Enhanced Boiling Heat Transfer by using micro-pin-finned surfaces for Electronic Cooling

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Contents

Background

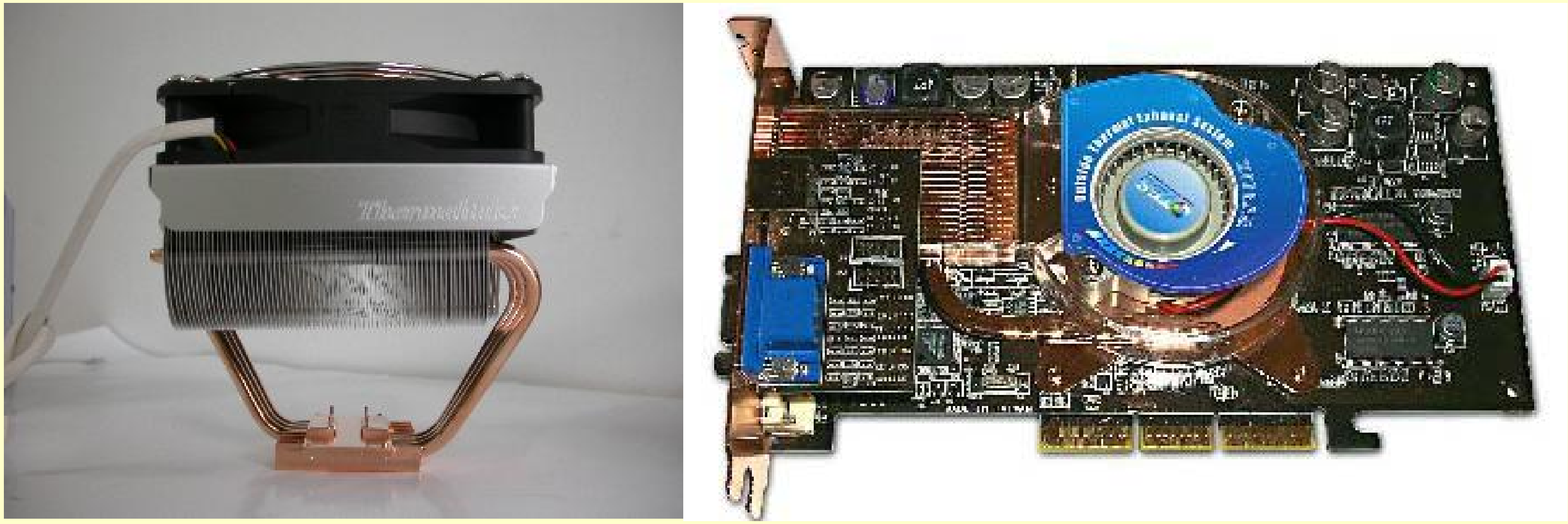
Trend of sing-chip packaging technology

	2006	2010
Performance	3.19 GH	9.54 GH
Integration	0.2 billion transistors	1 billion transistors
DRAM ½ pitch	80 nm	45 nm
Power density	70W/cm^2	85 W/cm^2
Junction temp	85 ^{o}C	85 ^{o}C

CPU型号	设计功率
Athlon 64 FX-55 (Clawhammer)	105W
Pentium 4 E 3.4GHz (Prescott)	103W
Pentium 4 E 2.8GHz (Prescott)	89W
Pentium 4 2.4GHz (Northwood)	66.2W
Athlon 64 3000+ (Winchester)	63W

