# Nucleate Boiling Heat Transfer Enhancement with Electrowetting

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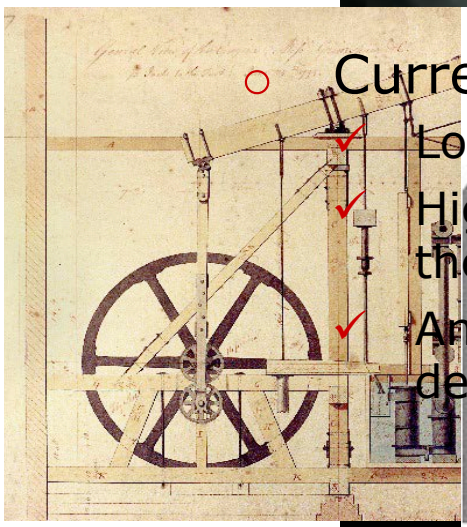
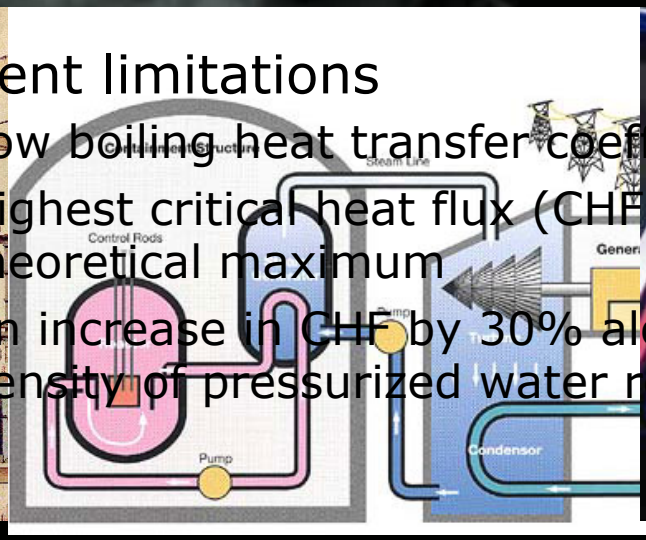
# Outline

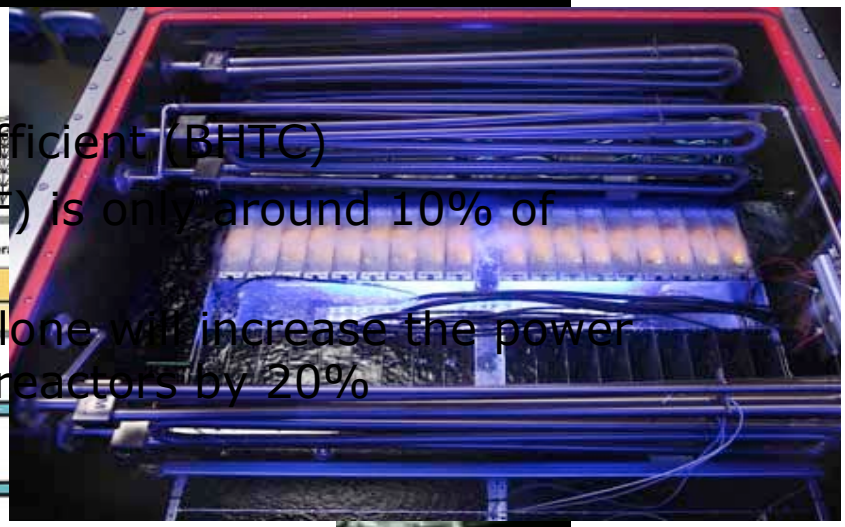
- Introduction
- Electrowetting
- Experimental design and measurements
- Electrowetting modulated nucleate boiling
- Conclusions

# Introduction

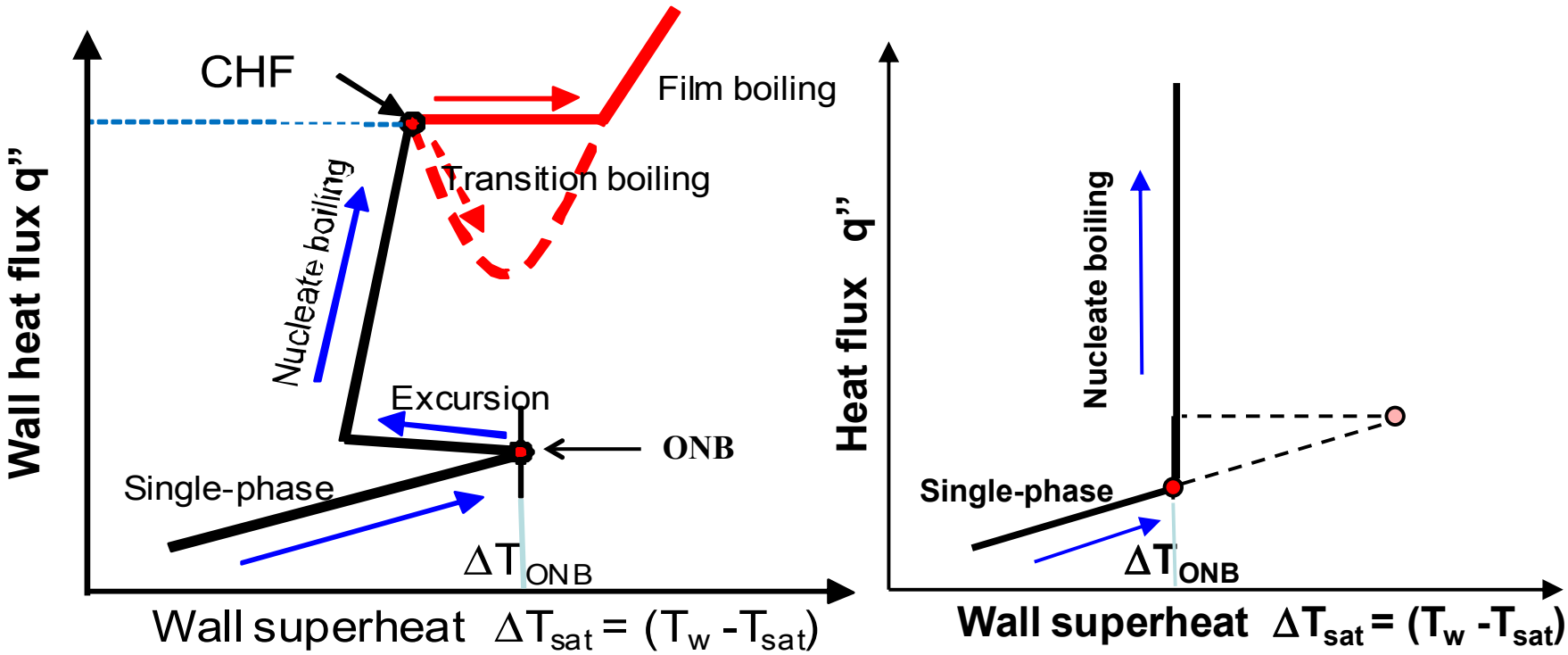
- Nucleate boiling – liquid-vapor phase change
  - One of the most efficient modes of heat transfer
    - ✓ Transfers enormous amount of heat with small driving temperature difference
  - Widely applied in [redacted] ration and thermal management
  - Current limitations
    - ✓ Low boiling heat transfer coefficient (BHTC)
    - ✓ Highest critical heat flux (CHF) is only around 10% of theoretical maximum
    - ✓ An increase in CHF by 30% alone will increase the power density of pressurized water reactors by 20%





# Boiling 101

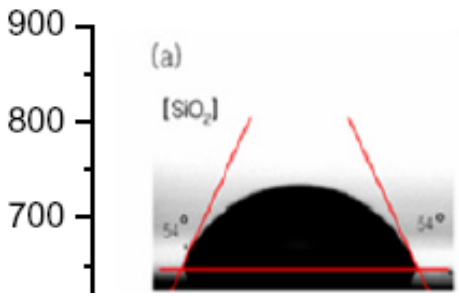



- Goals for boiling heat transfer enhancement
  - Onset of nucleate boiling (ONB) at low wall superheat
  - Steeper boiling curve – high HTC
  - Extremely high CHF

# Effects of Surface Wettability

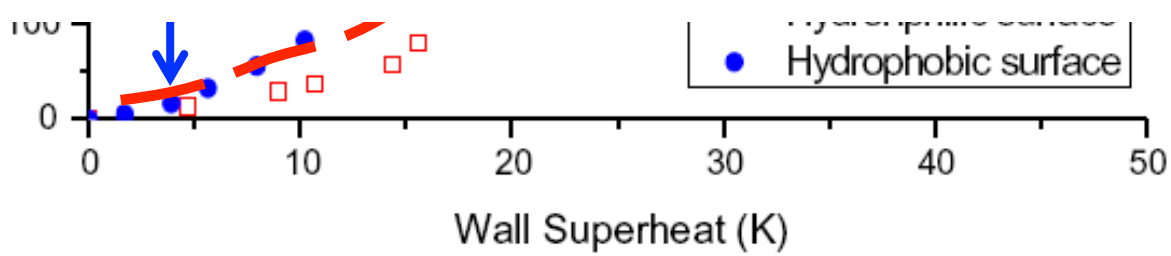
- Surface wettability plays a critical role in nucleate boiling
  - Hydrophobic surfaces have l[illegible]nergy barrier for nucleation and promot[illegible]
    ✔ Hydrophobicity
  - High HTC depends on: nucleati[illegible] site density, bubble departure size/frequen[illegible] contact line motion, etc.
    ✔ Complicated
  - Higher CHF can be obtained i[illegible]urface remains wetted by liquid and the vapor [illegible]boundary is restricted
    ✔ Hydrophilicity
- A dilemma: **On one hand, hydrophobicity promotes ONB; on the other hand, hydrophilicity enhances CHF**

