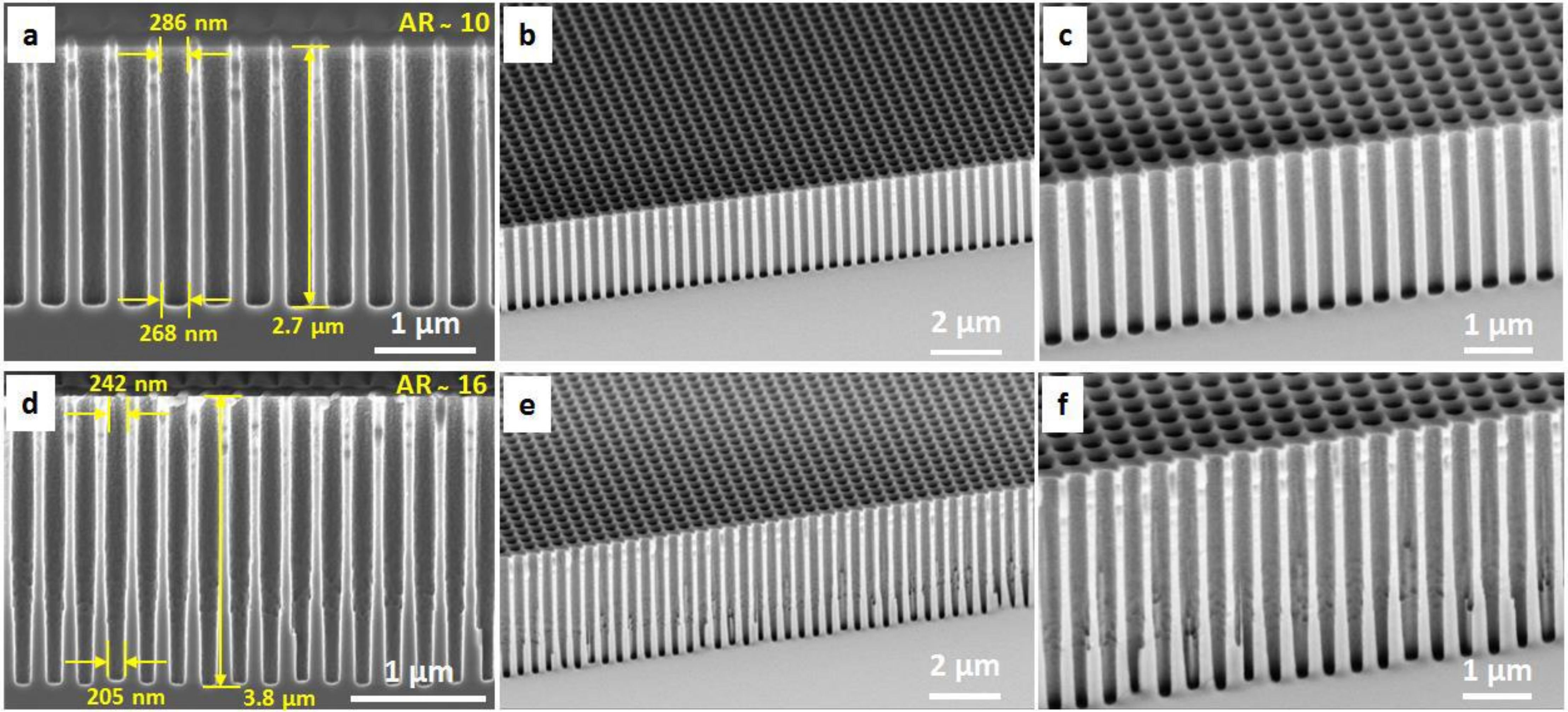




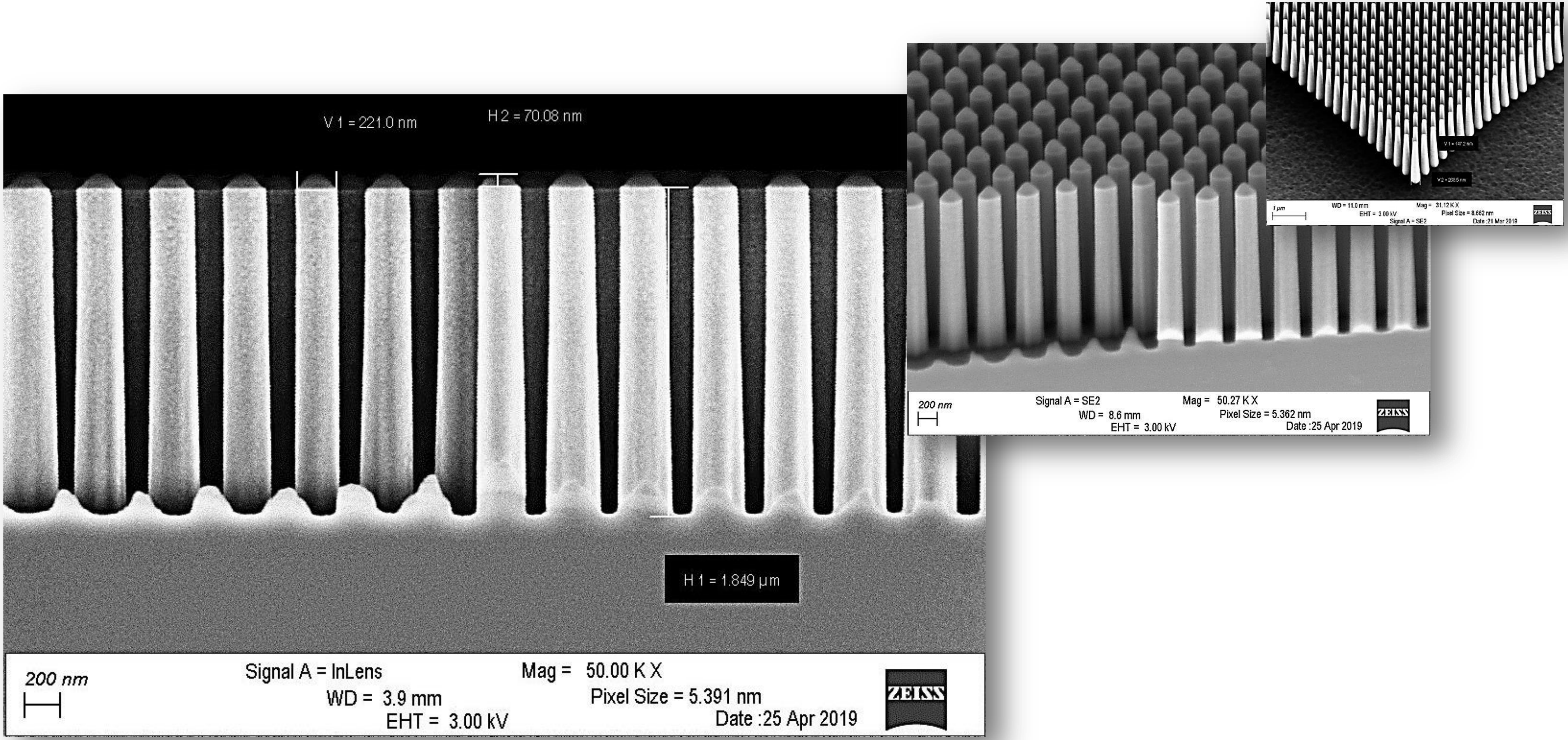
Switched FC DREM: AR=15 nanopillars



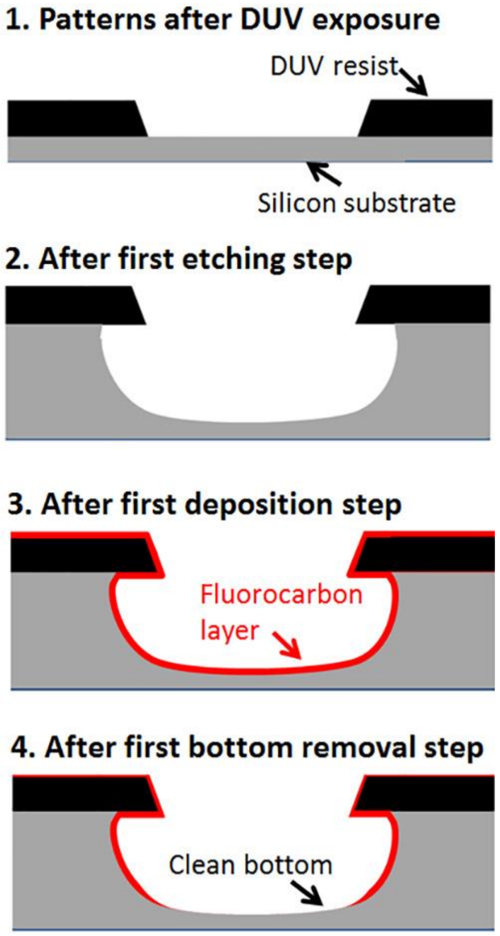
Switched FC: DREM Results: AR=10 submicron pores

