March 27, 2023. ACS Fall Meeting, Indianapolis

Li deposition mechanisms:

a perspective by combining imaging with theoretical analysis

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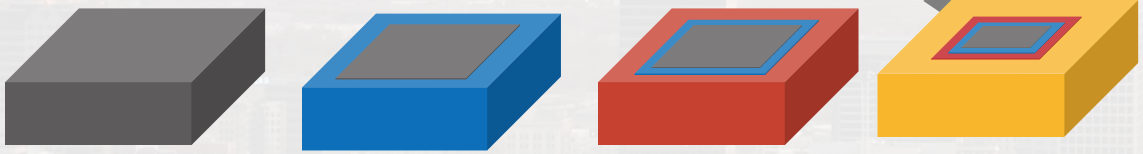

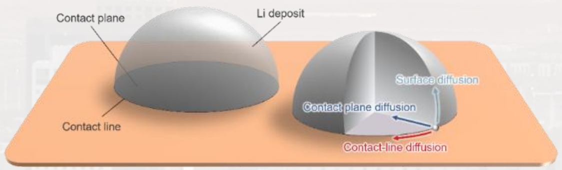

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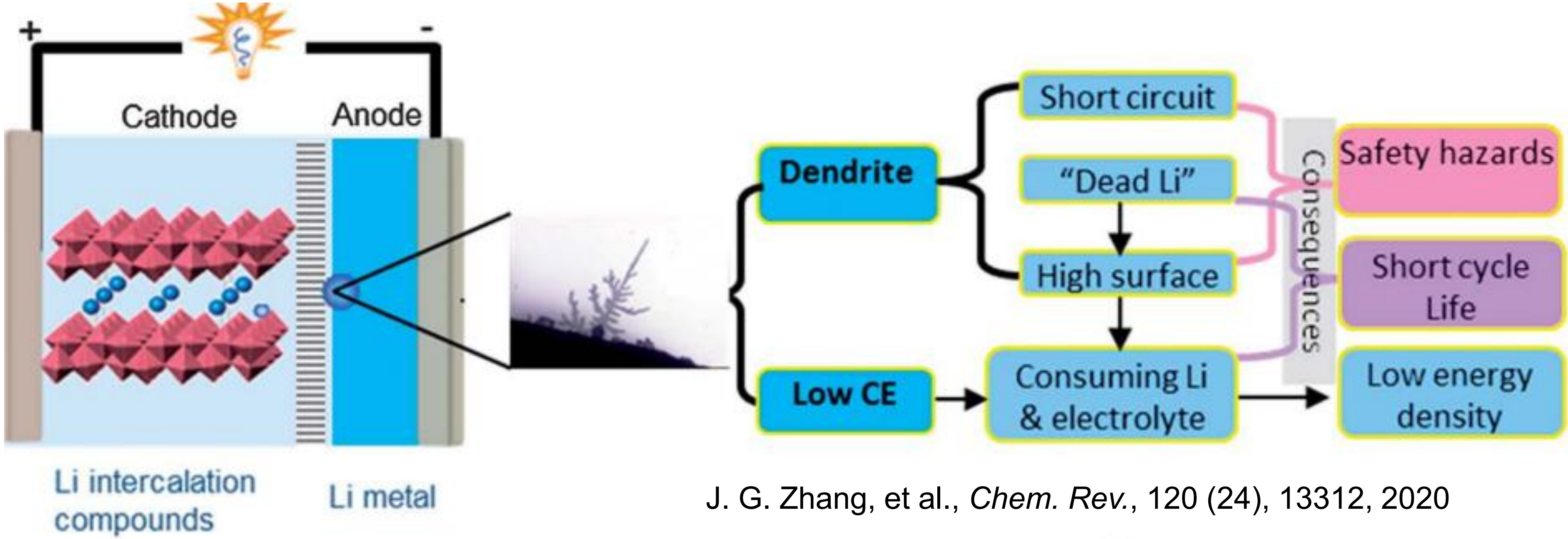
@TaoGao2020

Li metal anode: motivation and challenges

Motivation: High energy batteries, i.e., Li-S, Li-O_2, Li-NMC

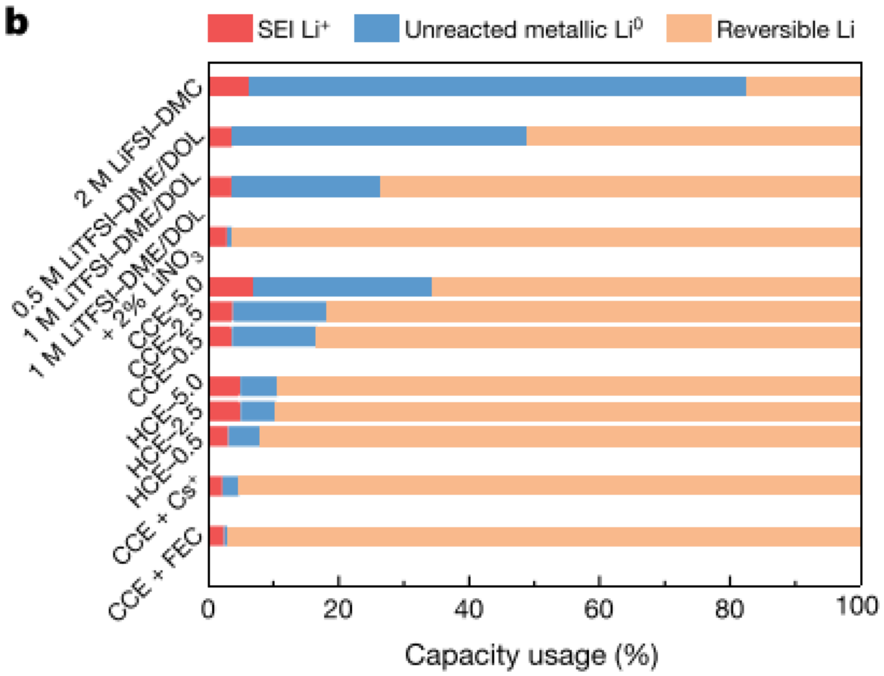


J. G. Zhang, et al., *Chem. Rev.*, 120 (24), 13312, 2020

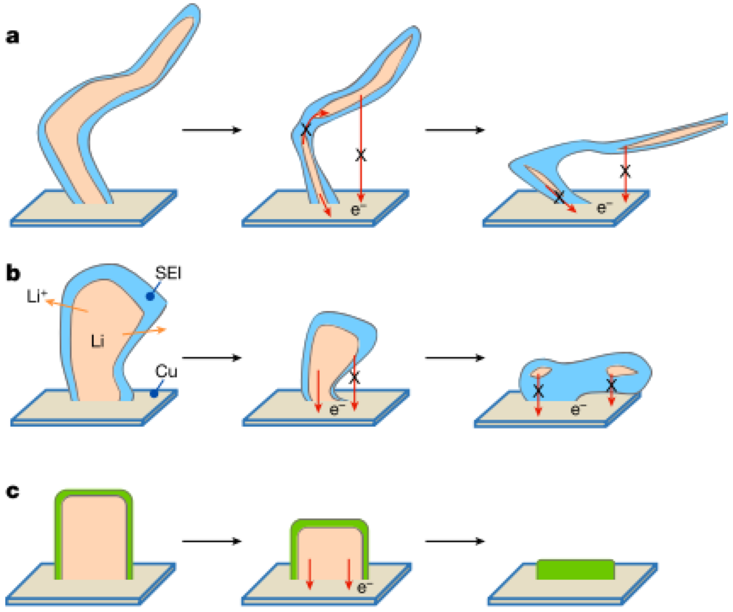
Challenges:

- Dendrite formation
- Low columbic efficiency (CE)
  - SEI formation
  - Dead Li

What prevents CE from reaching 100%?



Y. S. Meng et al, *Nature* **2019**, *572*, 511.

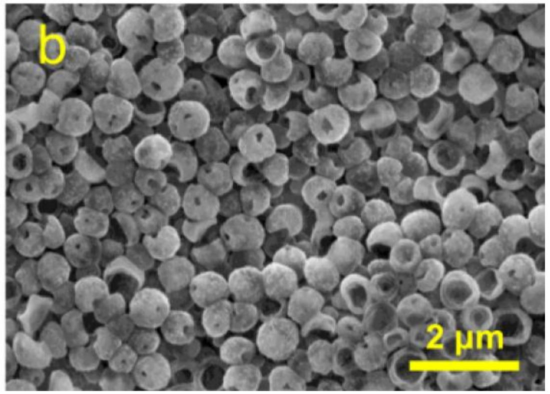


J. G. Zhang, et al., *Chem. Rev.*, 120 (24), 13312, 2020

- **Dead Li** is the major cause
- **Morphology matters**: skinny deposits with high surface area have more dead Li
- **Ideal** Li deposits:
  - Large granular size with low surface area
  - Uniform SEI to allow uniform dissolution

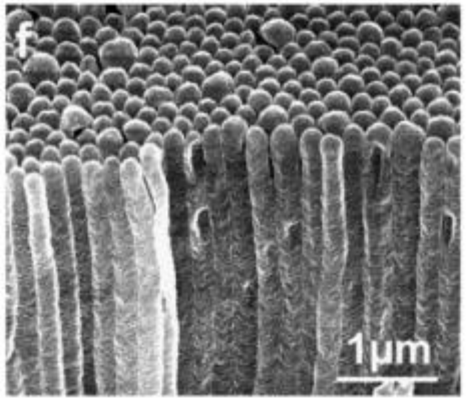
Many different morphologies observed

(hemi-)sphere



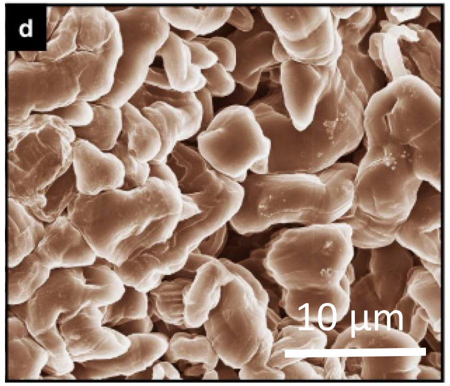
Y. Cui et al, *Nano Lett.*, 2017, 17(2), 1132

compact nanorods



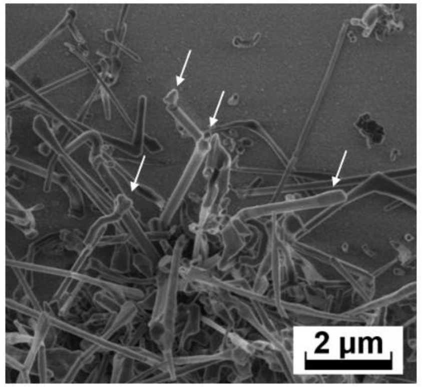
J. G. Zhang et al, *Nano Energy* **2015**, *15*, 135.

granular



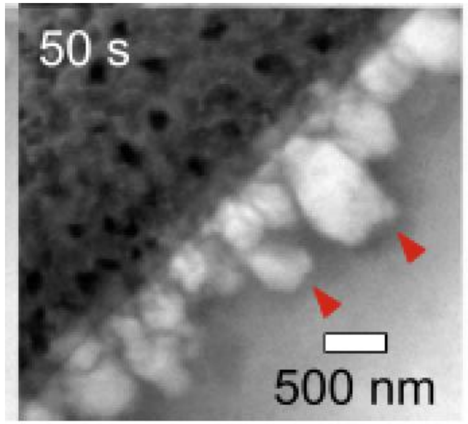
J. G. Zhang et al, *Nat. Commun.* **2015**, *6*

whisker



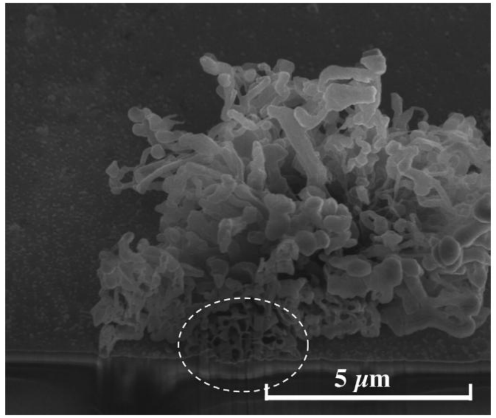
R. Monig, *J. Power Sources* **2014**, *261*, 112.

Eden-cluster



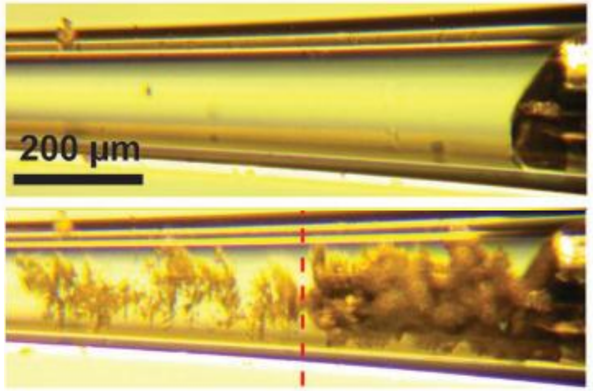
M. Z. Bazant, J. Li et al, Nano Energy **2017**, *32*, 271.

bushes



R. Monig et al, *Electrochim. Acta* **2014**, *136*, 529

tip-splitting dendrite

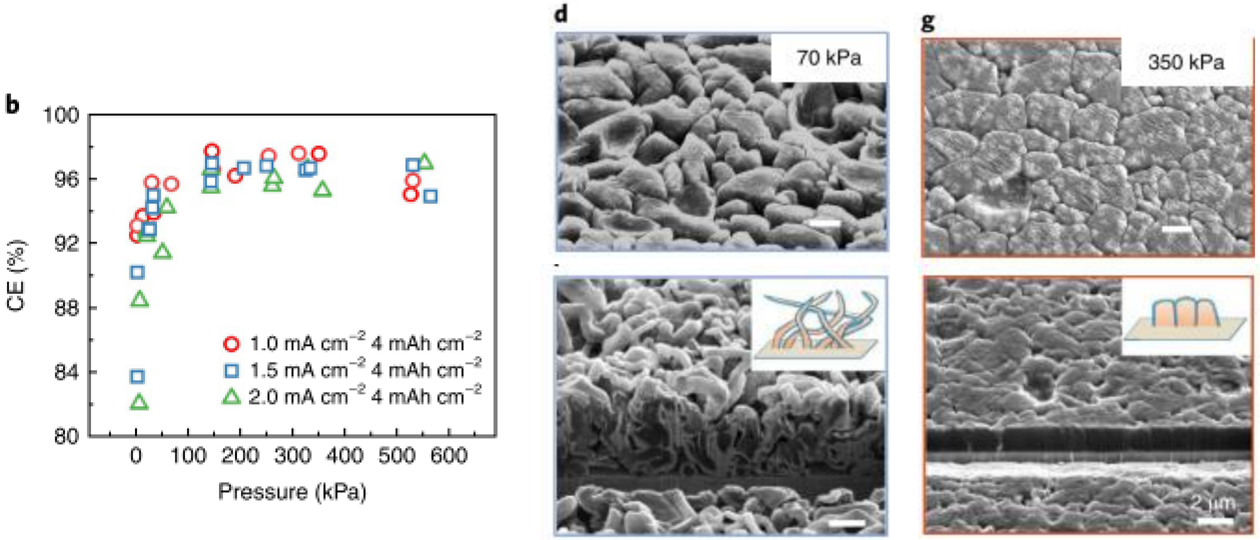


P. Bai, M.Z. Bazant et al, *Energy Environ. Sci.* **2016**, 13.

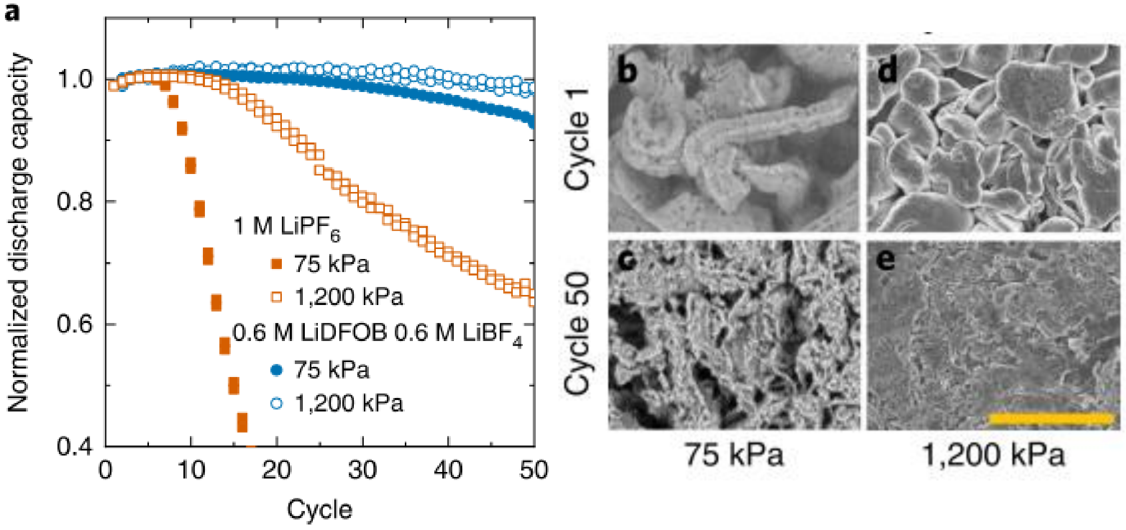
Fundamental Questions

- How do **different morphologies** form?
  - How do various **factors** regulate morphological evolution?
    - P, T, J, electrolyte, substrate…
- How does **morphology** correlate with **CE** and **safety**?

in-situ experiment can monitor the deposition in real-time



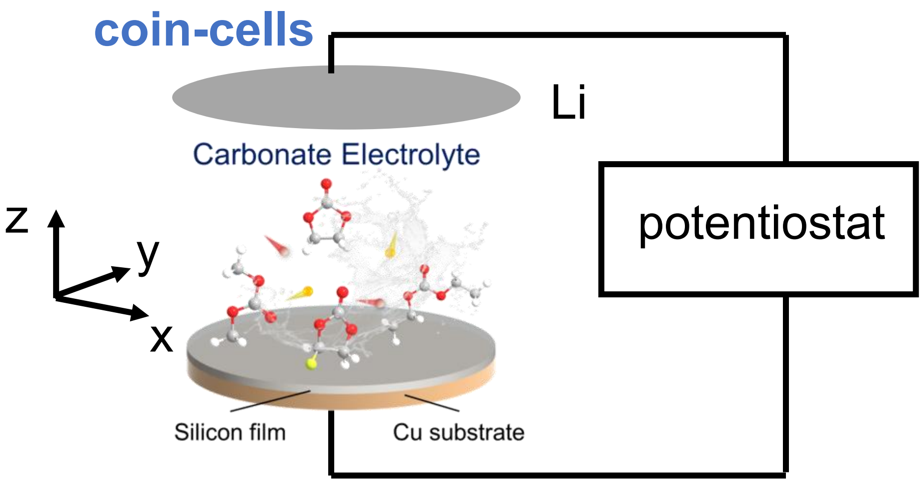
S. Y. Meng et al., Nature Energy, 2020,6,987



J. Dahn, et al, *Nature Energy*, 2019, *4*(8), 683–689.

ex-situ study can better reproduce the actual operation condition

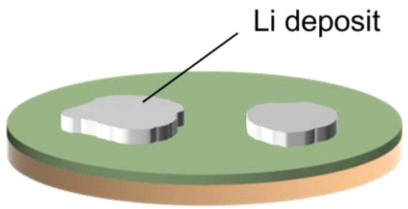
Ex-situ SEM imaging + theoretical analysis



deposition at different
Current (I)
Capacity (Q)
Pressure (p)
Temperature (T)

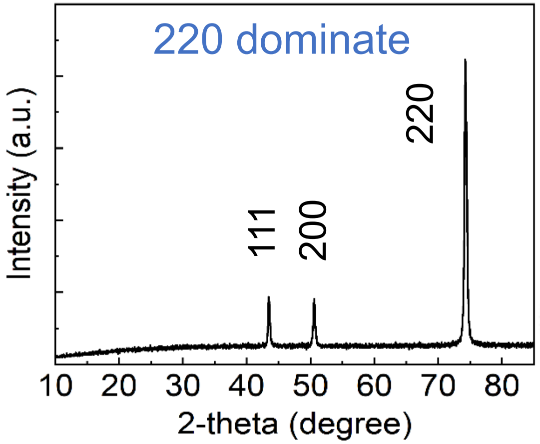
disassemble
within 5 mins

SEM imaging
+
theoretical analysis

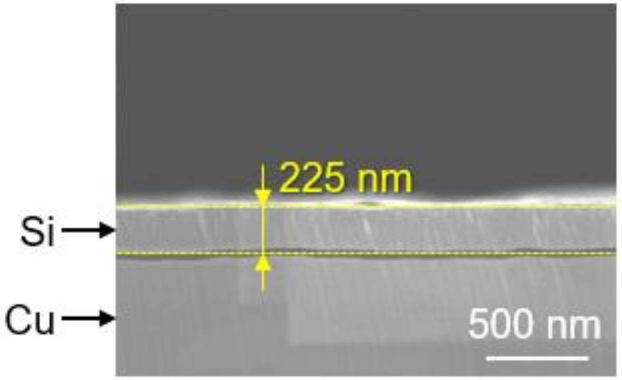


Electrolyte: 1M $LiPF_6$ in EC:DEC:DMC (1:1:1 vol) + 5wt% FEC

Cu: Commercial foil



Si: amorphous nano-film on Cu



Scope:

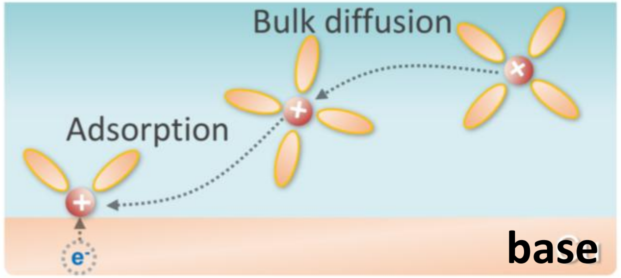
1) how Li **nucleates** and **grows**?
2) how does the **morphology** affect **CE** and **safety**?