# Effects of Surface Wettability





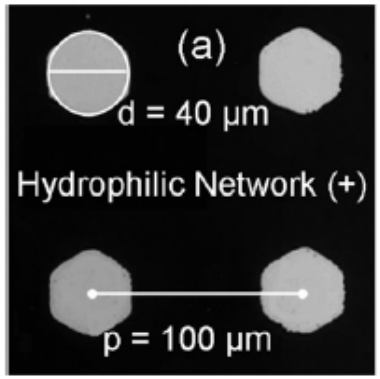
**How can we harness the benefits of both hydrophobicity and hydrophilicity?**

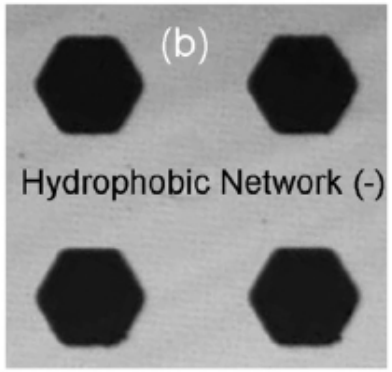


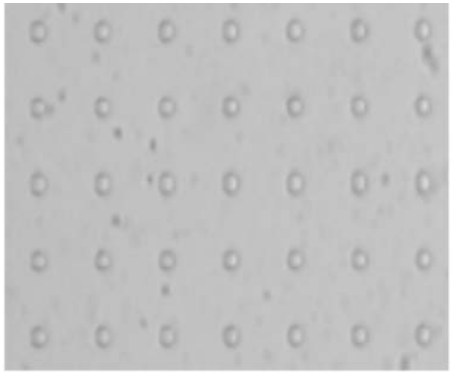

*Jo H. et al. 2011. IJHMT.' A study of nucleate boiling on hydrophilic, hydrophobic and heterogeneous wetting surfaces*

# Current Enhancement Technology

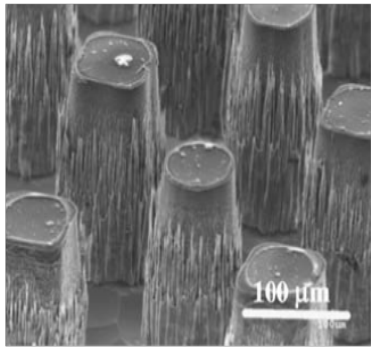
- Surfaces with hybrid wettability



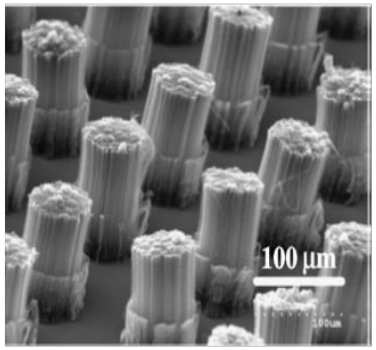



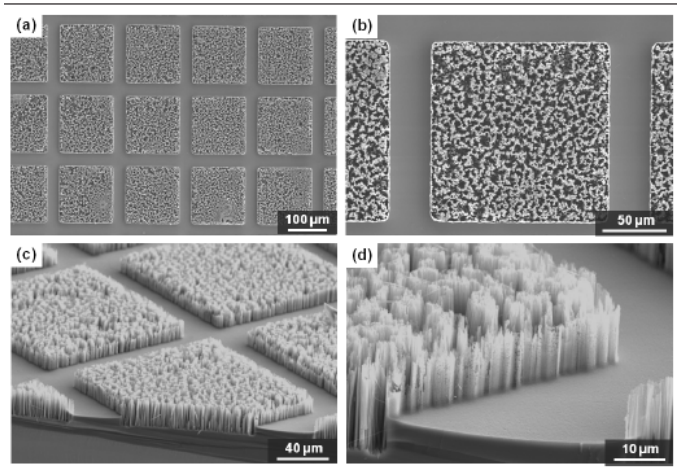
- Surfaces with hierarchical micro/nanoscale structures



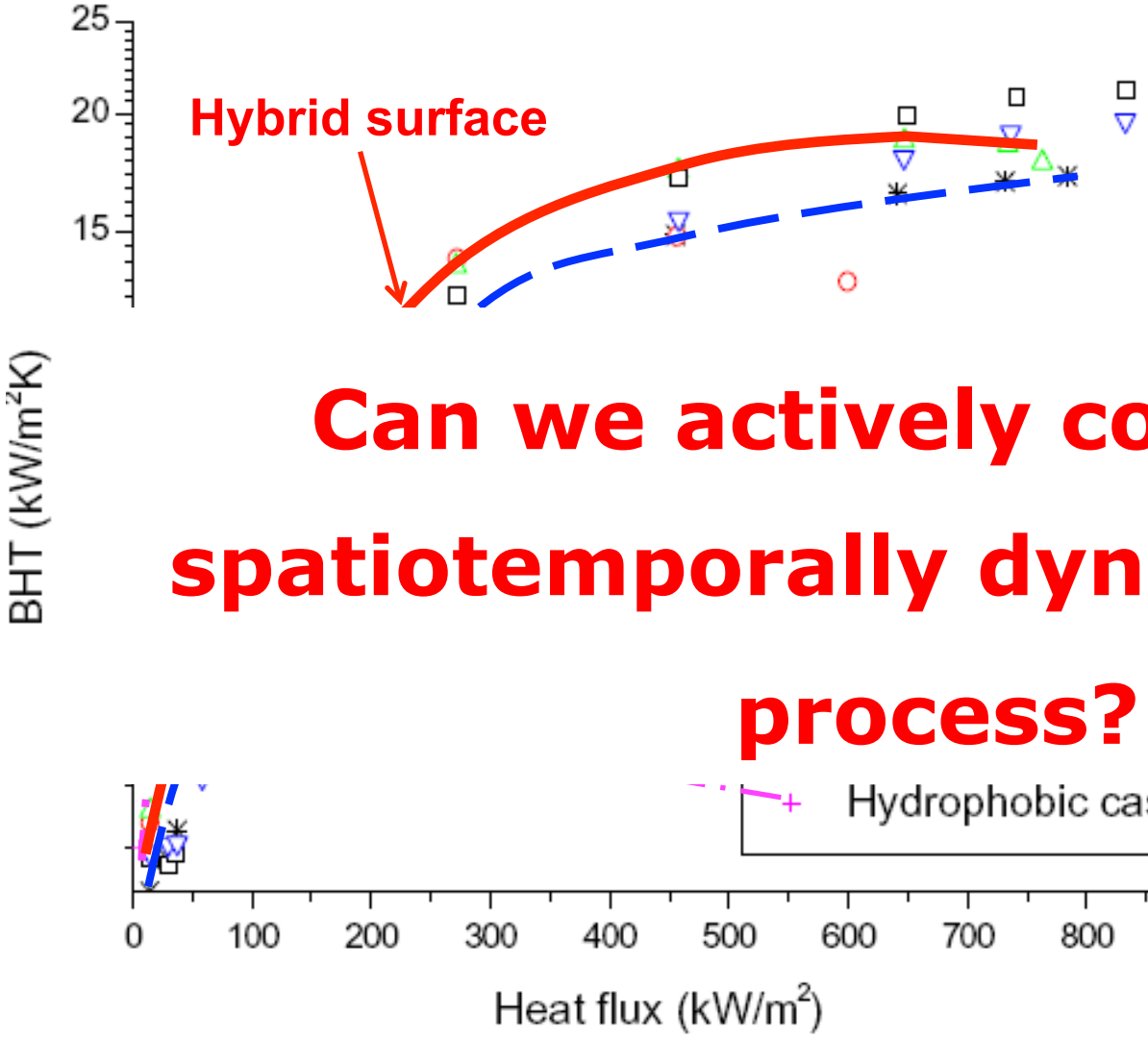

Silicon pin fin structure




Carbon nanotube pin fin array



# Current Enhancement Technology




- It is working!
- But …
  - Complicated to fabricate

**Can we actively control the spatiotemporally dynamic boiling process?**

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- Electrowetting
- Experimental design and measurements
- Electrowetting modulated nucleate boiling
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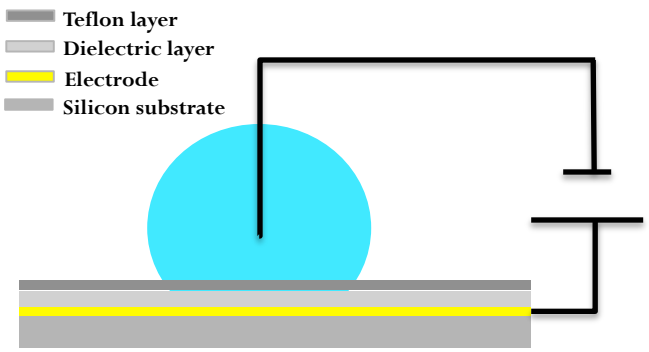
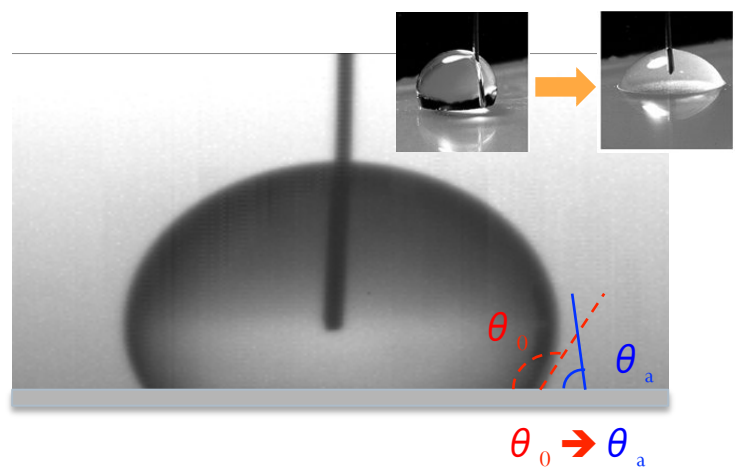
# Electrowetting

