MD simulations of chlorine plasmas interaction with ultrathin silicon films for advanced etch processes

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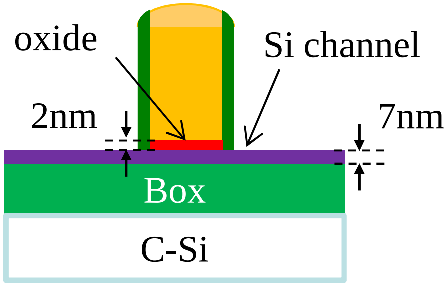
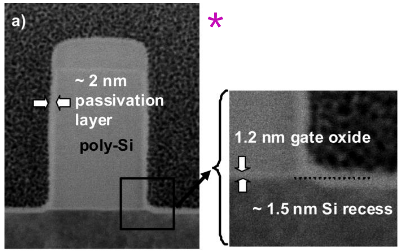
Advanced transistors etching challenge (1/2)

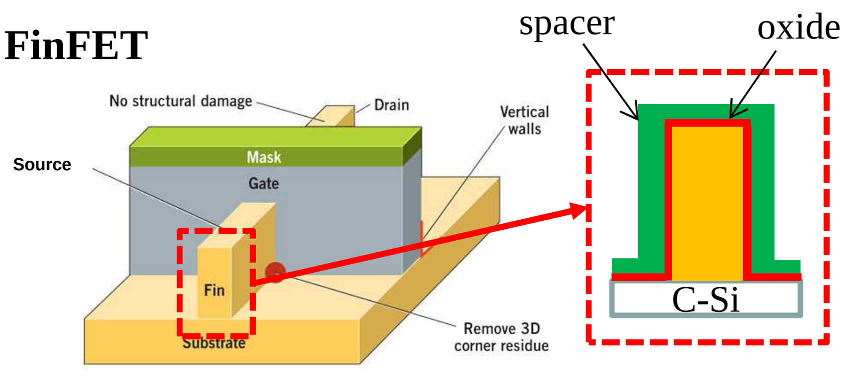
Challenge : etching of ultrathin films without damaging the active layers of advanced transistors

FDSOI

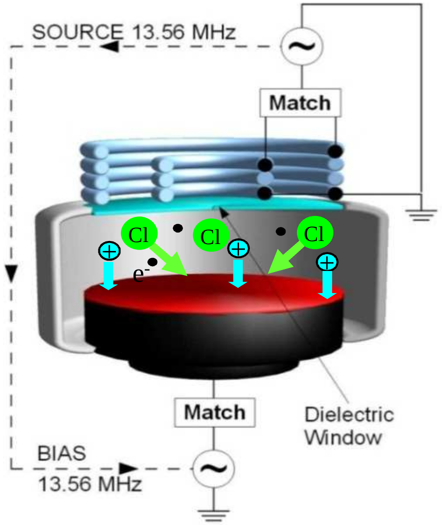




FinFET



Classical CW-ICP plasmas limitations :



RIE = ionic bombardment + chemical attack by radicals

E_{ion} >15-20eV ⇒ plasma induced damage ~ 2-3nm

Important dissociation ⇒ high etch rate

**Petit-Etienne et al, JVST B 30, 040604 (2012)*

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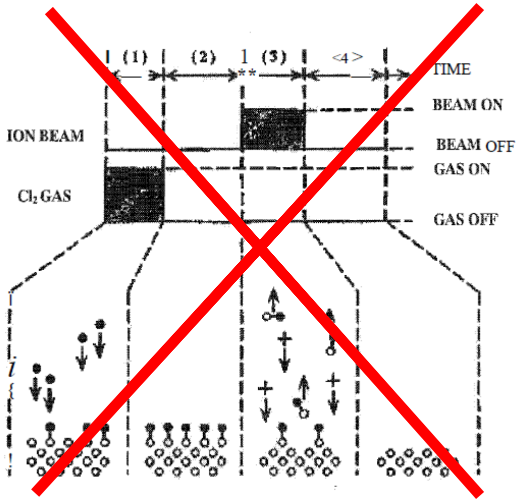
Advanced transistors etching challenge (2/2)

Challenge : etching of ultrathin films without damaging the active layers of advanced transistors

Possible solutions :

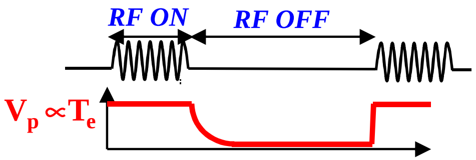
Current ALE



too slow for industrial purposes

Pulsed plasmas

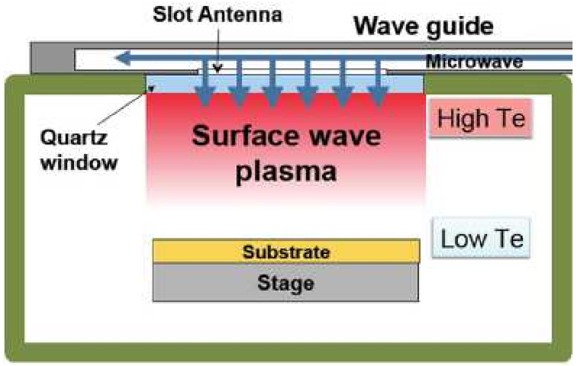
(LTM, AMAT, LAM)



- lower average ion energy
- dissociation rate (Cl/Cl_2) controlled by the duty cycle (DC)

Low T_e plasmas

(TEL, AMAT)