Temperature increases by 10^{o}C → **Fault probability increases by 50％**

Air cooling technology



Finned heat pipe radiator

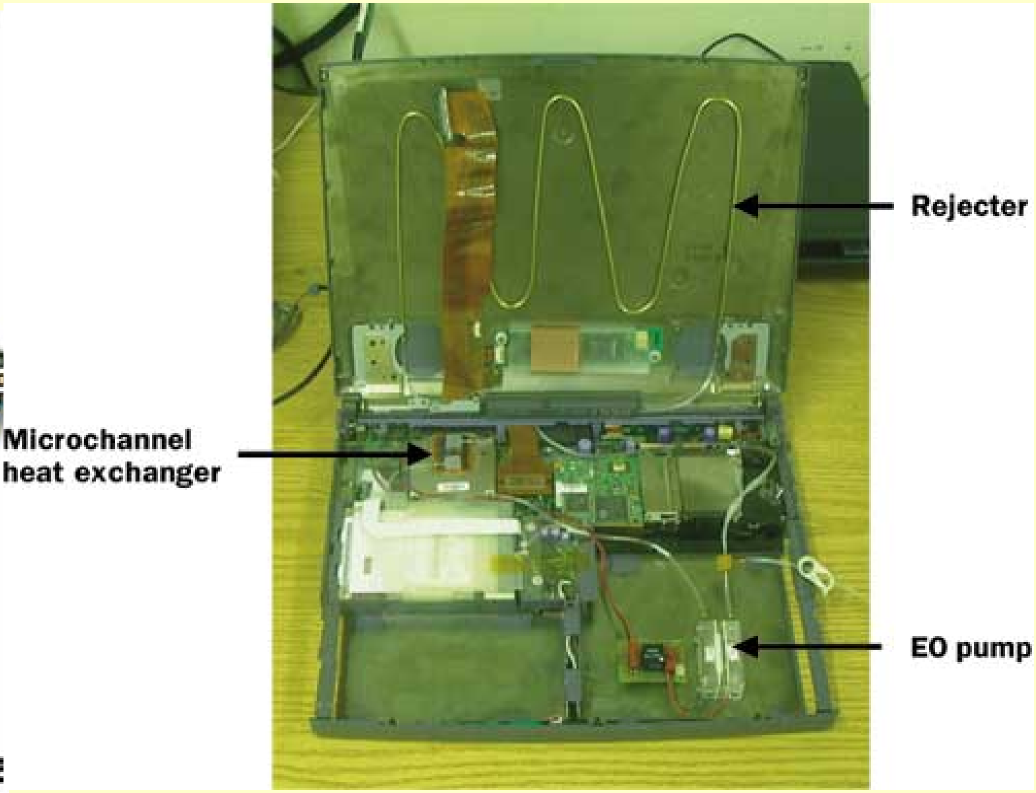
demerit

1 toward large volume and weight

2 nose increasing

3 Limited heat dissipation ability

Liquid cooling technology



Toshiba

Merit

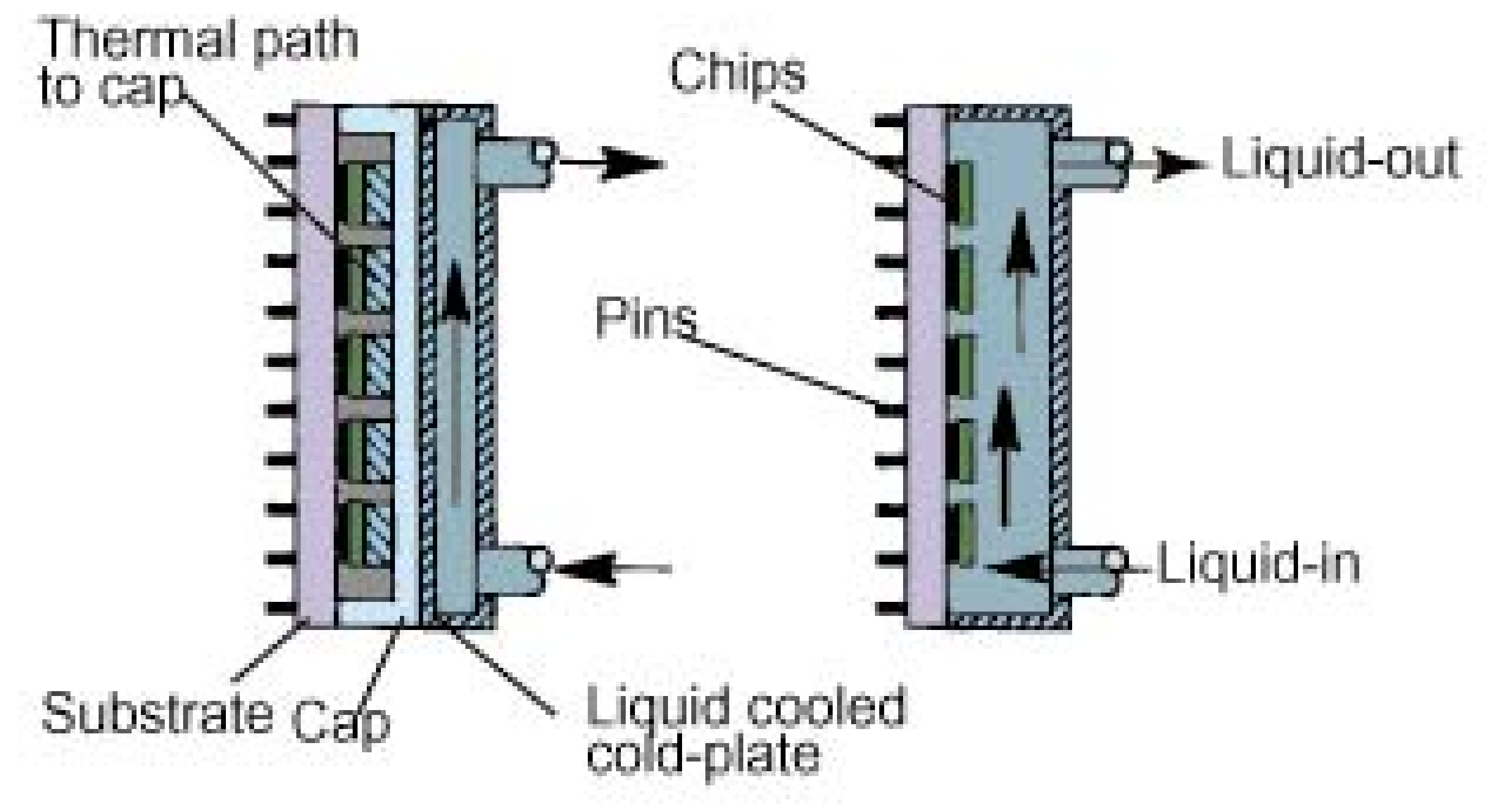
1high efficiency

2 low noise

Demerit

Poor security and reliability

Liquid cooling technology



Indirect liquid cooling

Direct liquid cooling

To use latent heat of phase change to get high heat dissipation

Direct Liquid cooling with phase change

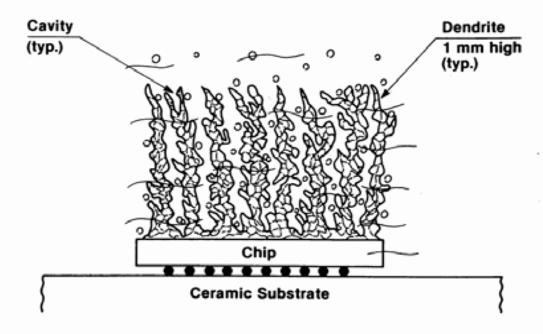
- Pool boiling

  * No pump, less complex, easier to seal

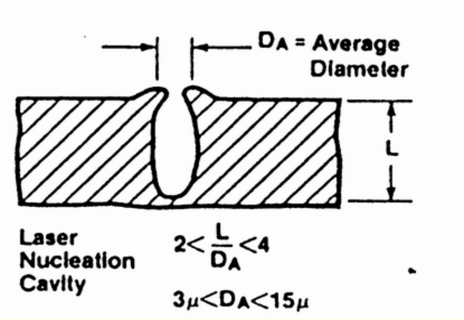
- Flow boiling

  Pump, circulation loop

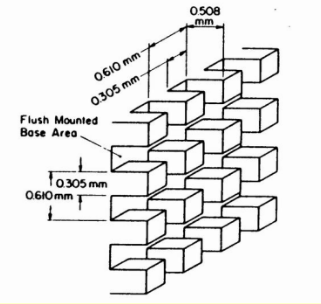
Treated Surfaces



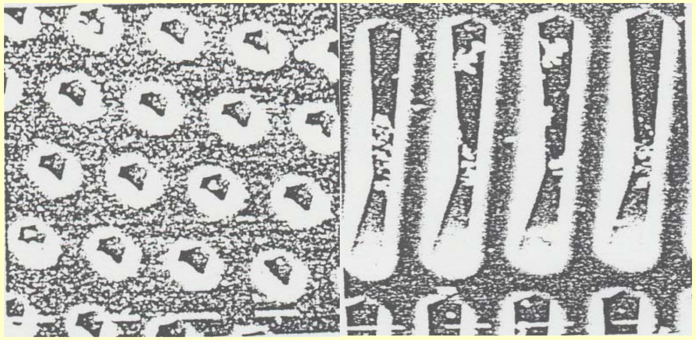
(a) Dendritic surface
(Oktay et al. 1972)



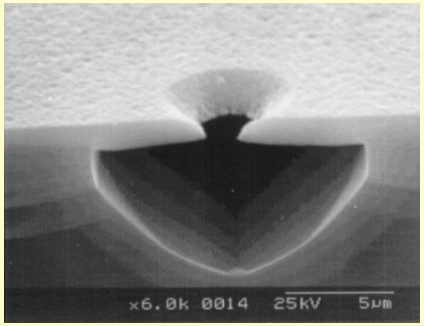
(b) Laser drilled cavity
(Chu and Moran, 1977)



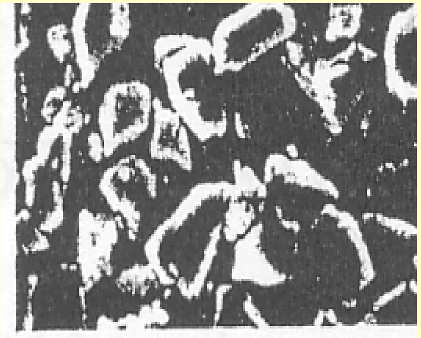
(c) Micro-Pin-Fin
(Mudawar and Anderson, 1989)



(d) Hexagonally dimpled and trenched surface
(Wright and Gebhart. 1989)



(e) Micro-reentrant cavity
(Kubo et al. 1999)

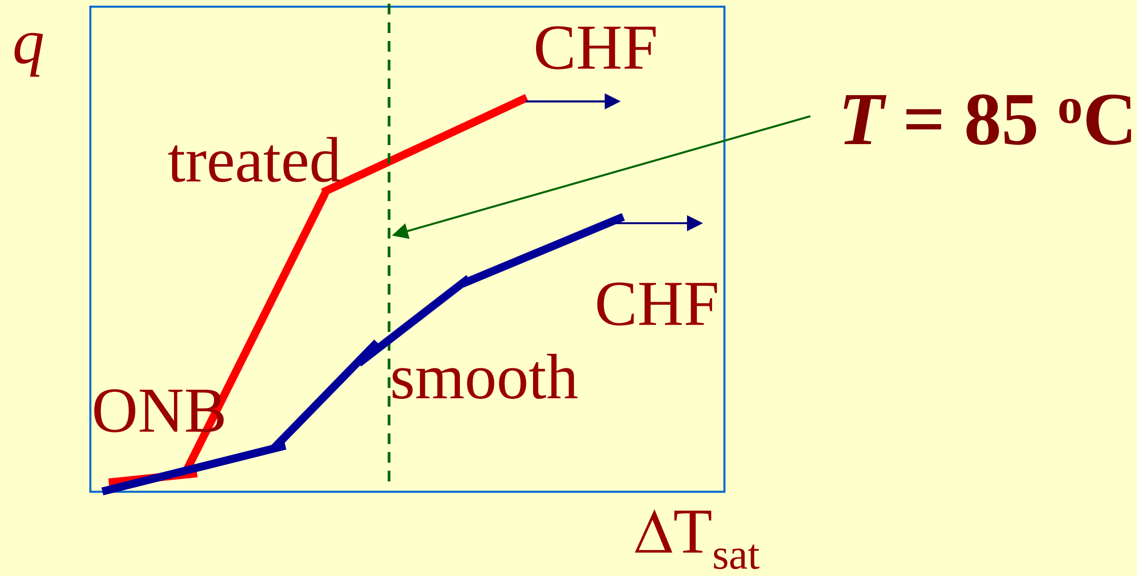


(f) Diamond treated surface
(O'Connor et al., 1991)

Problem

(1) **Severe boiling heat transfer deterioration in high flux region**

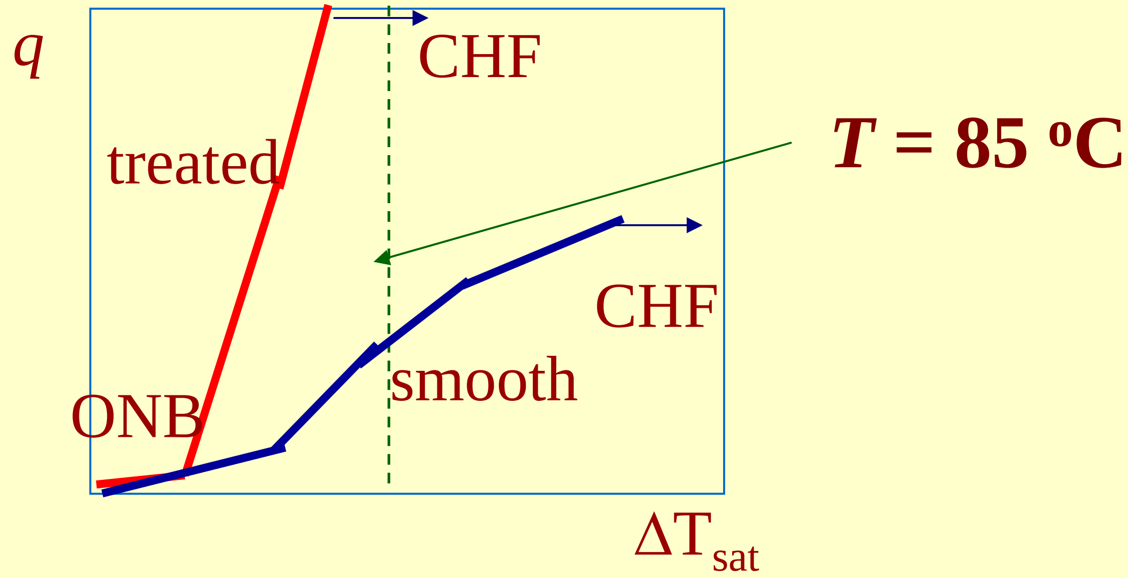
(2) **Critical heat flux occurs at *T* > 85 °C**