- Electrowetting (EW): Modification of surface wettability with an applied electric field, also termed “electrowetting on dielectric” (EWOD)
- EW is represented by the change of contact angle θ
  - Hydrophilic surface: θ < 90°
  - Hydrophobic surface: θ > 90° (Superhydrophobic: θ > 120°)




**EW of water droplet on Teflon-coated surface**

# Electrowetting Theory

- EW theory was first developed by Gabriel Lippmann in 1875, known as the Young-Lippmann equation

$$\cos\theta_a = \cos\theta_0 + \frac{\varepsilon_0 \varepsilon_d}{2d\sigma_{LV}} V^2$$

where

$\theta_0$: inherent contact angle;

$\theta_a$: apparent contact angle

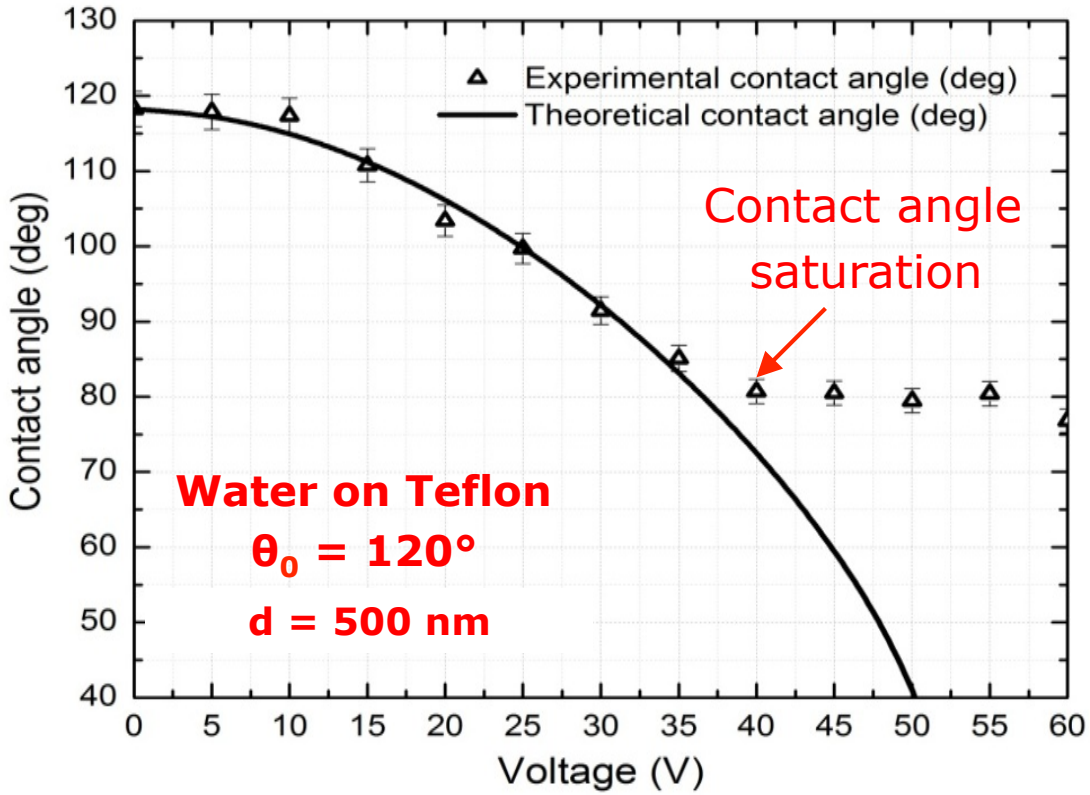
$\varepsilon_0$: permittivity in vacuum;

$\varepsilon_d$: relative permittivity

d: dielectric layer thickness;

V: applied voltage

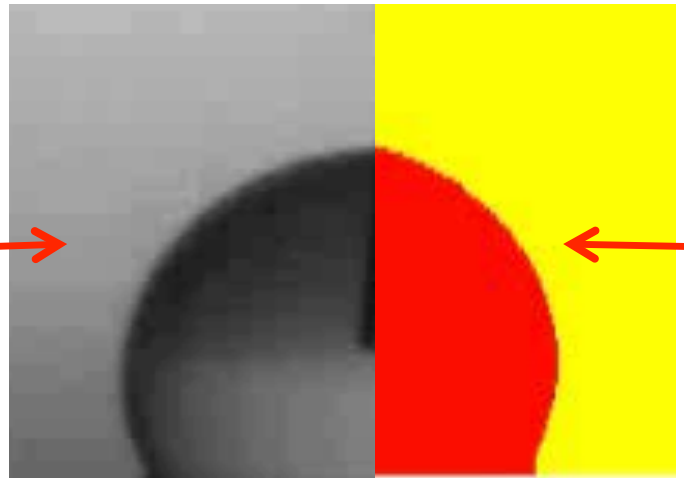
$\sigma_{LV}$: liquid surface tension



# Electrowetting - Droplets

- DC electrowetting

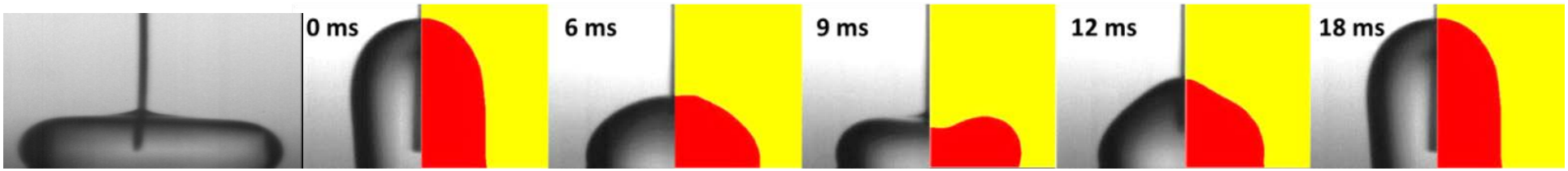
Visualization



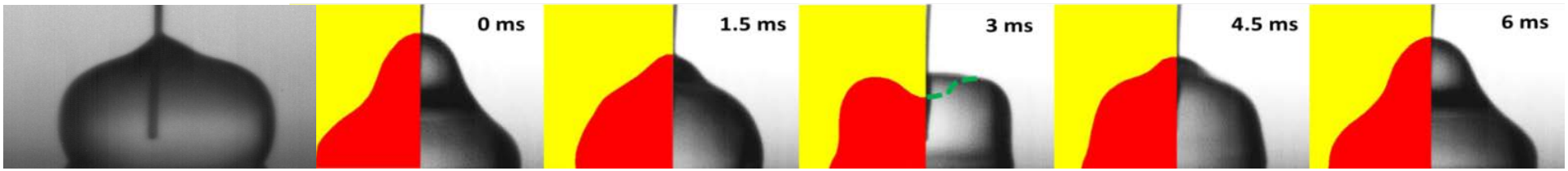
Simulation

- AC electrowetting

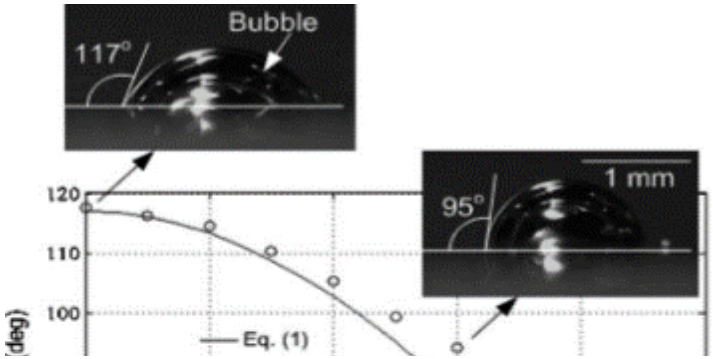
**$P_2$ mode (V = 32 V, f = 28 Hz)**

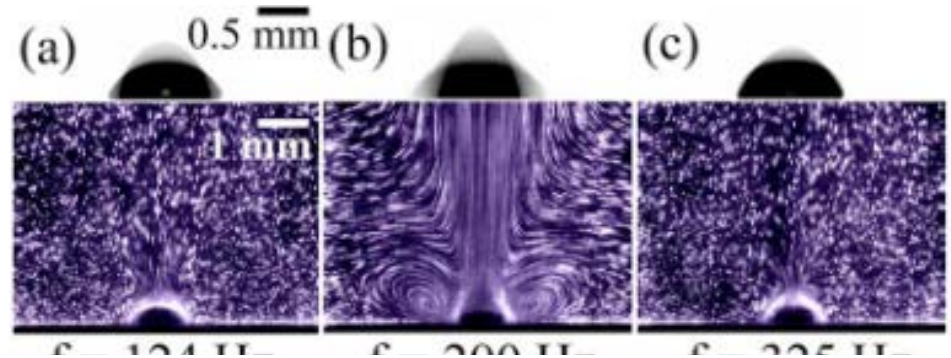



**$P_4$ mode (V = 32 V, f = 79 Hz)**



# Electrowetting - Bubbles




**It is possible to modulate/enhance nucleate boiling with EW!**

Applied Voltage ($V_{DC}$)