$E_{ion} < 5eV$

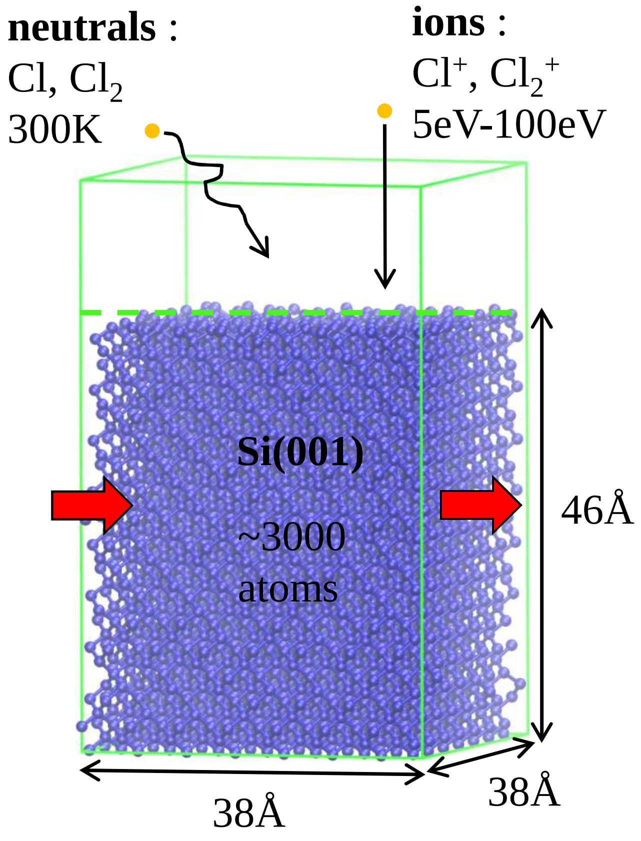
Problem : too many **control knobs** to tune an etching process in a plasma reactor

=> Parameter space too large to develop/understand such processes purely empirically

⇨ **modeling / atomistic simulations (MD)**

Molecular Dynamics (MD) simulations

Plasma = $\{Cl, Cl^+, Cl_2, Cl_2^+\}$



☐ Principles :

- computes $\mathbf{r}_i$, $\mathbf{v}_i$ for N interactive atoms, $\boldsymbol{F_i} = m\boldsymbol{a_i} = \boxed{-\dfrac{\partial U}{\partial \boldsymbol{r_i}}}$
- U : semi-empirical improved Tersoff-Brenner Si-Cl potential

☐ Method :

- random and alternative bombardment of **neutrals** (Cl/Cl_2) and **ions** (Cl^+/Cl_2^+)
- periodic boundaries
- average quantities on 2-3 simulations
- dose : $[10^{18}\text{-}10^{19}]$ ions.cm^{-2}
  1 monolayer (ML) = 98 ionic impacts

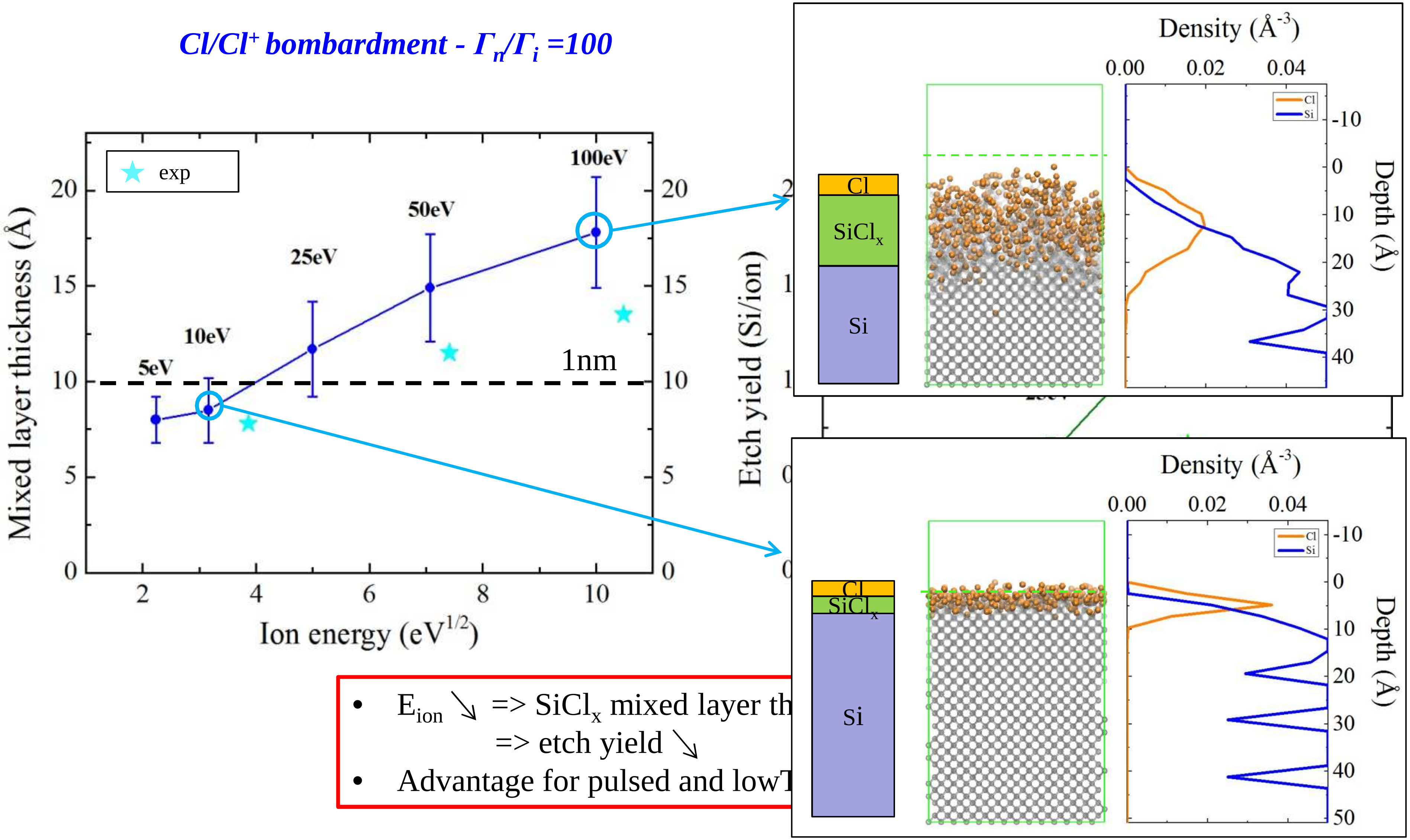
☐ Parameters : E_{ion}, $\alpha^+ = \dfrac{n_{Cl^+}}{n_{Cl^+} + n_{Cl_2^+}}$, $\alpha = \dfrac{n_{Cl}}{n_{Cl} + n_{Cl_2}}$, $\Gamma = \Gamma_n/\Gamma_i$

- How is the composition/structure of the layer modified ?
- What about the etch yield and etch products ?