Objectives

To develop a new surface microstructure for effective boiling heat transfer

-----to solve the above problems for electronic cooling application



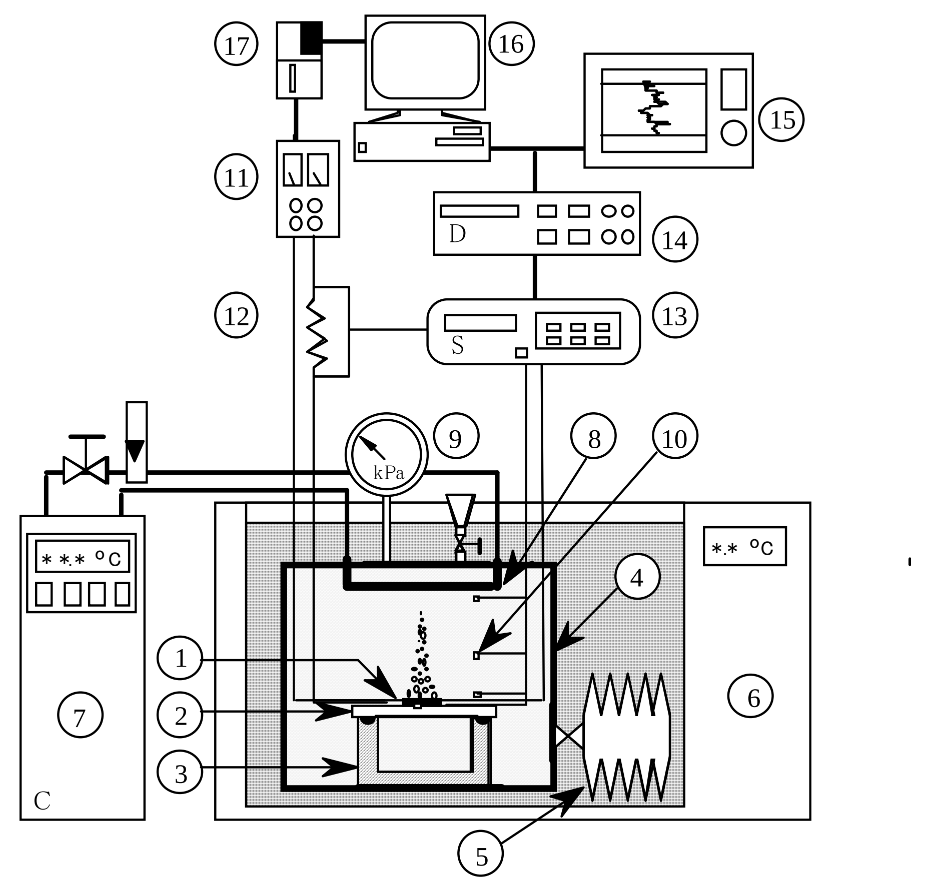
Studies

Micro-pin-fins and submicron-scale roughness were fabricated on the surface of silicon chip for enhancement of boiling heat transfer of FC-72.

1. **Size and height of micro-pin-fins**
2. **Roughness**
3. **Subcooling**
4. **Dissolved gas content**
5. **Chip orientation**

Contents

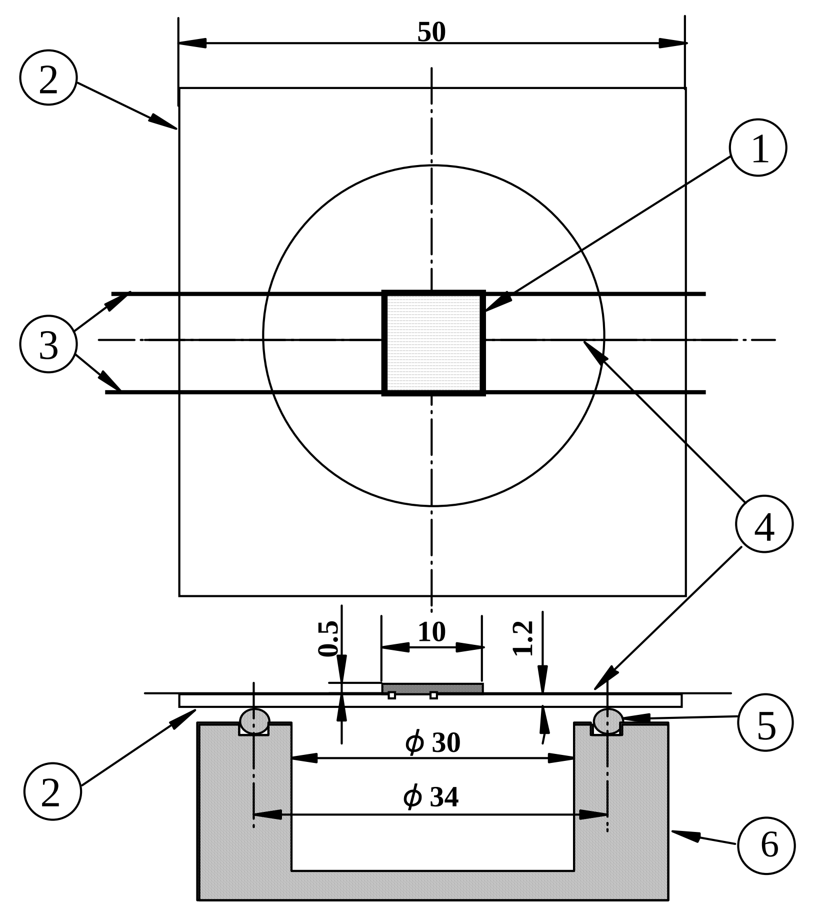
Experimental Apparatus



1. Test chip
2. Glass plate
3. Vacuum chuck
4. Test vessel
5. Rubber bag
6. Water bath
7. Cooling unit
8. Condenser
9. Pressure gauge
10. Thermocouples
11. DC power supply
12. Standard resistor
13. Scanner
14. Digital multimeter
15. Pen recorder
16. Computer
17. Power supply controller

