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Nonequilibrium mechanical-electrochemical coupling in Li-ion batteries

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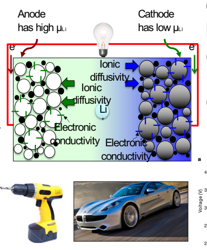
Introduction and Background

Introduction:

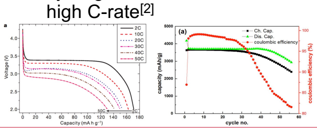
- Lithium-ion batteries are critical to modern and emerging technologies such as electric vehicles, high-power tools.
- It stores and release energy by Li-ion's diffusion between anode and cathode.



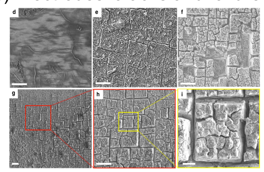
Current Problems of Li-ion battery

(a) Poor power performance under high C-rate[1]

(b) Irreversible capacity loss after cycling and limited lifetime under high C-rate[2]

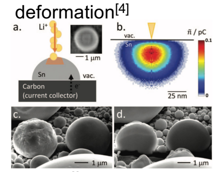


(c) Electrodes' cracks and failure[3]



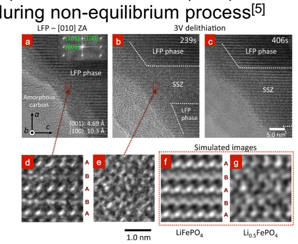
Si anode SEM images after (d) 3, (e) 8, (f) 50 and (g–i) 30 cycles. Scale bar, 20μm (d–h), 3 μm (i).

(d) Li-ion diffusion were affected by mechanical deformation[4]



Li-ion diffusion under FIB doping

(e) Solid solution zone (SSZ) observed during non-equilibrium process[5]



Objective:

- Describe and predict electrical potential, capacity, stress and strain under high C-rate (dis)charging.
- Present the relation between stress/strain and solid solution zone (SSZ) during non-equilibrium process
- Develop approaches to improve Li-ion battery's cyclic life at high C-rates

Methods and Current Results

Model Architecture based on Continuum Mechanics and Non-Equilibrium Thermodynamics

Constitutive models

$$\dot{\boldsymbol{\Omega}} = \dot{\boldsymbol{\Omega}}\left(\lambda, G, \rho, \mathbf{g}, \dot{\mathbf{e}}^{(e)}, \boldsymbol{\sigma}, \dot{\mathbf{e}}, \kappa, x_{(k)}, \boldsymbol{\varepsilon}^{(e)}\right)$$

$$\mu_{(12)} = \mu_{(12)}\left(x_{(k)}, \boldsymbol{\varepsilon}^{(e)}, \rho\right)$$

$$ds = \sum_l -\bar{\gamma}^{(l)ij} d\bar{\varepsilon}^{(l)}_{(2)ij} + c_{Vx}\frac{dT}{T} + \left(\frac{\partial s}{\partial x_{(\alpha)}}\right)_{\varepsilon_{(2)},T} dx_{(\alpha)}$$

Momentum equation

$$\rho\frac{d\mathbf{v}}{dt} = \nabla\cdot\mathbf{p} + \sum_k^K \rho_{(k)}\mathbf{F}_{(k)}$$

Dissipation models

$$\lambda^{(P)\pm} = C^{(p)\pm}\exp\left(-\frac{E_A^{(p)\pm}}{RT}\right)$$

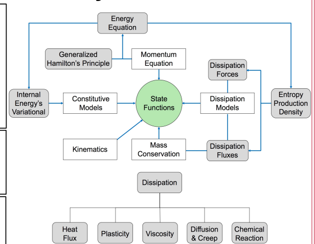
$$\tau^{(e)} = \tau^{(e)}\left(\dot{e}^{(e)}, \lambda^{(p)\pm}\right)$$

$$J_{(k)} = -\frac{L^{(kq)}}{T}\cdot\underline{\nabla}T - \sum_k\frac{L^{(kk')}}{T}\cdot\underline{\nabla}(\psi_{(k')} - \psi_{(n)}) - \frac{L^{(ke)}}{T}\cdot\underline{\nabla}\phi$$

$$r_+^{(j)} = C_+^{(j)\prime}\exp\left(\alpha^{(j)}\beta\sum_k \mu_{(k)M}\delta^{(kj)}\right)$$

Mass conservation

$$\rho\frac{dx_{(k)}}{dt} + \nabla_i J^i_{(k)} = \sum_j \xi^{(j)}_{(k)} J^{(j)} \qquad F\int_V J_M dV = I$$