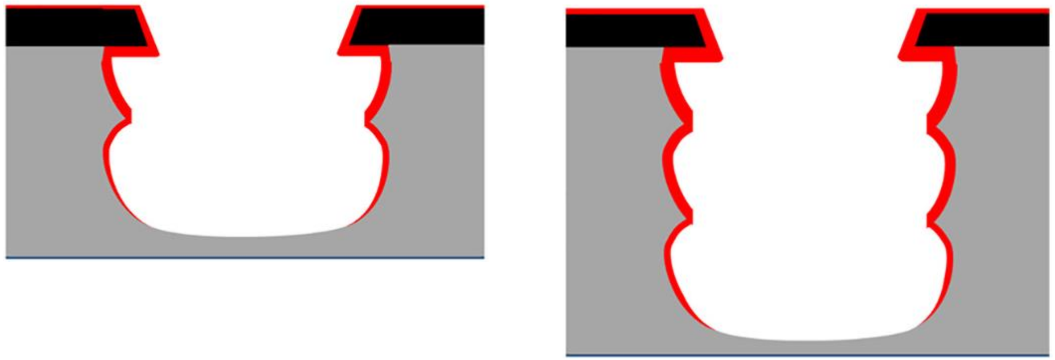


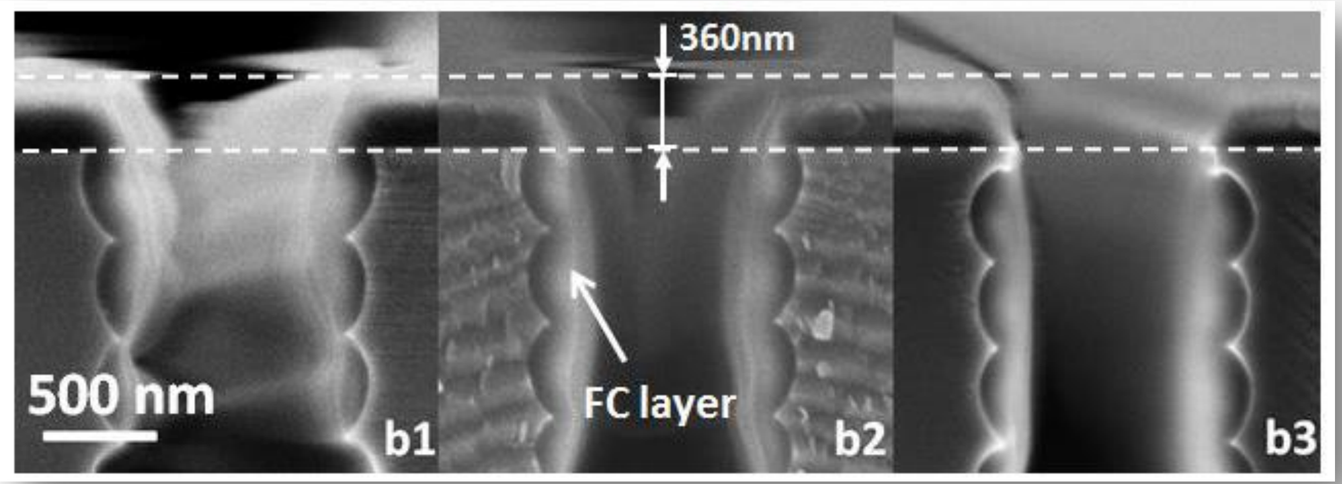
Switched FC DREM: Lower ICP power (to suppress scallops)



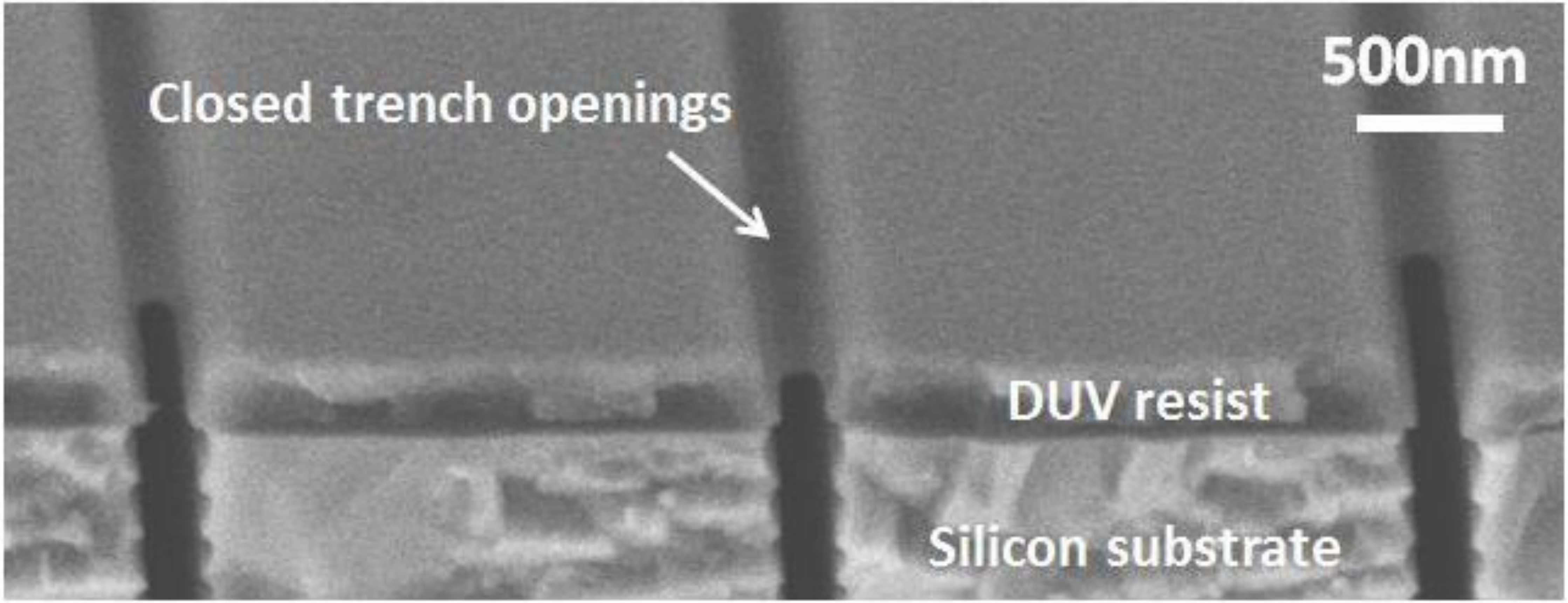
Switched FC DREM and the infinite selectivity





