Microscopic Thermal-Fluids Engineering for Next-generation Energy and Electronic Systems

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Power generation

> 80% of electricity in US through steam cycles

EIA, 2017;

Building 15-20% of all energy in US

Heat

Source

Heat - Work - Waste heat

Garimella, 2011

Electronics

Half of energy used is for cooling

Safety

> 80% of electricity in US through steam cycles

EIA, 2017;
Electronics and Energy Storage

Manage extreme heat flux

Electronic Devices
- Phone CPU: ~1 W/cm²
- Computer CPU: ~100 W/cm²
- Power electronics: ~1000 W/cm²
- Sun: 6300 W/cm²

Heat Generation

Batteries
- Li anode: ~μm
- Cathode: ~cm

Fundamental understanding of thermal effect

Dimension
Thermal Management of Electronics

- Thermal management is a critical bottleneck
- Liquid-to-vapor phase-change
  - High latent heat

CPU

GaN power electronics

100 W/cm²

1000 W/cm²

UC Chowdury, TriQuint Semiconductor Inc.

Two-Phase Microchannel Heat Sink

Flow boiling in microchannels

Challenges

- Flow instabilities
- Critical heat flux (CHF)

Key:
Sustain liquid film to prevent dry-out
Our Design: Capillarity

- Structures – sustain film evaporation via capillarity
- Sidewalls – nucleation


\[ \frac{dP}{dx} \]

Liquid Flow

Capillarity

[Diagram showing the design with inlet, nucleation, film evaporation, and outlet.]
Fabricated Microchannels

Superhydrophilic structures capillary wicking

Experimental Setup

**Will the microstructures address dry-out problems?**

Suppression of Flow Instability (ms)

Smooth surface microchannel

Structured surface microchannel

\[ G = 100 \text{ kg/m}^2\text{s} \quad q \approx 400 \text{ W/cm}^2 \]

Suppression of Flow Instability (s)

$q'' = 430$ W/cm$^2$

$q'' = 520$ W/cm$^2$

$q'' = 615$ W/cm$^2$

Mass flux $= 300$ kg/m$^2$·s

Significant enhancement

- Maximum CHF of 969 W/cm² (>50% enhancement)
- Reduced temperature rise (max 40%)
- Similar pumping power

Modeling Framework

1. Force Balance

\[ \kappa(x) = \frac{P_v - P_l(x)}{2\sigma} \quad (1) \]

Pressure ↔ Interface shape

2. Momentum Equation

\[ \Gamma = f\left(\frac{dP}{dx}, d, l, h, \kappa(P)\right) \quad (2) \]

Flow rate ↔ Pressure gradient
Interface shape

example:
\[ \frac{dP}{dx} = -1 \text{, Pa/µm} \]

3. Mass Conservation and Enthalpy Balance

\[ (\Gamma^{i-1} - \Gamma^i) h_{fg} = l^2 q \quad (3) \]

Flow rate
\[ ml^2 \]
\[ m h_v l^2 \]

Link all cells

Micropillar geometry
surface length
heat flux
Fluid property

Optimal geometry \((d/h \sim 0.4-0.6, \, l/d \sim 3)\) due to the balance of capillary pumping and viscous drag

- Microstructures are desired for high heat flux \((h=50 \, \mu m, \, CHF \sim 250 \, W/cm^2)\)

• Capillarity (fluid wicking) is the mechanism for increased flow stability and enhanced heat transfer
Thermal Issues in Batteries

Safety – thermal runaway

Keyser et al., J. Power Sources, 2017

Extreme fast charging

Y Liu, Y Zhu, Y Cui, Nat. Energy, 2019

Finegan et al, Nat. Commun., 2015
The Effect of Temperature

Previous work: uniform temperature

Ishikawa et al., 1999

Love et al., 2014

Reality: temperature heterogeneity

Localized hotspot

Internal heat

External cooling

Tabs

Defects/Dendrite

Joule heat [$\mu$W/mm$^3$]