Brichon et al, JVST A 32, 021301 (2014)

Key parameter to control the etching : E_{ion}

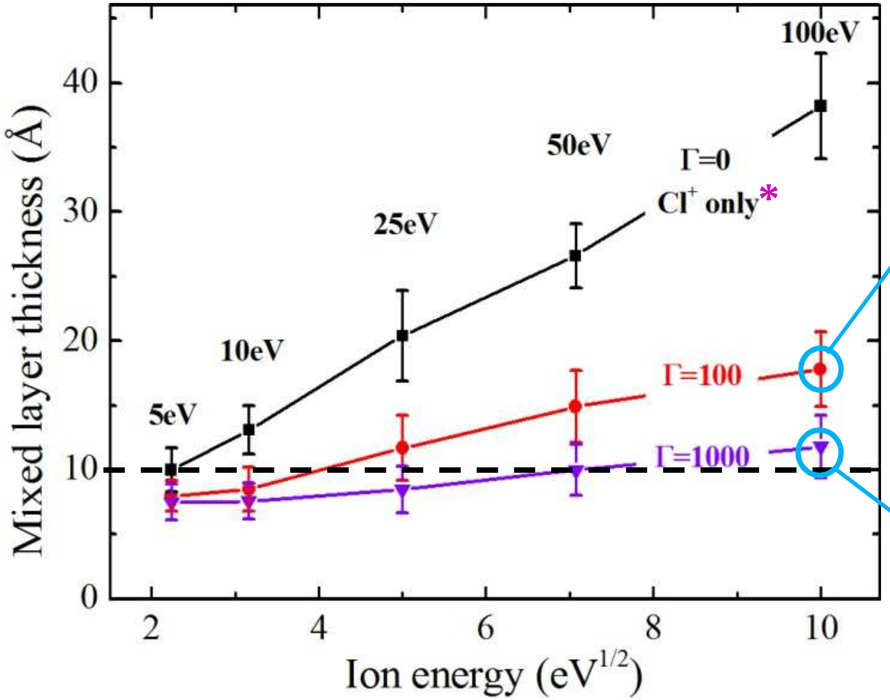
Cl/Cl^+ bombardment - $\Gamma_n/\Gamma_i = 100$

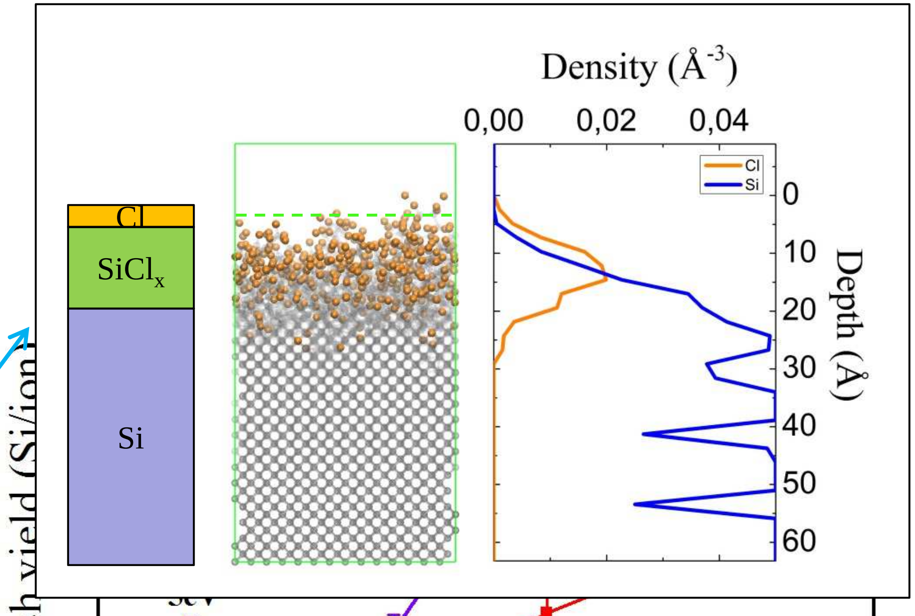


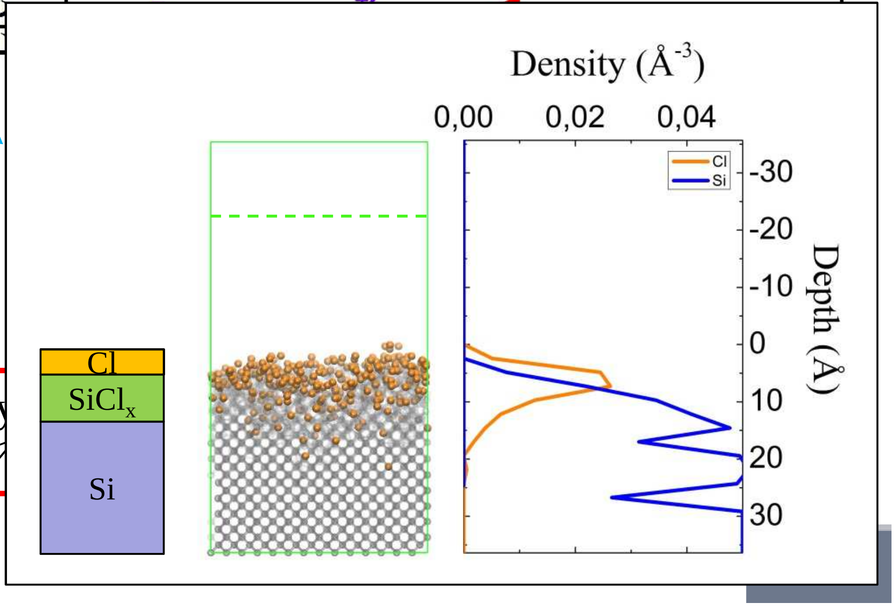
- E_{ion} ↘ => $SiCl_x$ mixed layer th
  => etch yield ↘
- Advantage for pulsed and lowT

Secondary parameters to control the etching :
neutral-to-ion flux ratio ($\Gamma=\Gamma_n/\Gamma_i$) & dissociation rate ($\alpha=n_{Cl}/n_{Cltot}$)