Schematic diagram of experimental apparatus

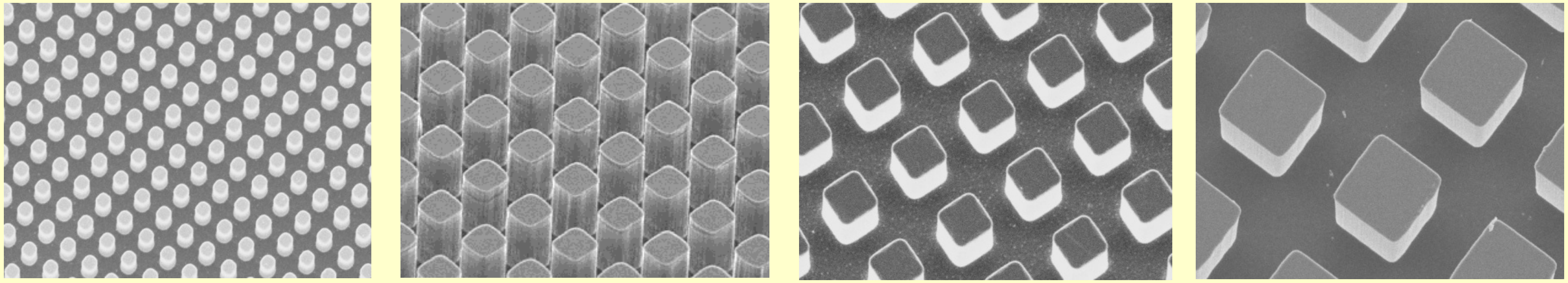
Test Section



1. Silicon chip
2. Pyrex glass plate
3. Copper lead wire
4. Thermocouple
5. O ring
6. Vacuum chuck

Details of test section

Micro-Pin-Finned Chips

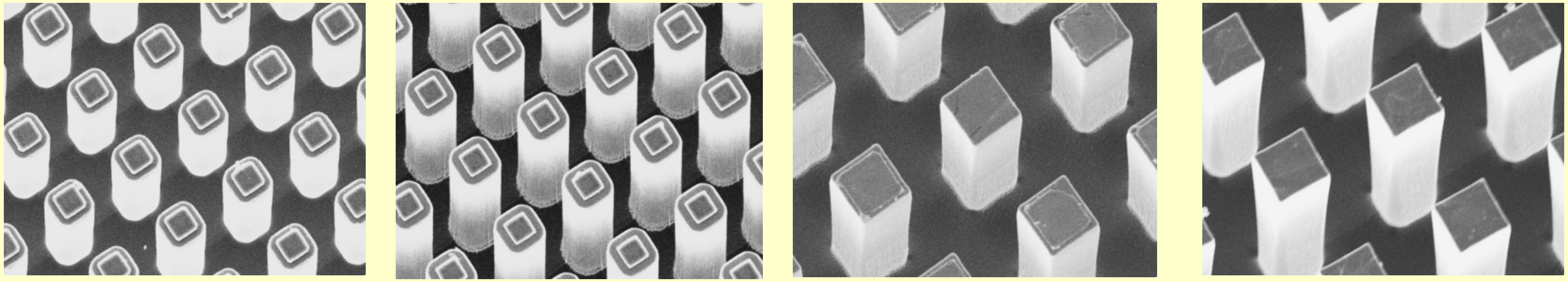


(a) Chip PF10-60 10×10×60 μm³

(b) Chip PF20-60 20×20×60 μm³

(c) Chip PF30-60 30×30×60 μm³

(d) Chip PF50-60 50×50×60 μm³



(d) Chip PF30-120 30×30×120 μm³

(e) Chip PF30-200 30×30×200 μm³

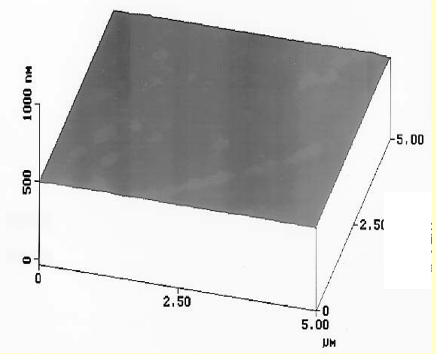
(f) Chip PF50-200 50×50×200 μm³

(g) Chip PF50-270 50×50×270 μm³

SEM images of micro-pin-fins

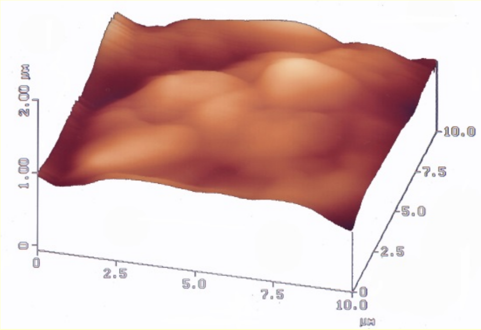
Rough Surfaces

- Chip S



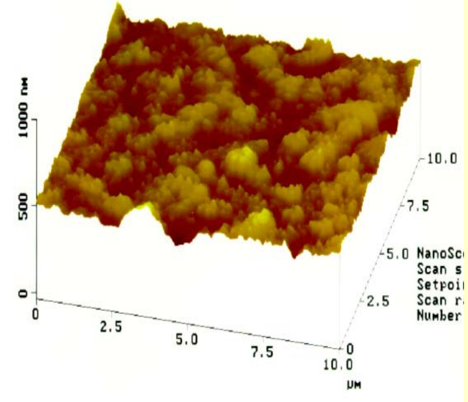
RMS Roughness 2.3 nm

- Chip C



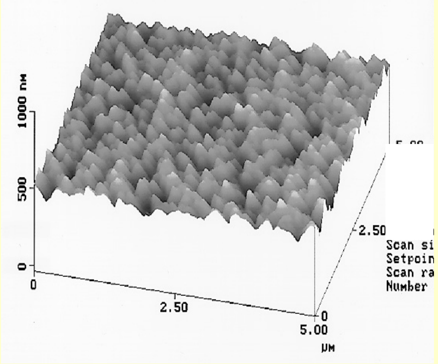
RMS Roughness 72.7 nm

- Chip E



RMS Roughness 23.8 nm

- Chip EPF50-60



RMS Roughness 32.0 nm

Photographs of heater surface

Experimental Conditions

Test chips(12)	8 micro-pin-finned surfaces
	2 roughed surfaces
	1 roughed micro-pin-finned surface
	1 smooth surface
Chip orientation	Horizontal and vertical
Working fluid	FC-72(Saturation temp. 56^{o}C)
Liquid subcooling	45K (Liquid temp. 11^{o}C)
	25K (Liquid temp. 31^{o}C)
	3K (Liquid temp. 53^{o}C)
	0K (Liquid temp. 56^{o}C)
Air concentration	3-6 Vol. % (Degassed)
	36-40 Vol. % (Gas dissolved)

Contents

Effects of Micro-Pin-Fins and Submicron-Scale Roughnes

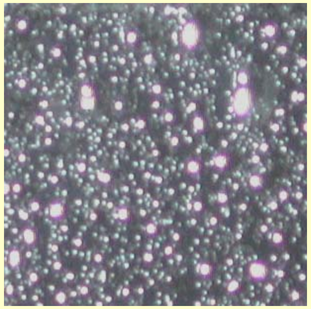
- Effects of Roughness and Micro-Pin-Fin
- Effect of Liquid Subcooling
- Effect of Heater Orientation
- Effect of Dissolved Gas

Boiling Phenomena: Surface Effect

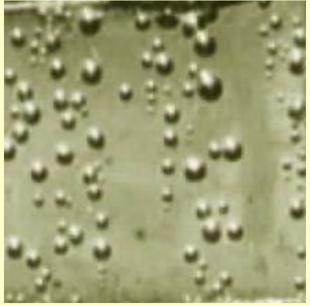
Chip S

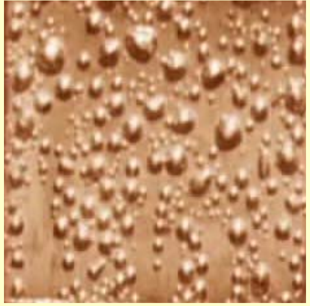

(a) q =2.71W/cm^2


(b) q =5.98W/cm^2


(c) q =11.8 W/cm^2

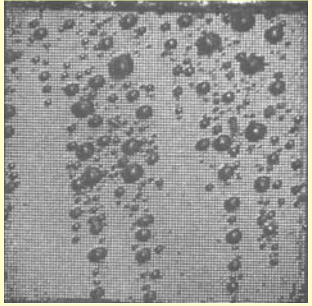
Chip C

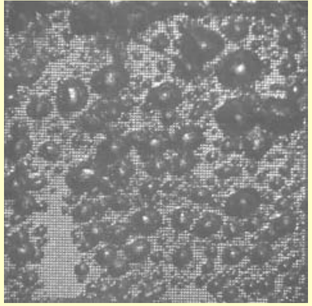

(d) q =4.72W/cm^2

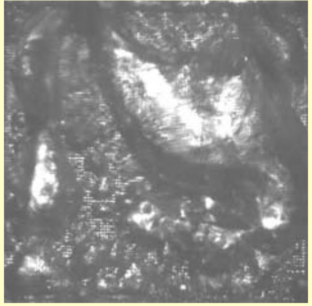

(e) q =12.2W/cm^2


(f) q = 30.8 W/cm^2

Chip EPF50-60


(g) q =4.83W/cm^2

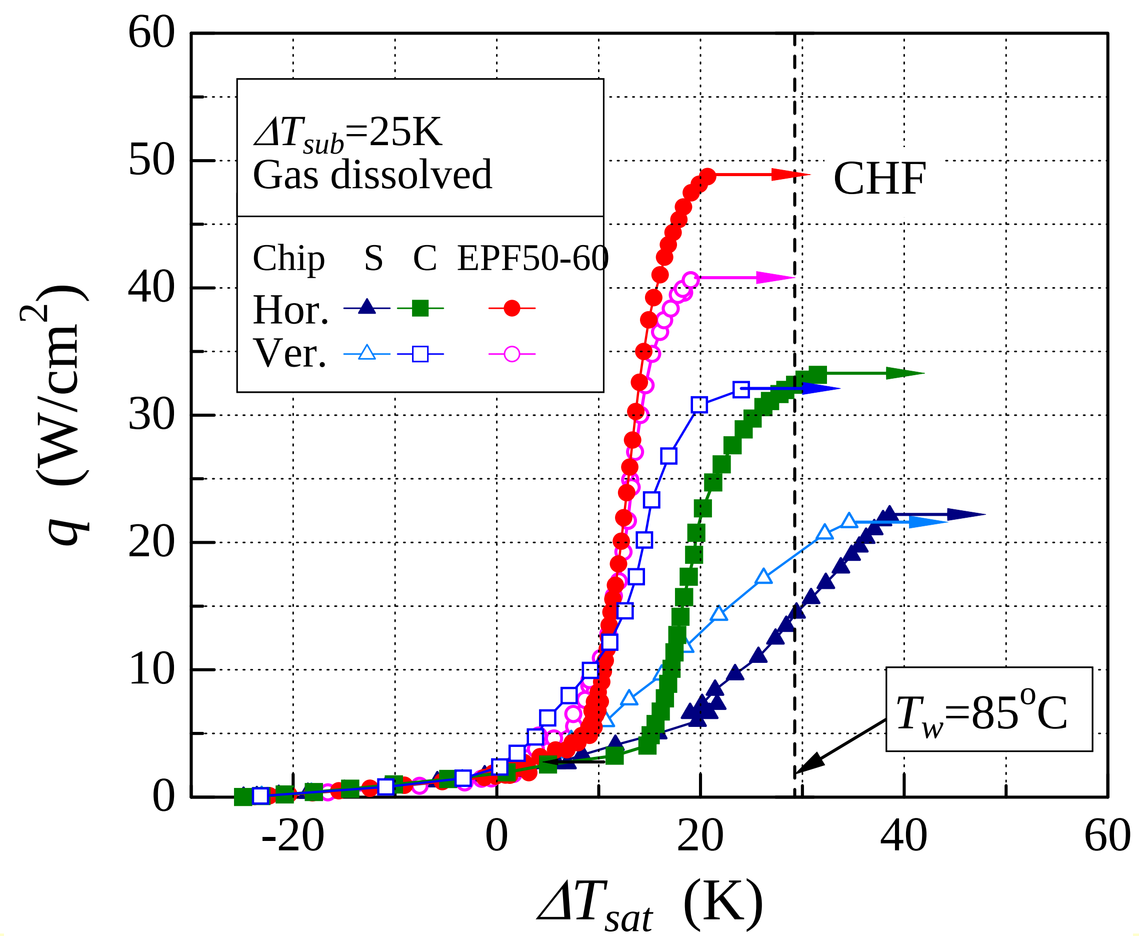

(h) q =15.8W/cm^2


(i) q = 39.6 W/cm^2

$\Delta T_{sat} \approx 4.0\mathrm{K}$ $\Delta T_{sat} \approx 11.0\mathrm{K}$ $\Delta T_{sat} \approx 19.0\mathrm{K}$