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

Physico-chemical processes in Li deposition

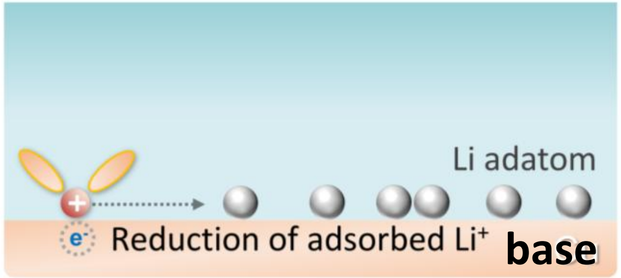
Bulk diffusion in the electrolyte

long-range, 10^2 µm, D_{elyte}



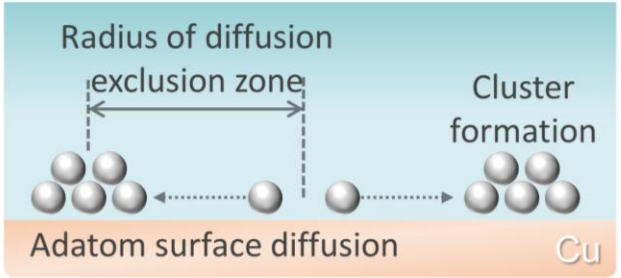
Reaction

de-solvation, electron transfer, J_0



Surface diffusion

Short-range, nm, $D_{elyte\text{-}cu}$

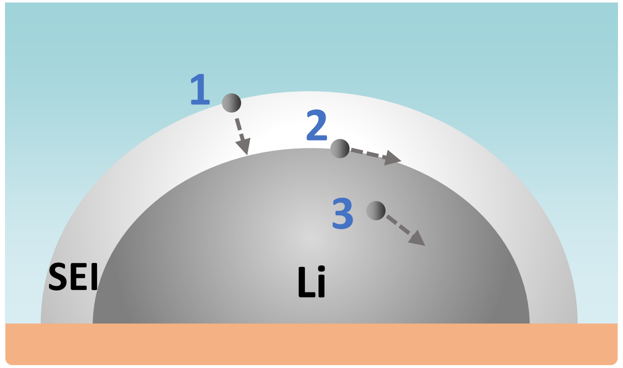


nucleation

growth

1. transport through SEI

short-range, 10 nm, D_{SEI}



2. Interface diffusion

short-range, nm, $D_{SEI\text{-}Li}$

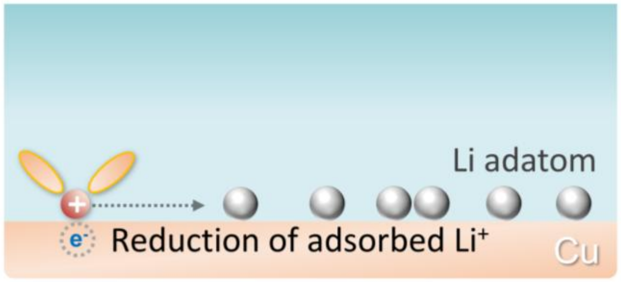
3. bulk diffusion in Li

short-range, nm, D_{Li}

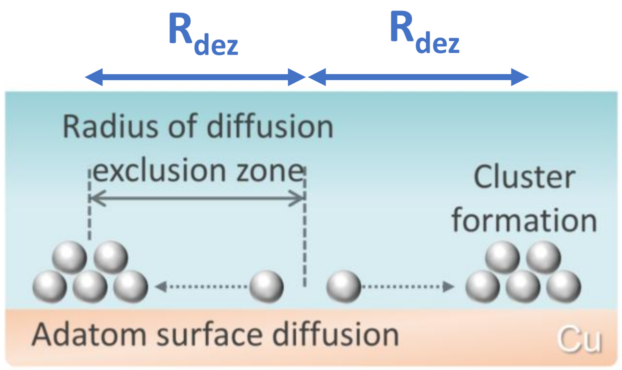
J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

Nucleation: theory

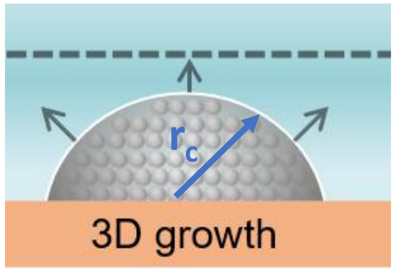
Classical nucleation theory*

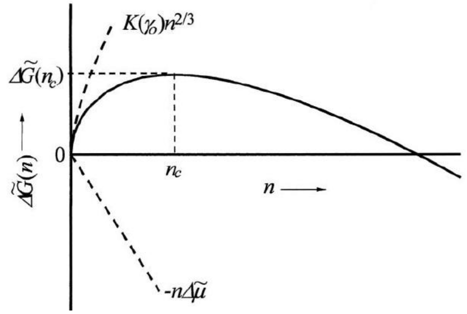


Reduction of Li⁺ to form adatom



- Adatom surface diffusion
- Cluster formation





Stable nuclei forms once passing r_c

Thermodynamics

$Li^{+}+e^{-} \dashrightarrow Li^{0}$

$$\underbrace{r^3[(\mu_{Li+}+\mu_{e-})-\mu_{Li0}]}_{\text{driving force}}=\underbrace{r^2\sigma+\text{strain}}_{\text{barrier}}$$

Larger overpotential
→larger driving force
→more nuclei

$$N_{crit} = \frac{8BV_m^2\sigma^3}{27(ze|\eta|)^3}$$

Mass transport

Higher $D_{elyte\text{-}cu}$ ➡ Large R_{dez} ➡ less nuclei

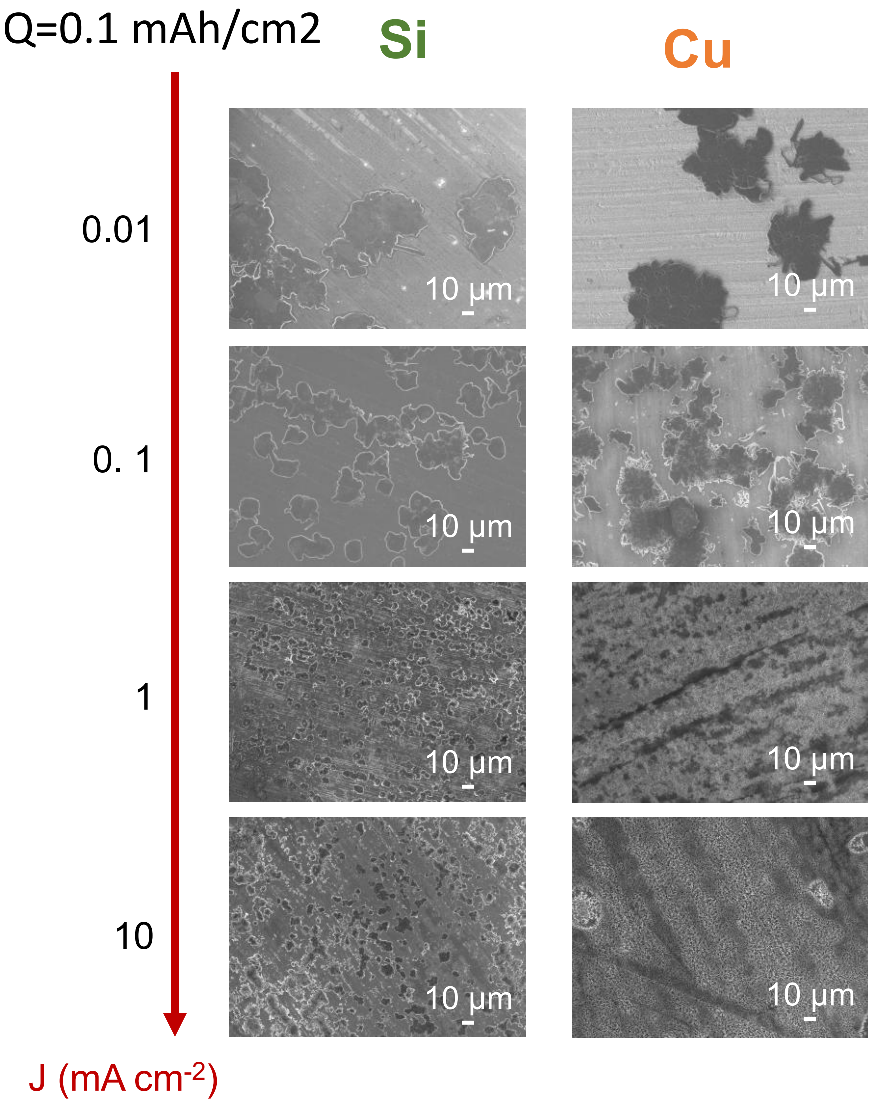
$D_{SEI\text{-}cu}$ If considers SEI

*Budevski, E. B., Staikov, G. T. and Lorenz, W. J. (1996) *Electrochemical phase formation and growth: an introduction to the initial stages of metal deposition*. John Wiley & Sons.

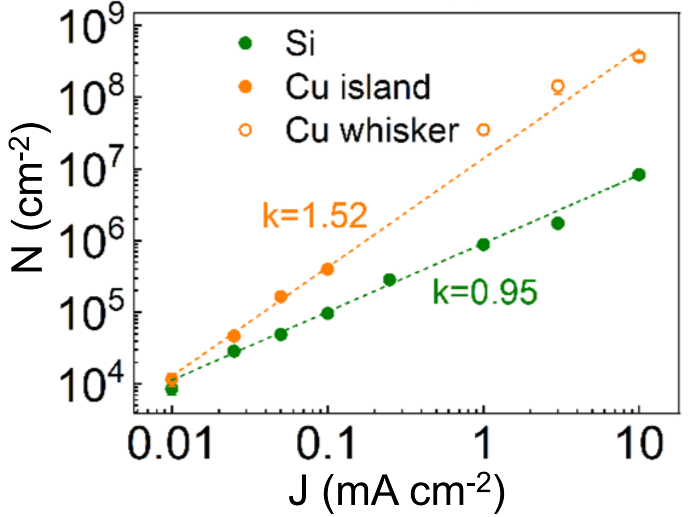
*Gamburg, Y. D. and Zangari, G. (2011) *Theory and practice of metal electrodeposition*. Springer Science & Business Media.

*Milchev, A. (2002) *Electrocrystallization: fundamentals of nucleation and growth*. Springer Science & Business Media.

Nucleation: dependence on current

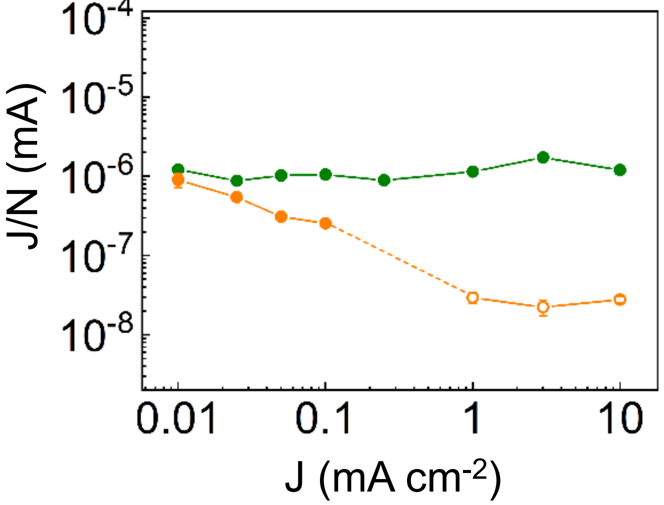


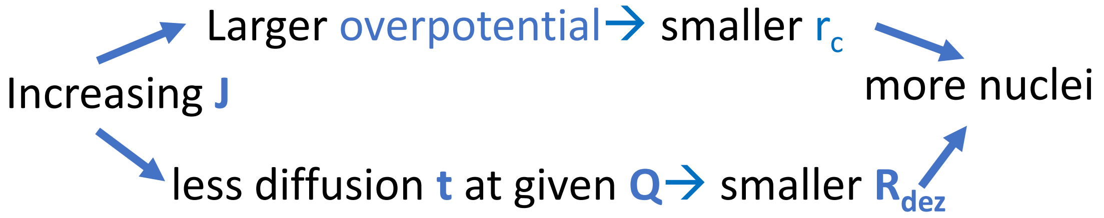
N_{si}~J N_{Cu}~$J^{1.5}$



J/N_{si} constant

J/N_{Cu} decrease





Increasing J

Larger overpotential→ smaller r_c

less diffusion t at given Q→ smaller R_{dez}

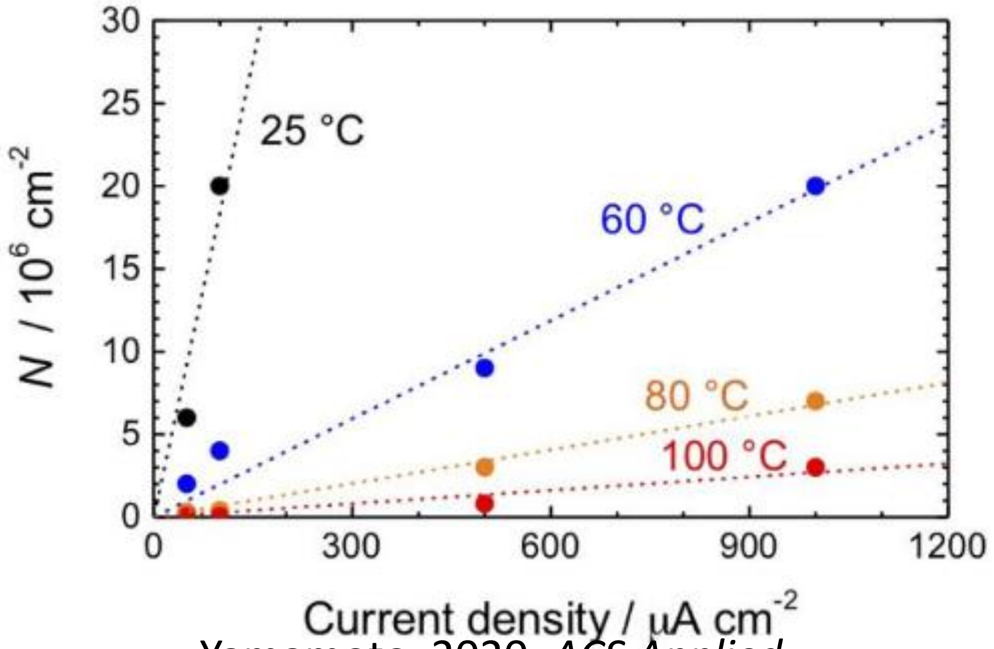
more nuclei

- **Si responds to J by proportionally increasing N. Current per Li island is invariant at given T**
- **for Si, nucleation is governed by surface diffusion: N~ R_{dez}^{-2}, R_{dez}~ $(Dt)^{0.5}$, t~$J^{-1,}$ so N~D^{-1}J**
- **For Cu, nucleation is not.**

J. Liu, **Gao, T,** Wang. F**,** et al, *Energy Environ. Sci.* **2022**.

- Similar linear N~J correlation observed for Li deposition on li-wetting materials

Li deposition at LiPON|Cu interface



Yamamoto, 2020, *ACS Applied Materials & Interfaces*, *207*, 4894.

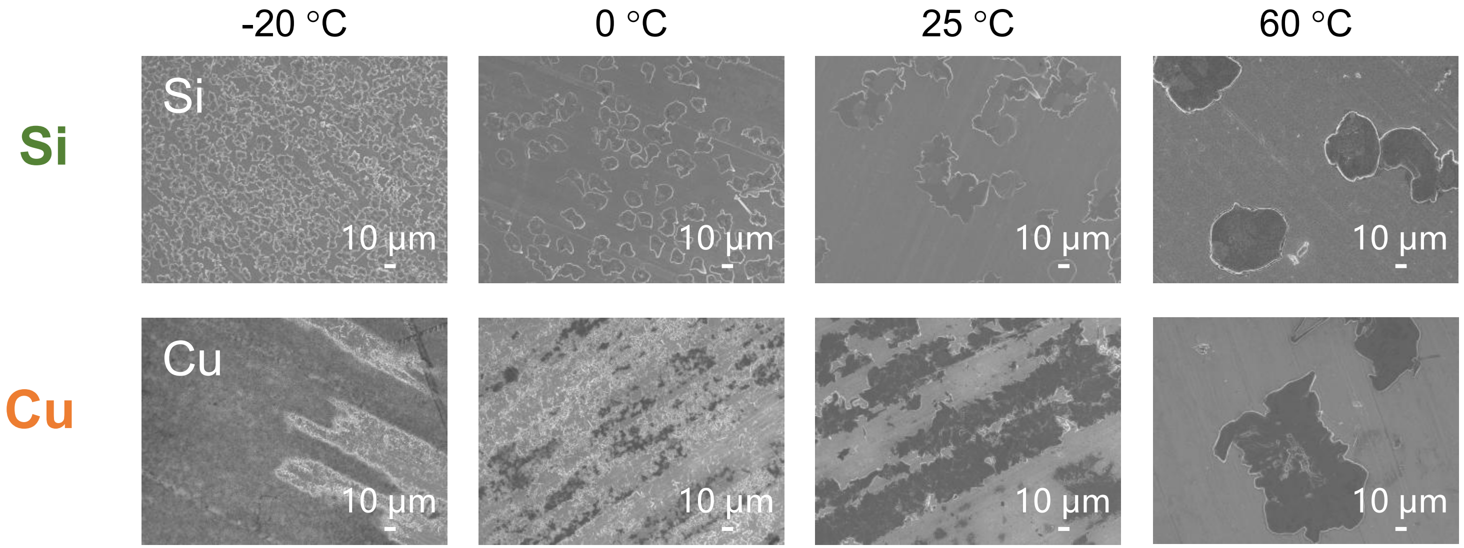
E=0.53 eV > $E_{s,cu} = 0.33\ eV$

Liquid: N=10^4 cm-2 at J=0.025 mA cm-2 and RT
Solid: **N=**10^6 cm-2 at similar condition