*Zhao Y. and Cho S.K., 2006, Lab Chip, "Micro air bubble manipulation by electrowetting on dielectric"*

f = 423 Hz  f = 603 Hz  f = 735 Hz

*Ko et al., 2009, App Phy Lett, "A synthetic jet produced by electrowetting-driven bubble oscillation in aqueous solutions"*

- Contact angle variation is significant enough to reverse the surface wettability
- Under AC EW, interfacial oscillation generates strong streaming flow around the bubble

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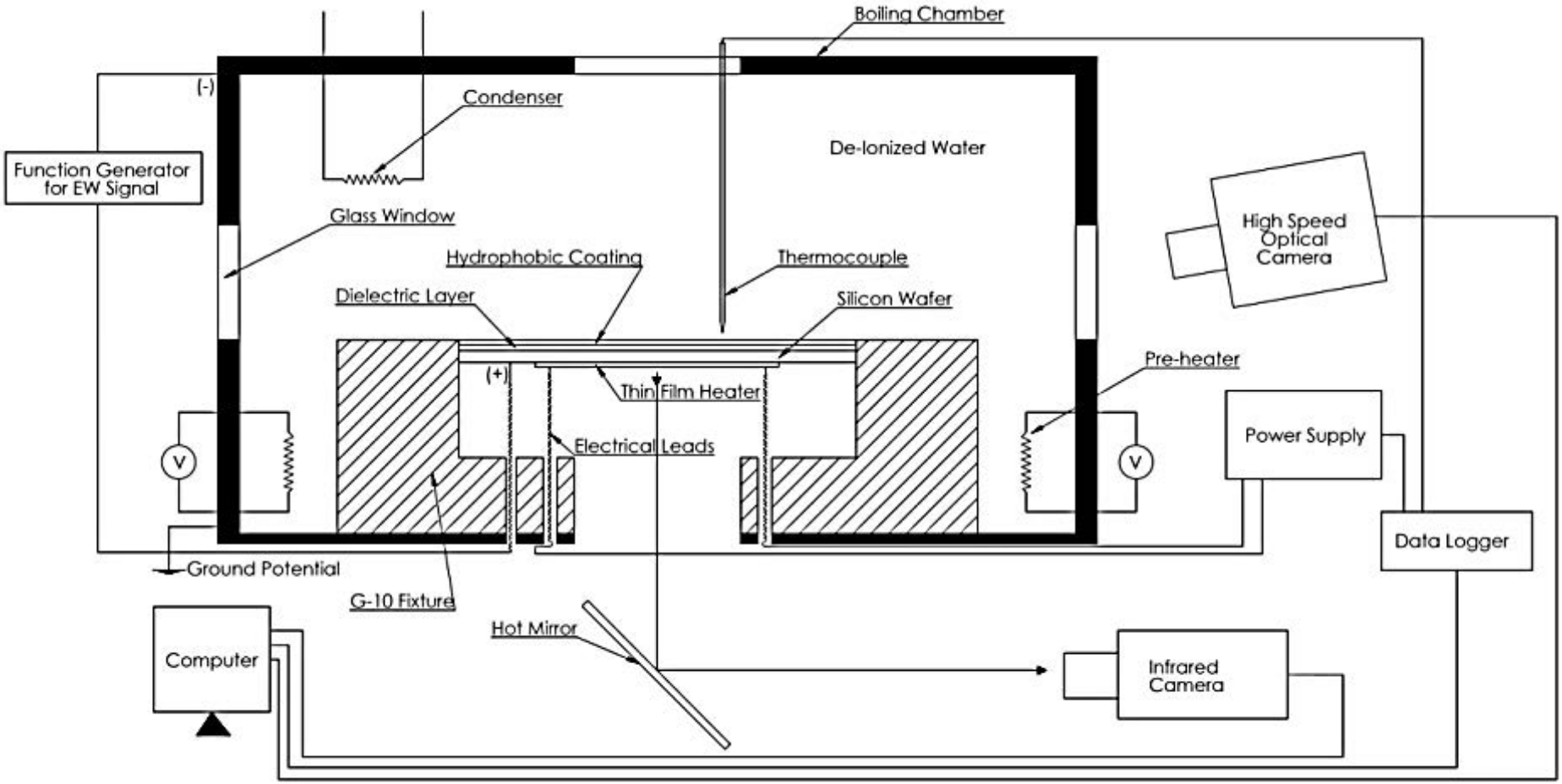
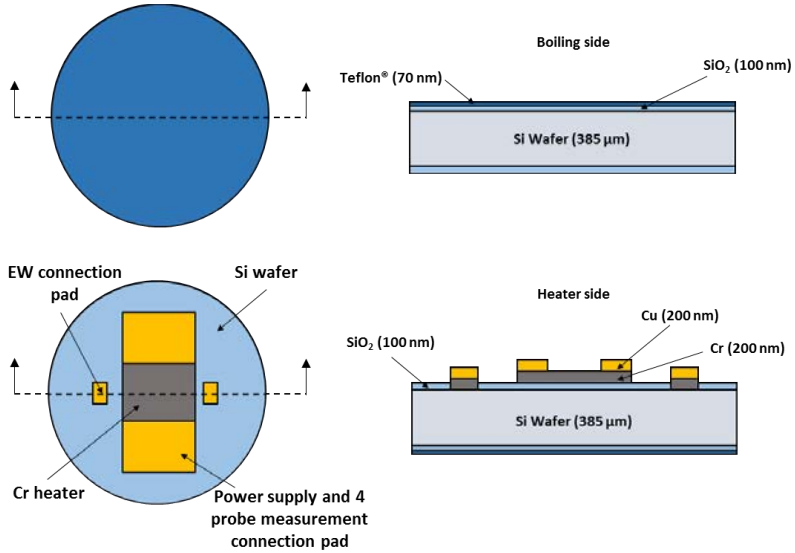
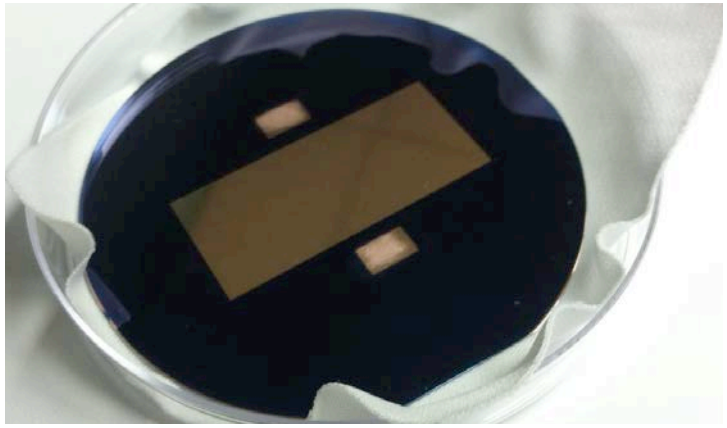
# Experimental Setup

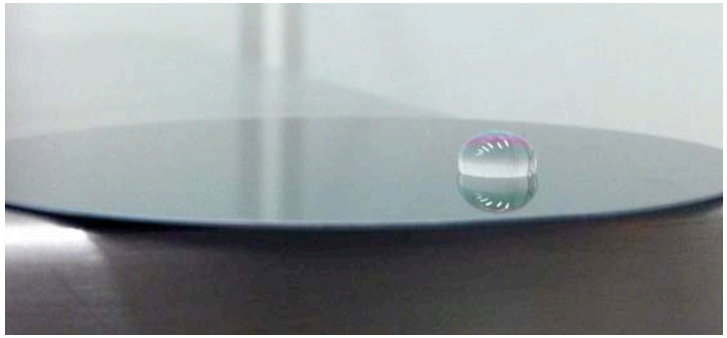


# Test Device



- Coating material: DuPont™ Teflon® (AF1600) dissolved in FC40 (2%)
- Adhesion promoter: Fluorosyl™ FCL-52 in fluorosolvent FSM660-4 (0.4%)
- Fabrication method
  - Dip coat Fluorosyl solution
  - Spin coat Teflon