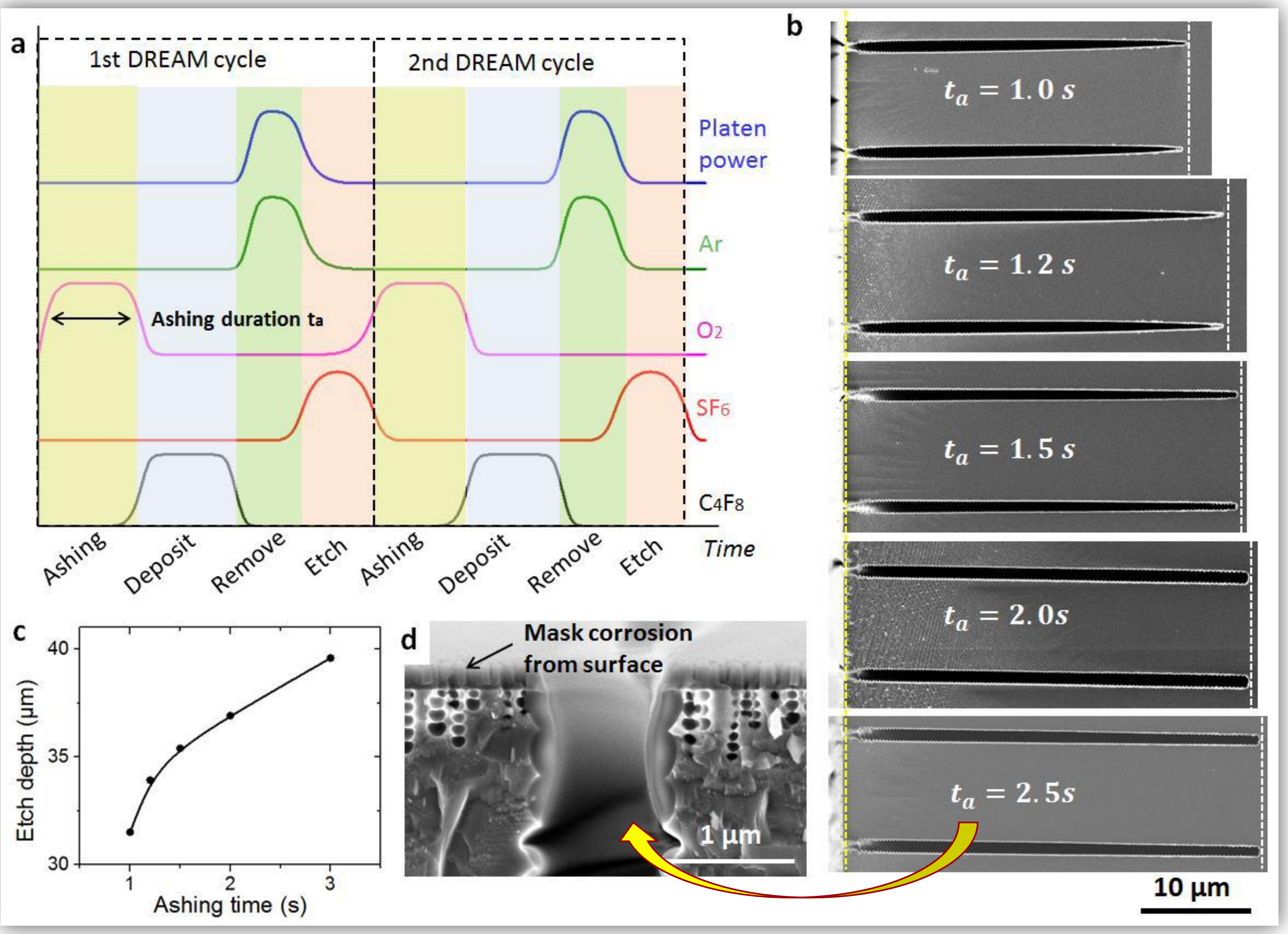


Switched FC DREM and the closing trenches



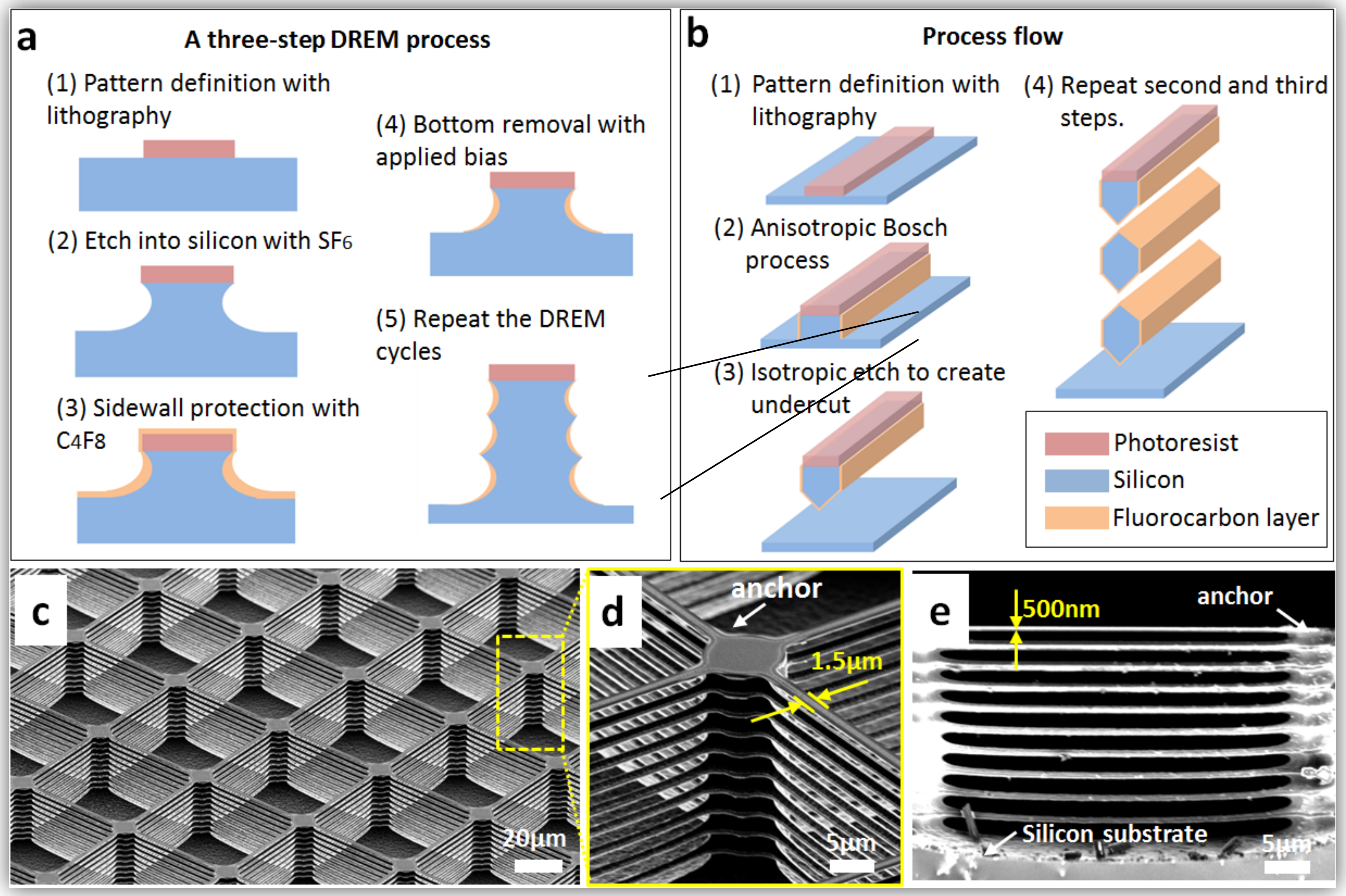
Beyond DREM
4-steps and 3D

The DREAM process (A for Ash)