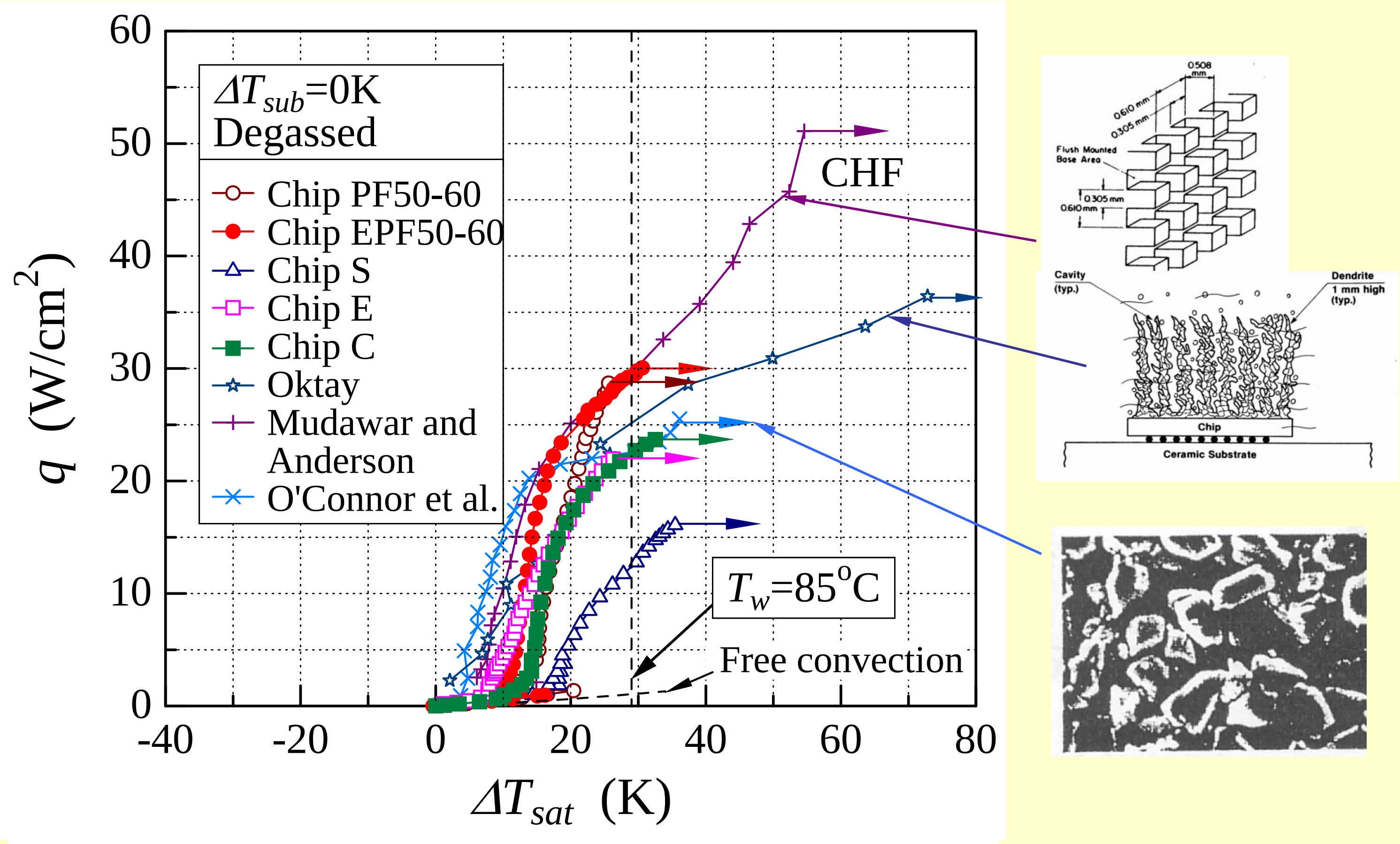
Effects of Micro-Pin-Fins and Submicron-Scale Roughness

Boiling Curves: Orientation Effect



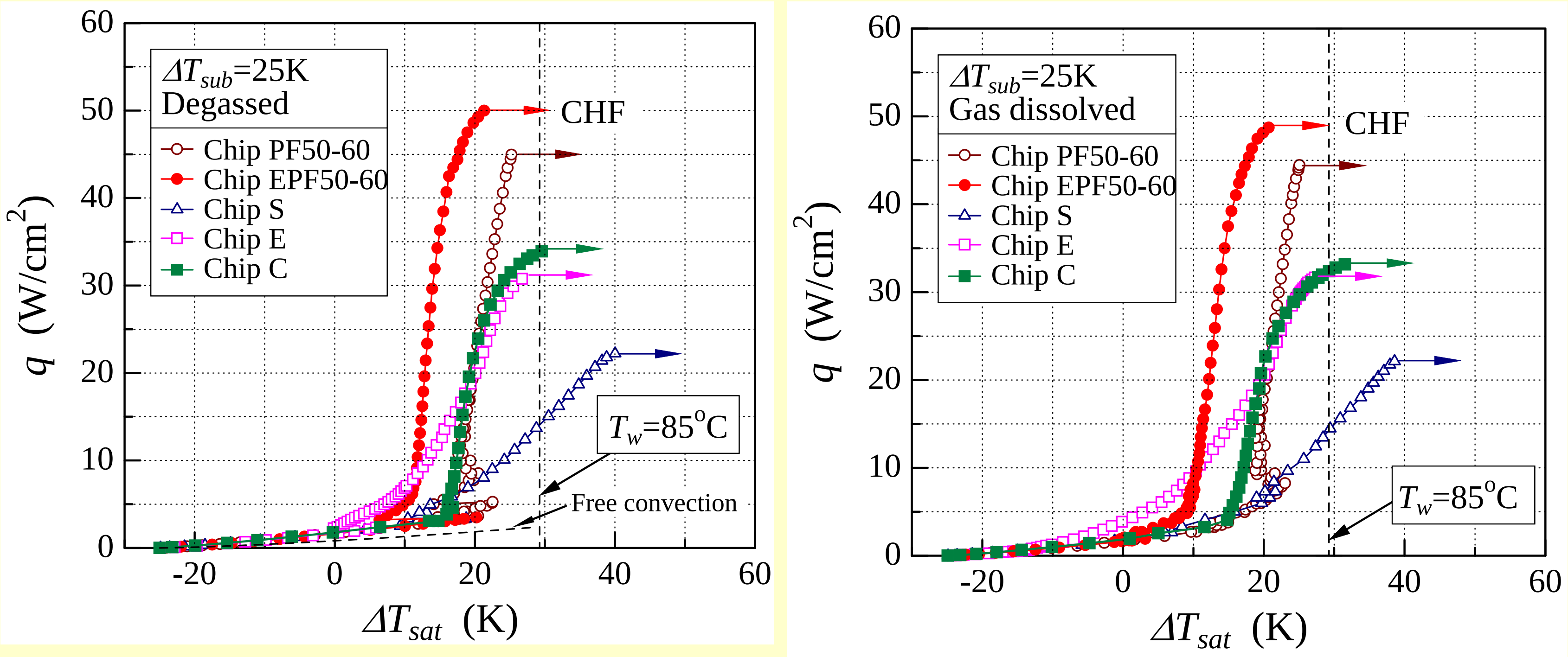
Comparison of boiling curves for vertically and horizontally mounted chip S, C and EPF50-60