Cl/Cl^+ bombardment







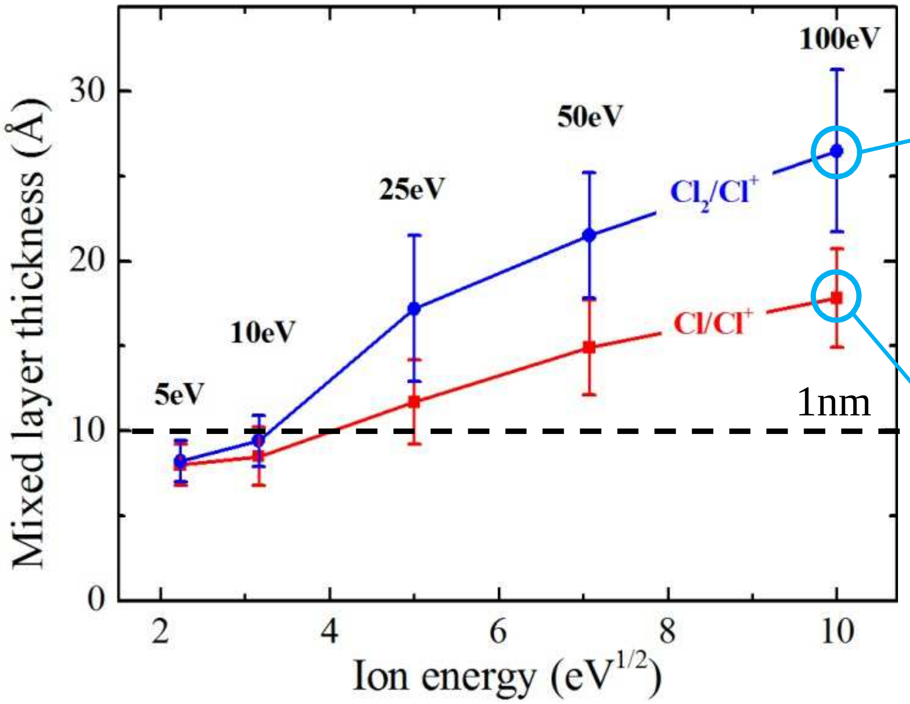
Γ_n/Γ_i ↗ => $SiCl_x$ mixed lay

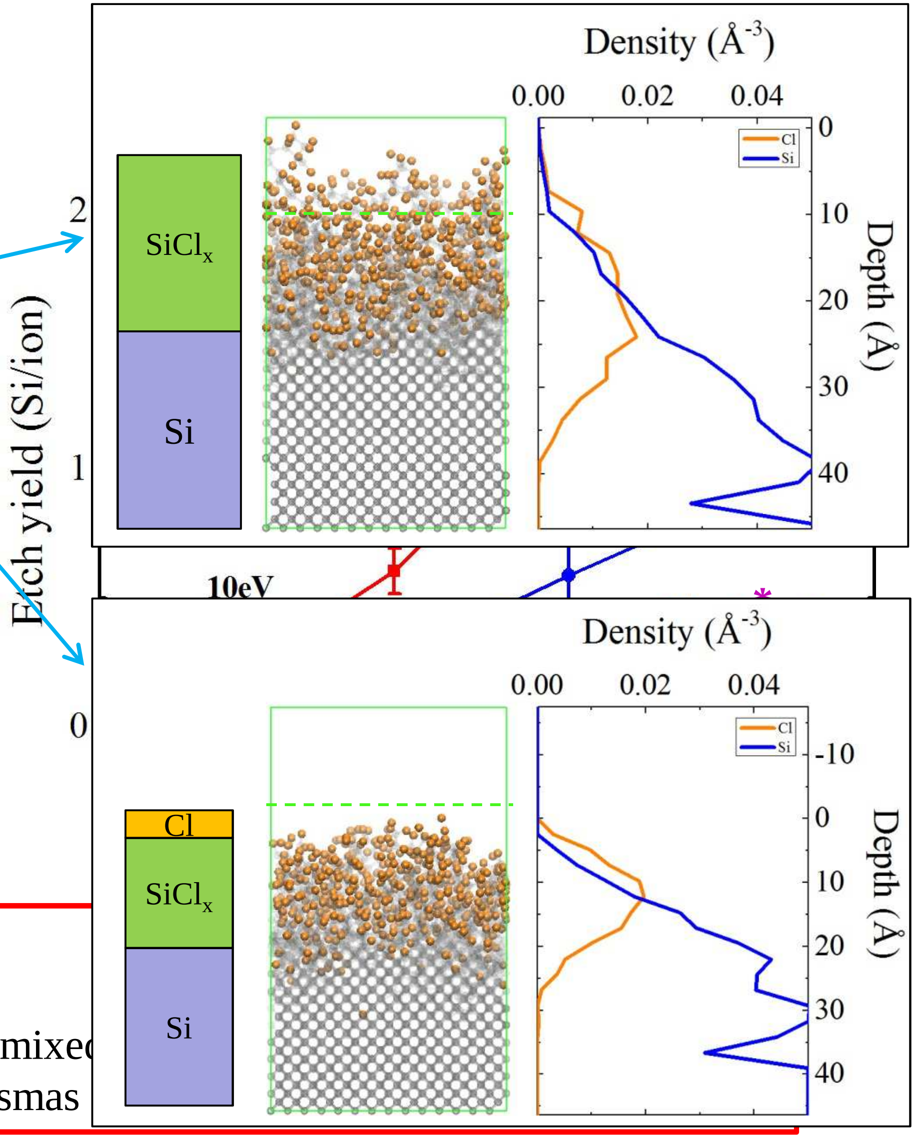
=> etch yield ↗

***Brichon et al, JVST A 32, 021301(2014)**

Secondary parameters to control the etching : neutral-to-ion flux ratio ($\Gamma=\Gamma_n/\Gamma_i$) & dissociation rate ($\alpha=n_{Cl}/n_{Cltot}$)