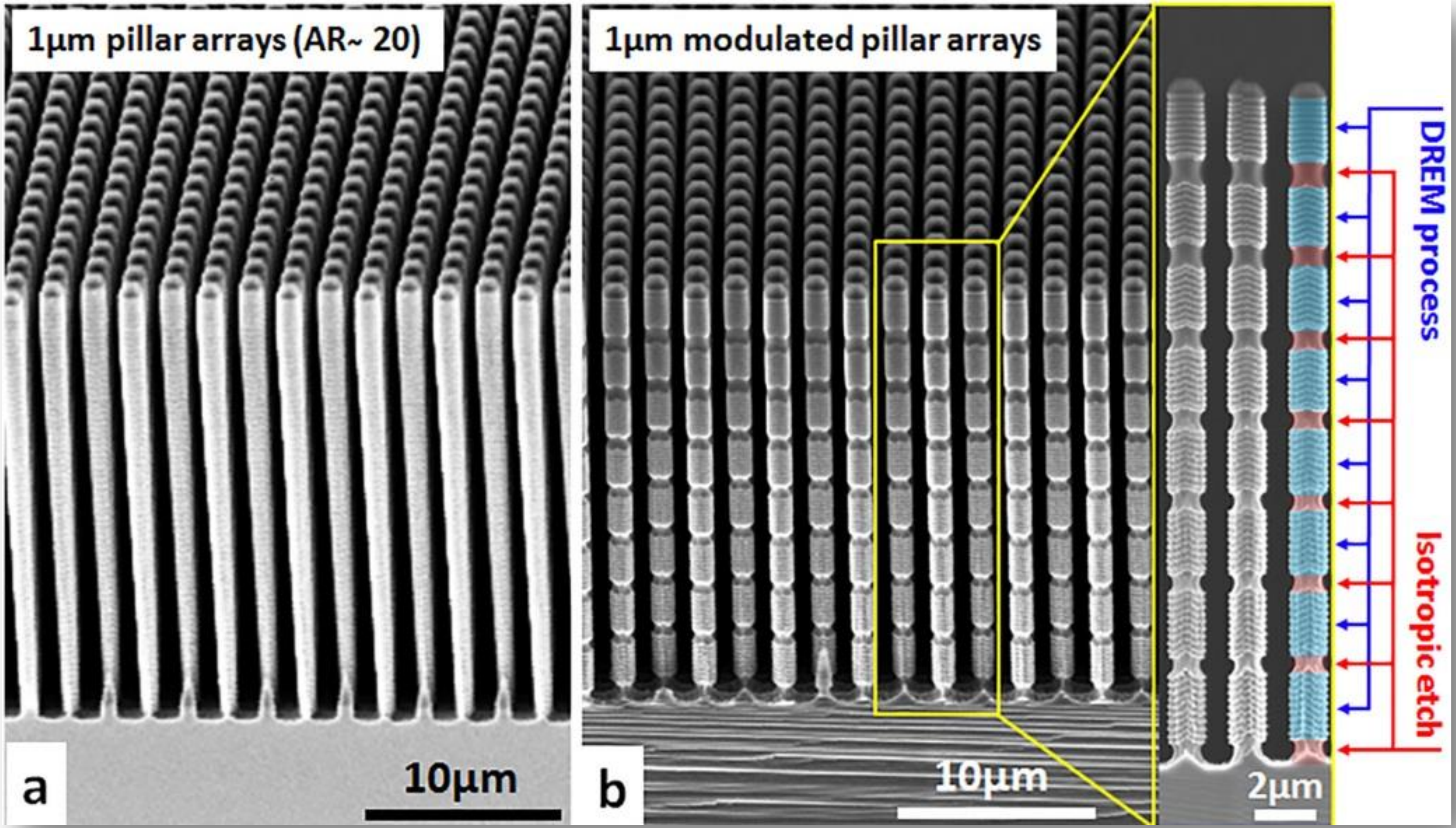


Increasing ash time

3D silicon nanosculpturing: DREM within a DREM



3D silicon nanosculpturing: DREM within a DREM

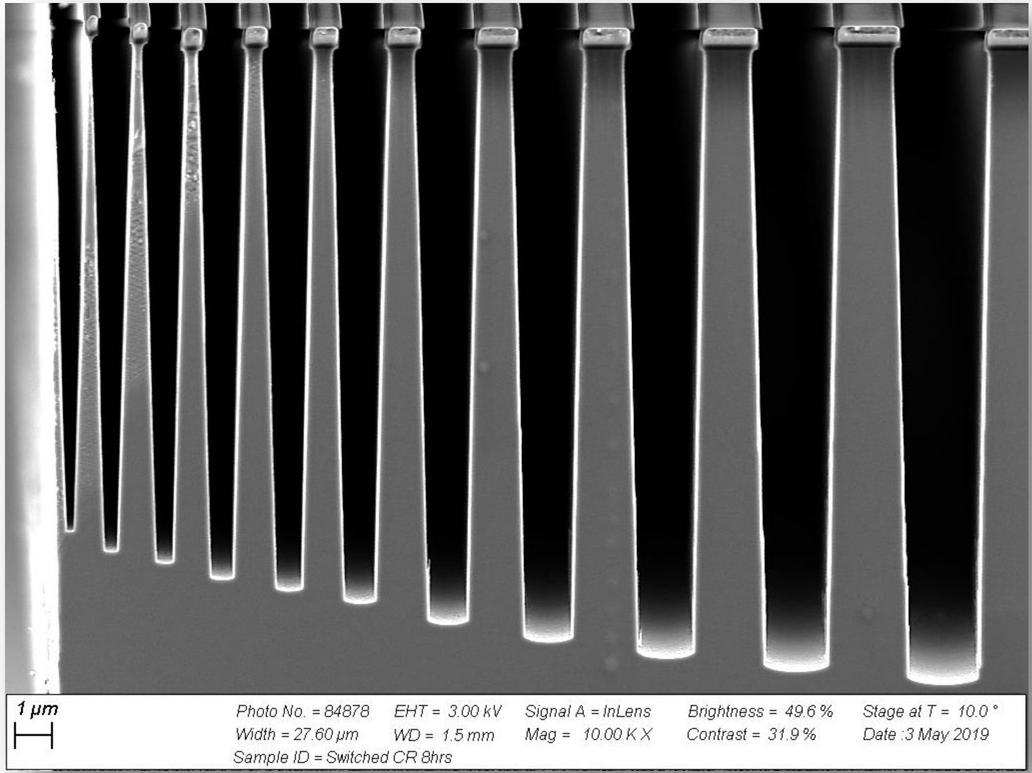


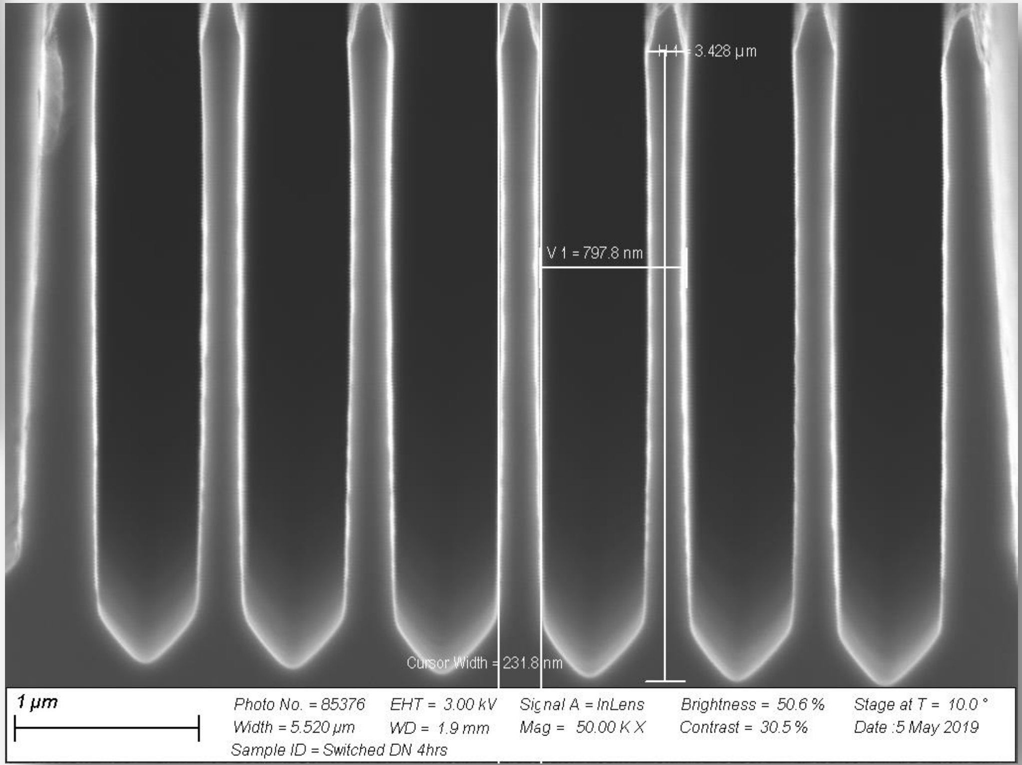
A DREAM Within a DREAM by Edgar Allan Poe

I stand amid the roar
Of a surf-tormented shore,
And I hold within my hand
Grains of the golden sand —
How few! yet how they creep
Through my fingers to the deep,
While I weep — while I weep!
O God! Can I not grasp
Them with a tighter clasp?
O God! can I not save
One from the pitiless wave?
Is all that we see or seem
But a dream within a dream?

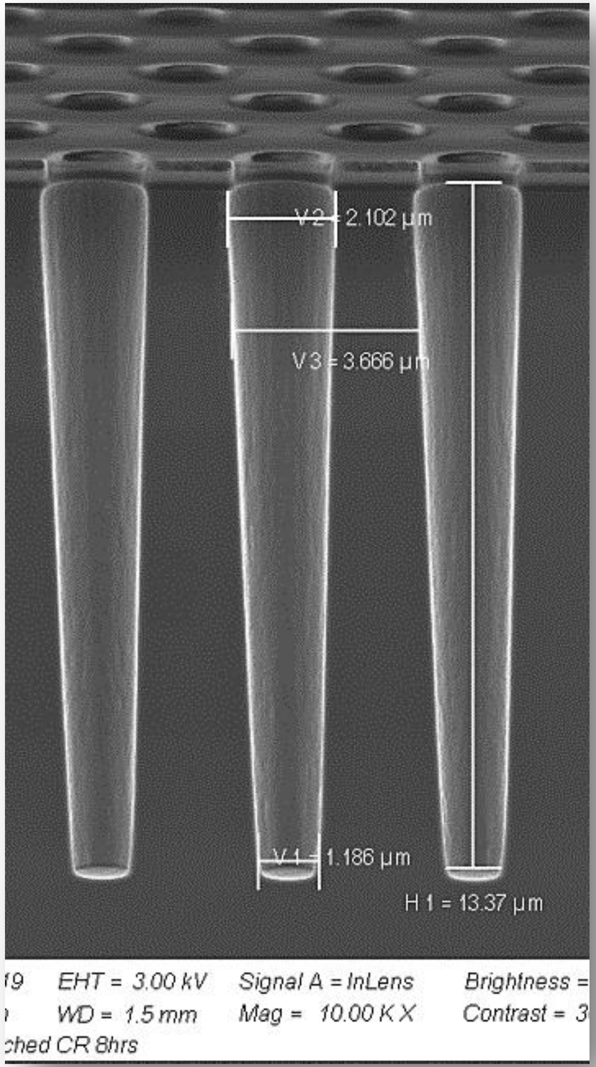
Switched O_2 mode
4-steps CORE

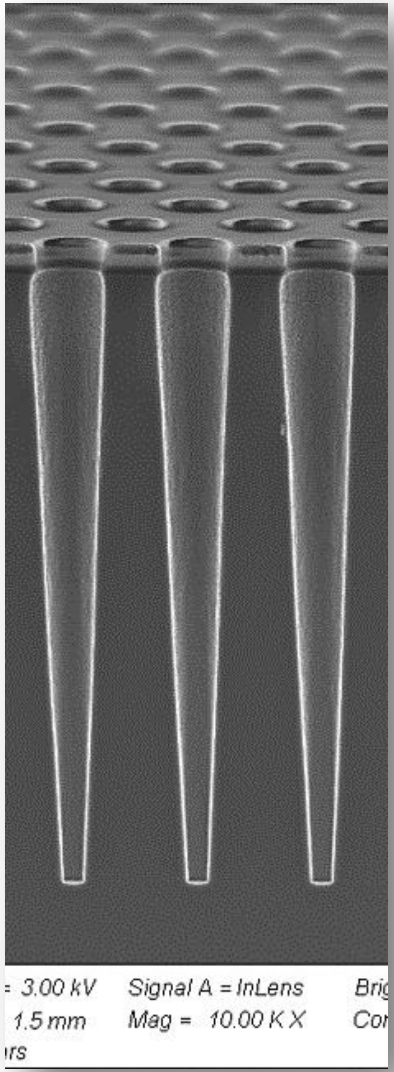
Switched O_2 and trenches, lines, or gratings