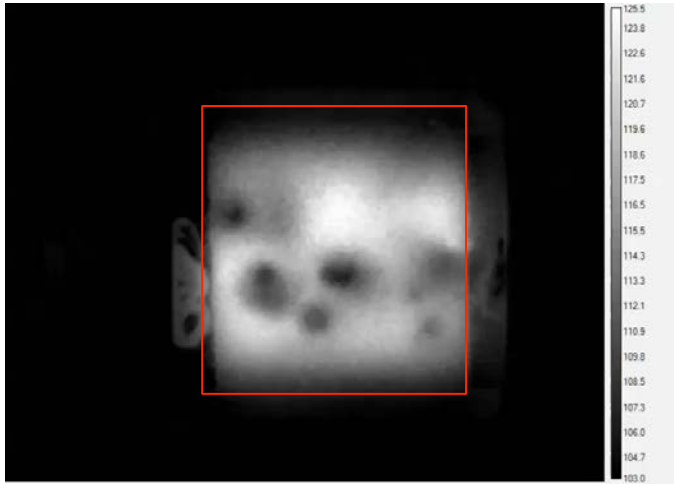
# Measurement Parameters

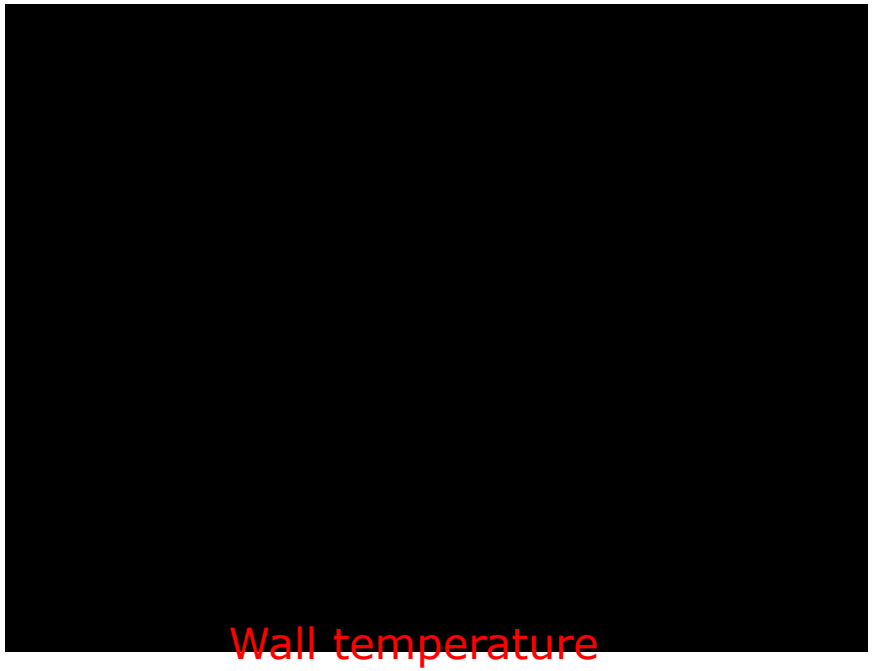
- Optical imaging
  - Nucleate bubble dynamics
  - Boiling regime identification
- IR thermography
  - Boiling surface wall temperature
  - Heat flux
- Data acquisition
  - Power supply to heater
  - Liquid pool temperature

**Synchronous**

# Wall Temperature and Heat Flux

IR Image

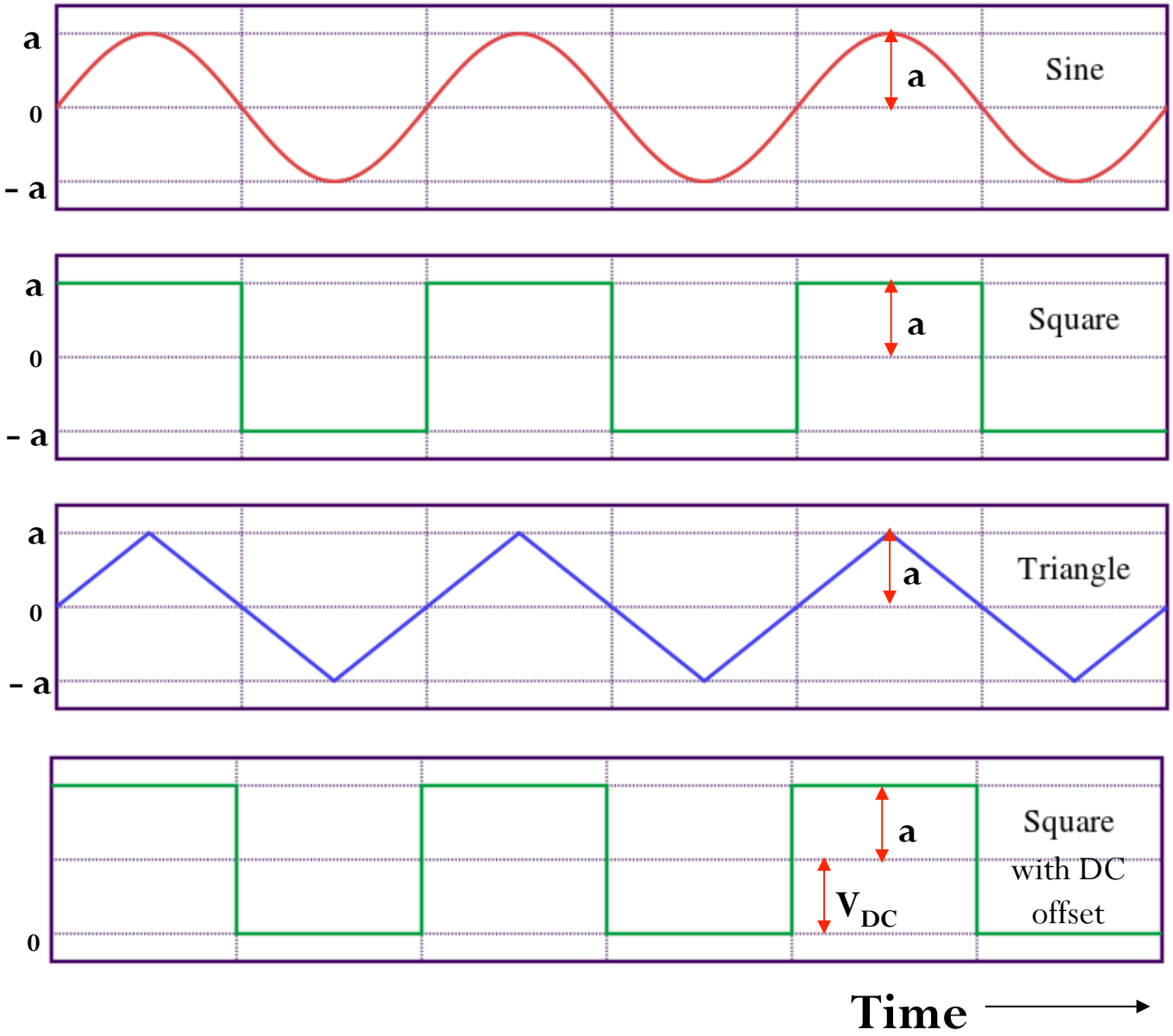


Wall temperature

Heat flux

# Electrowetting Signals




$$V_{r.m.s} = a / \sqrt{2}$$

$$V_{r.m.s} = a$$

$$V_{r.m.s} = a / \sqrt{3}$$

$$V_{r.m.s} = \sqrt{a^2 + V_{DC}^2}$$

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- Introduction
- Electrowetting of droplets vs. bubbles
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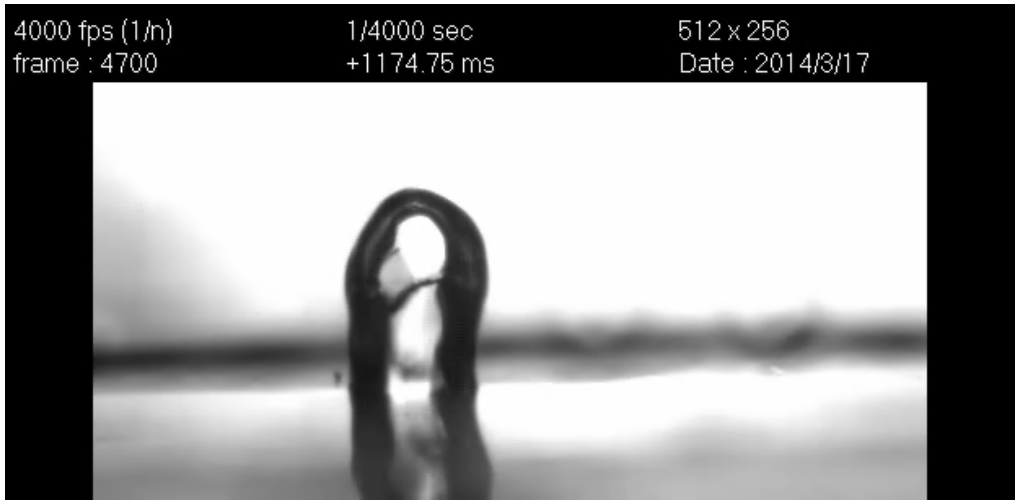
# Onset of Nucleate Boiling

Hydrophobic Surface
$q'' = 3.7\ kW/m^2$

EW modulated
($V_{r.m.s} = 78$ V, f = 10 Hz)