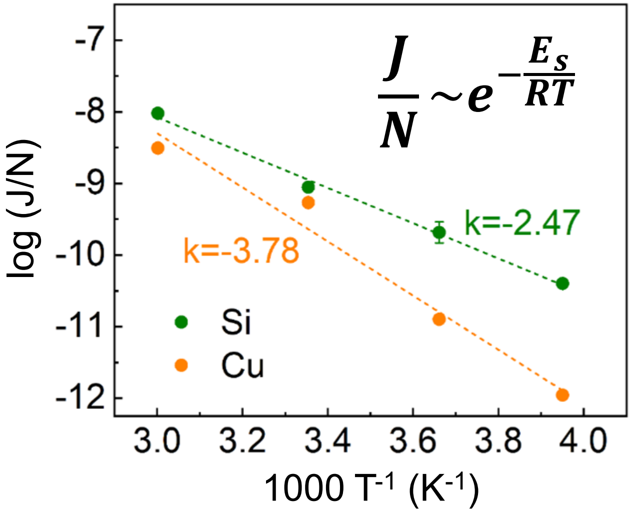
Surface diffusion in liquid electrolyte is easier than solid electrolyte

Nucleation: dependence on temperature

Q=0.1 mAh/cm2, J=0.025 mA/cm2

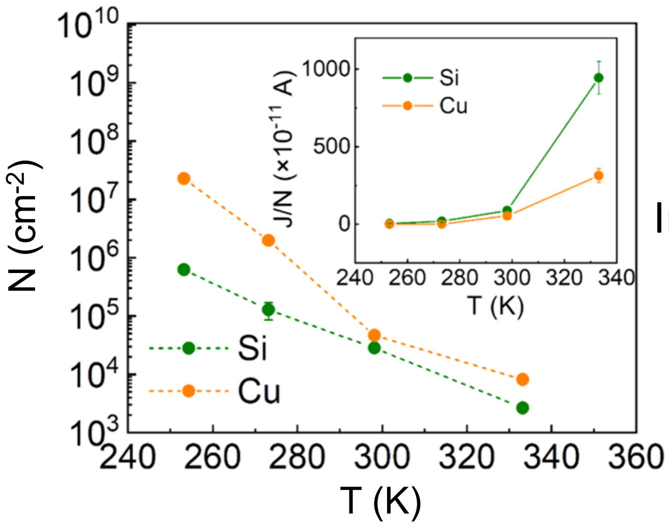


Arrhenius behavior



$E_{s,si} = 0.21\ eV$

$E_{s,cu} = 0.33\ eV$



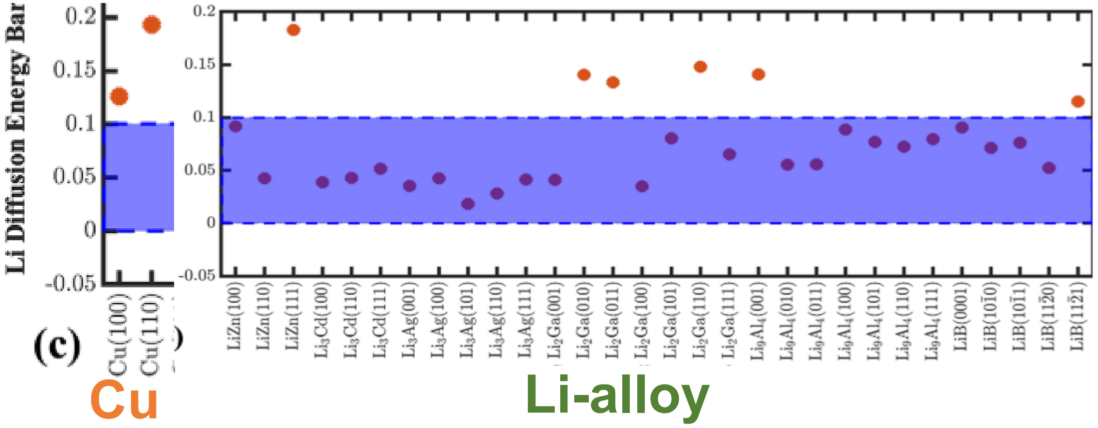
J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

Increasing **T**

less overpotential → l

higher $D_{elyte-cu}$ → larger

surface-diffusion-controlled

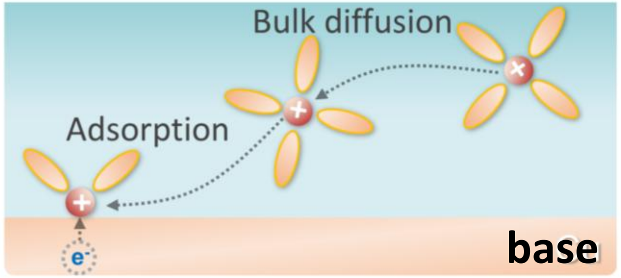


Viswanathan, 2019, *ACS Energy Letters*, 4(12), pp. 2952

Which controls the growth of Li deposit?

Bulk diffusion in the electrolyte

long-range, 10^2 µm, D_{elyte}

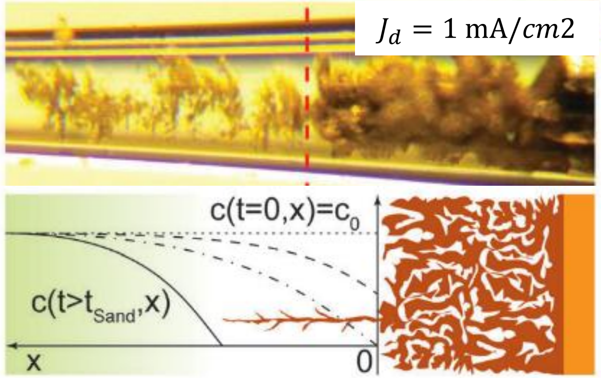


$$J_d = \frac{2cFD_{elyte}}{t_a L}$$

Brissot, *et al.* 1999, *Journal of Power Sources*

unlikely the control step

electrolyte-diffusion-controlled



Bai, Bazant et al, *Energy Environ. Sci.* **2016**

For Li metal batteries, L=25 µm, tortuosity=5

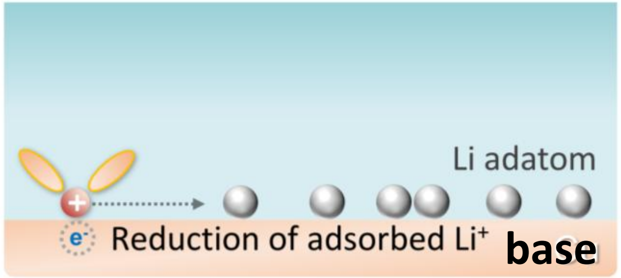
$$J_d = \frac{2cFD_{eff}}{t_a L} = 40\ \mathrm{mA/cm2}$$

For 5 mAh/cm2 loading

40 mA/cm2 ≈ **8C** charging

Reaction

de-solvation, charge transfer, J_0

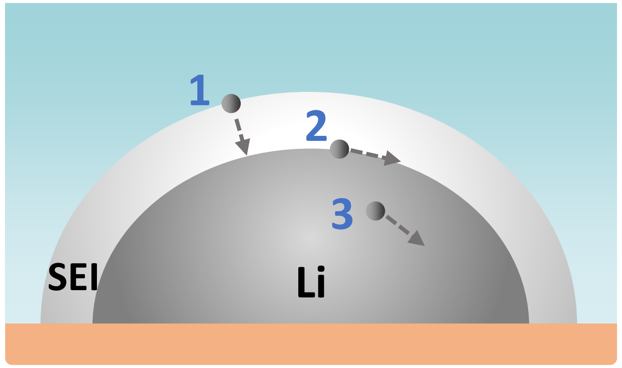


$$J_0 = \frac{RT}{FR_{ct}}$$

$= 0.2\ \mathrm{mA/cm2}$

Bard and Faulkner, 2001, *Electrochemical Methods Fundamentals and Applications*

can be the control step



1. transport through SEI
short-range, nm, D_{SEI}

2. Interface diffusion
short-range, nm, $D_{SEI\text{-}Li}$

3. bulk diffusion in Li
short-range, nm, D_{Li}

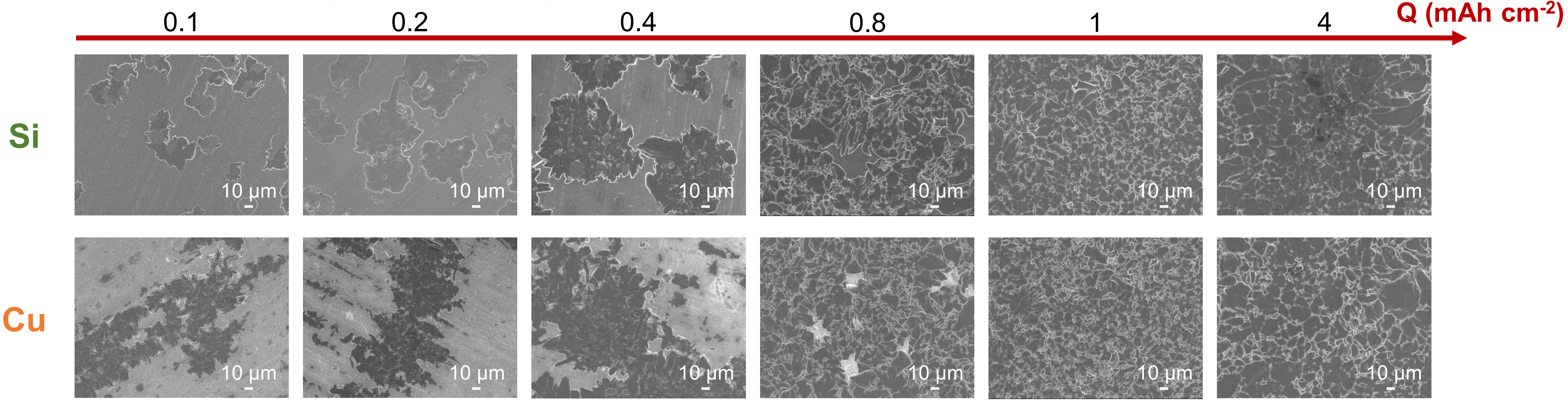
explicit boundary N/A

unknown parameter or length scale

How Li deposit grows under **quasi-eq** ($J \ll J_0 < J_d$) and **rxn-controlled** condition($J_0 < J < J_d$)?

Li deposition under quasi-equilibrium

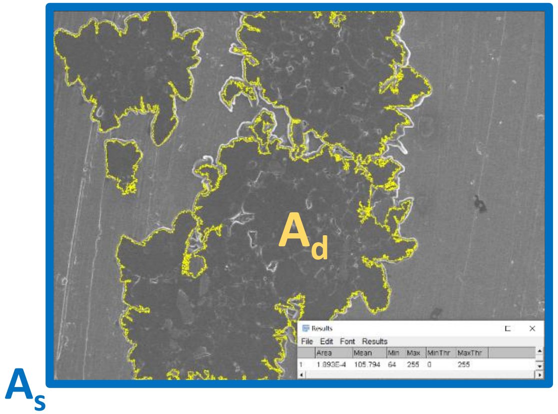
J=0.025 mA/cm2, J_d=40 mA/cm2, J_0=0.2 mA/cm2



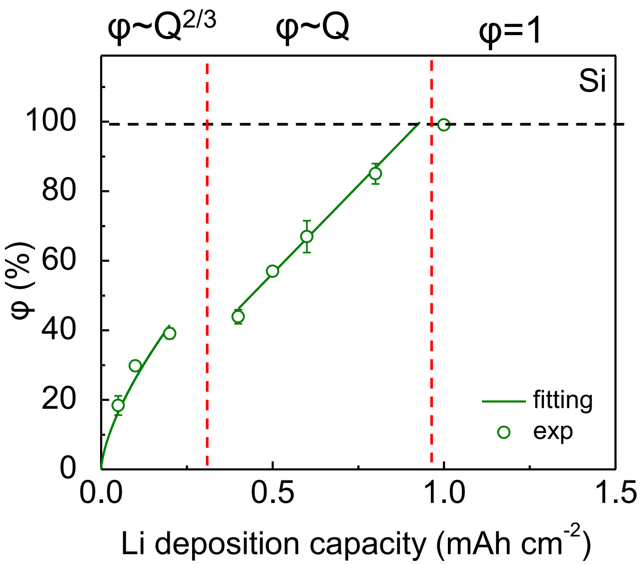
surface coverage

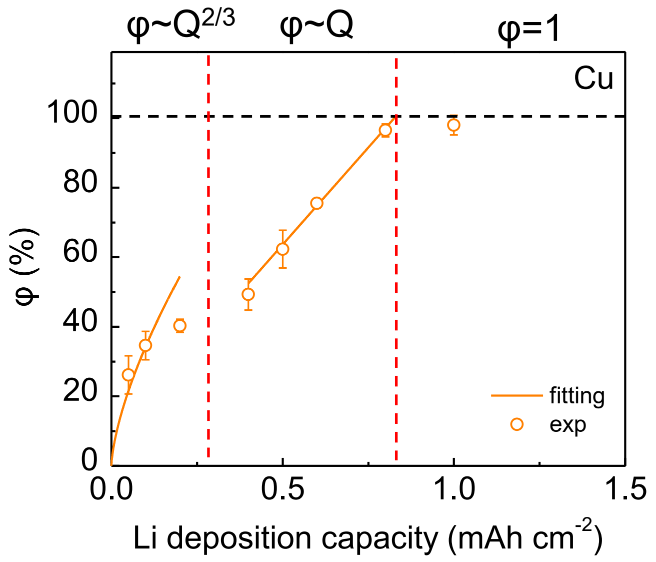
$$\varphi=\frac{A_d}{A_s}$$

Computing in-plane area of deposits (A_d)

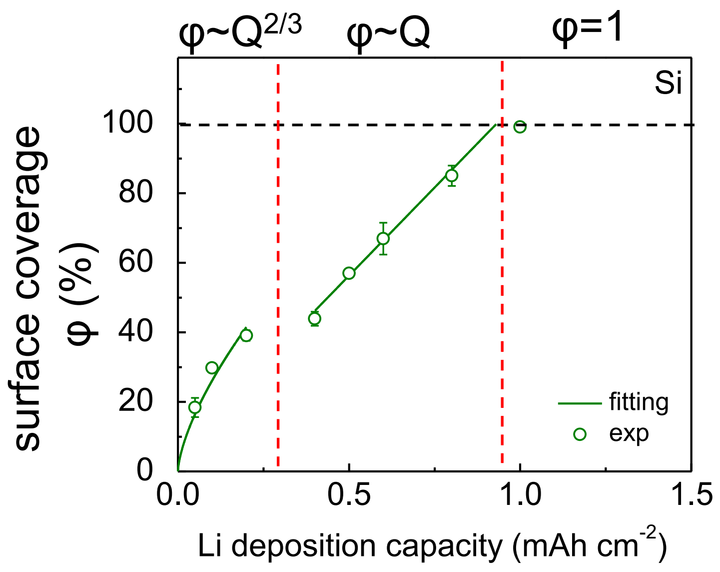


The area of the substrate (A_s)



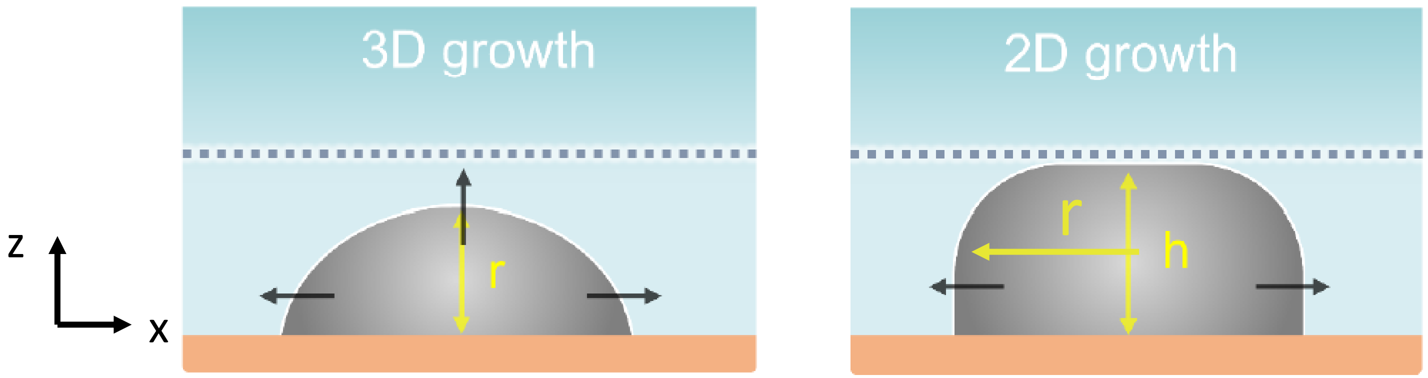


3-stage growth for both Cu/Si under quasi-eq



$\varphi \sim Q^{2/3}$

$\Phi \sim Q$

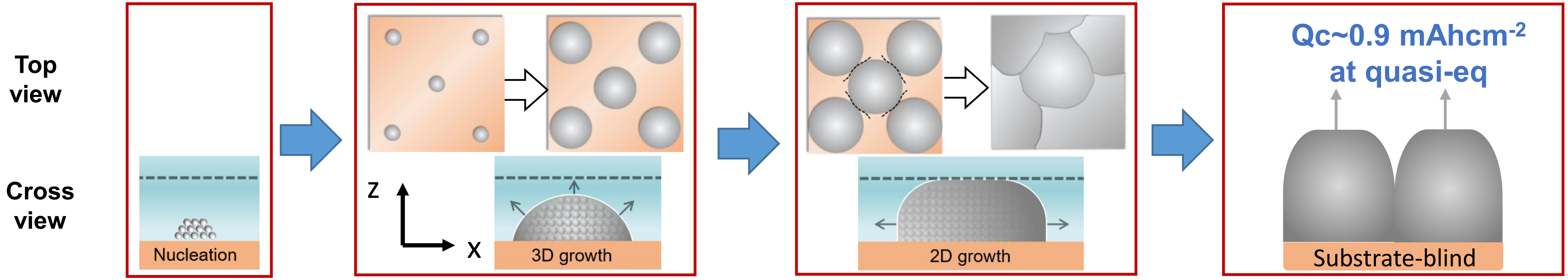


$Q \sim r^3N$, $\varphi \sim r^2N$ → $r \sim Q^{1/3}N^{-1/3}$, $\varphi \sim Qr^{-1}$ → $\varphi \sim Q^{2/3}N^{1/3}$

$Q \sim r^2hN$, $\varphi \sim r^2N$ → $\varphi \sim Qh^{-1}$

φ:surface coverage, r:radius of the deposit, N:density of nuclei, h: height of the deposit

nucleation **Stage 1: 3D growth** **Stage 2: 2D growth** **Stage 3: substrate-blind growth**



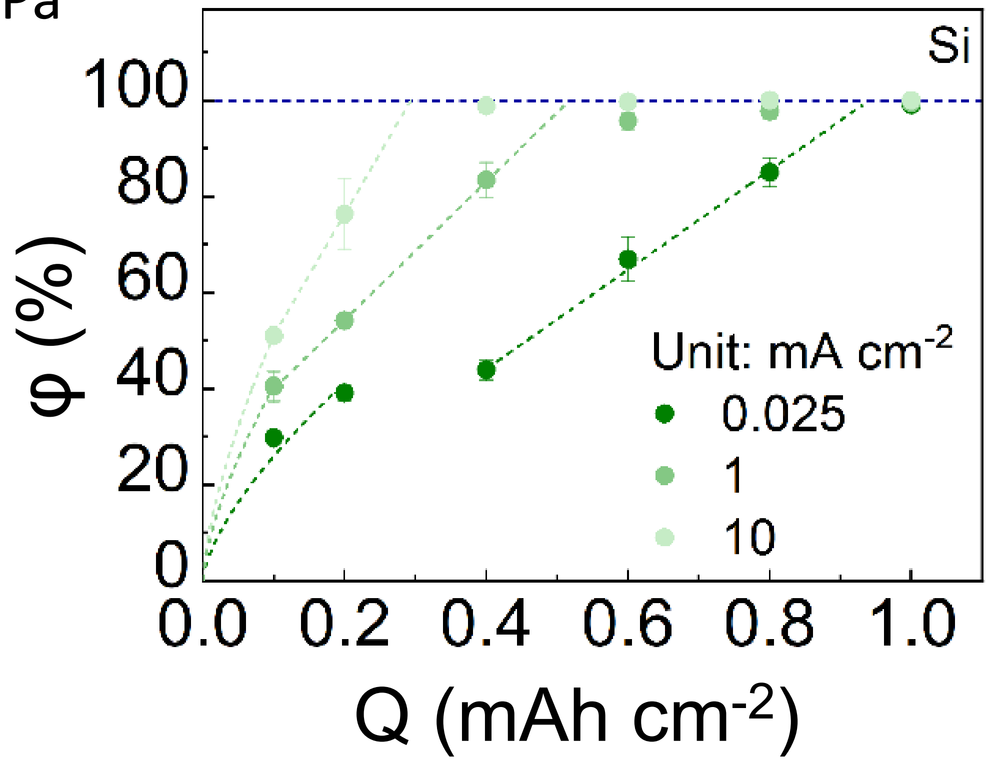
J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