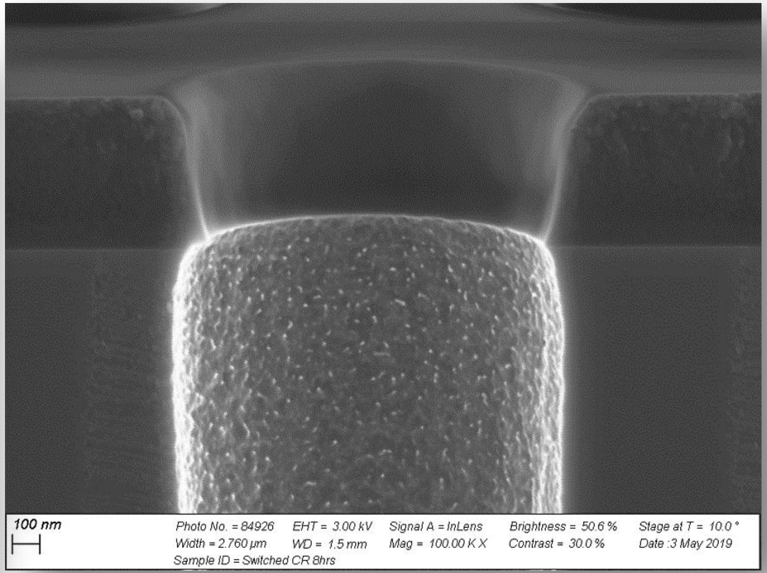


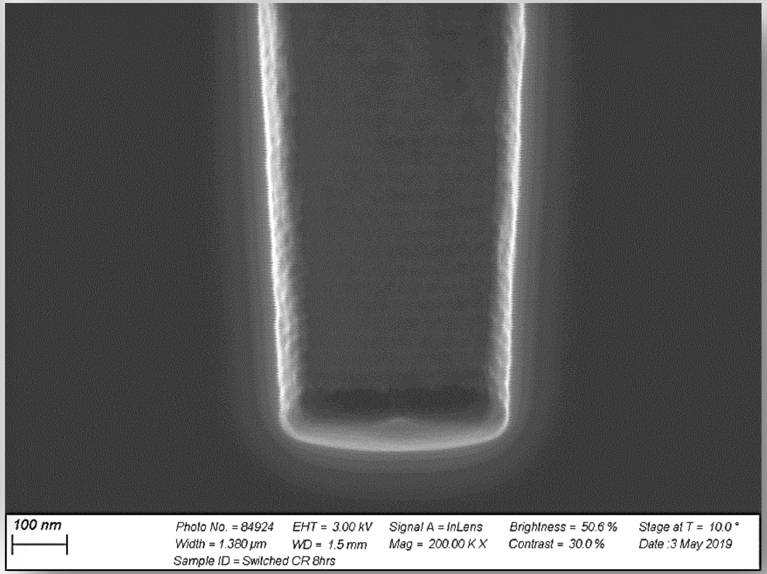


Switched O_2 and holes

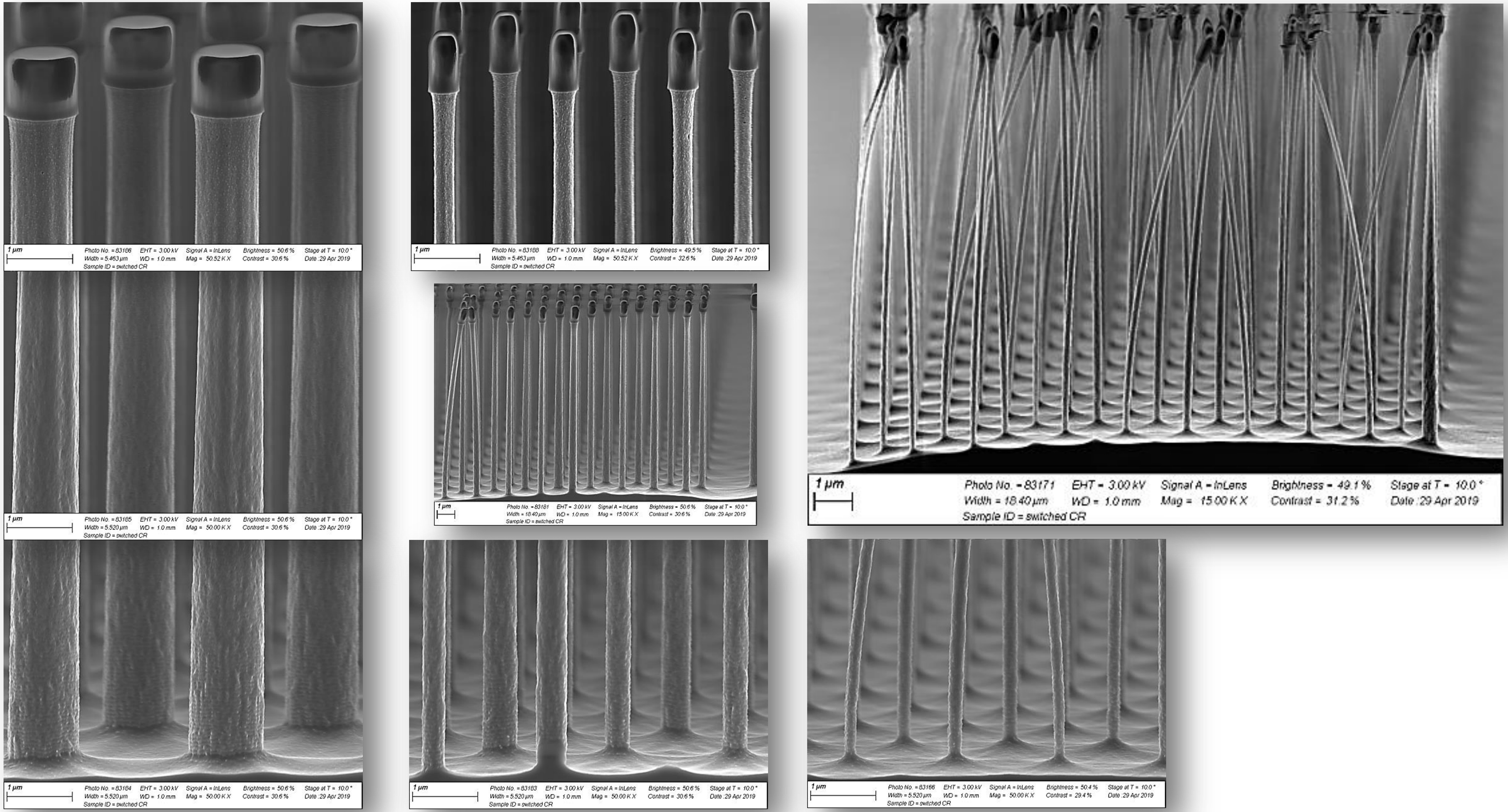




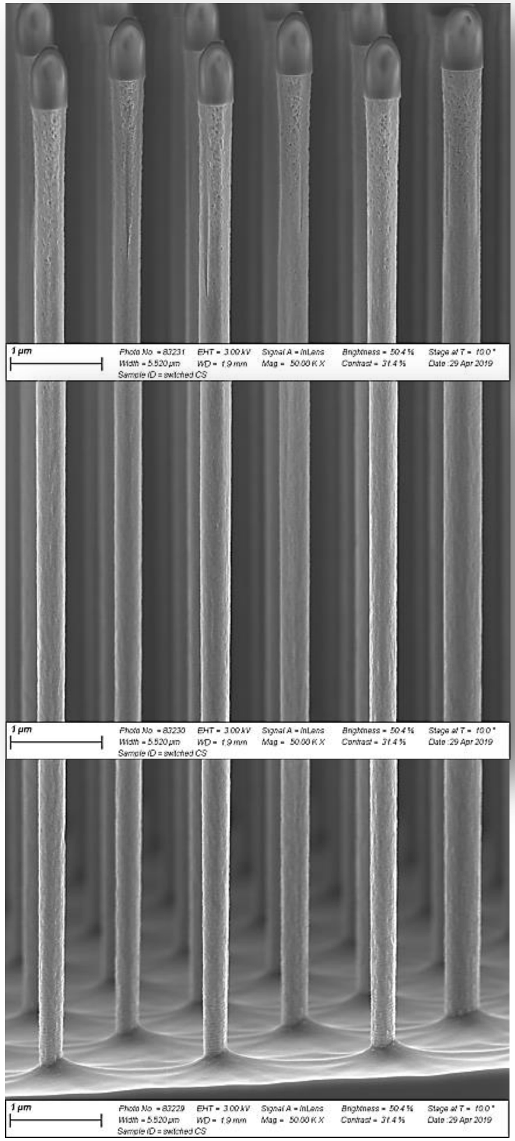


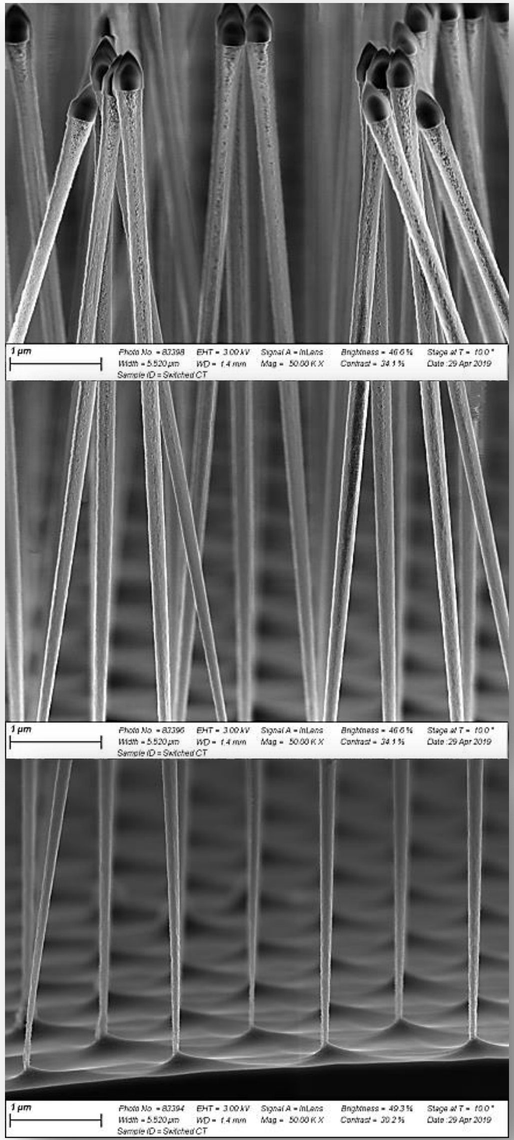


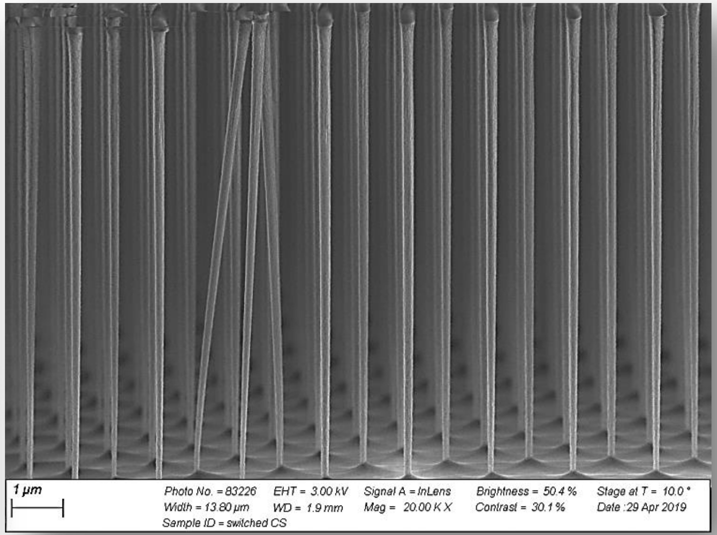
Switched O_2 and pillars