Cl_x/Cl^+ bombardment - Γ_n/Γ_i =100



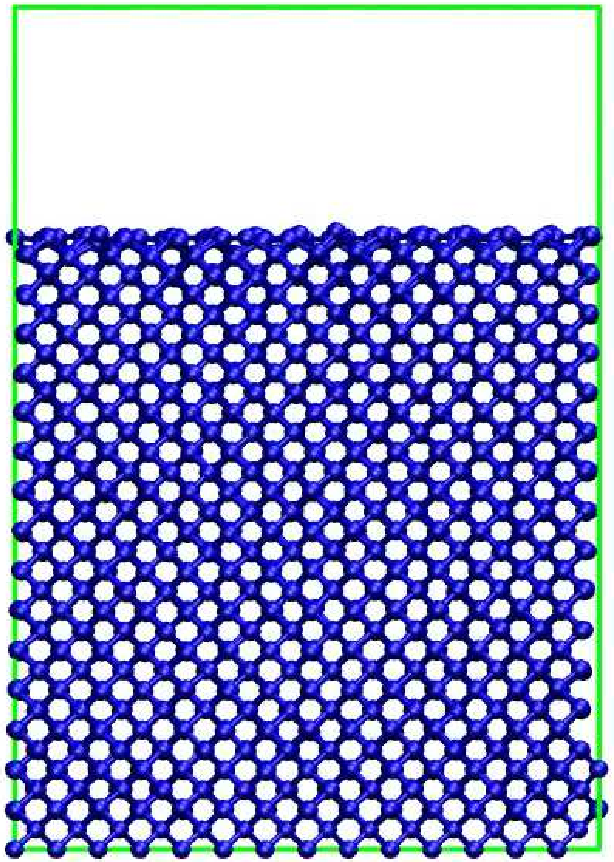


- α ↗ => $SiCl_x$ mixed layer thickness ↘
  => etch yield ↗
- By controlling the plasma chemistry, the $SiCl_x$ mixe
  => advantage for pulsed plasmas

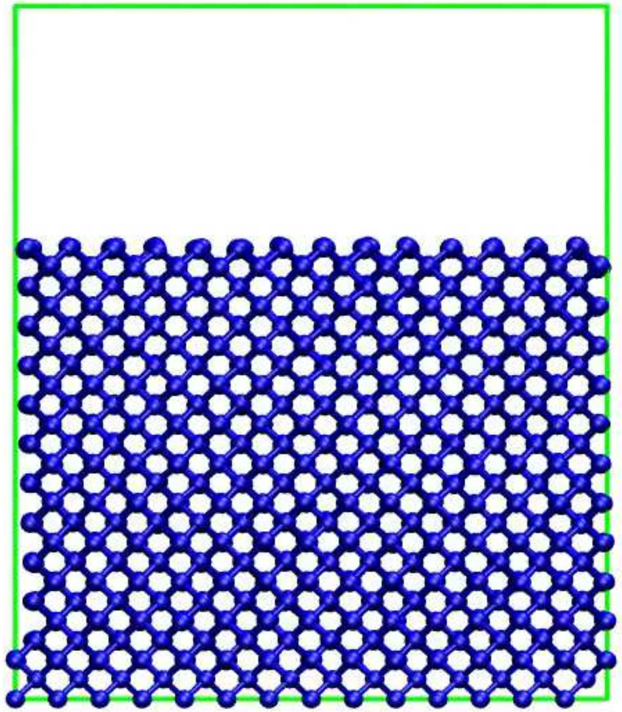
**Brichon et al., JVST A 32, 021301(2014)*

Advanced transistors etching challenge (1/2)

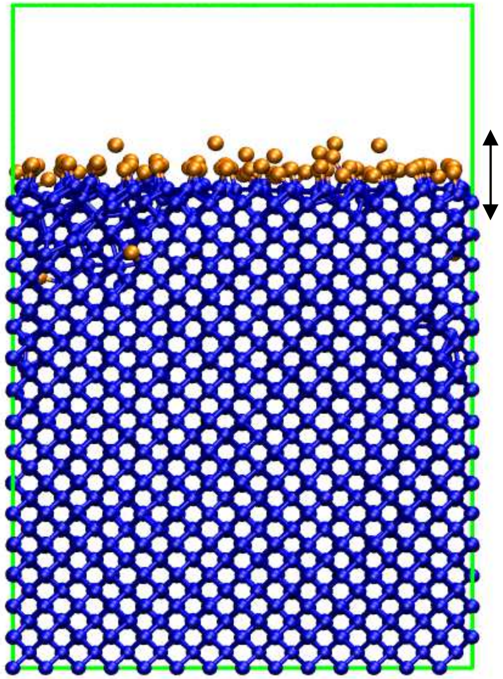
Cl/Cl^+ bombardment @100eV
$\Gamma_n/\Gamma_i = 100$



Cl_2/Cl^+ bombardment @100eV
$\Gamma_n/\Gamma_i = 100$



How can we achieve sub 1 nm thick reactive layers in reactive plasmas ?