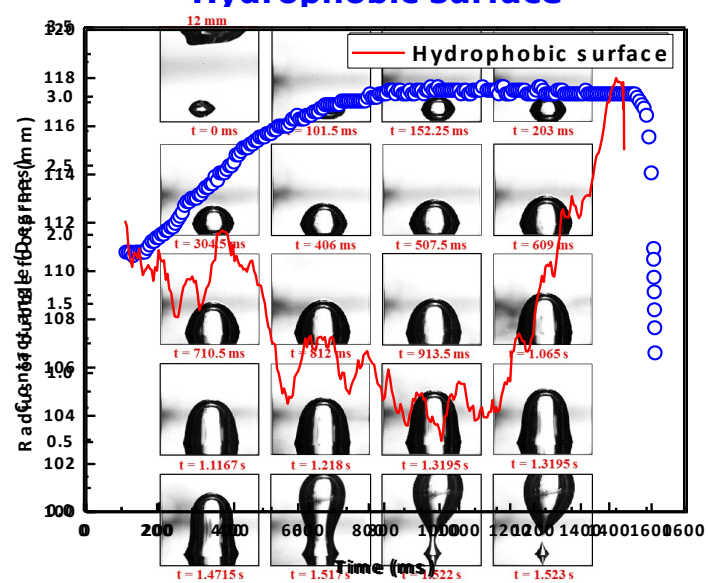
$q'' = 6.8\ kW/m^2$



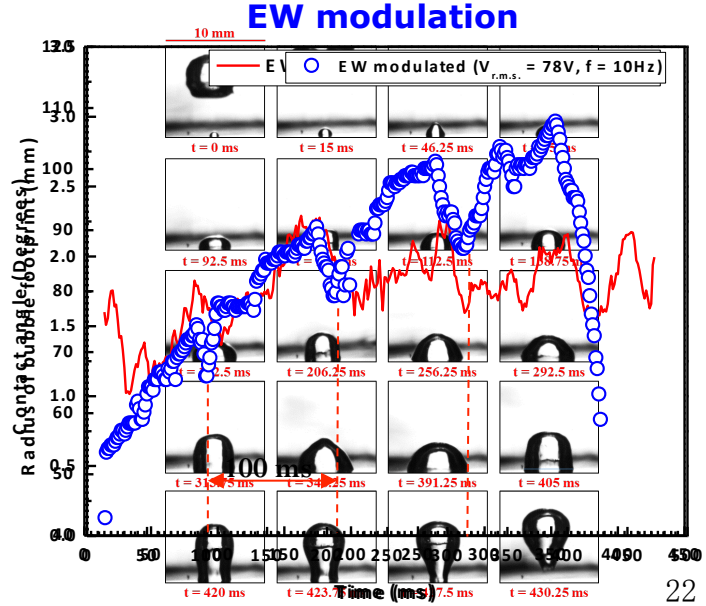
# Onset of Nucleate Boiling

- Change in bubble geometry
  - Absence of vapor patch upon departure
- Delayed ONB
  - Hydrophobic surface = 3.7 kW/m$^2$
  - EW modulated = 6.8 kW/m$^2$
- Shorter bubble departure time
  - Hydrophobic surface = 1.5 sec
  - EW modulated = 430.25 ms
- Decreased bubble footprint size
  - Hydrophobic surface, radius = 3 mm
  - EW modulated, radius = 2.75 mm
- Reduced contact angle
  - Hydrophobic surface ~ 104 – 118 °
  - EW modulated ~ 80 °