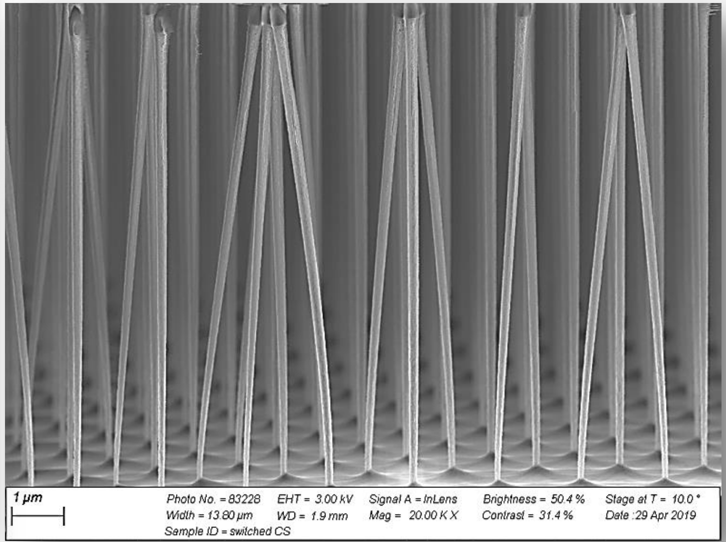


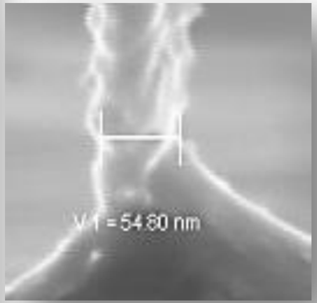
Switched O_2 and pillars



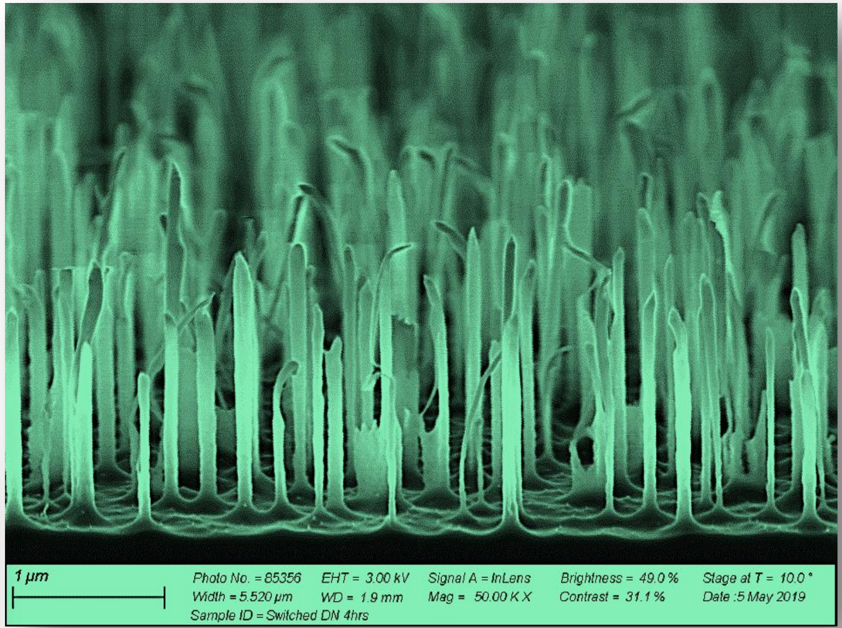


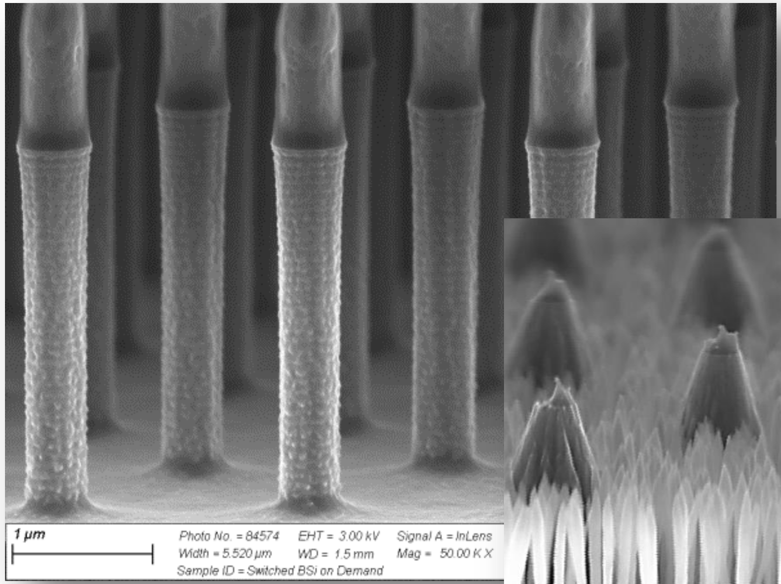


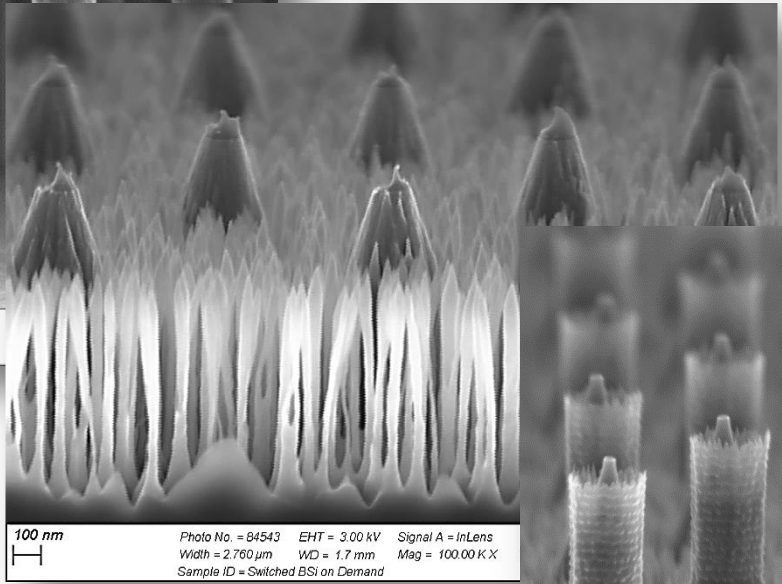


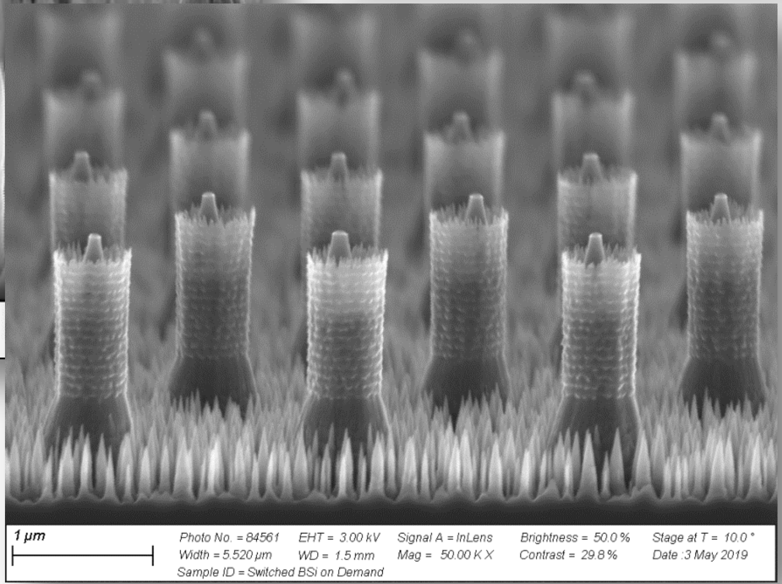


Switched O_2 and Black Silicon on Demand