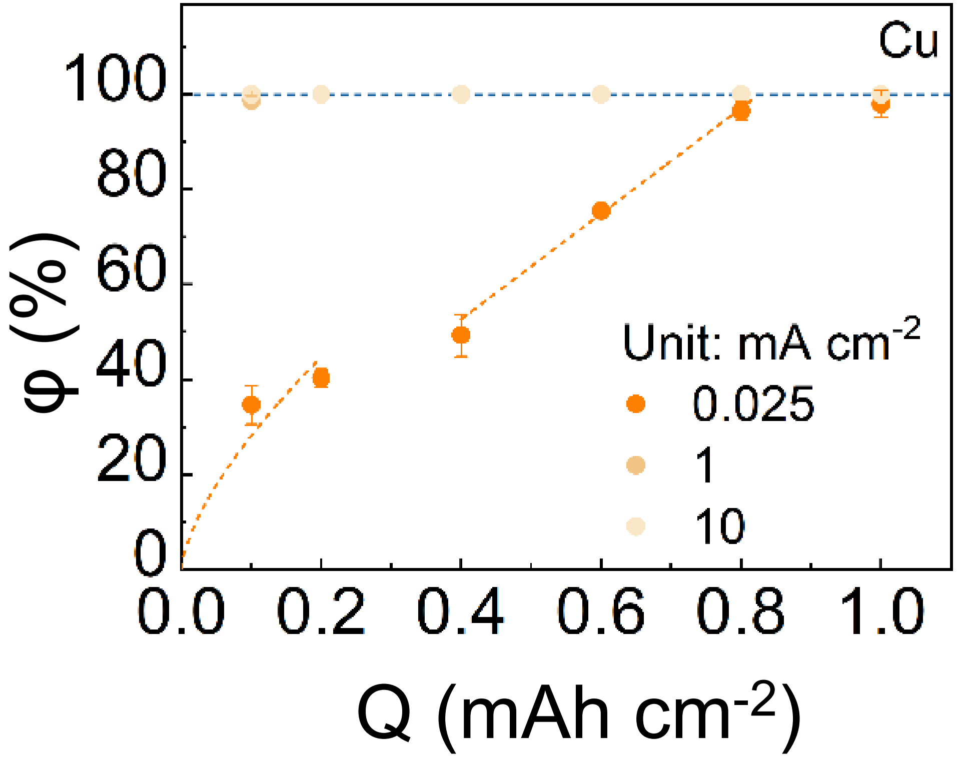
3-stage growth: current effect

Pressure=81.2 kPa

J_d=40 mA/cm2
J_0=0.2 mA/cm2

Current: more nuclei



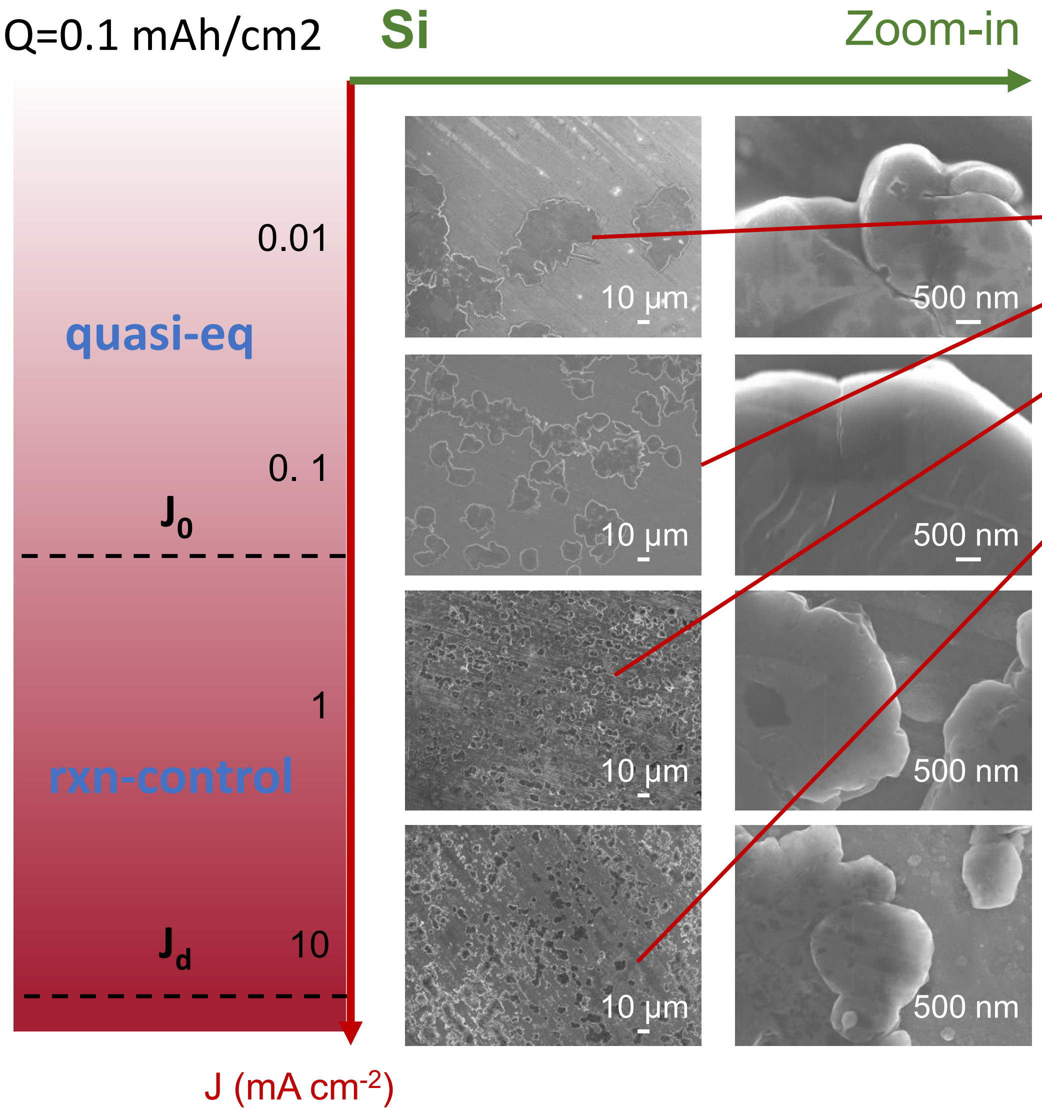


3-stage growth:

- **Si at both quasi-eq and reaction-controlled.**
- **Cu ONLY at quasi-eq**

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

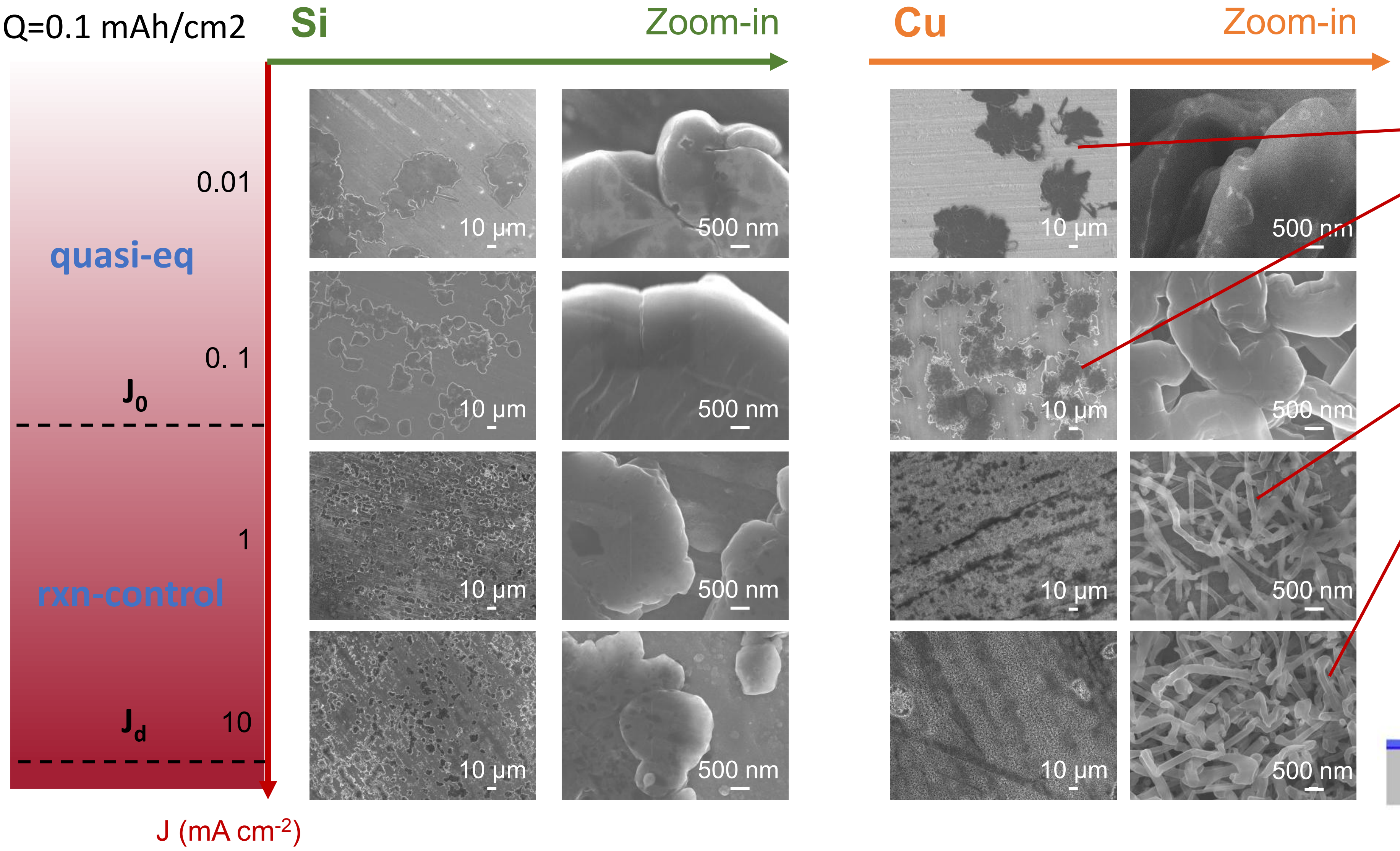
Why Cu differs from Si?



Li deposits as islands

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

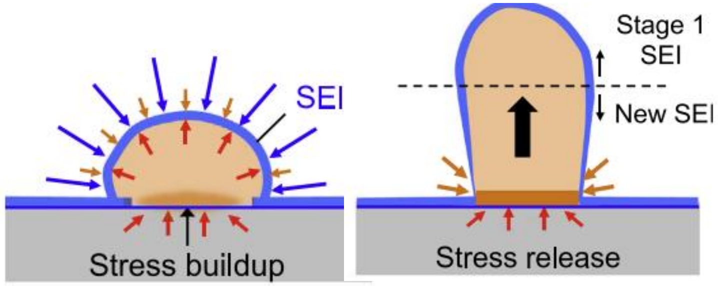
Why Cu differs from Si?



Island with hair

Skinny needle-like deposit
Invariant diameter in length direction

"Whisker"



Bazant, Li et al, Nano Energy **2017**, *32*, 271.

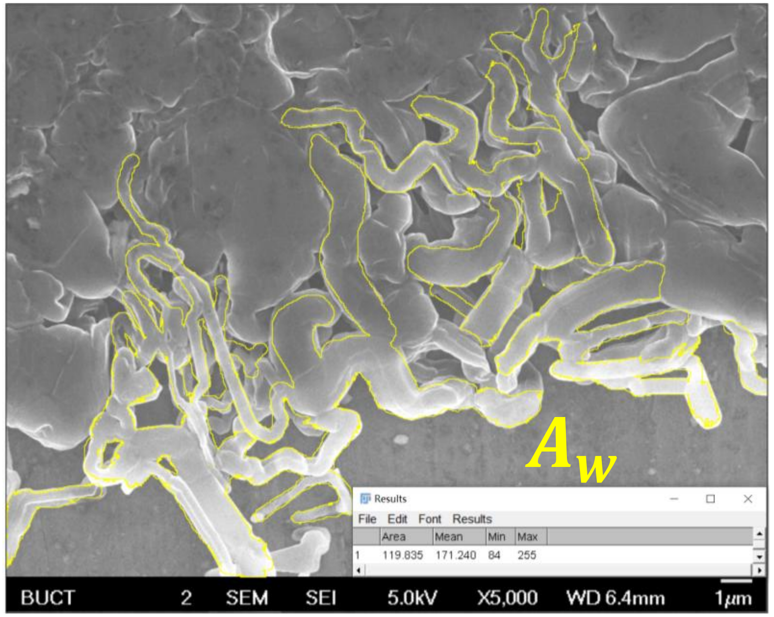
Li whisker tends to form on Cu at high current

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

How prone is Cu to form whiskers?

Whisker:

Li deposit with $l_w/d_w \geq 5$

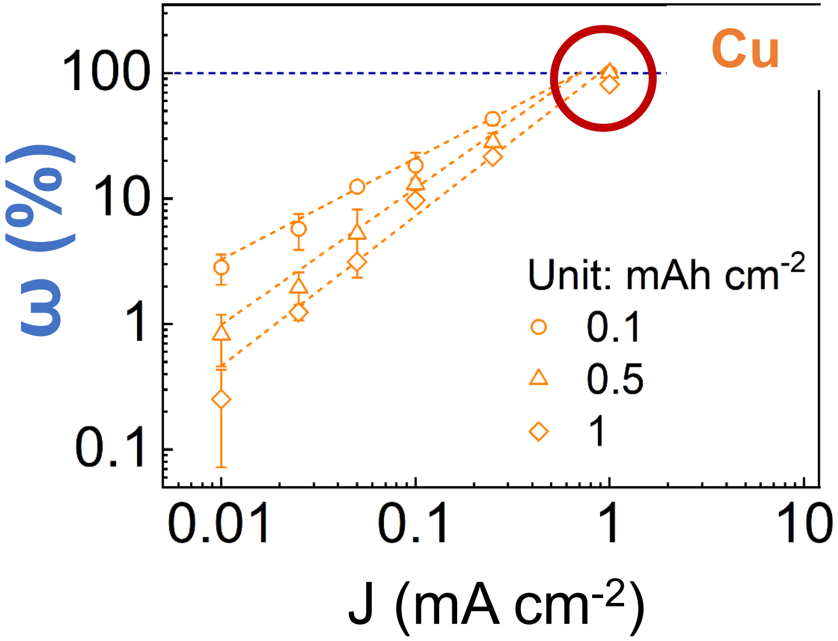


	Area	Mean	Min	Max
1	119.835	171.240	84	255

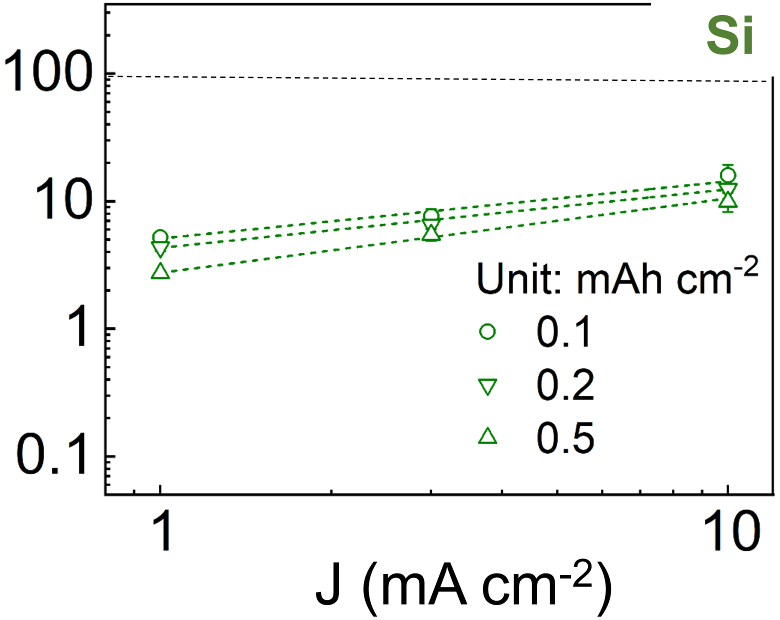
Fraction of whisker

$$\omega = \frac{A_w}{A_d}$$

$J_{w,cu}$=0.79 ± 0.1 mA/cm2



$J_{w,si}$>> **10** mA/cm2



- J_w: intrinsic property of electrolyte-substrate pair
- Can be used to measure how prone to form whisker

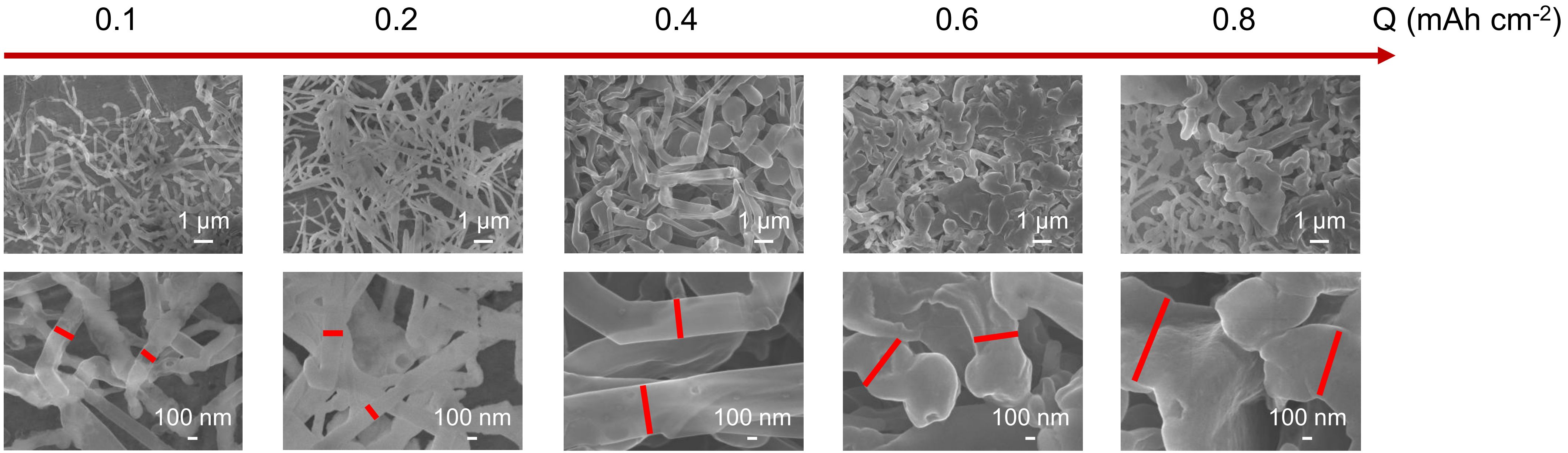
J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

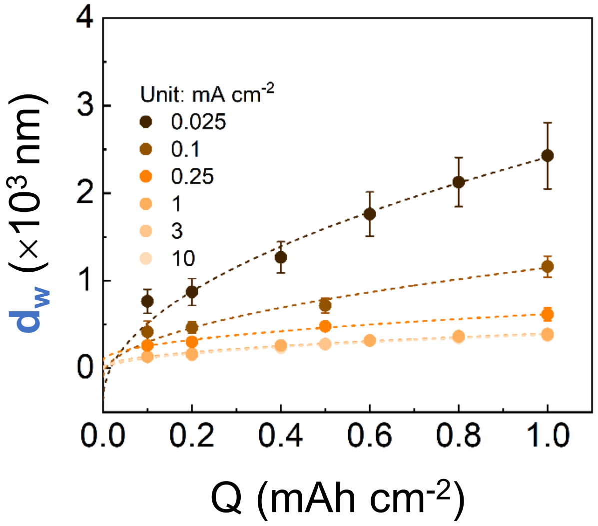
What will happen to the formed whisker?