Boiling Curves



Boiling curves; ΔT_{sub}=0 K, degassed

Boiling Curves

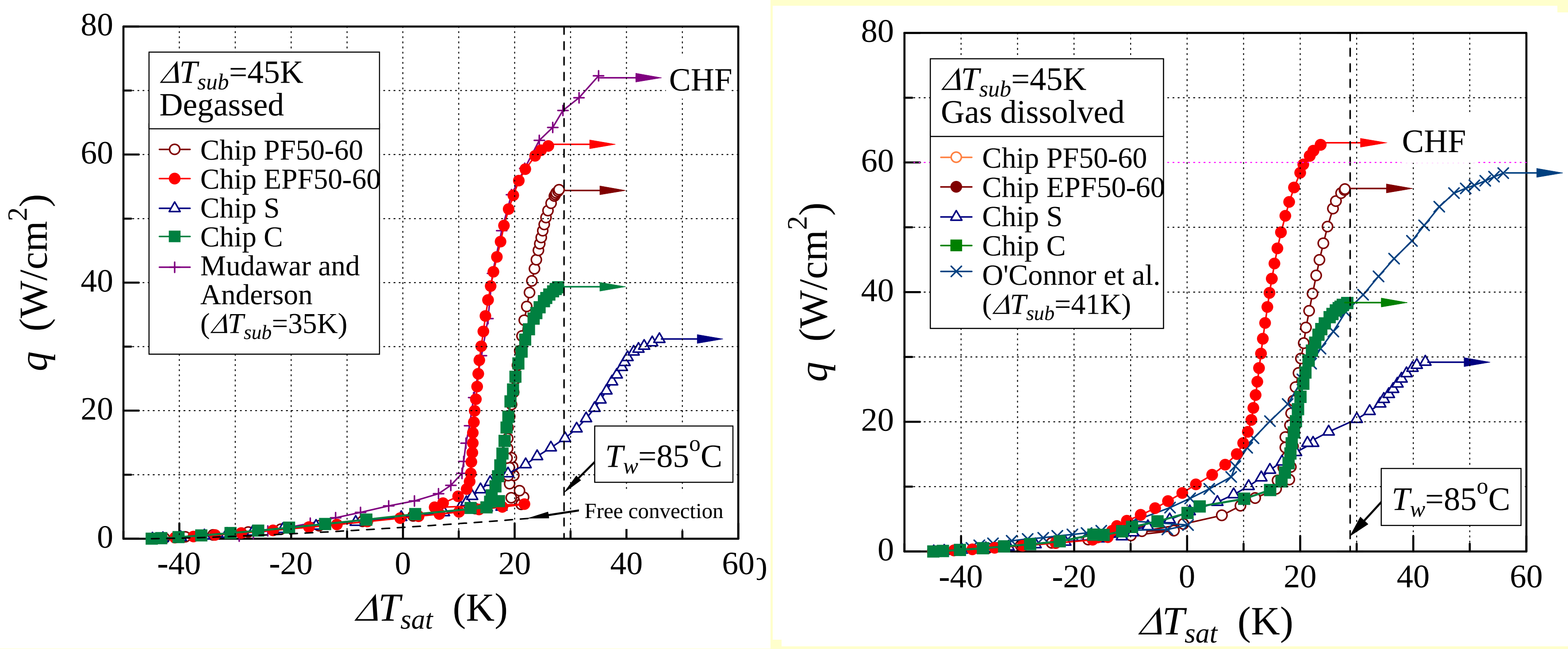


(a) Degassed

(b) Gas dissolved

Boiling curves; ΔT_{sub}=25 K

Boiling Curves

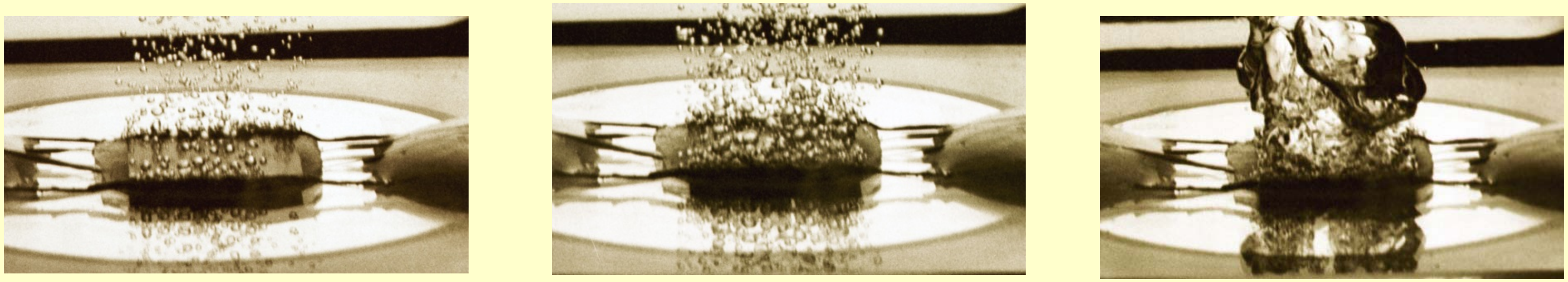


(a) Degassed

(b) Gas dissolved

Boiling curves; ΔT_{sub}=45 K

Boiling Phenomena: Effect of Subcooling

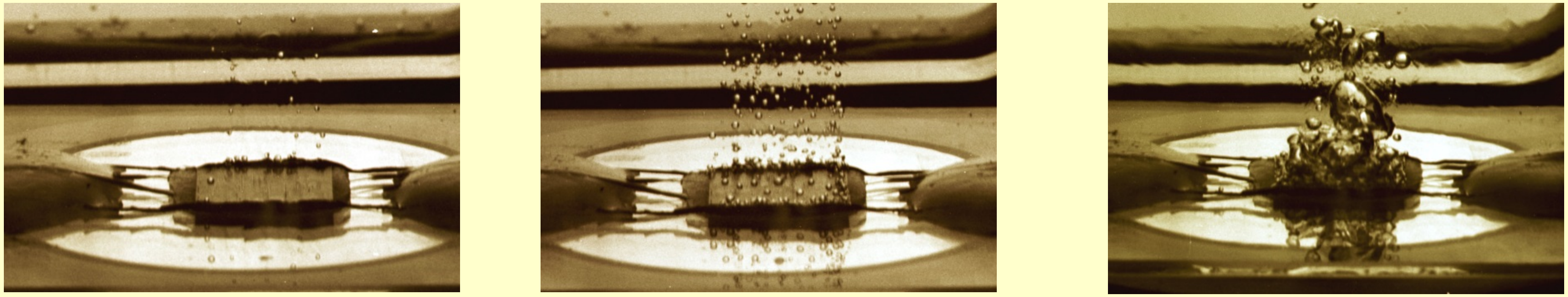


(a) $q = 2.055\ \mathrm{W/cm^2}$
$T_w = 69.9\ ^\circ\mathrm{C}$

(b) $q = 5.102\ \mathrm{W/cm^2}$
$T_w = 73.8\ ^\circ\mathrm{C}$

(c) $q = 30.53\ \mathrm{W/cm^2}$
$T_w = 81.0\ ^\circ\mathrm{C}$

$\Delta T_{sub} = 3\ \mathrm{K}$



(d) $q = 2.724\ \mathrm{W/cm^2}$
$T_w = 66.1\ ^\circ\mathrm{C}$

(e) $q = 6.641\ \mathrm{W/cm^2}$
$T_w = 76.1\ ^\circ\mathrm{C}$

(f) $q = 44.46\ \mathrm{W/cm^2}$
$T_w = 81.1\ ^\circ\mathrm{C}$

$\Delta T_{sub} = 25\ \mathrm{K}$

Boiling phenomena; Chip PF50-60

Boiling Phenomena: Dissolved Gas Effect

Degassed

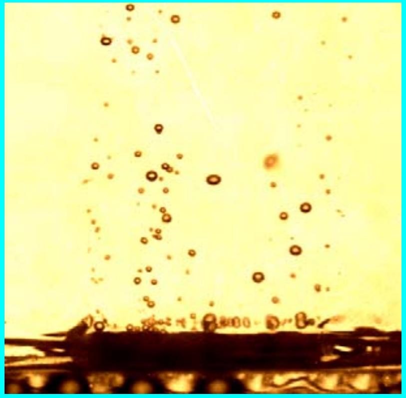
(a) q =3.60W/cm^2 T_w = 71.2 ° C

(b) q =16.8 W/cm^2 T_w = 73.0 ° C

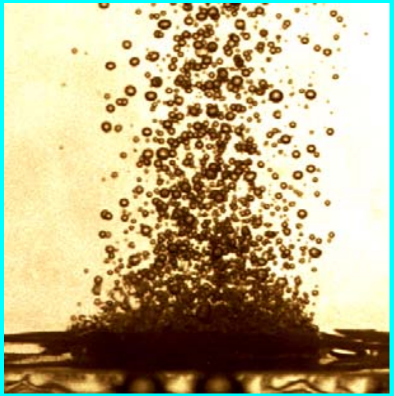
(c) q =47.5 W/cm^2 T_w = 74.0 ° C

Chip PF30-60

Gas-dissolved



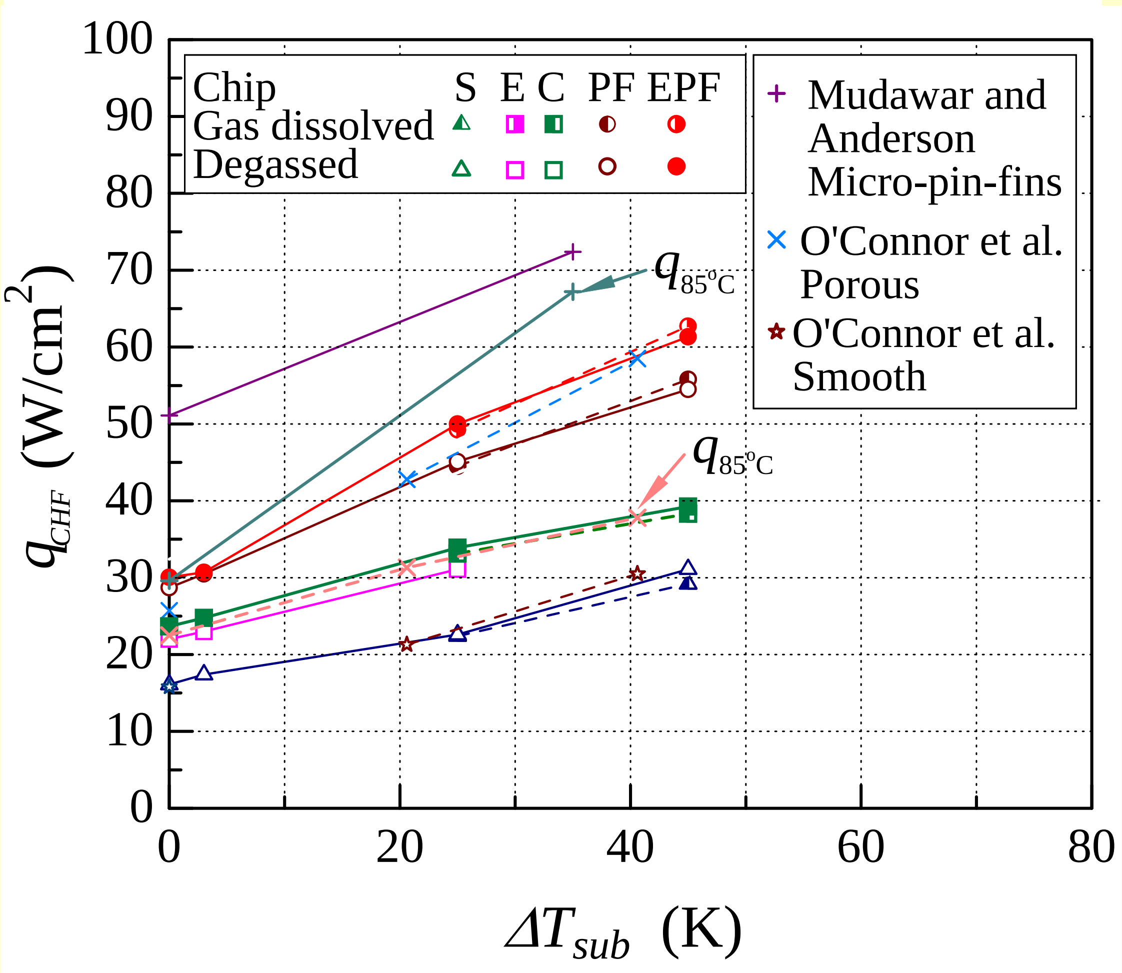
(d) q =2.84 W/cm^2 T_w = 66.6 ° C



(e) q =16.6 W/cm^2 T_w = 71.6° C