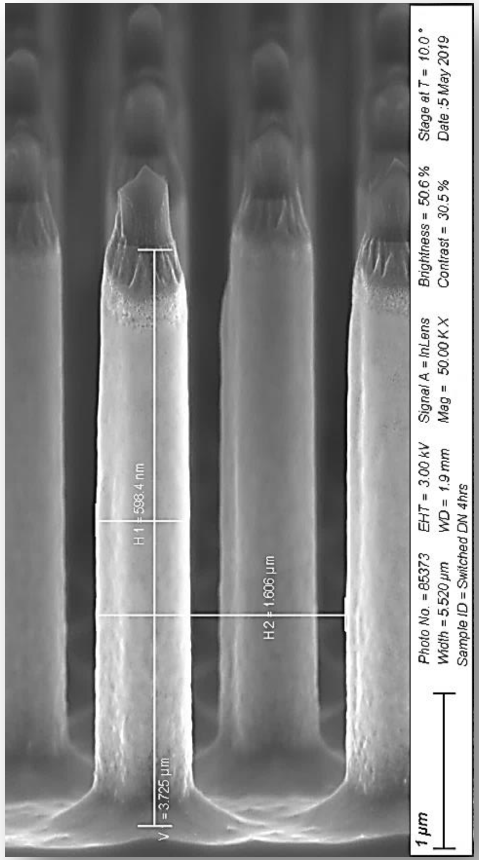


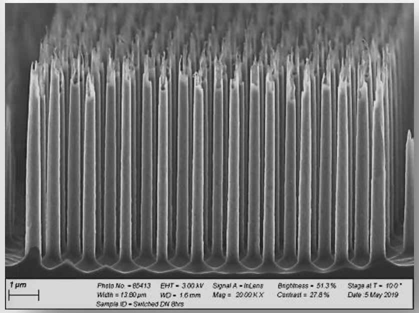


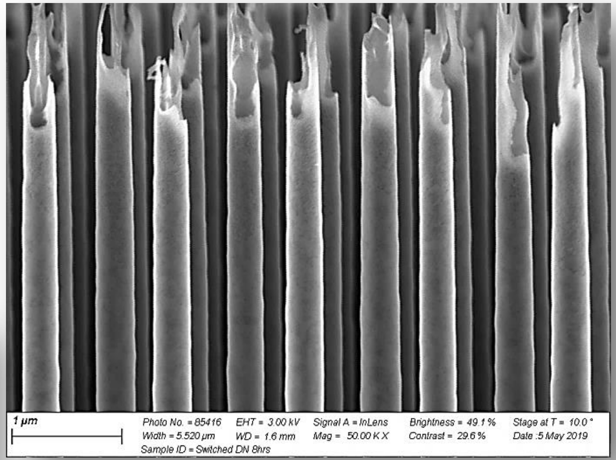
To be presented at MNE2019
by Vy

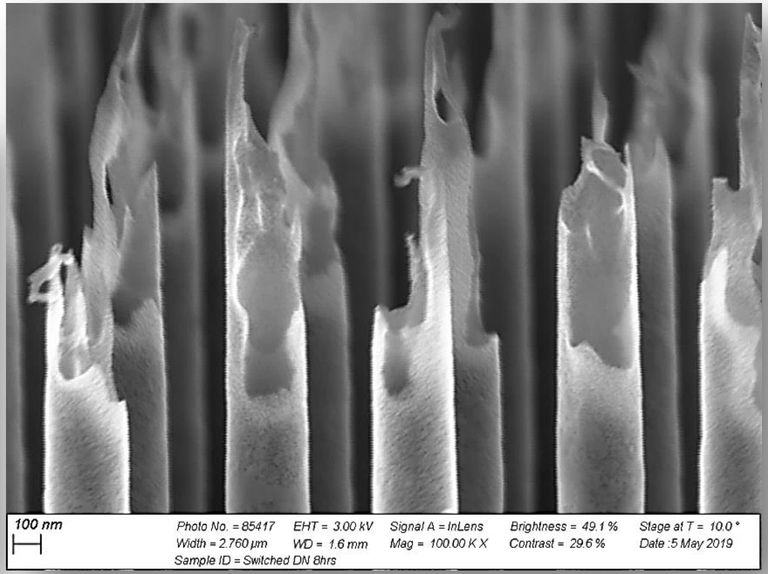
Combined O_2 mode 4-steps

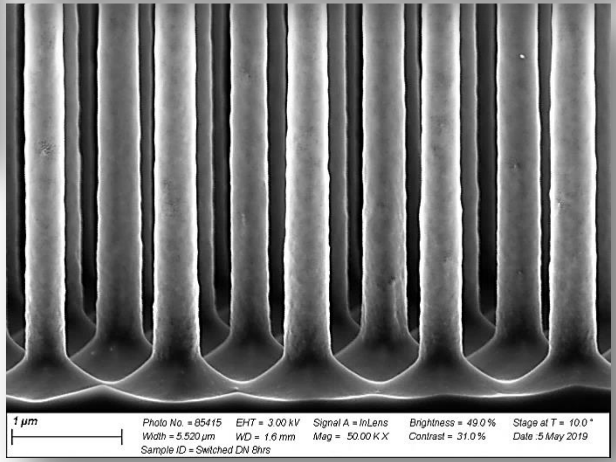
Combined O_2 and pillars: reducing scallops