**Hydrophobic surface**



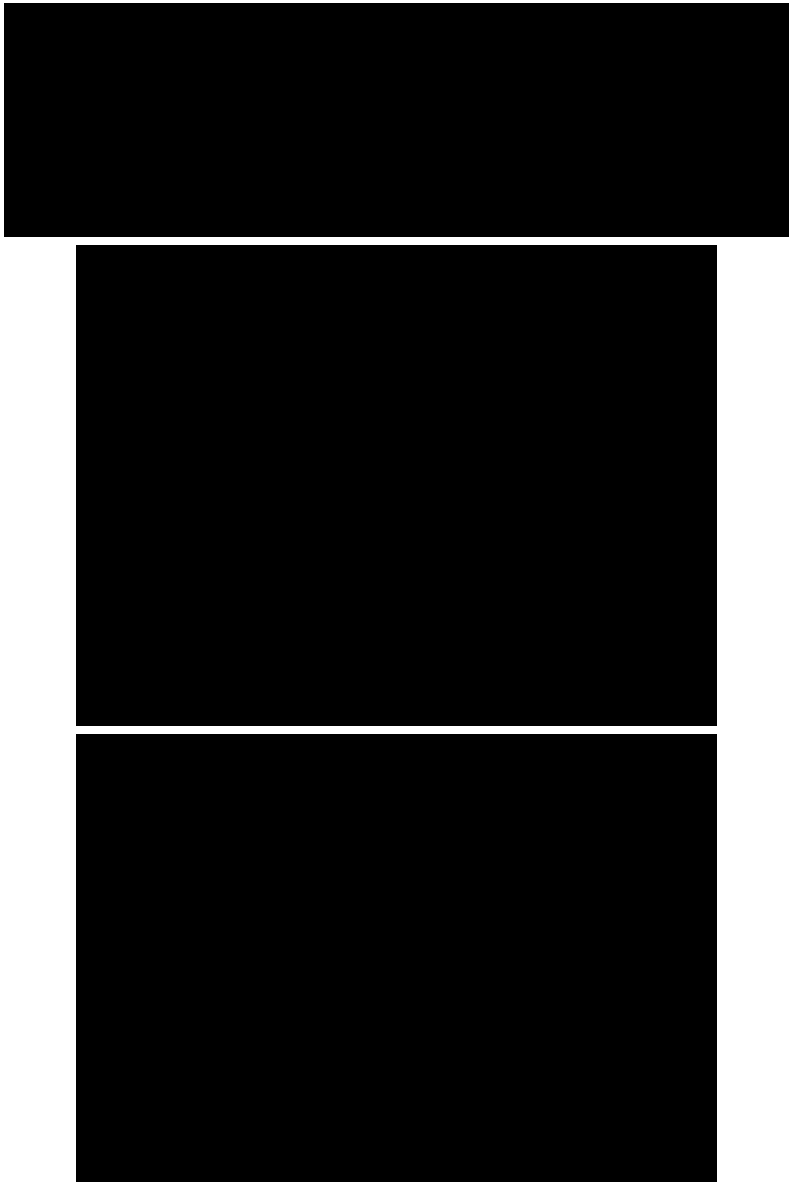

**EW modulation**



# Fully-Developed Nucleate Boiling

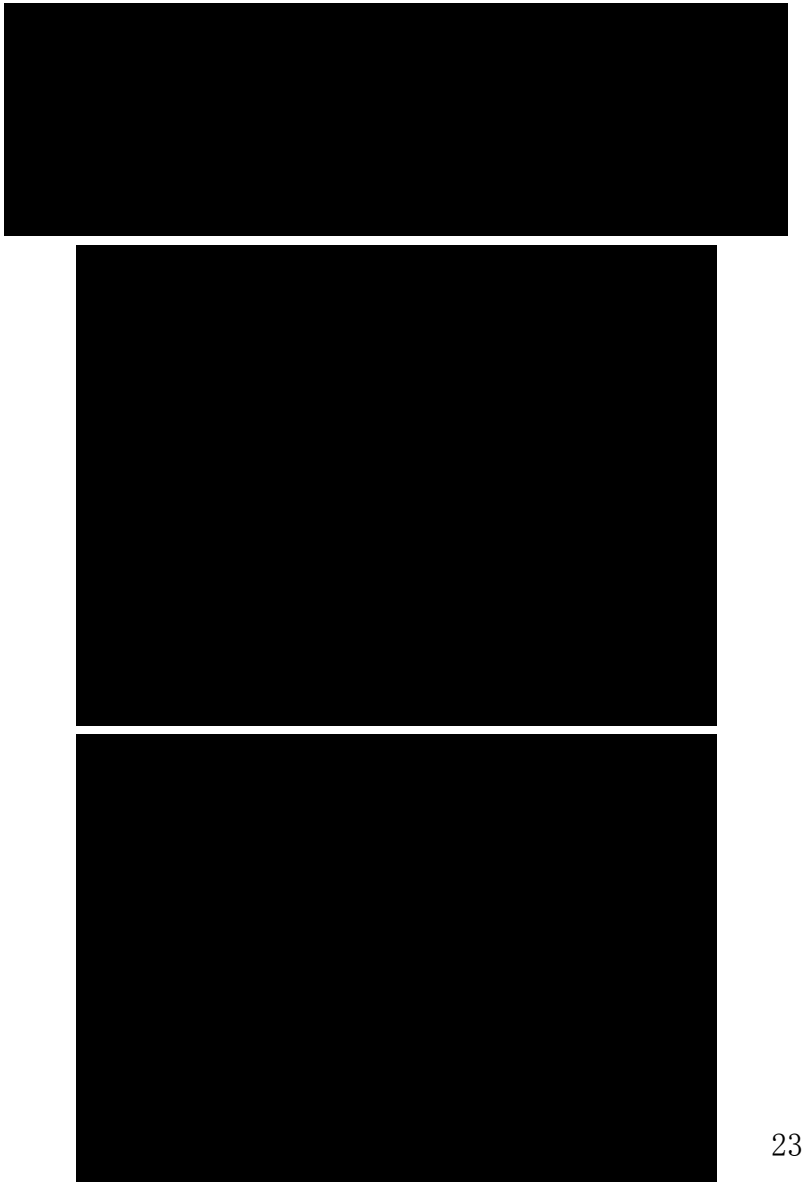
**Hydrophobic surface**

**q" = 62.6 kW/m²**



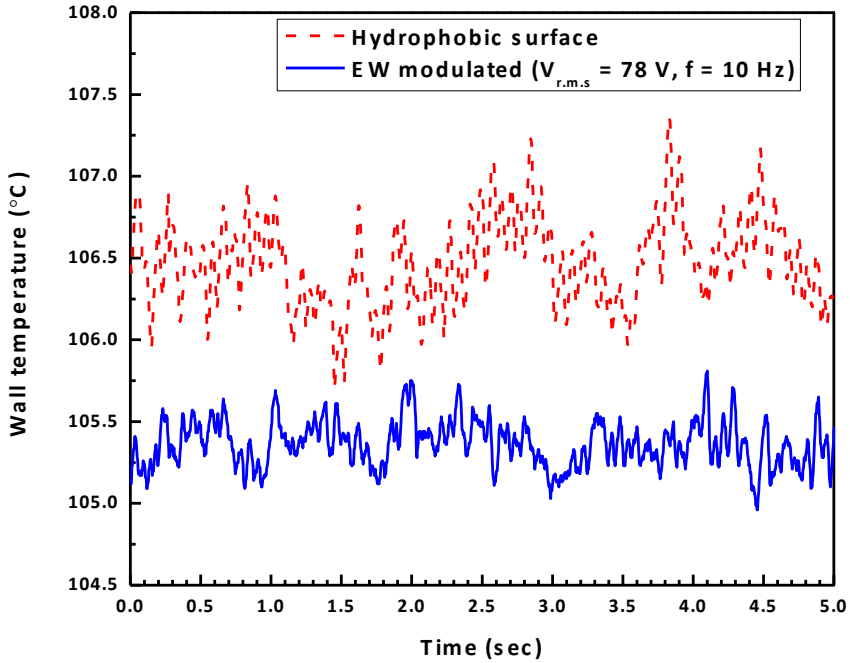
**EW modulated**

**q" = 62.6 kW/m²**

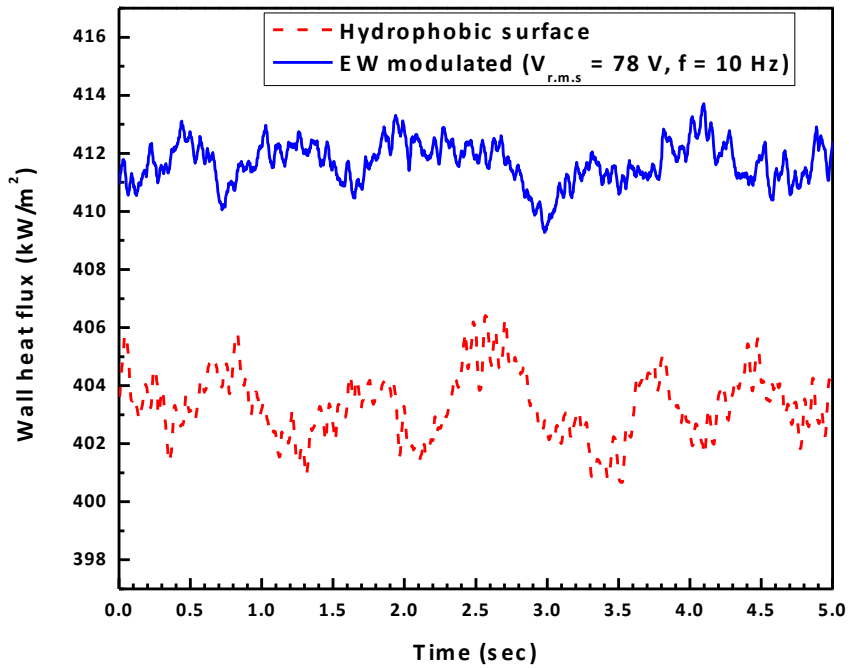


# Fully-Developed Nucleate Boiling

**Average wall temperature**




**Average boiling heat flux**



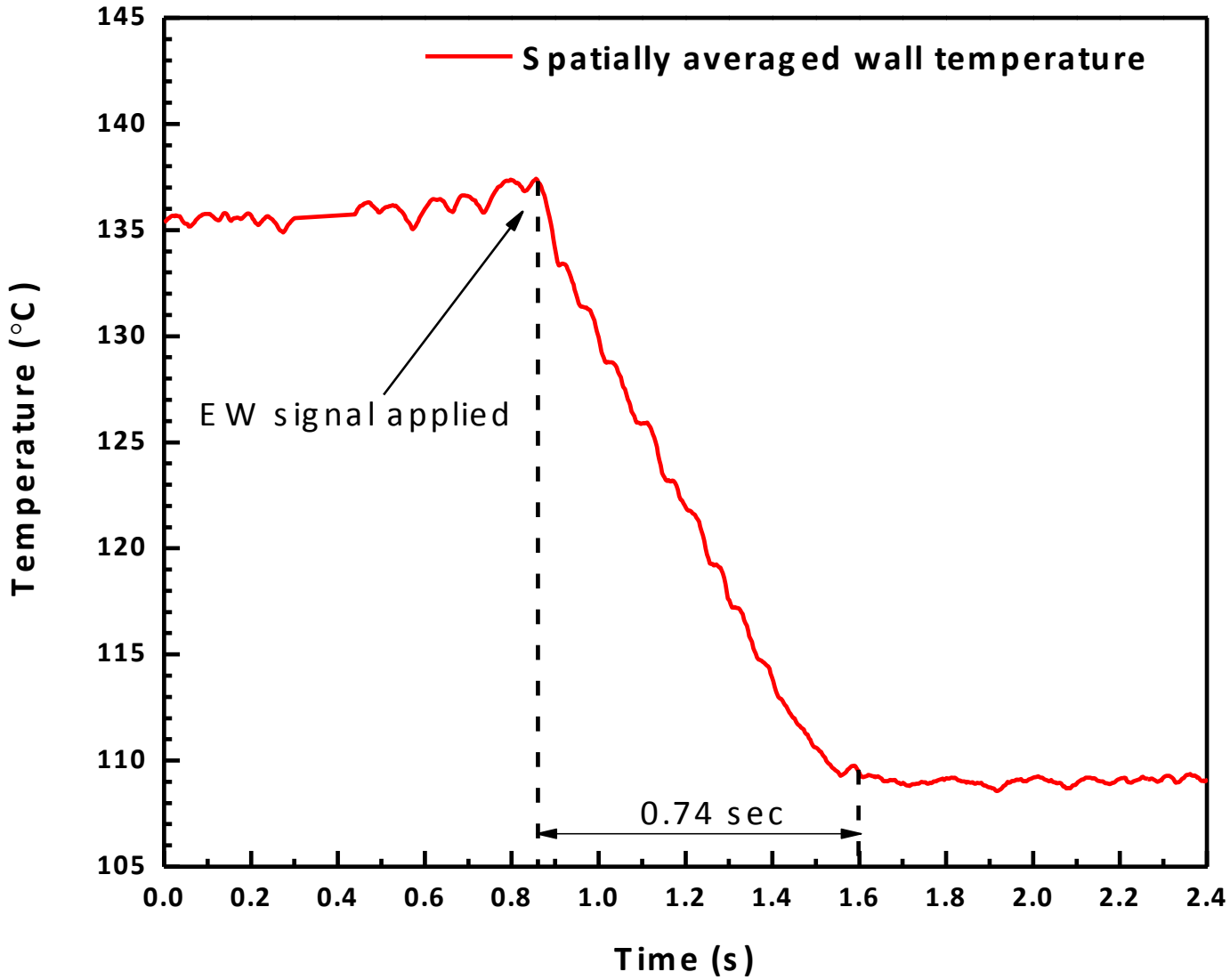

- Effect of AC EW
  - Decrease in average wall temperature by 1.5ºC
  - Increase in boiling heat flux by 10 kW/m$^2$

# Film Boiling to Nucleate Boiling Transition

**Applied heat flux = 82 kW/m$^2$**

**EW waveform applied**

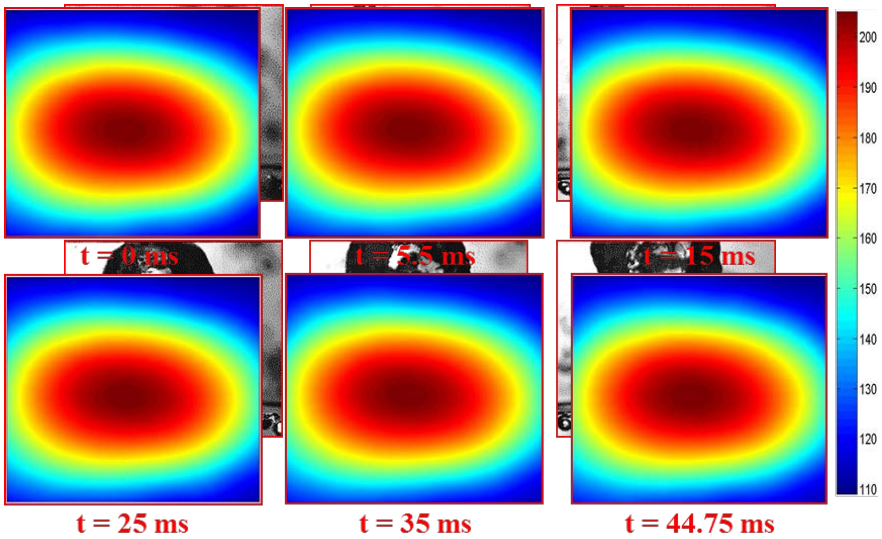
# Wall Temperature Variation



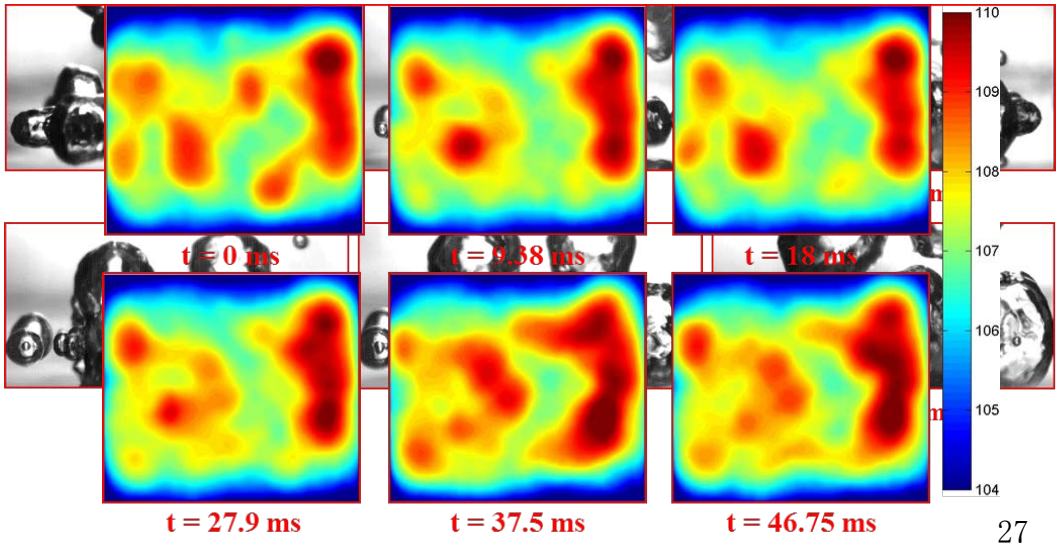
# CHF Enhancement

- Wall heat flux = 86.9 kW/m$^2$
- EW effect on boiling regime
  - Absence of vapor film
  - Surface exposed to bulk fluid
  - Delayed onset of film boiling
  - Higher departure frequency
  - Smaller departure size
- EW effect on wall temperature
  - Lower wall temperature
    - Hydrophobic surface > 200 °C
    - EW modulated ~ 110 °C
  - Enhanced HTC
  - Enhanced wall heat flux