(f) q =47.5 W/cm^2 T_w = 75.6 ° C

Critical Heat Flux



Variation of q_{CHF} with ΔT_{sub}

Contents

1. Background and objective

2. Experimental apparatus and conditions

3 Effects of micro-pin-fins and submicron-scale roughness on boiling heat transfer

※ 4 Effects of fin size on boiling heat transfer

5 Enhancement Mechanism for micro-pin-fins

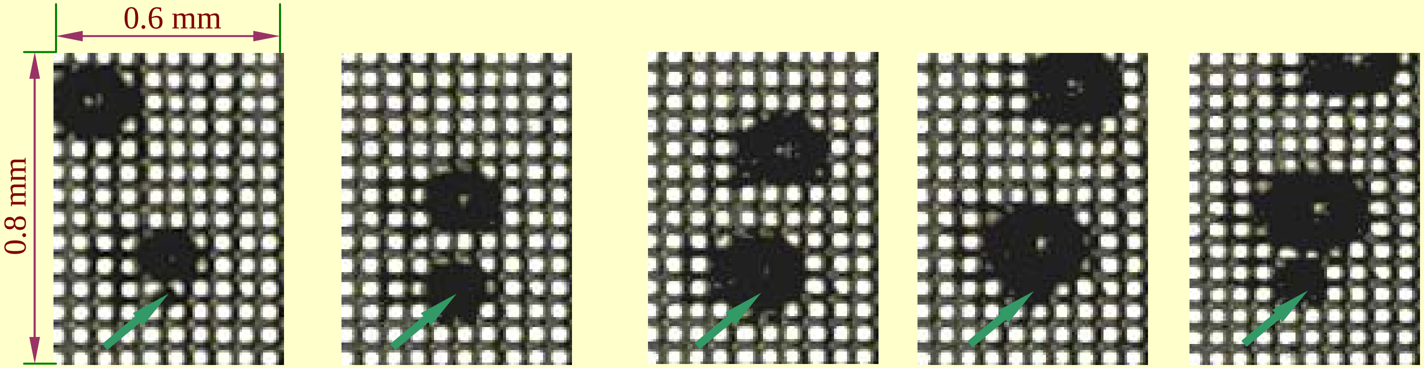
6 Conclusions

Size Effects of Micro-Pin-Fin

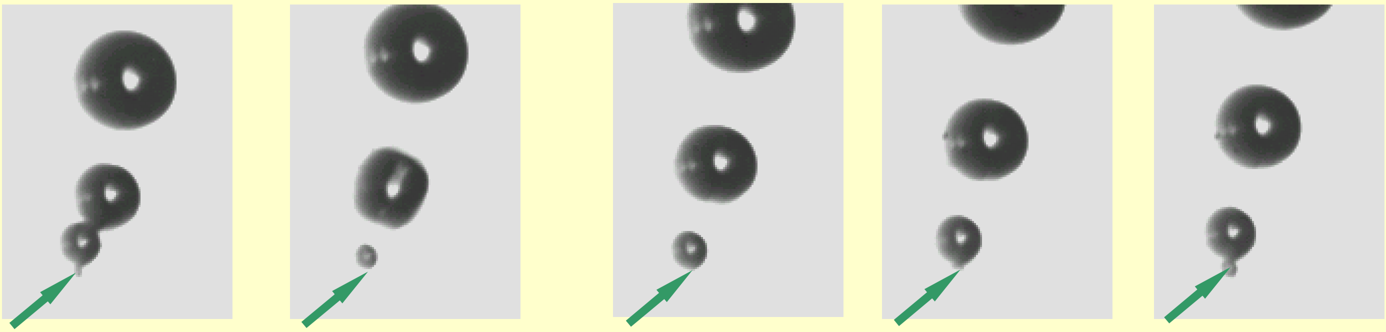
Optimum size of micro-pin-fin?

- Effects of Cross-sectional Size and Height
- Effect of Liquid Subcooling
- Effect of Heater Orientation
- Effect of Dissolved Gas

Boiling Phenomena:Bubble Growth



t = 0 ms t = 4 ms t = 8 ms t = 12 ms t = 14 ms

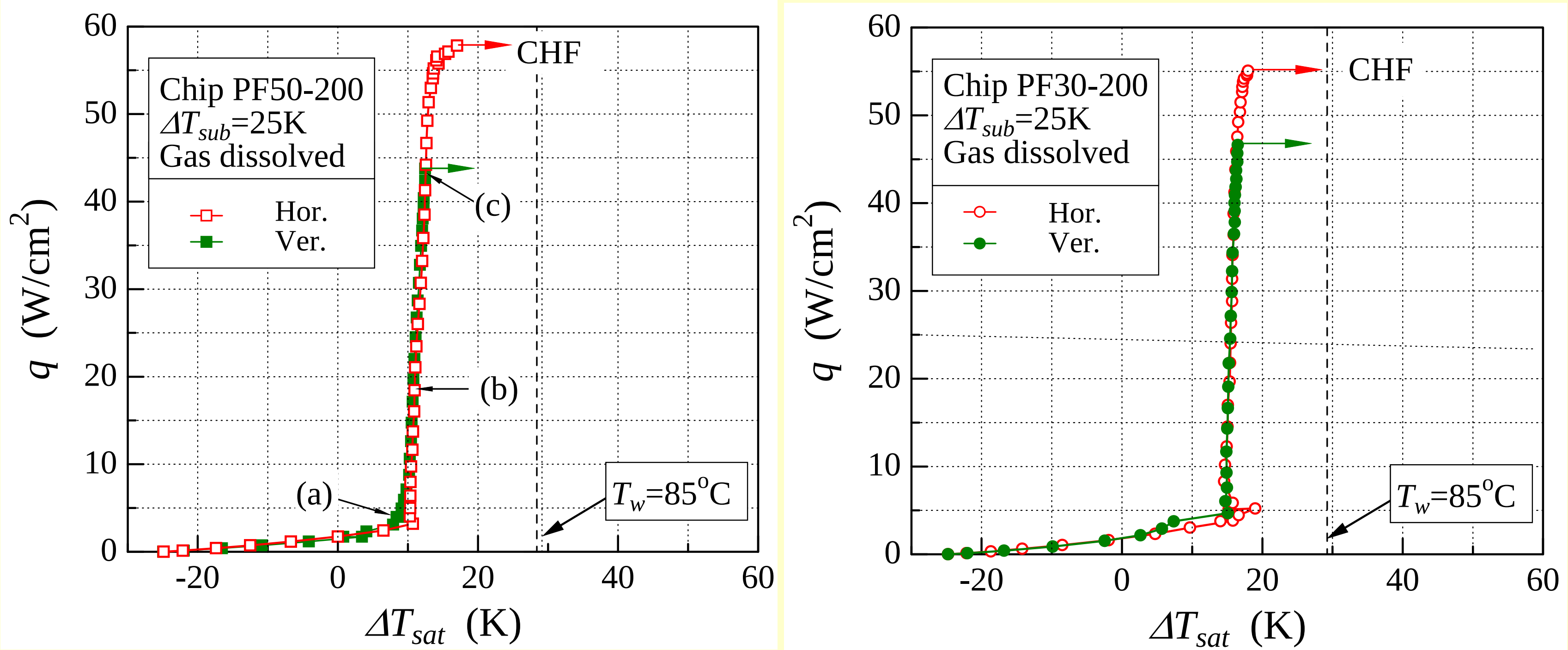


t = 0 ms t = 2 ms t = 4 ms t = 6 ms t = 7 ms

Sequence of boiling phenomena on vertically mounted chips PF30-200 (q=5.10 W/cm^2, ΔT_{sat}=13.5 K) and S (q=6.02 W/cm^2, ΔT_{sat}=9.2 K; gas-dissolved

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin

Boiling Curves: Orientation Effect

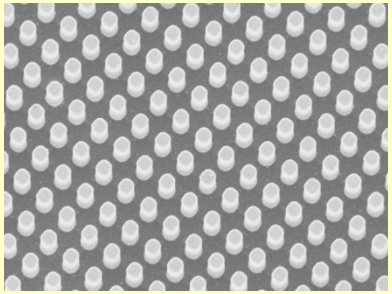


(a) Chip PF50-200

(b) Chip PF30-200

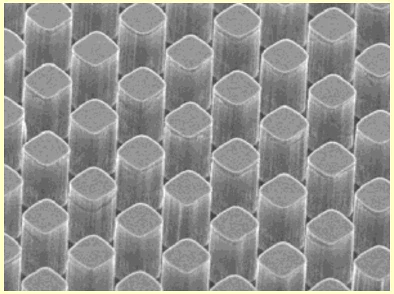
Comparison of boiling curves for vertically and horizontally mounted chips