less than 1.0 nm

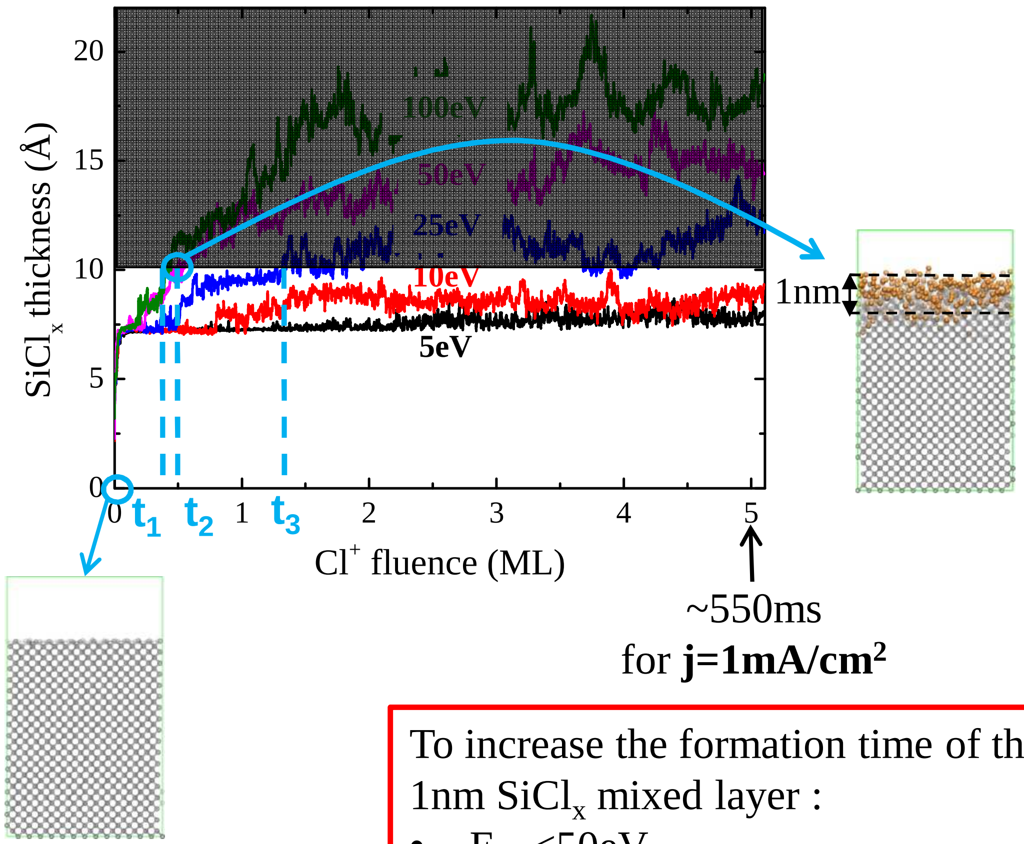
- ❑ Etch with low energy ions
- ❑ Etch in pulsed plasmas
- ❑ **Control the dynamics of the reactive layer formation ?**

⇨ 2 steps

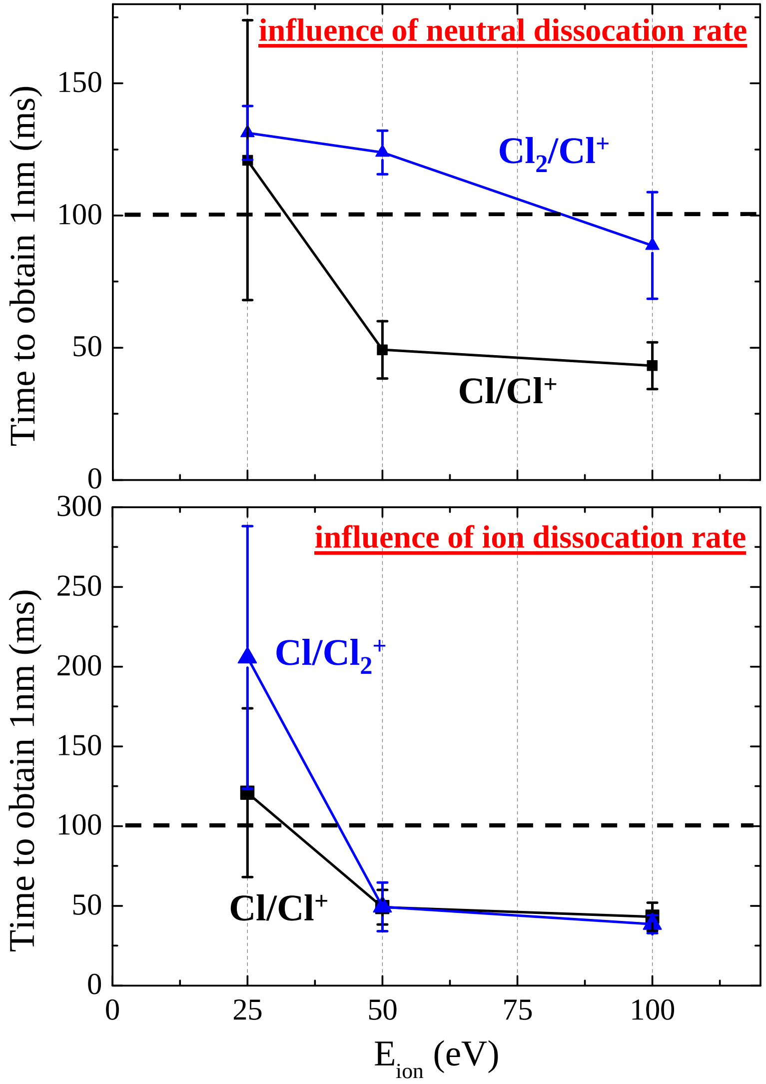
Dynamics of the $SiCl_x$ mixed layer formation