Kinematics

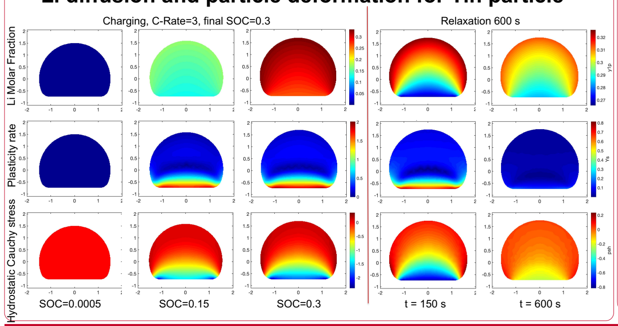
$$\dot{e}_{(2)ij} = \frac{\partial\varepsilon_{(2)ij}}{\partial t} = \frac{1}{2}\frac{\partial g_{(2)ij}}{\partial t}$$

$$\dot{e}_{(2)ij} = \dot{e}^{(e)}_{ij} + \dot{e}^{(p)}_{ij} \qquad \dot{e}_{(2)ij} = \frac{1}{2}\left(\nabla_i v^L_{(2)j} + \nabla_j v^L_{(2)i}\right)$$

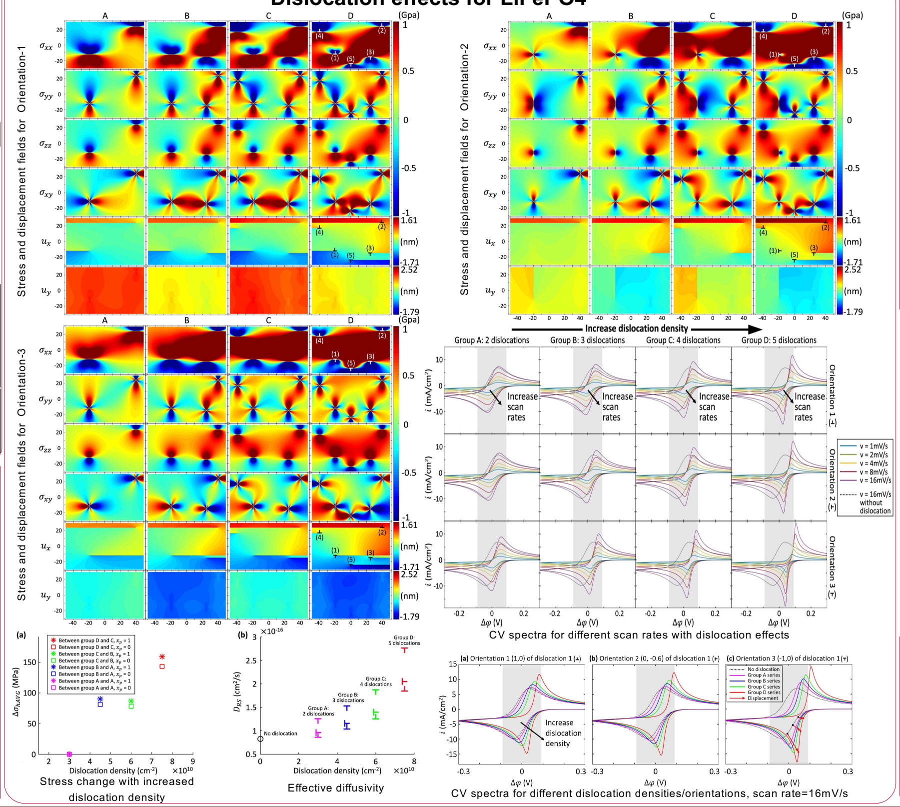
Dislocation effects

$$\boldsymbol{\sigma}_{DC} = \boldsymbol{\sigma}_{DC}\left(b_x, b_y, r_x, r_y\right) \quad \mathbf{u}_{DC} = \mathbf{u}_{DC}\left(b_x, b_y, r_x, r_y\right)$$

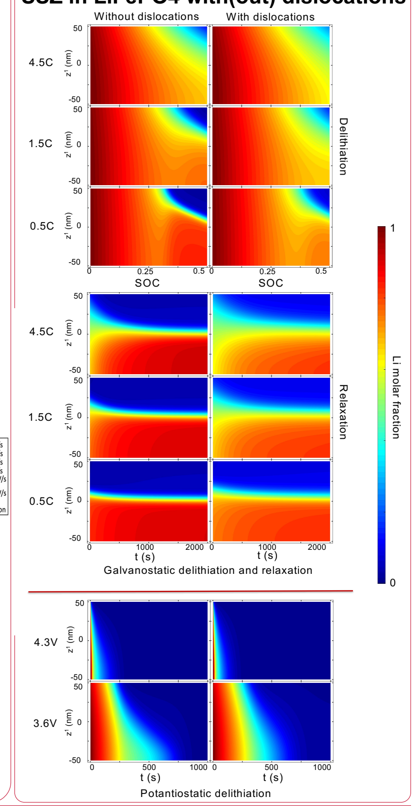
Li diffusion and particle deformation for Tin particle



Dislocation effects for LiFePO4



SSZ in LiFePO4 with(out) dislocations



Future Work

- Simulate whole (dis)charging process and cycling for large deformation of Si anode.
- Investigate the Influences of material's parameters on the evolution of SSZ. Multi-particle modeling.
- Damage and irreversible capacity loss modeling.

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[1] Kang & Ceder, Nature 458, 190-193; [2] J. Xie et al, doi: 10.1149/2.0091503jes; [3] Shi et al, doi: 10.1038/ncomms11886; [4] Saya Takeuchi et al., doi:10.1149/2.1161606jes; [5] Niu et al., dx.doi.org/10.1021/nl501415b