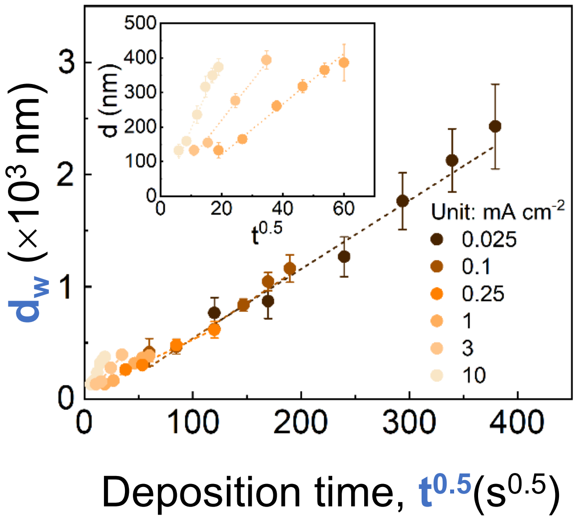
Cu

J=1 mA/cm2

> $J_{w,cu}$







For J≤1 mA/cm2, all curves collapse on the same master curve

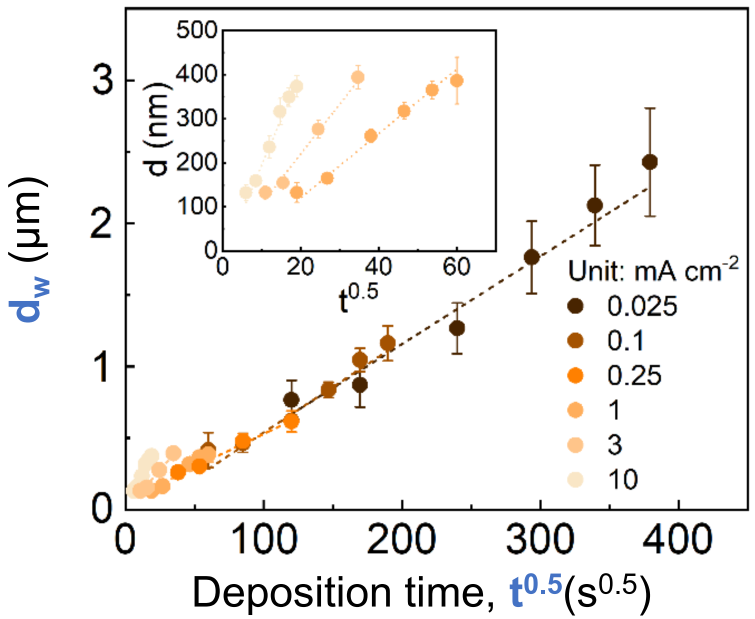
$$d_w \sim t^{0.5}$$

The growth of whisker in the radial direction is **diffusion-controlled**

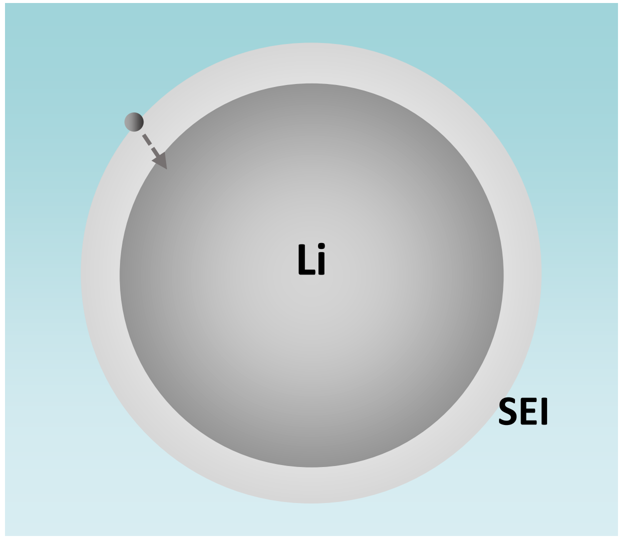
J. Liu, **Gao, T**, Wang. F, et al, *Energy Environ. Sci.* **2022**.

Diffusion of Li through SEI

$d_w \sim t^{0.5}$



Cross-section of whisker



not to scale

transport through SEI

short-range, nm, D_{Li}^{SEI}

Given SEI growth is limited by the diffusion of solvent molecule (D_{sol}^{SEI})*

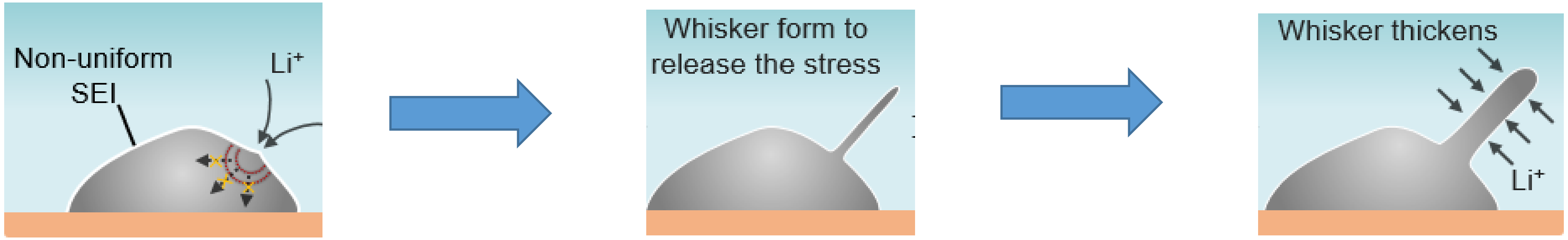
$$d = k \frac{D_{Li^+}^{SEI}}{\sqrt{D_{sol}^{SEI}}} t^{0.5}$$

From the slope of the fitting, D_{Li}^{SEI} calculated to be ~10^{-12} cm^2/s

J. Liu, **Gao, T,** Wang. F**,** et al, *Energy Environ. Sci.* **2022**.

*Pinson & Bazant, 2012. *J. Electrochemical Society, 160,A243*

Whisker: formation and growth



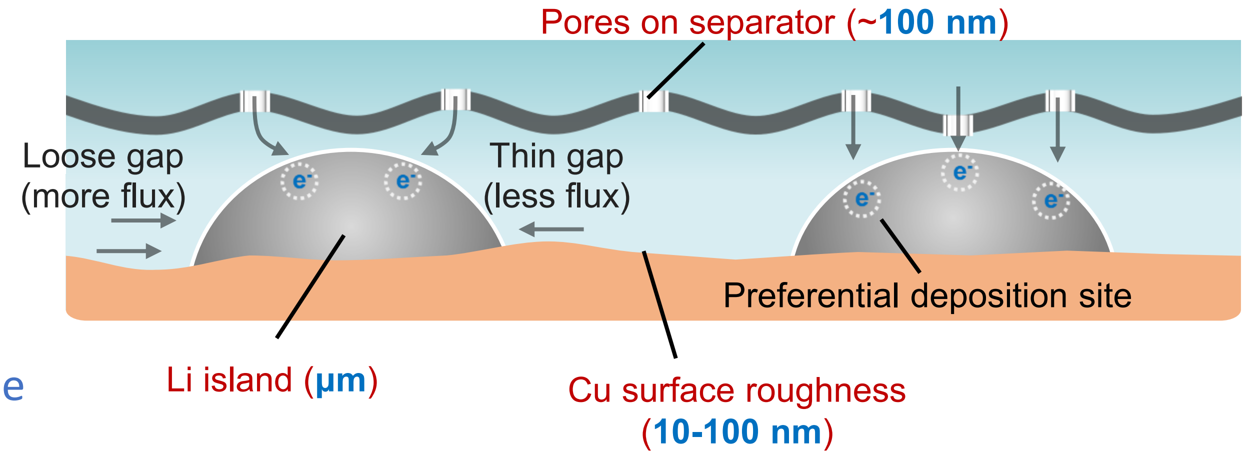
- Non-uniform deposition
- Stress accumulation

- Stress-release by cracking SEI
- Li shoots out by coble creep

- Whisker grows in radial direction (controlled by through-SEI diffusion)

Why non-uniform deposition?

- Non-uniform SEI
  - Potential dependent decomposition of electrolyte
  - Surface defects/impurity on substrate
- Non-uniform local flux
  - Spatially heterogeneous separator/substrate interface

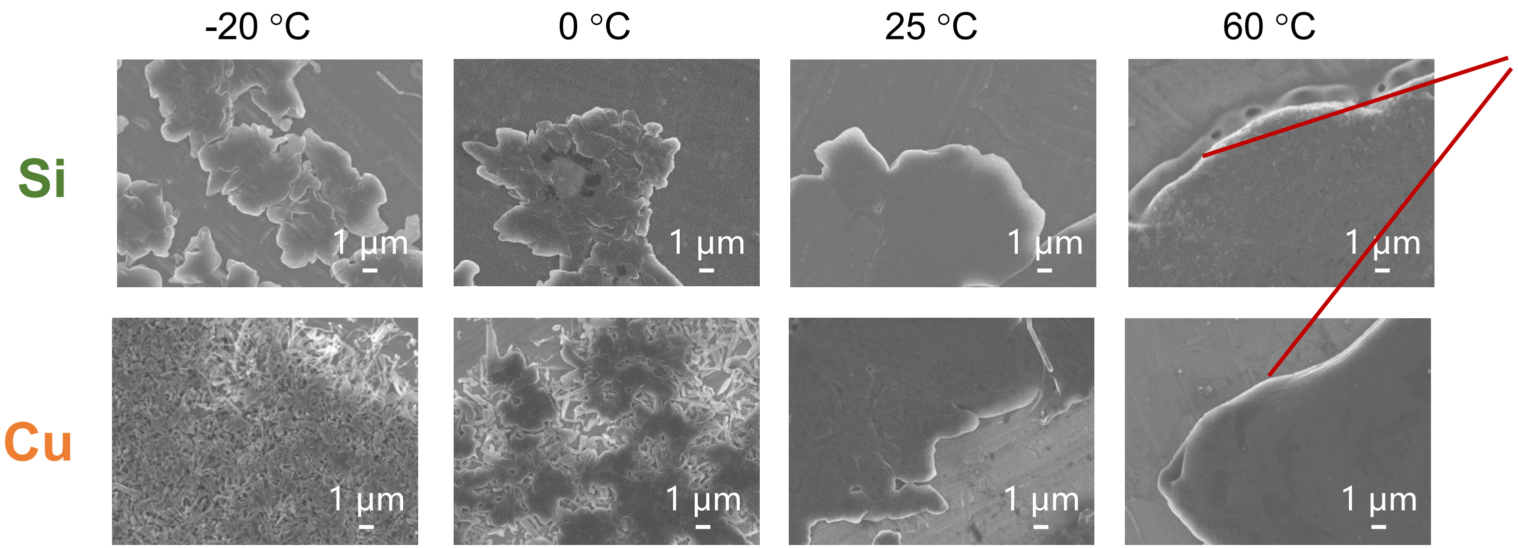


Why Cu is more prone to whisker than Si?

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

Morphology of Li deposit at different T

Q=0.1 mAh/cm2, J=0.025 mA/cm2 (quasi-eq condition).



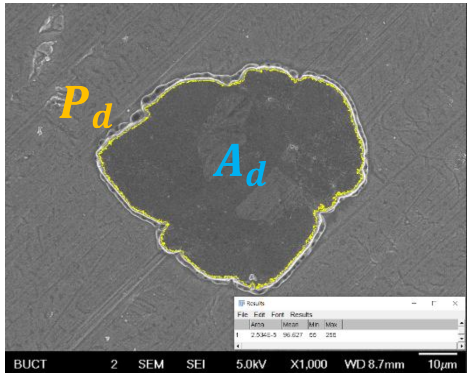
The edges become **smoother** at **high T**

Thermodynamically,
The deposit wants to **reduce P_d** to
minimize **surface energy**

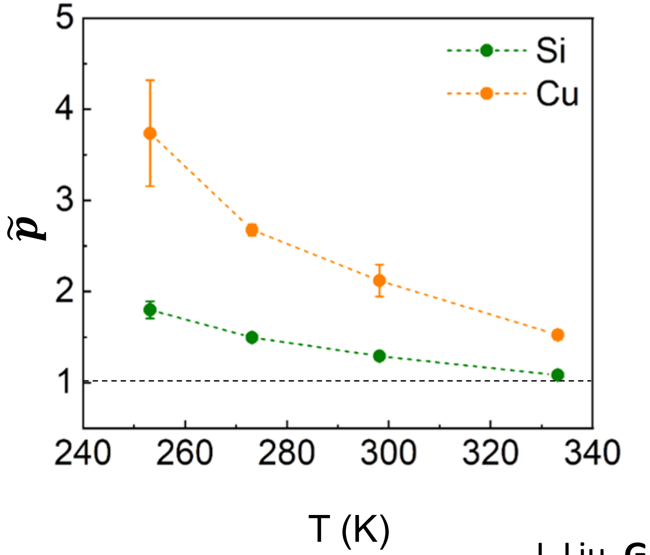
dimensionless perimeter

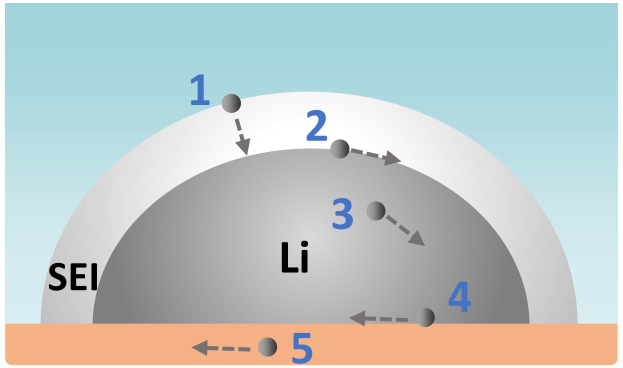
$$\widetilde{p} = \frac{P_d}{\sqrt{4\pi A_d}}$$

=1 for circle



Li deforms faster when on Si





2. Interface diffusion ($D_{SEI\text{-}Li}$)
3. bulk diffusion in Li (D_{Li})
4. Interface diffusion($D_{Li\text{-}substrate}$)
5. bulk diffusion in substrate ($D_{substrate}$)

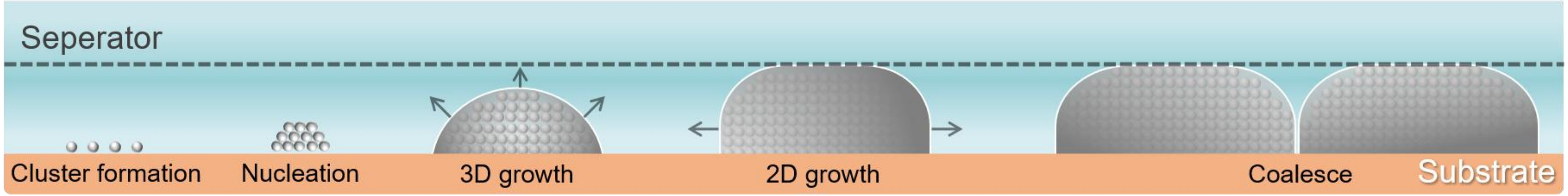
Diffusion in $LiSi_x$ alloy and **along Li-$LiSi_x$ interface**
reduces whisker tendency

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

Summary of Li deposition mechanism

quasi-eq

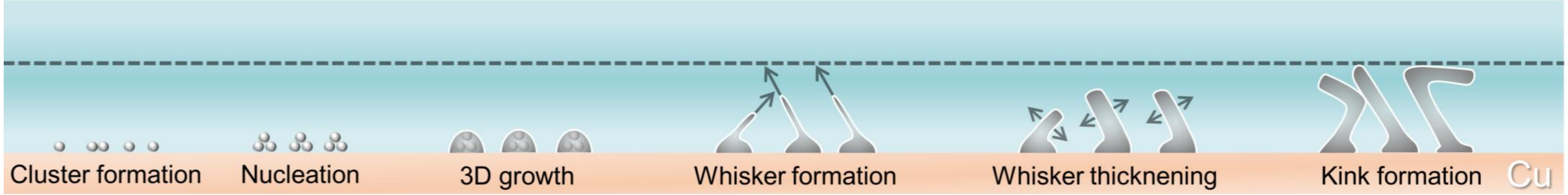
$J<<J_0<<J_d$



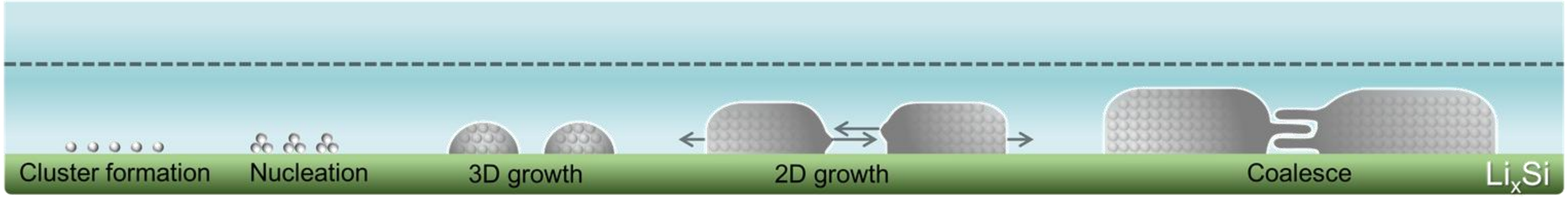
Qc~0.9 mAhcm^{-2}

rxn-control

$J_0<J<J_d$



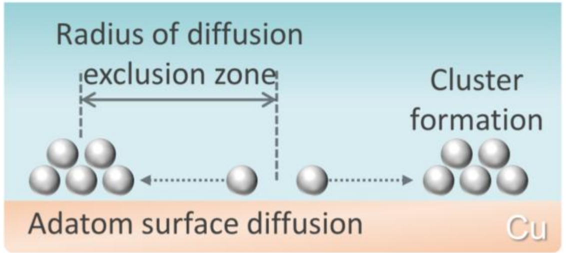
Cu more prone to whisker formation



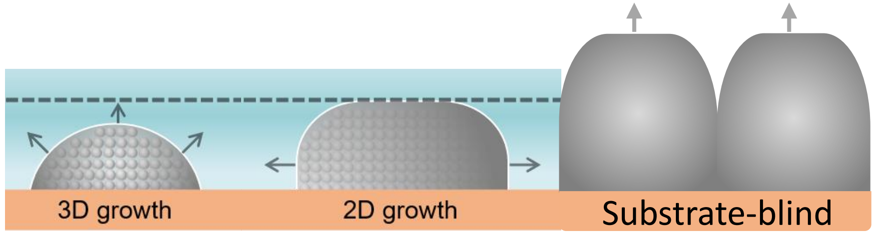
J. Liu, **Gao, T,** Wang. F**,** et al, *Energy Environ. Sci.* **2022**.