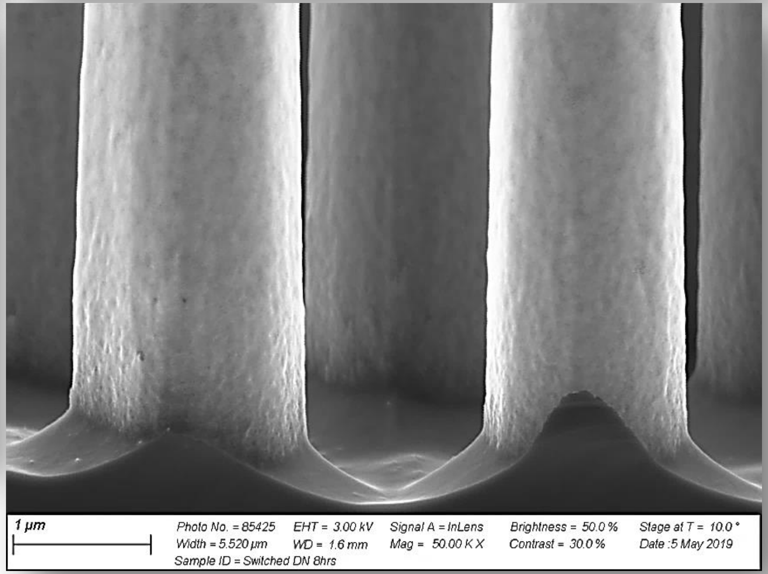




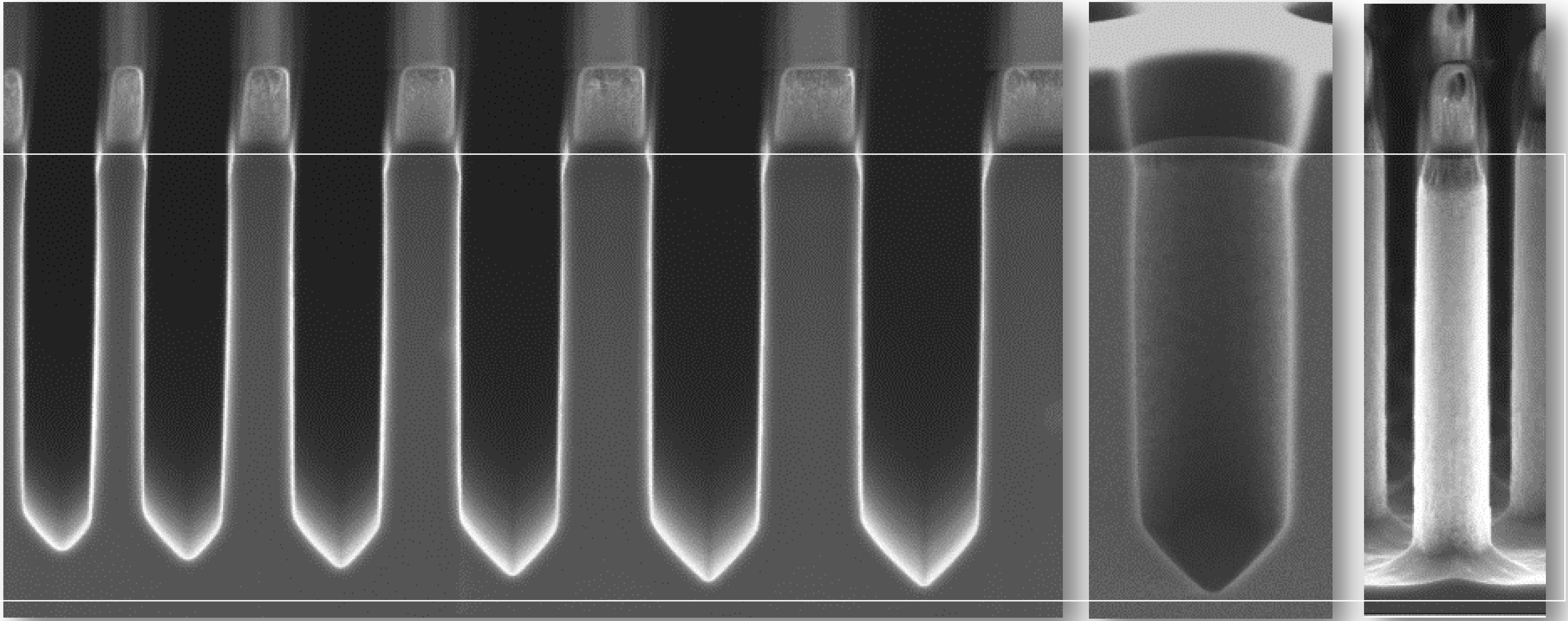




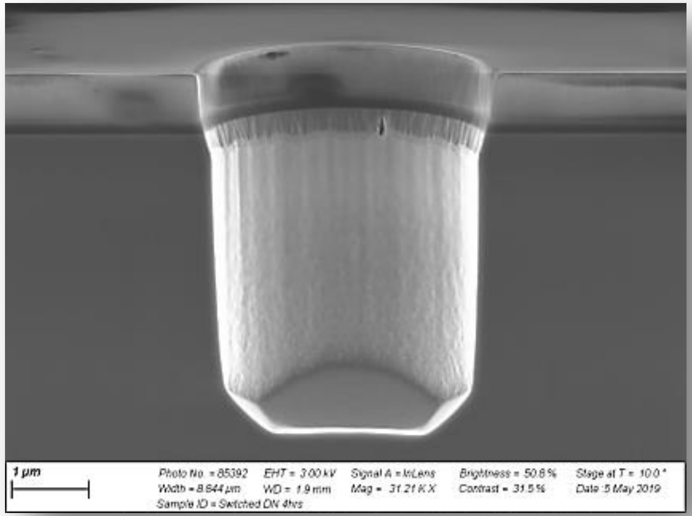


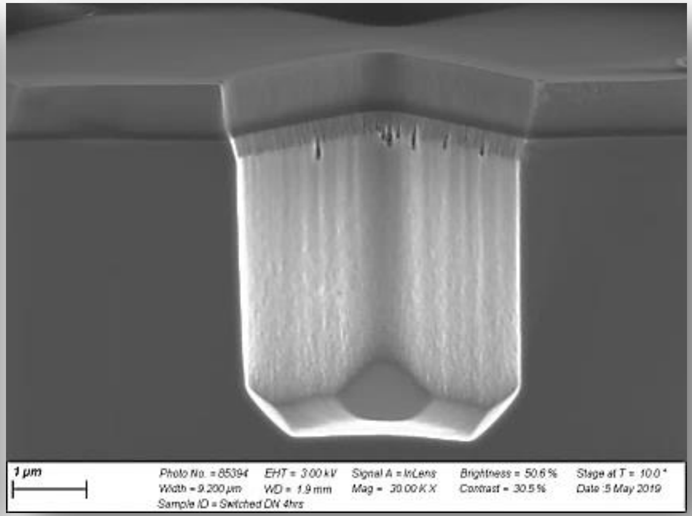


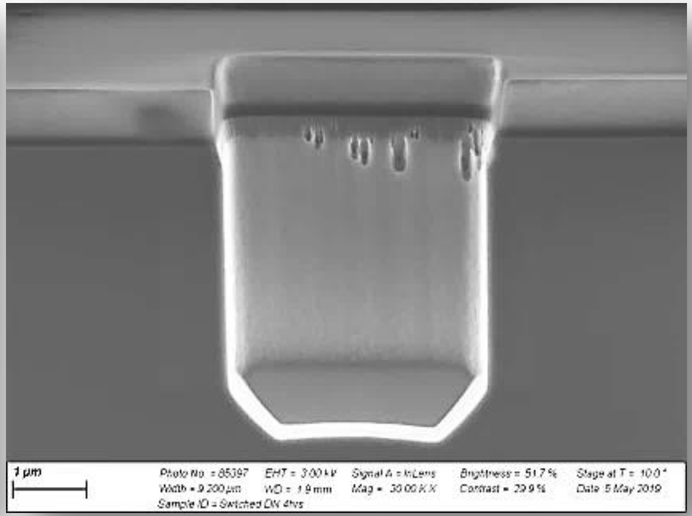
Combined O_2 and pattern dependency



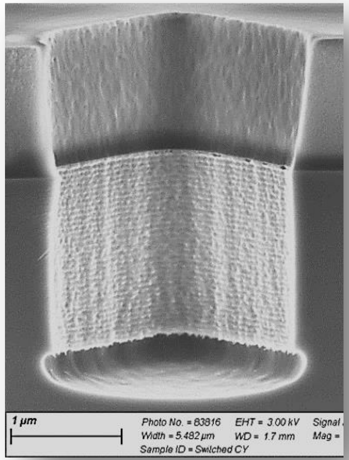
Combined O_2 and crystal plane dependency

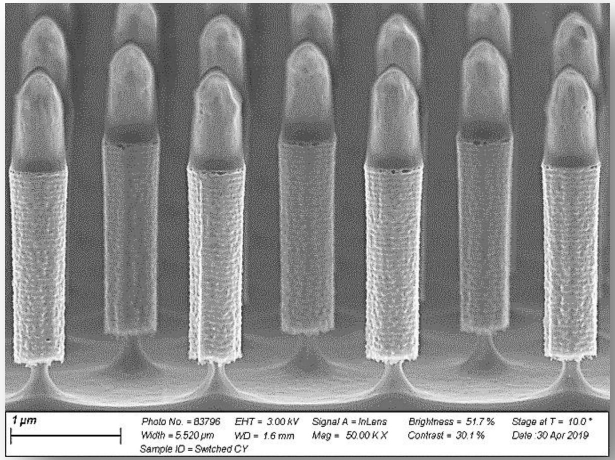


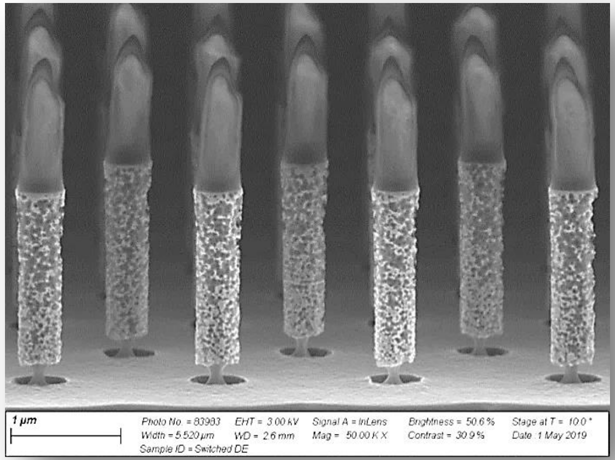


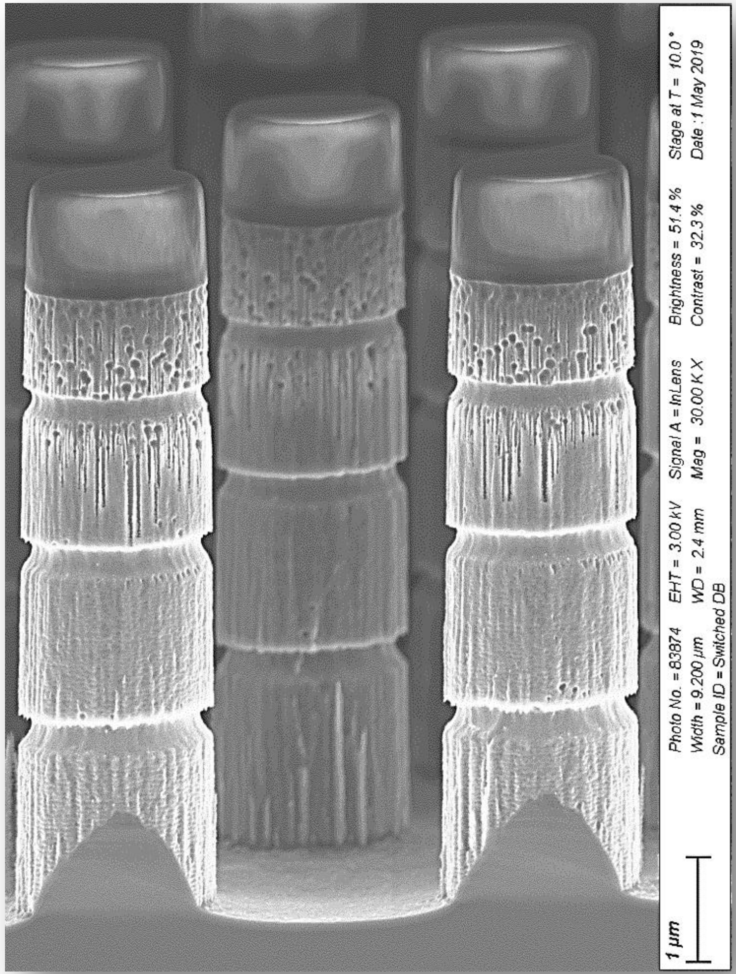


Switched O_2 and 3D










That's all Folks!