Li metal

cathode

• Microscopic temperature effect is less understood

Samini et al., 2016

Comsol Multiphysics

Beckert et al., 2013

Mukhopadhyay et al., 2018
Challenge: Microscopic Temperature Sensing

Remote/External
- Saw et al., *J. Power Sources*, 2014

Macroscopic
- Finegan et al., *Nat. Commun.*, 2015

Invasive
- Lin et al., *IEEE T Contr Syst T*, 2013

Desired technique
- Local
- Microscopic
- Non-invasive

Our platform - Raman spectroscopy
- High spatial resolution (< 1 μm)

How Temperature Hotspot Affects Lithium Growth

Raman spectroscopy as a thermometer

$\omega_0 - \omega_s = f(T)$

Li metal battery

- highest specific capacity
- issue: uncontrolled growth

Battery

- Anode
- Separator
- Cathode

Sample

- Graphene
- glass
- working electrode (Cu)
- electrolyte
- counter electrode (Li)

Y Zhu*, J Xie*, Y Cui et al., Nature Communications, 2019
Temperature Measurement with Graphene

- Calibrate graphene $\Delta \omega / \Delta T$

\[
\begin{align*}
\text{Raman peak (cm}^{-1}) & \quad \text{Measurement} \\
\text{Linear fit} & \quad -0.0559 \pm 0.009 \text{ cm}^{-1}/^\circ\text{C}
\end{align*}
\]

- Measure $T$ with graphene

\[
\begin{align*}
\text{Temperature (}^\circ\text{C)} & \quad \text{Laser power (mW) }
\end{align*}
\]
Lithium Growth on the Hotspot

• Significantly enhanced Li growth on the temperature hotspot

Y Zhu*, J Xie*, Y Cui et al., Nature Communications, 2019
Temperature Promoted Reaction Kinetics

- dominant cause is the exchange current density of Li/Li\(^+\) redox at the electrode-electrolyte interface

\[ j_0 = e^{\left(\frac{-E_a}{RT} + 32.01\right)} \]
Temperature and Li Deposition Distribution

- Sensitivity of electrochemistry within battery to temperature fluctuations

\[ j_0 = e \left( \frac{-E_a}{RT(r)} + 32.01 \right) \]
Can shorting be triggered by a local heating event?

Battery Safety

K Liu, Y Cui et al., Sci. Adv., 2018
Local Heating Triggers Shorting

![Diagram showing laser heating and shorting](image)

Galvanostatic charging at 30 μA
Video played 80X faster

Y Zhu*, J Xie*, Y Cui et al., Nature Communications, 2019
Hotspot Caused Li Shorting

Y Zhu*, J Xie*, Y Cui et al., Nature Communications, 2019
• Embedded a micro-fabricated temperature sensor

• T hotspot triggers further temperature rise

Y Zhu*, J Xie*, Y Cui et al., Nature Communications, 2019
Heterogeneous temperature effect

Temperature hotspot effect on Li-metal battery

Platform

Li deposition

Failure mechanism

Local temperature

Y Zhu*, J Xie*, Y Cui et al., Nature Communications, 2019

Failure of Li-ion battery (Li plating) caused by temperature variation

- Non-uniform temperature causes non-uniform equilibrium potential
- Plating of Li at hot regions

H Wang*, Y Zhu*, Y Cui et al., in review

- Demand for thermal-management to achieve a uniform temperature
Outlook – Future Research

Applications

Phase-change Phenomena
- Micro-Raman
- Thermo-fluids chamber

Energy Storage
- Thick electrode
- High current
- Scan probe

Catalysis
- Electrolyte / liquid
- Enhanced gas flux
- Liquid flow

Foundations

Thermo-fluids Transport
- Reservoir
- Reservoir

Materials / Structures
- 500 µm
- 50 µm
- 20 µm

Metrology / Modeling
- Tube lens
- Objective

References:
- Wang*, Zhu*, Cui et al., in review
- Li, Zhu et al, *Joule*, 2018
- Li, Chen, Zhu et al, *Nat. Catalysis*, 2018
- Zhu et al, *APL*, 2017
- Zhang*, Zhu* et al., *APL*, 2018
Thank you!

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