More quantitatively…

Nucleation

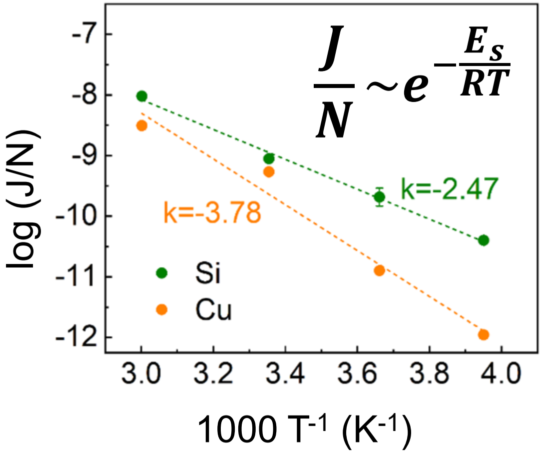


Growth



Whisker formation and growth

Surface diffusion controlled

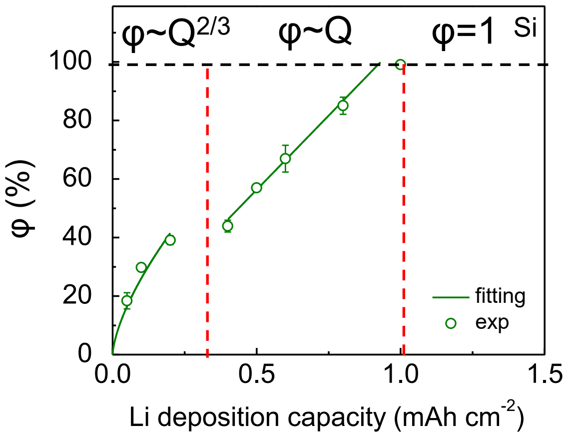


surface diffusion

$E_{s,si} = 0.21\ eV$

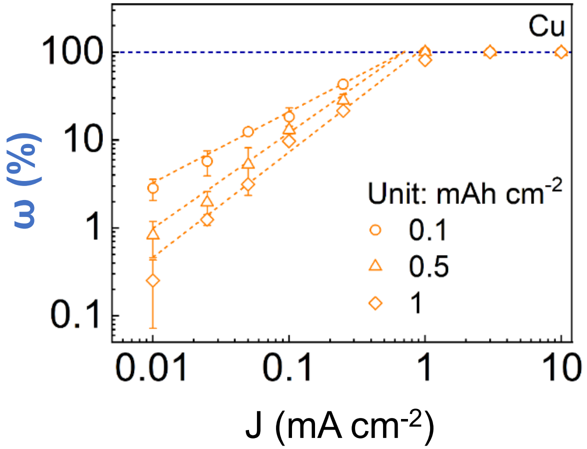
$E_{s,cu} = 0.33\ eV$

3-stage



Qc~0.9 mAhcm^{-2} at quasi-eq
0.5 at J=1 mA/cm2
0.3 at J=10

J_w: the tendency to form whisker

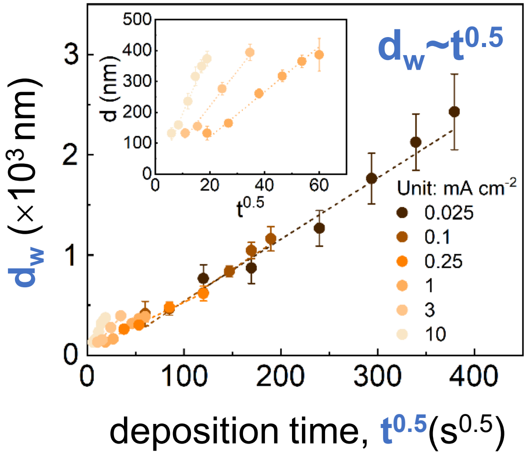


$J_{w,cu}$=0.79 mA/cm2

$J_{w,si}$>> 10 mA/cm2

Diffusion in LiSi$_x$ suppress whisker

Through-SEI diffusion controlled

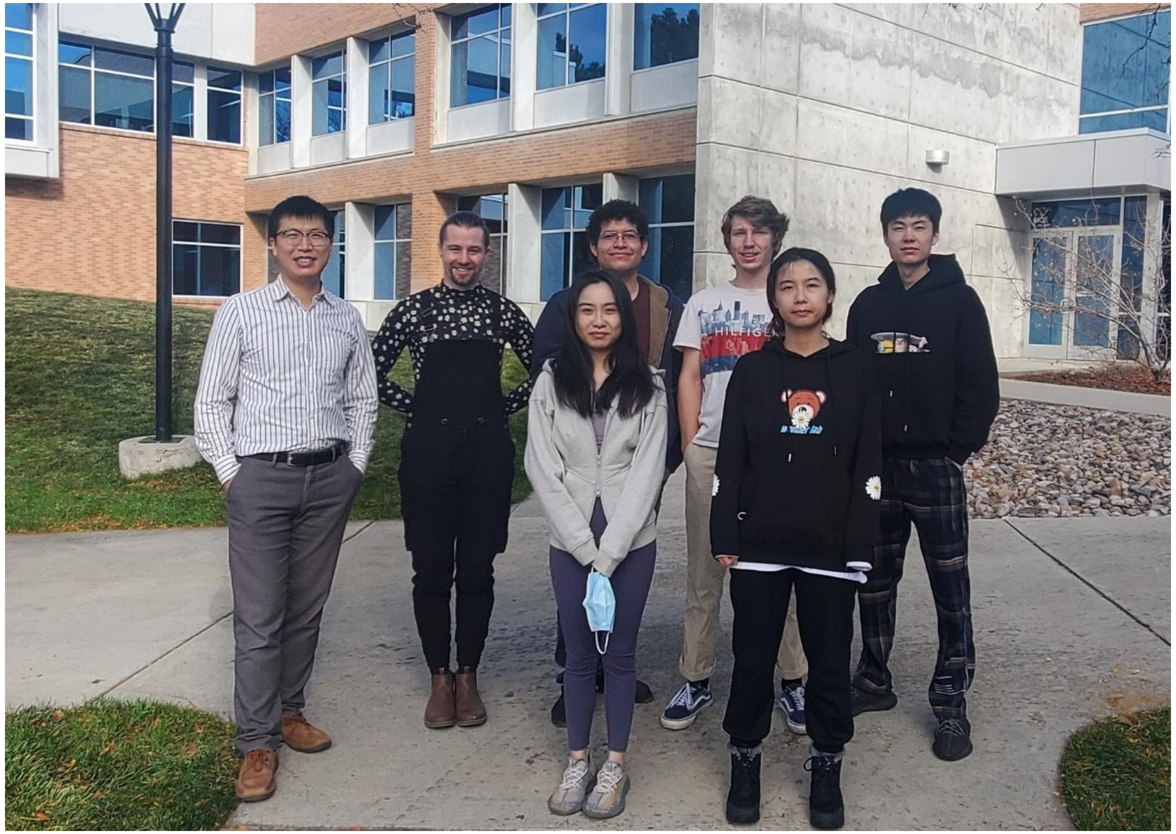


transport through SEI

D_{Li}^{SEI}:10^{-12} cm^2/s

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

Acknowledgement



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Nico Andreas

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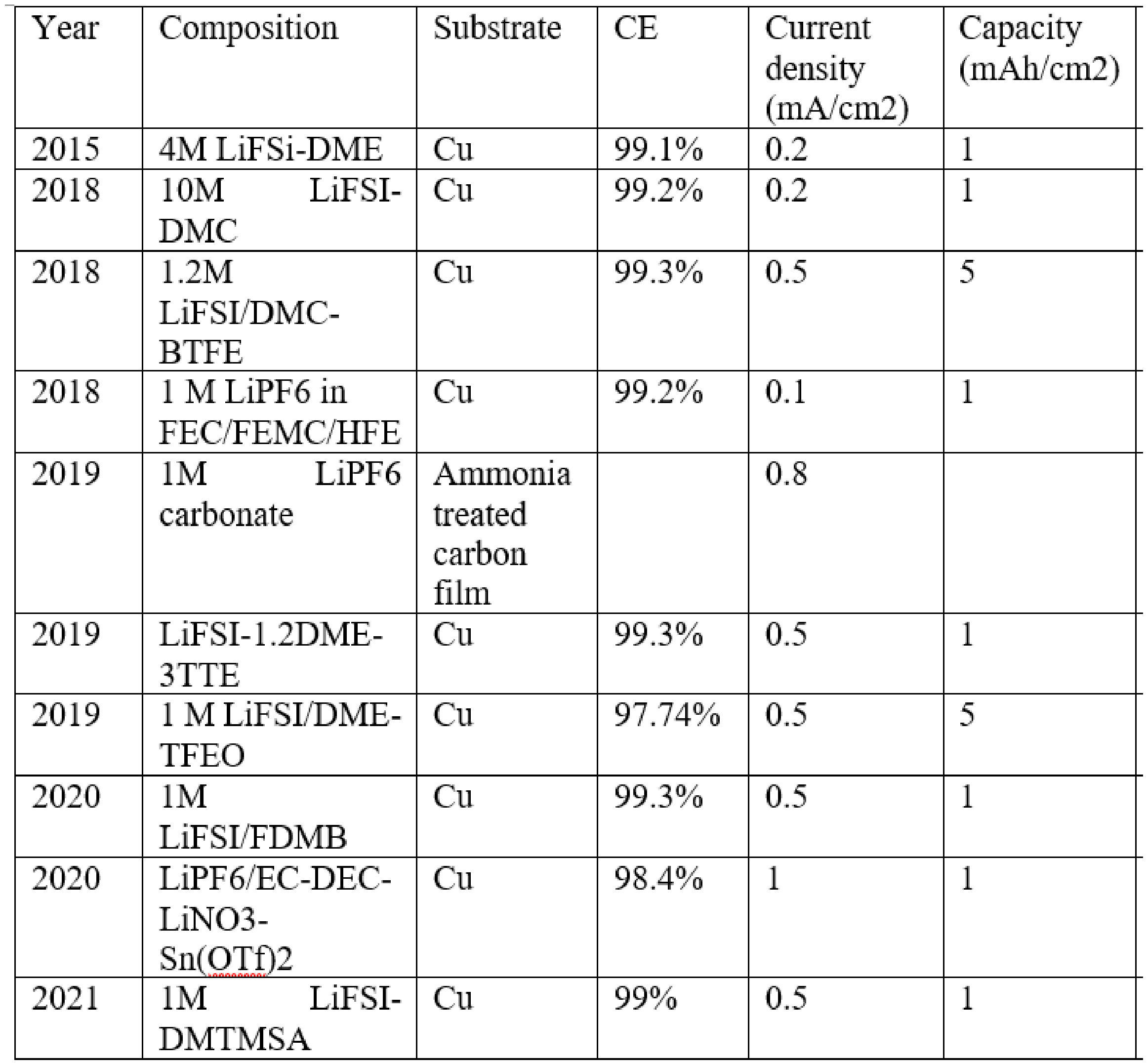
The challenge of improving CE

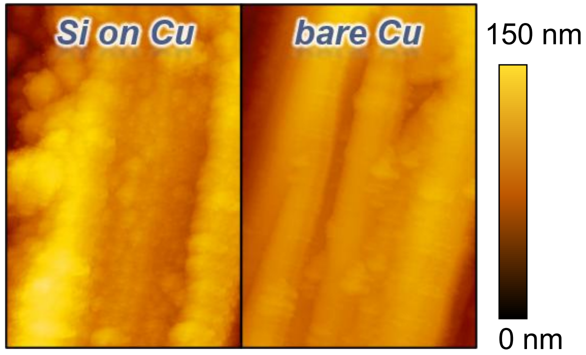


Year	Composition	Substrate	CE	Current density (mA/cm2)	Capacity (mAh/cm2)
2015	4M LiFSi-DME	Cu	99.1%	0.2	1
2018	10M LiFSI-DMC	Cu	99.2%	0.2	1
2018	1.2M LiFSI/DMC-BTFE	Cu	99.3%	0.5	5
2018	1 M LiPF6 in FEC/FEMC/HFE	Cu	99.2%	0.1	1
2019	1M LiPF6 carbonate	Ammonia treated carbon film		0.8	
2019	LiFSI-1.2DME-3TTE	Cu	99.3%	0.5	1
2019	1 M LiFSI/DME-TFEO	Cu	97.74%	0.5	5
2020	1M LiFSI/FDMB	Cu	99.3%	0.5	1
2020	LiPF6/EC-DEC-LiNO3-Sn(OTf)2	Cu	98.4%	1	1
2021	1M LiFSI-DMTMSA	Cu	99%	0.5	1

- **Electrolyte design** has increased CE up to **99.3%** at J ≤ **1 mA/cm^2**
- **80% capacity** at **1000th cycle**, CE **>99.98%**
- **Fundamental knowledge** required to guide the design of electrolyte and substrate

J.-G. Zhang, et al. *Nat. Commun.* **2015**, *6*, 6362
J. G. Zhang, W. Xu, et al. *Joule* **2019**, *3*, 1662.
J. G. Zhang, et al. *Nat. Energy* **2019**, *4*, 796.
Y. Cui, Z. Bao, et al. *Nat. Energy* **2020**, *5*, 526.
Y. Lu, et al. *Adv. Mater.* **2020**, *32*, 1.

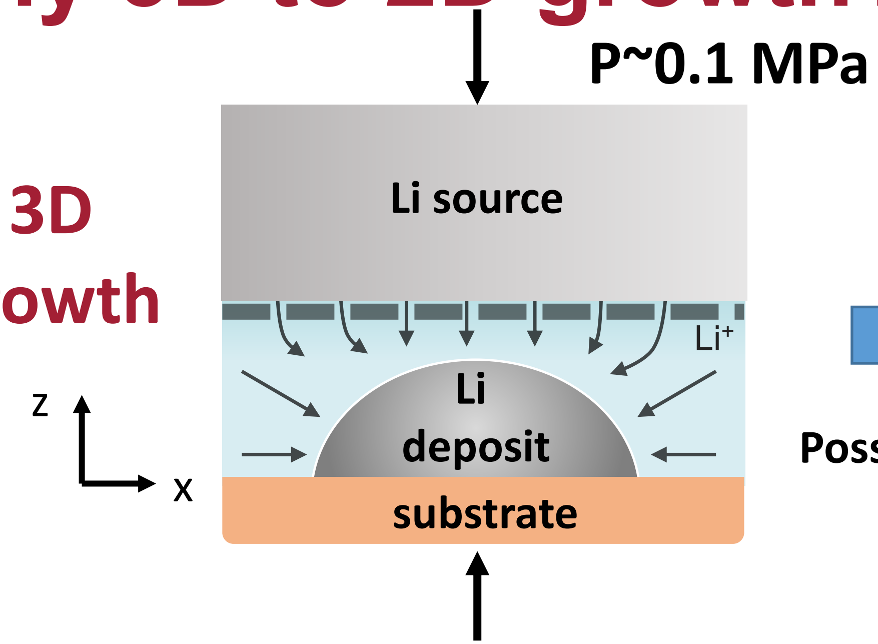
J. Li, et al. *Nat. Energy* **2021**, *6*.
K. Xu, C. Wang, et al. *Nat. Nanotechnol.* **2018**, *1*
C. Wang, et al. *Chem* **2018**, *4*, 174
J. G. Zhang, et al. *Adv. Mater.* **2018**, *30*, 1.
J. Liu, et al. *Nat. Nanotechnol.* **2019**, *14*, 594



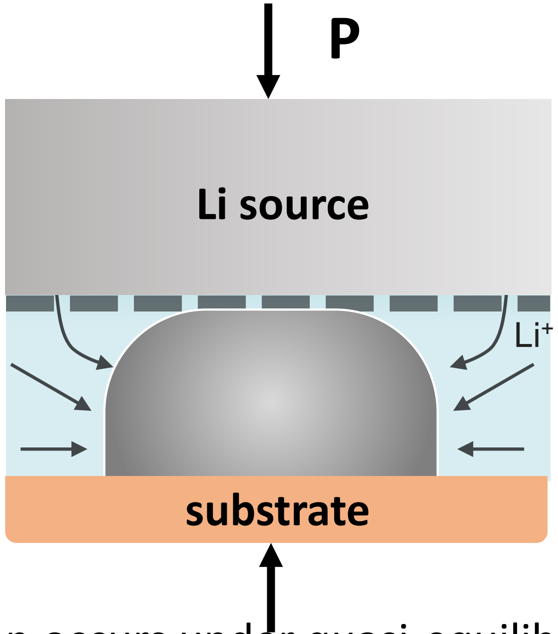
Roughness 10-100 nm

Why 3D to 2D growth?

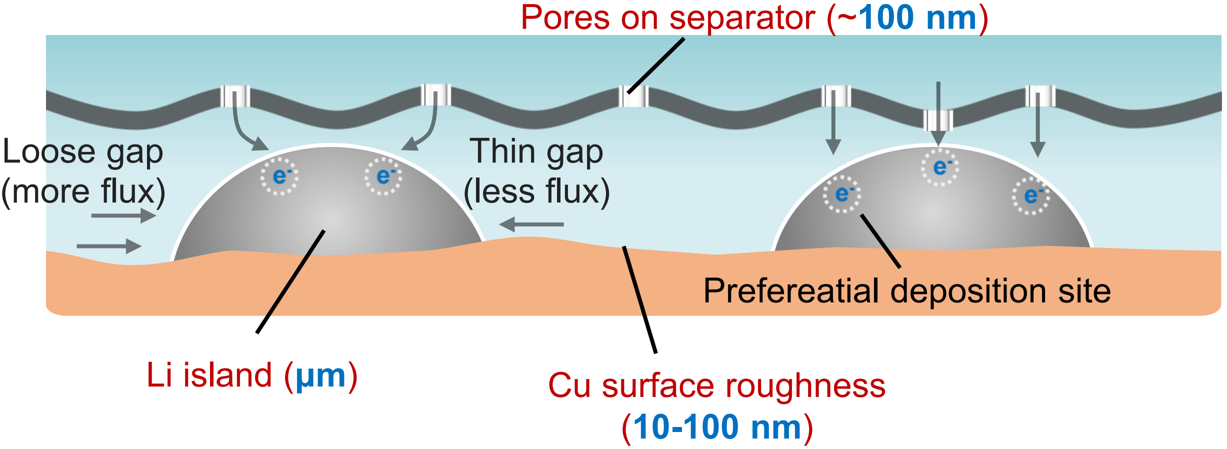
3D growth



Possibly due to constrained z-direction transport



2D growth



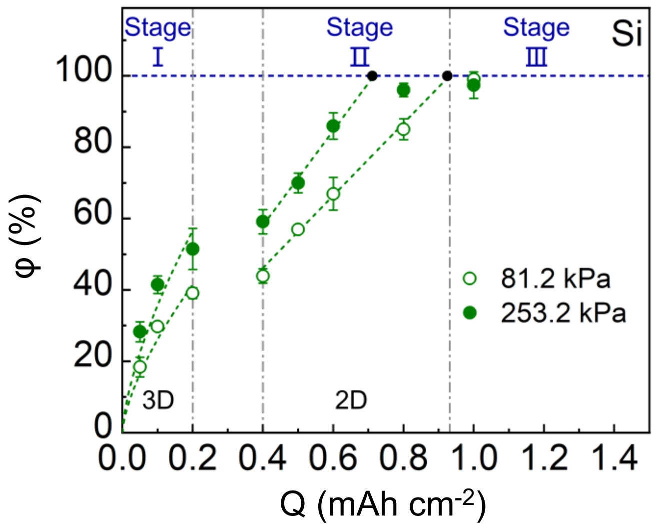
- The deposition occurs under quasi-equilibrium condition ($J \ll J_0 < J_d$), so the effect of Li transport in the electrolyte and reaction heterogeneity are negligible
- due to the surface roughness of the substrate and the separator, there is some small voids between the separator and the substrate despite of the pressure. These voids should be where nucleation occurs due to smaller nucleation barrier (no stain energy from the separator)
- Once the Li island grows to certain height, the stain from the separator makes the z-direction growth thermodynamically difficult. Growing into the nano-pores of the separator is also thermodynamically unfavorable due to the large surface energy.