**Hydrophobic surface**

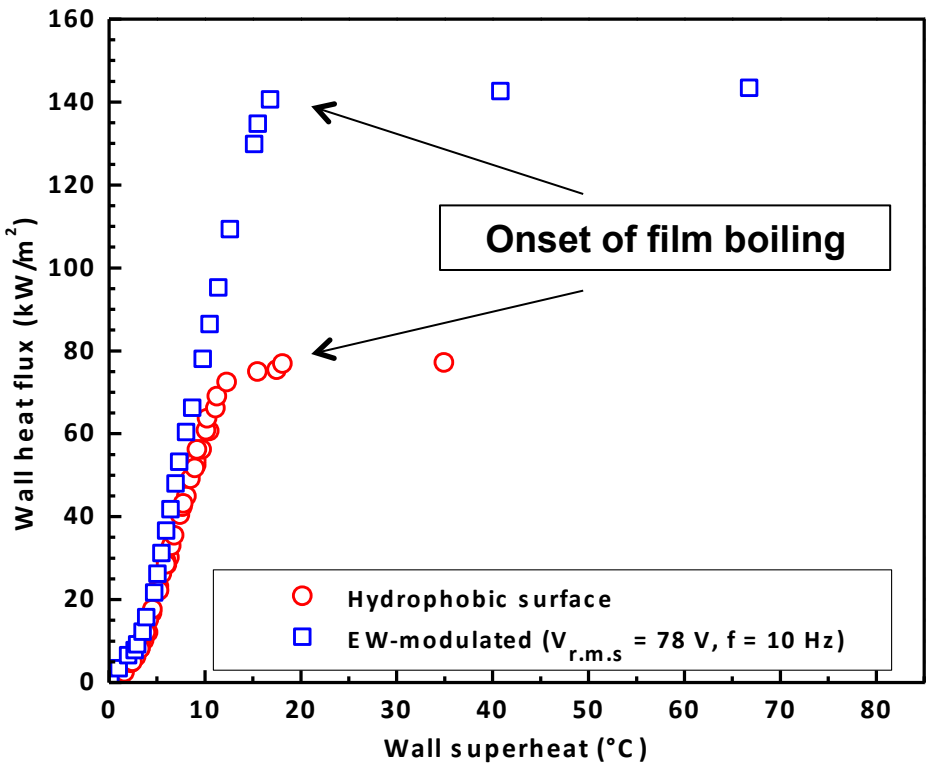



**EW modulation**

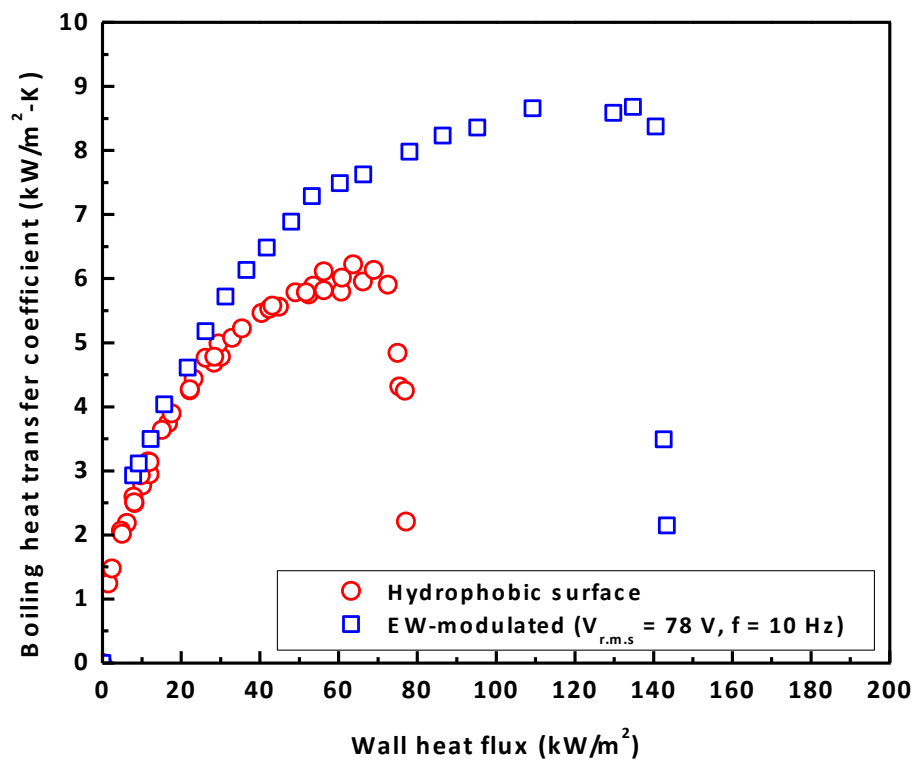


# EW-Enhanced Boiling Heat Transfer

**Boiling curve**

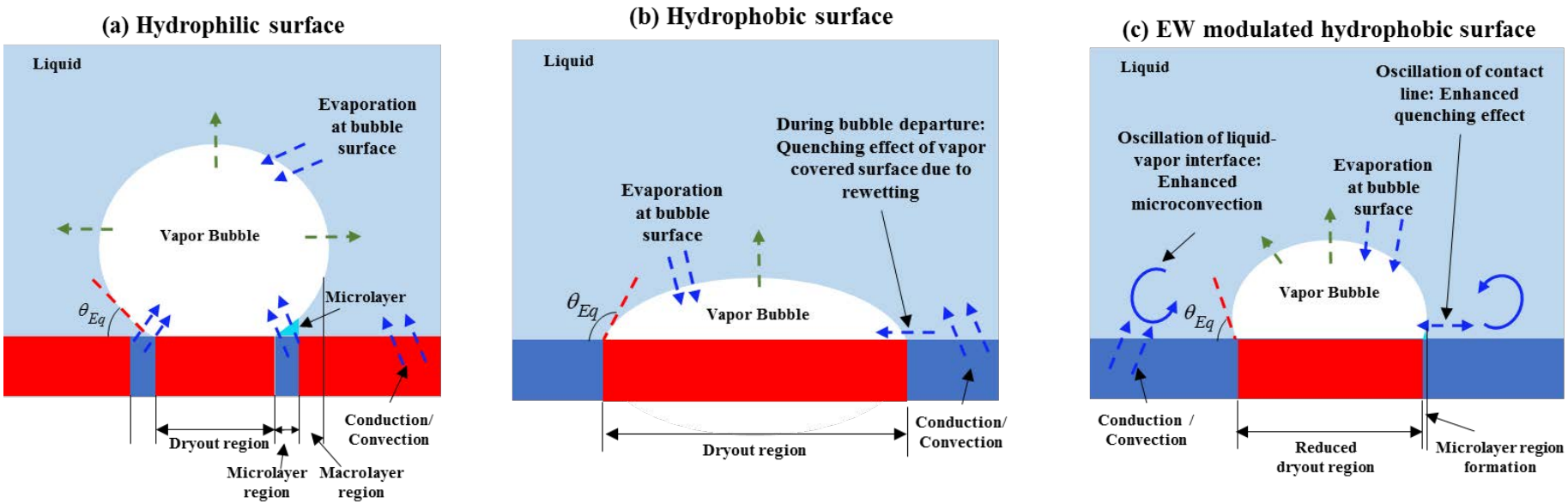



**Boiling heat transfer coefficient**




- Delayed onset of film boiling
- CHF is enhanced under the influence of EW
- Overall enhancement of boiling HTC

# Enhancement Mechanisms




- Nucleate boiling regime
  - Altering the bubble dynamics
  - Enhancing microcovection in the liquid
  - Re-creating the microlayer
  - Augmenting the quenching heat transfer
- Filmwise transition boiling
  - Destabilizing the liquid-vapor interface

# Conclusions

- We have demonstrated that the bubble dynamics can be effectively controlled by EW and nucleate boiling heat transfer can be favorably improved over the entire range of boiling regimes.
- We have developed experiments and are developing theoretical/numerical models to understand the physical mechanisms of EW-enhancement of nucleate boiling.

# Acknowledgements


- Financial support from
  - National Science Foundation (NSF)
  - University of Houston