Step I : stop the formation of the SiClx layer at 1nm

Cl/Cl⁺ bombardment - $\Gamma_n/\Gamma_i=100$



~550ms
for **j=1mA/cm²**

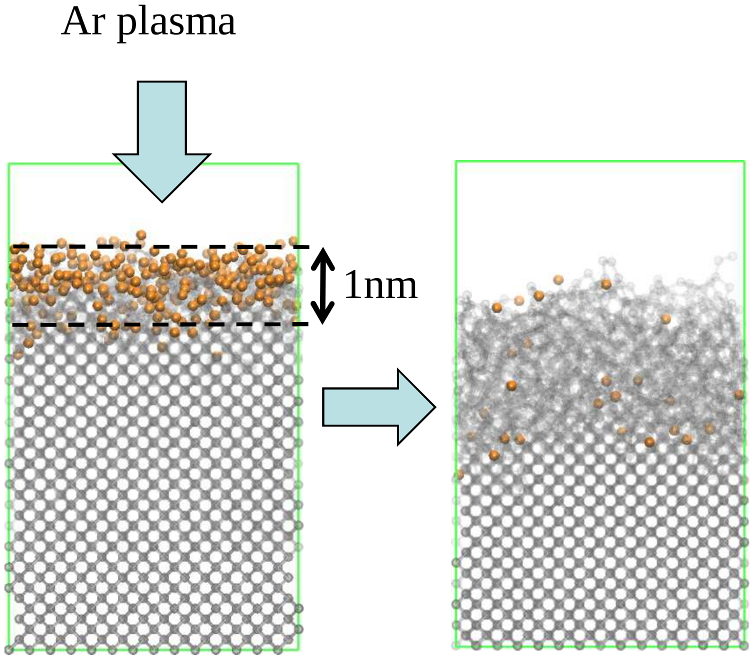


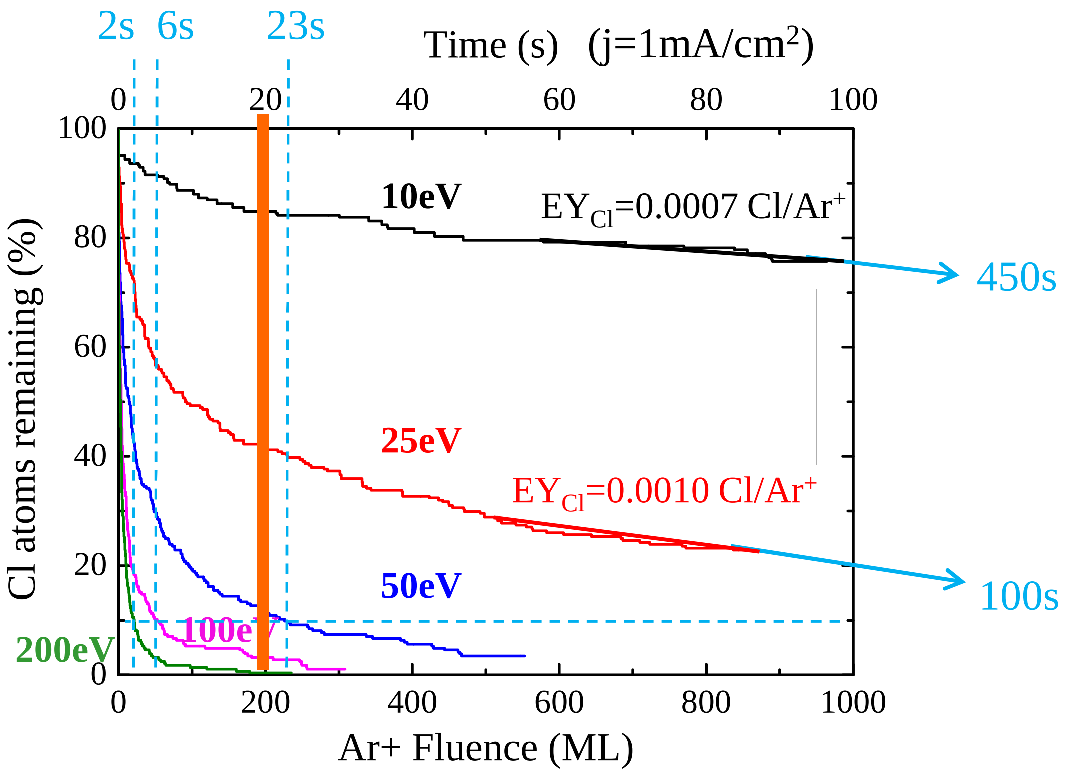
To increase the formation time of the 1nm $SiCl_x$ mixed layer :

- $E_{ion}<50eV$
- Use a less dissociated plasmas

SiCl$_x$ removal under Ar plasma

Step II : remove the 1 nm SiCl$_x$ layer





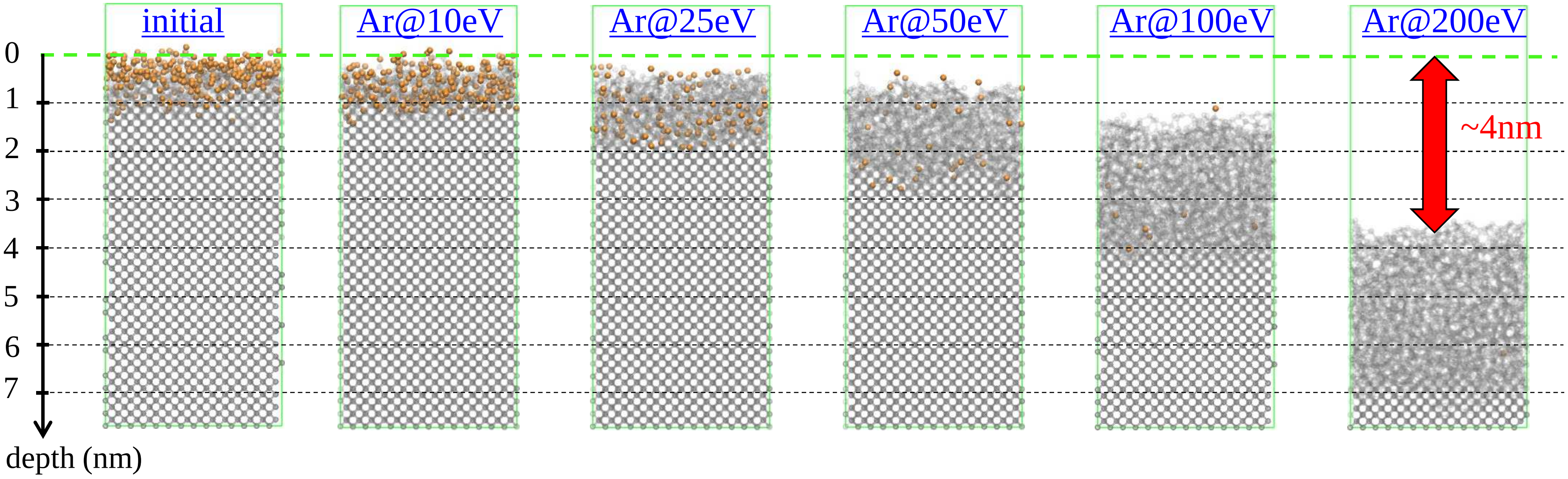
- Quick Cl removing at E$_{ion}$>50eV
- Time can be reduced by increasing j
- Etch yield and plasma induced damage ↗