3-stage growth: pressure effect

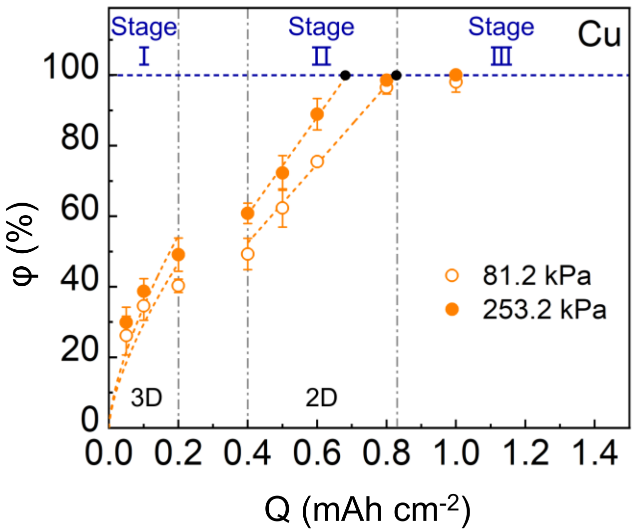
pressure effect

J=0.025 mA/cm2

Si



Cu



pressure: more nuclei, dense

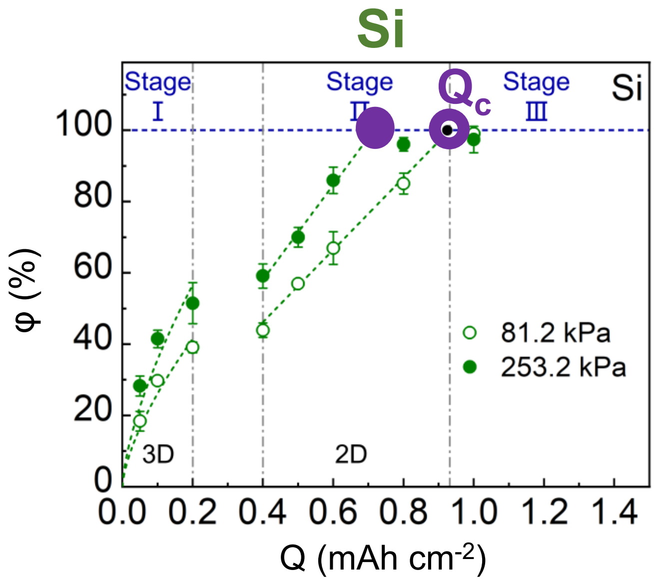
3-stage growth: Si at quasi-eq and reaction-controlled. Cu ONLY at quasi-eq

J. Liu, **Gao, T,** Wang. F, et al, *Energy Environ. Sci.* **2022**.

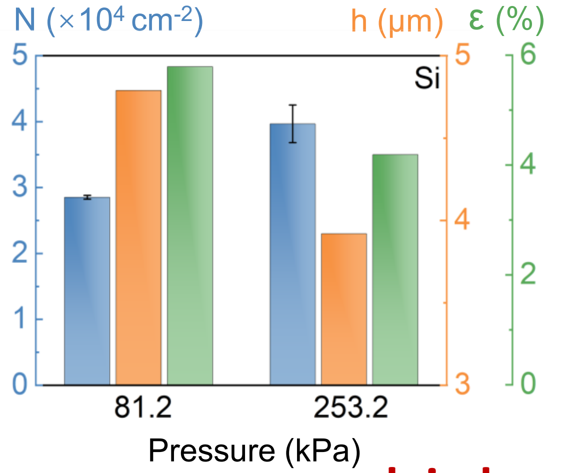
3-stage growth: pressure and current effect

pressure effect

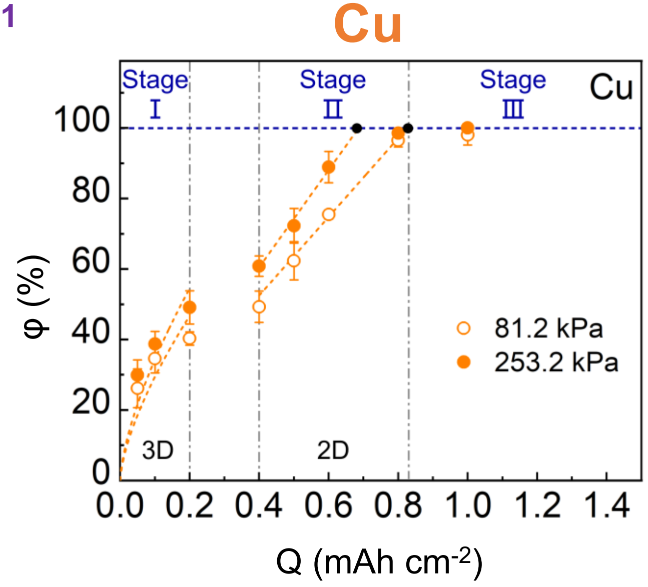
J=0.025 mA/cm2


Si

$\varphi \sim Q^{2/3}N^{1/3}$ $\varphi \sim Qh^{-1}$ $\varepsilon \sim hQ_c^{-1}$



pressure: more nuclei, dense

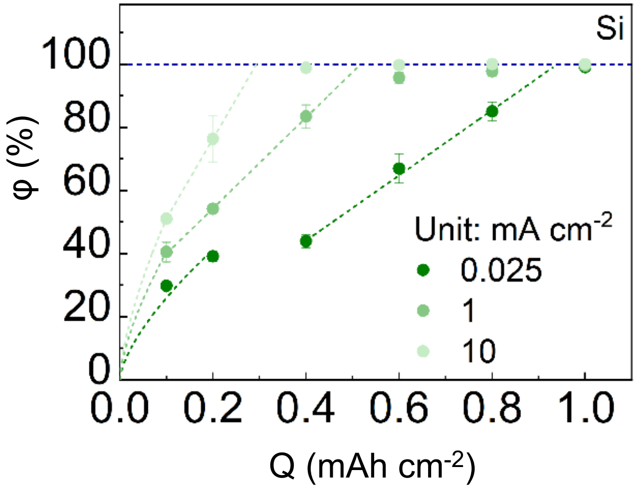

Cu

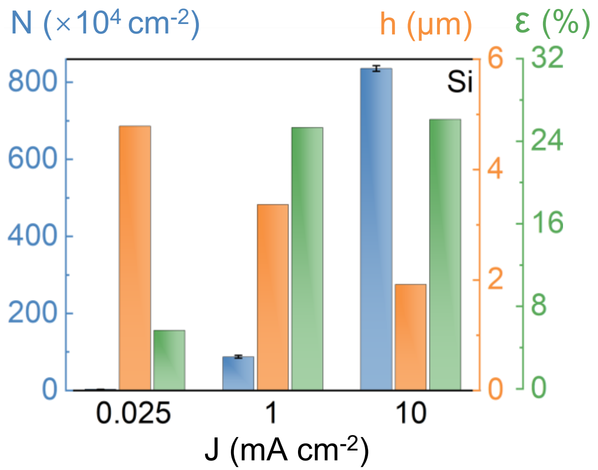
current effect

p=81.2 kPa

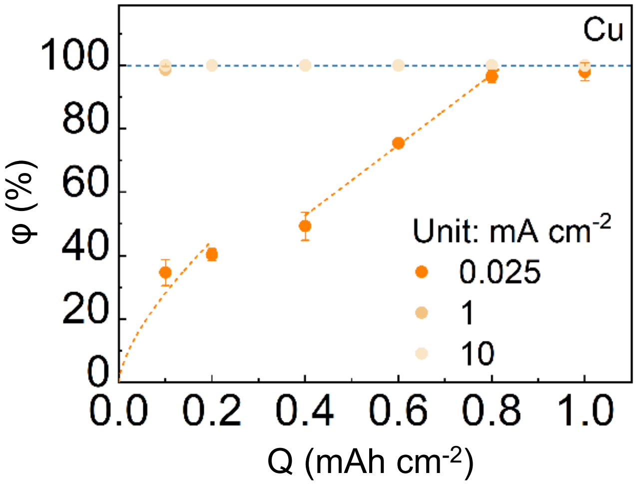
J_d=40 mA/cm2

J_0=0.2 mA/cm2





current: more nuclei, loose



T. Gao, *et al. under review*

3-stage growth: Si at quasi-eq and reaction-controlled. Cu ONLY at quasi-eq

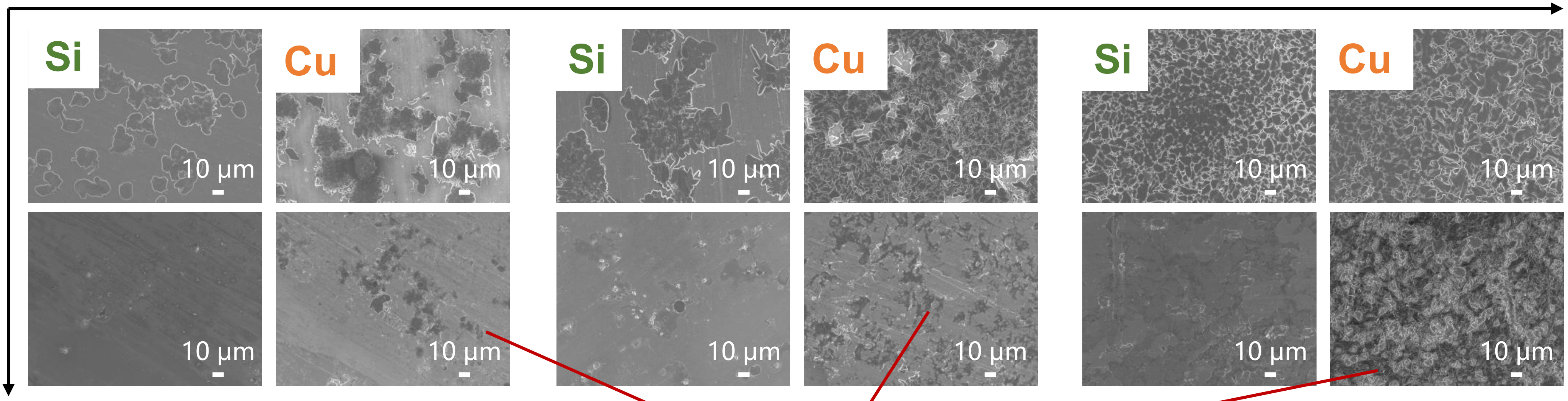
Reversibility of Li deposition/stripping

J=0.1 mA cm2

0.1 mAh cm^{-2} 0.5 mAh cm^{-2} 3 mAh cm^{-2}

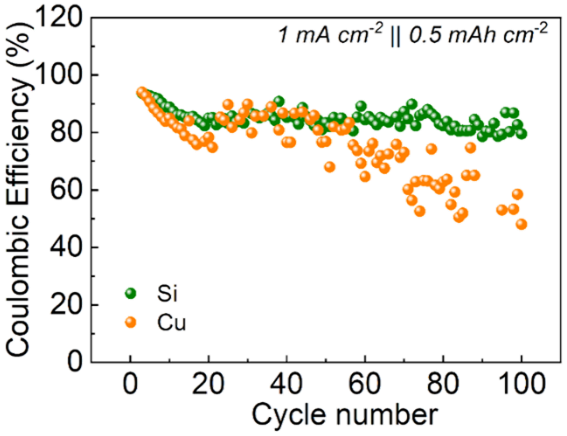
1st deposition

1st stripping

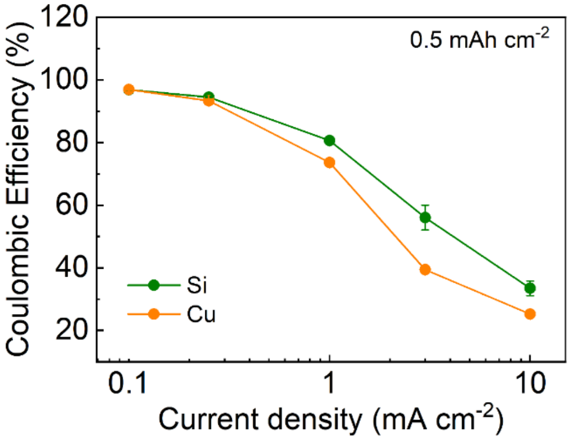


Dead Li

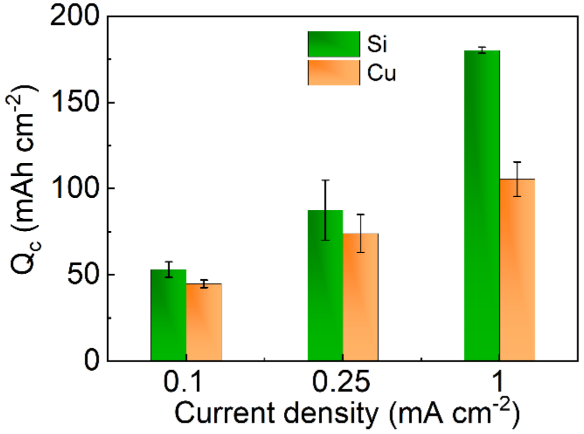
CE



CE



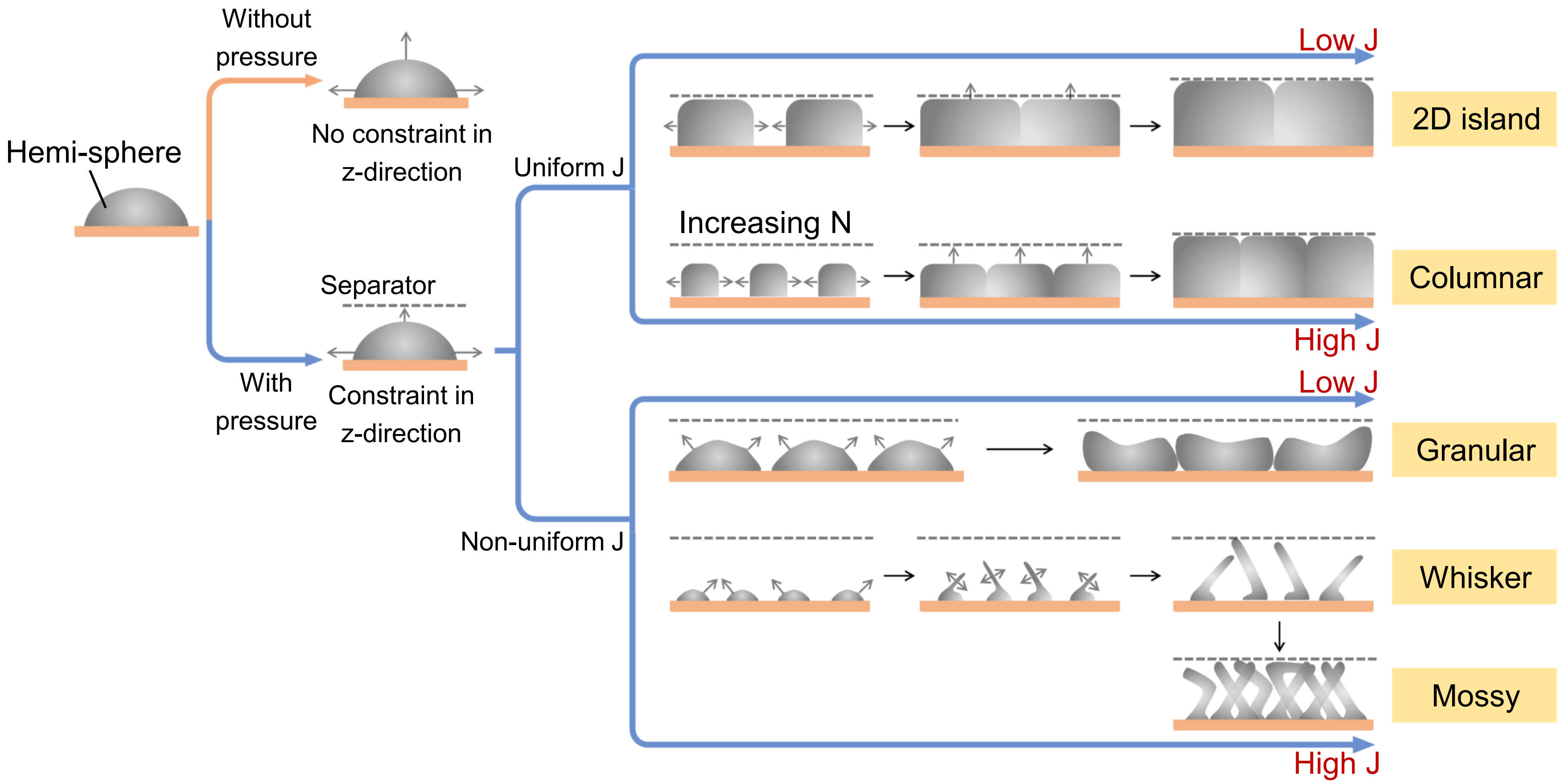
Short-circuit time

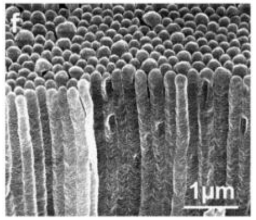


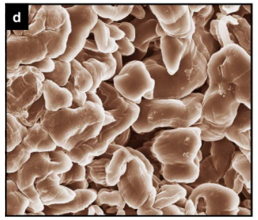
T. Gao, *et al. in prep*

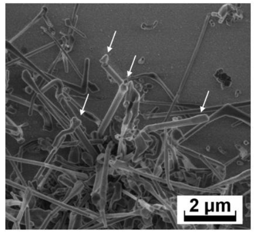
How different morphologies form?

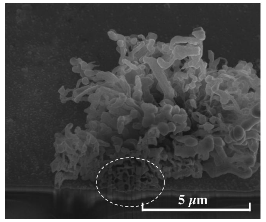
Reaction-controlled growth $J_0=0.2<J<<J_d=40$ mA/cm2







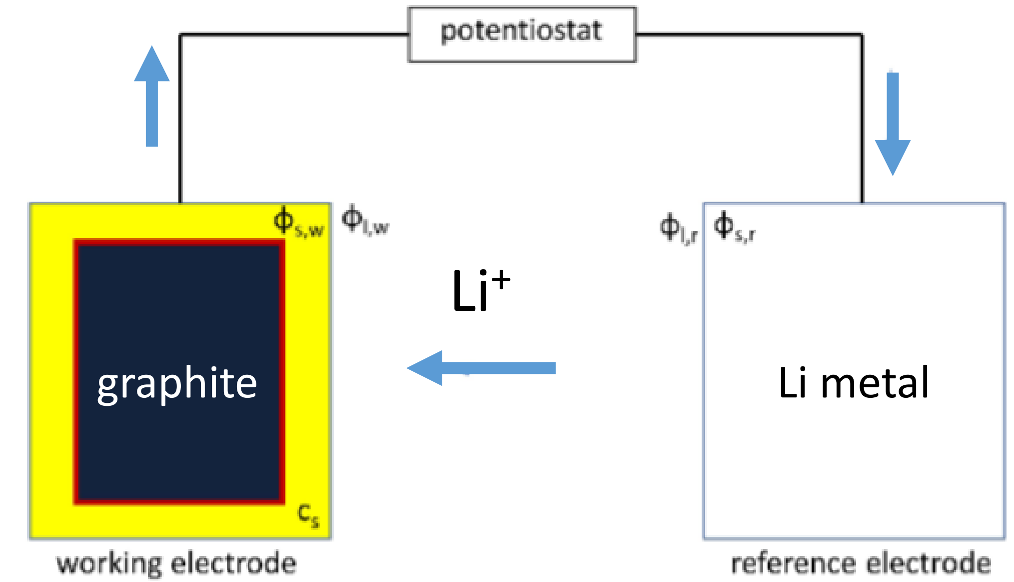




T. Gao, *et al. in prep*

Back up slides

Fundamental insights into $V_{graphite}$



$$Li^+ + e^- + M \iff LiM \qquad Li^+ + e^- \iff Li$$

Negative (lithiation)

$$V \approx \boxed{-\frac{\mu_s}{e}} + \boxed{\eta_w} \; \mathbf{<0}$$

zero when saturated

reference

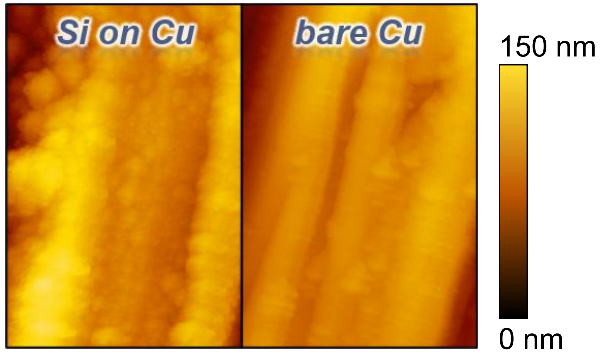
Fast Li/Li⁺ reaction at RE

$$V = \phi_w - \phi_r = \Delta\phi_w - \Delta\phi_r + (\phi_{l,w} - \phi_{l,r}) = -\frac{\mu_s - \cancel{\mu_{Li}}}{e} + \cancel{\frac{\mu_{Li^+,w} - \mu_{Li^+,r}}{e}} + (\eta_w - \cancel{\eta_r}) + (\cancel{\phi_{l,w} - \phi_{l,r}})$$