Step II – Si etching and surface induced damage

Ar^+ fluence : 200ML ⇔ 20ms for $j=1mA/cm^2$

Steady state for $e_{amorphe}$ & etch yield

Cl removing efficiency ↗

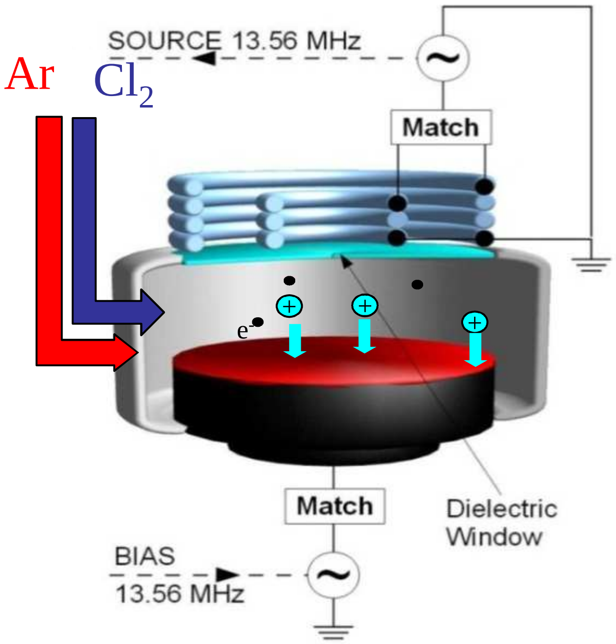


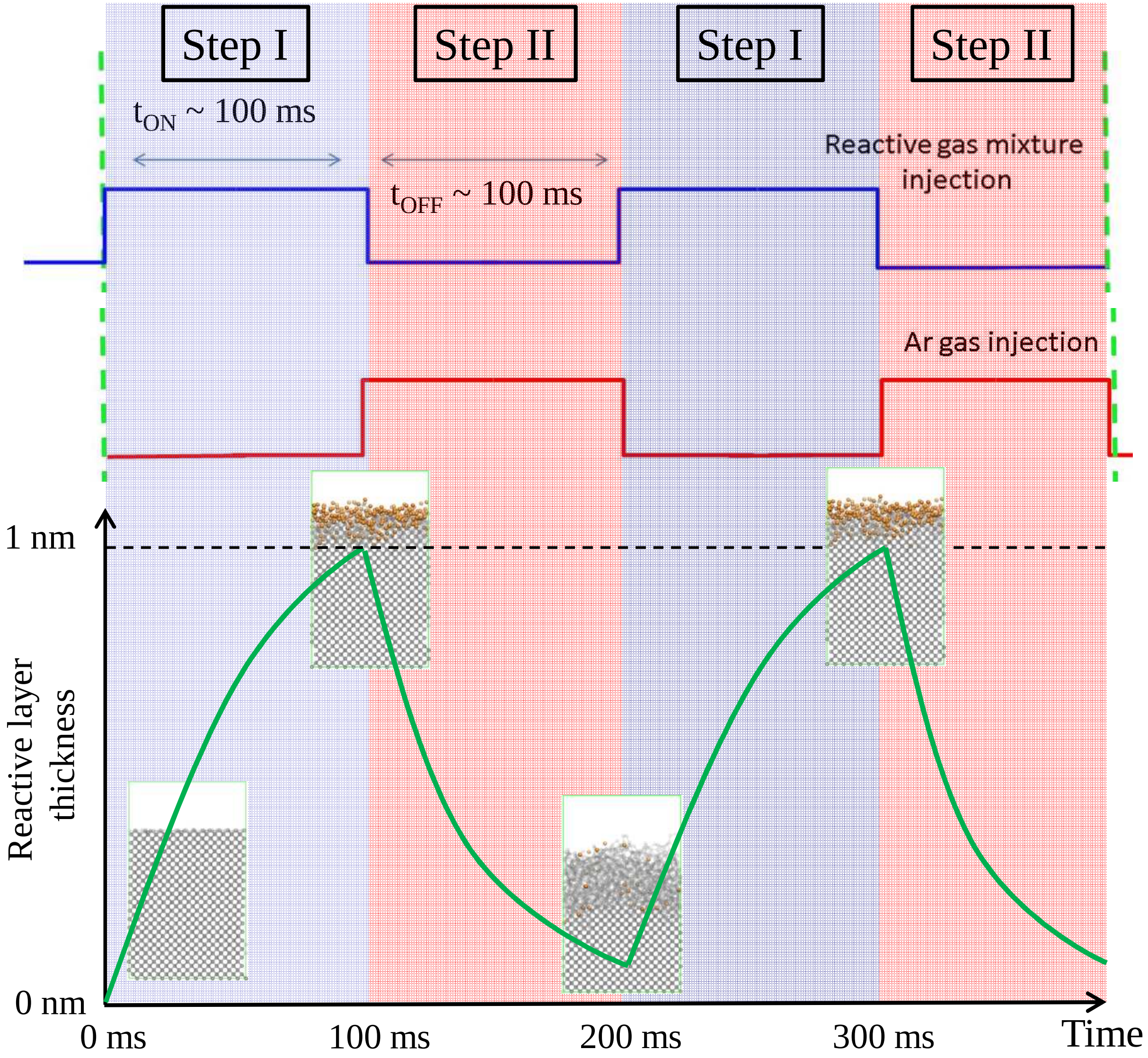
Si etching ↗

Amorphous layer thickness ↗

Best process : compromise Cl removing vs. amorphisation/Si etching => 25eV ?

New gas pulsing technology (τ ~ 100ms)

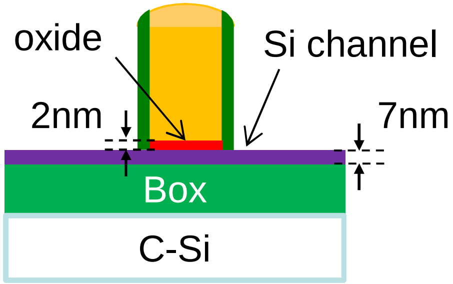




Conclusion

❑ **Challenge :** etching of ultrathin films without damaging the active layers of advanced transistors

- ➢ reduce plasma induced damages
- ➢ control the etch rate



❑ **Technolgies :**

- LowTe plasmas :
  - ✓ $E_{ion} < 5eV$ => mixed layer thickness ↘
    => etch yield ↘ but very low
- Pulsed plasmas :
  - ✓ lower average E_{ion}
  - ✓ Control of plasma dissociation via the DC :
    dissociation ↗ => mixed layer thickness ↘
    => etch yield ↗
- Gas pulsing ?
  - ✓ control of the mixed layer thickness
  - ✓ patent pending, still under study