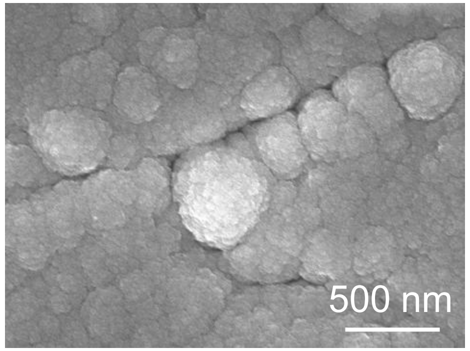
No conc. gradient

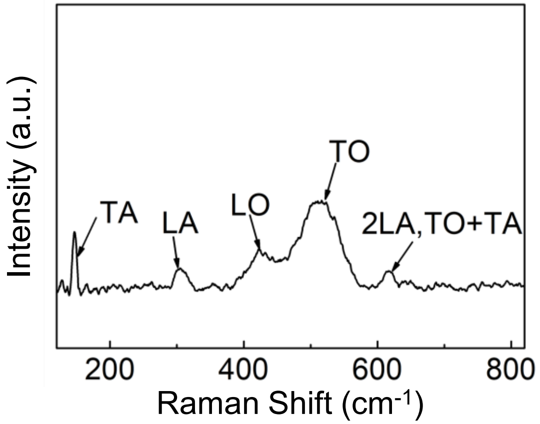
High conductivity of electrolyte

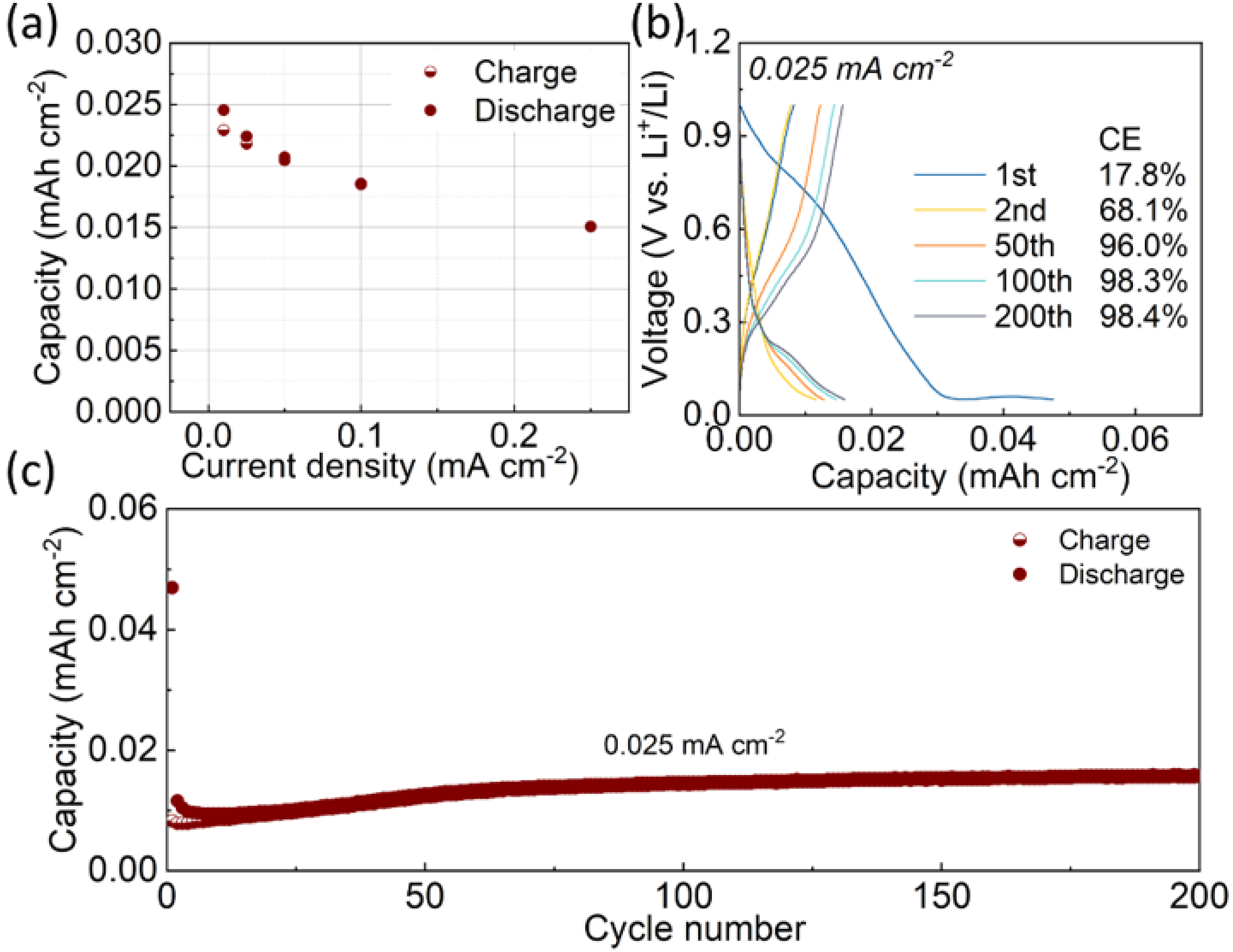
T. Gao, *et al. Joule, 2021,* 5, 1–22



Roughness 10-100 nm







Supporting Figure S2. The electrochemical properties of the silicon film.

3D growth:

$$Q = \frac{{}^{2}/_{3}\,\pi r^3 \rho C_s}{A}, r \sim Q^{1/3}$$

$$S = \frac{\pi r^2 N}{A}$$

$$\frac{S}{Q} = \frac{3N}{2\rho C_s}\frac{1}{r}$$

$$S = \frac{3N}{2\rho C_s}\frac{1}{r}Q$$

$$S = aQ^{2/3}$$

$$a = \frac{3\sqrt[3]{3}}{2\sqrt[3]{2}\sqrt[3]{\pi}\sqrt[3]{\rho^2}\sqrt[3]{C_s^2}}N$$

2D growth:

$$Q = \frac{S_{dep} r_c \rho C_s}{A}$$

$$S = \frac{S_{dep}}{A}$$

$$\frac{S}{Q} = \frac{1}{\rho C_s}\frac{1}{r_c}$$

$$S = \frac{1}{\rho C_s}\frac{1}{r_c}Q$$

$$S = kQ$$

$$k = \frac{1}{\rho C_s}\frac{1}{r_c}$$

Si-Single spacer:

3D:a= 121.28±7.26

N=2.7±0.1 $\times 10^4$ (cm^{-2})

2D:k= 101.35

r_c=4.79 (μm)

Si-Double spacer:

3D:a= 165.53±14.57

N=3.7±0.3$\times 10^4$ (cm^{-2})

2D:k= 123.51

r_c=3.92 (μm)

Cu-Single spacer:

a= 136.5±17.15

N=3.0±0.4 $\times 10^4$ (cm^{-2})

2D:k= 101.35

r_c=4.34 (μm)

Cu-Double spacer:

a= 159.27±15.75

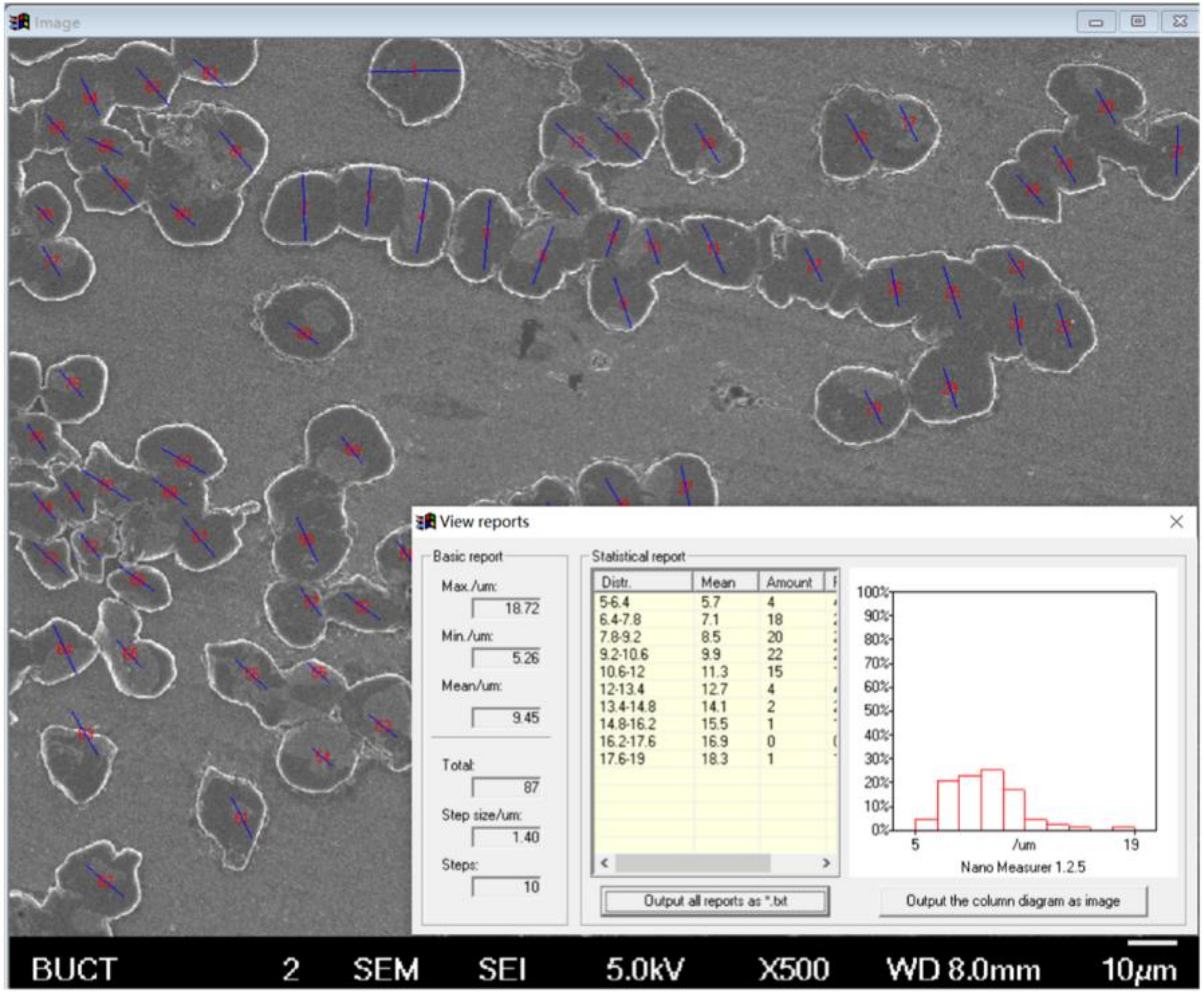
N=3.55±0.35 $\times 10^4$ (cm^{-2})

2D:k= 138.08

r_c=3.51 (μm)

$$\rho = 0.534\ g\ cm^{-3}$$

$$C_s = 3860\ mAh\ g^{-1}$$



View reports

Basic report

Max./um: 18.72

Min./um: 5.26

Mean/um: 9.45

Total: 87

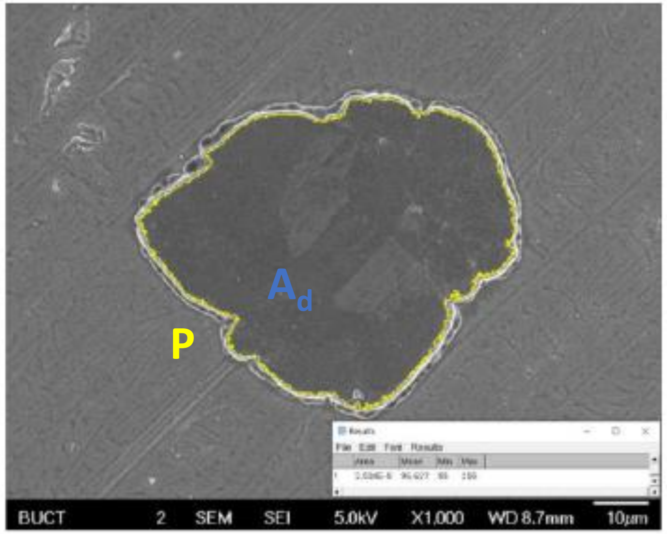
Step size/um: 1.40

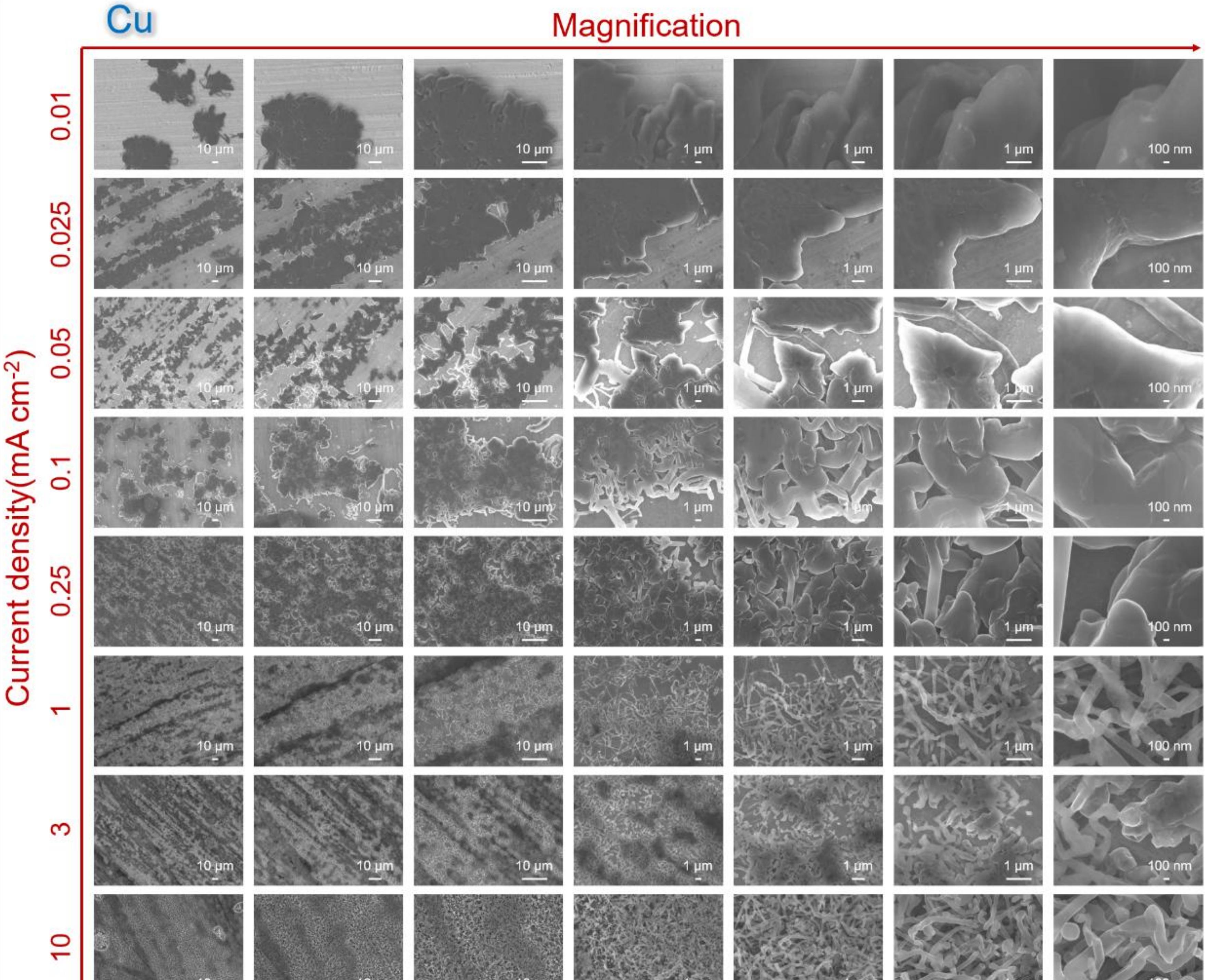
Steps: 10

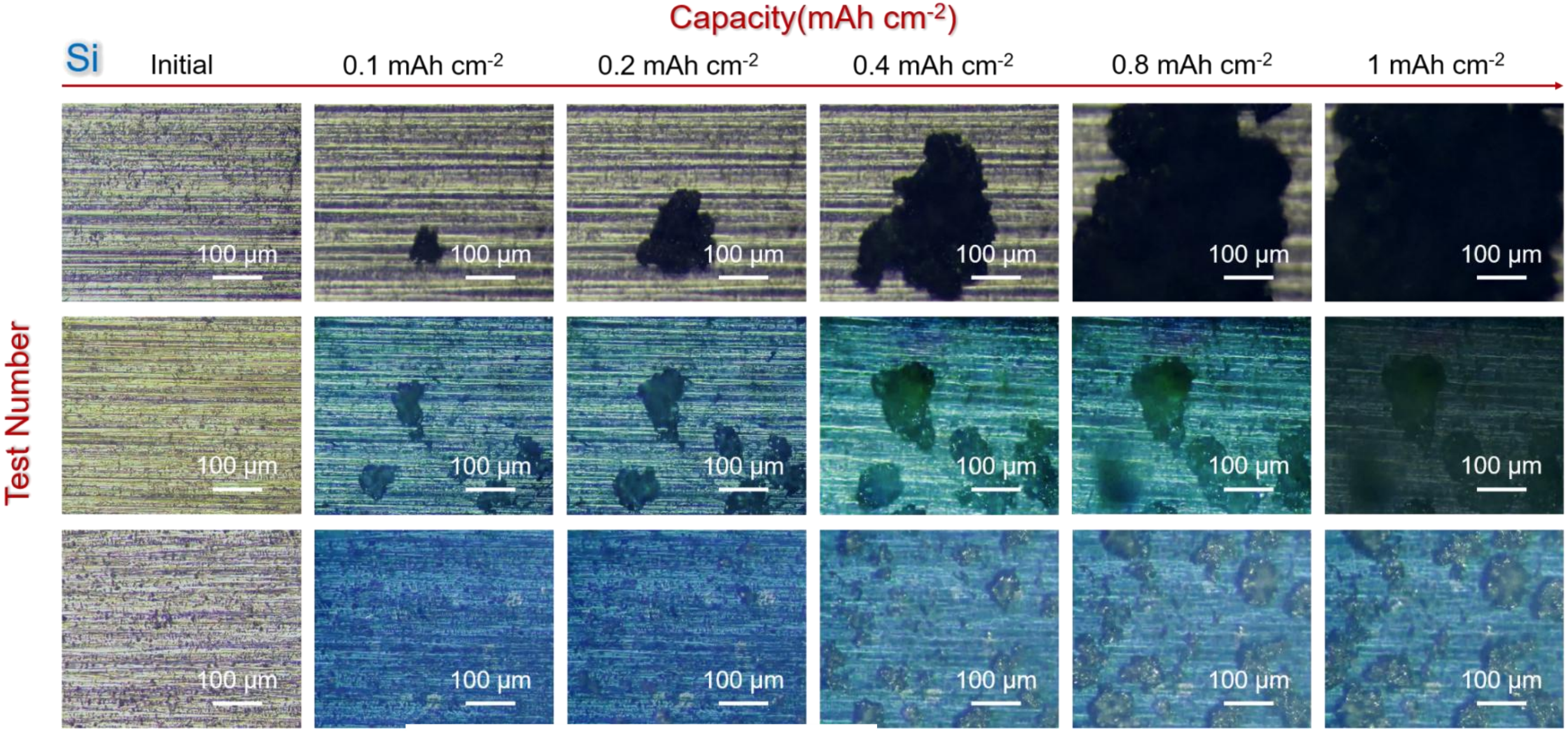
Statistical report

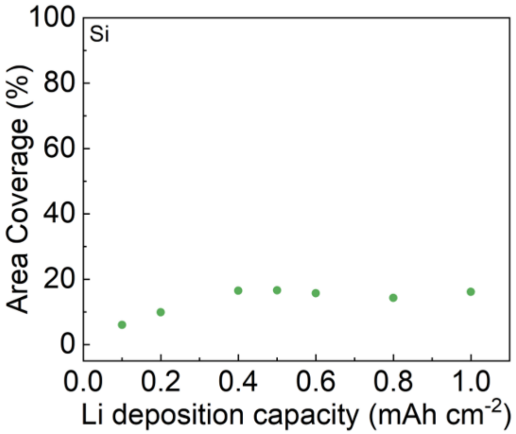
Distr.	Mean	Amount
5-6.4	5.7	4
6.4-7.8	7.1	18
7.8-9.2	8.5	20
9.2-10.6	9.9	22
10.6-12	11.3	15
12-13.4	12.7	4
13.4-14.8	14.1	2
14.8-16.2	15.5	1
16.2-17.6	16.9	0
17.6-19	18.3	1

compute P and A_d with ImageJ




Cu
Magnification
Current density(mA cm-2)
0.01
0.025
0.05
0.1
0.25
1
3
10
10 µm
1 µm
100 nm


Capacity(mAh cm^{-2})
Si
Initial
0.1 mAh cm^{-2}
0.2 mAh cm^{-2}
0.4 mAh cm^{-2}
0.8 mAh cm^{-2}
1 mAh cm^{-2}
Test Number
100 μm


Si
Area Coverage (%)
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
Li deposition capacity (mAh cm^{-2})