Fin Cross-Sectional Size



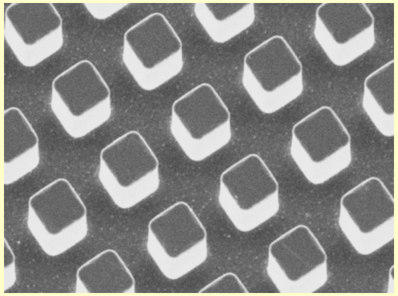
(a) Chip PF10-60

$10 \times 10 \times 60\ \mu m^3$



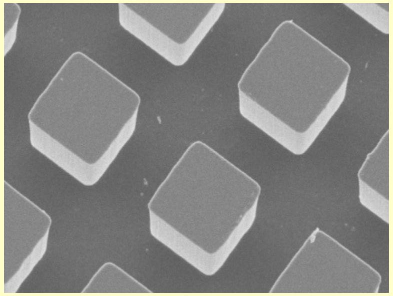
(b) Chip PF20-60

$20 \times 20 \times 60\ \mu m^3$



(c) Chip PF30-60

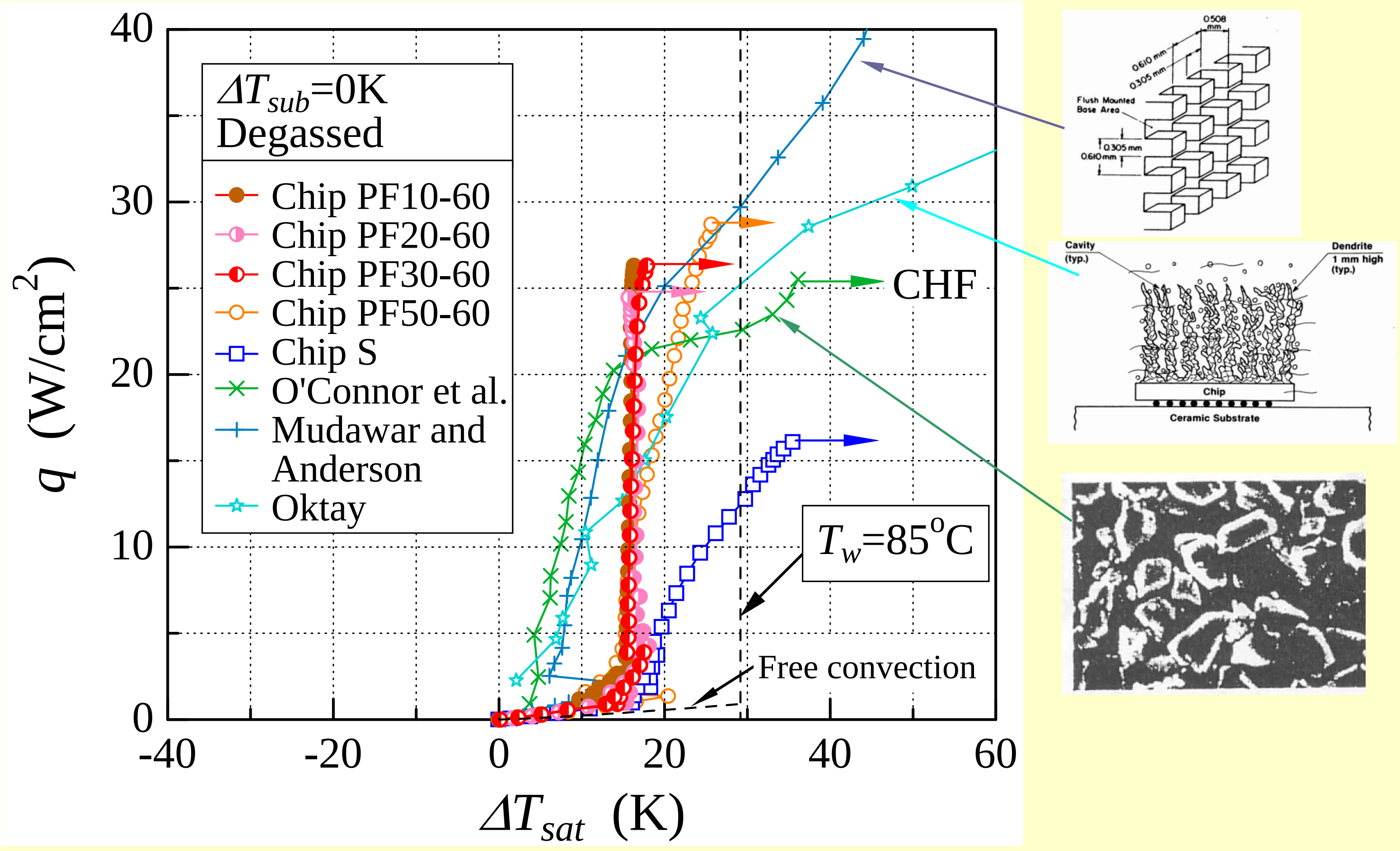
$30 \times 30 \times 60\ \mu m^3$



(d) Chip PF50-60

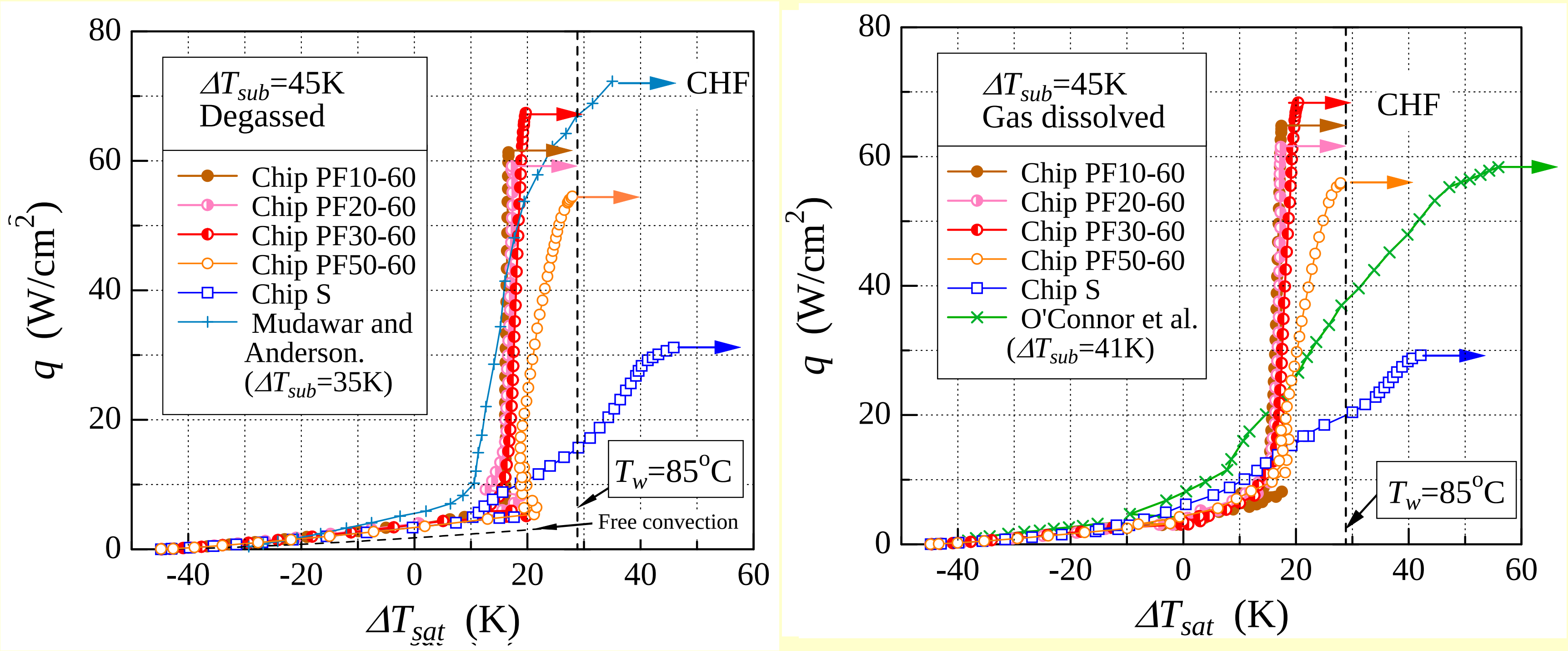
$50 \times 50 \times 60\ \mu m^3$

Boiling Curves:Fin Cross-Sectional Size



Boiling curves; ΔT_{sub}=0K, degassed

Boiling Curves:Fin Cross-Sectional Size

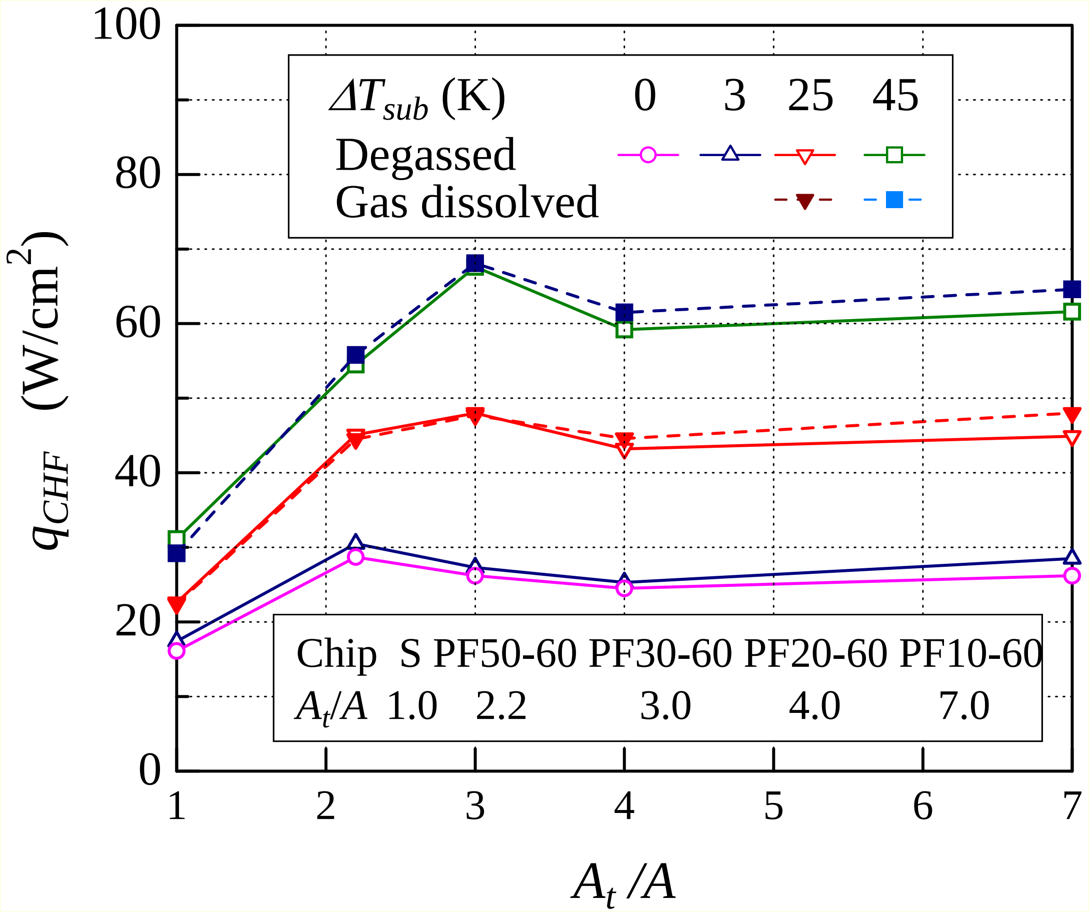


(a) Degassed

(b) Gas dissolved

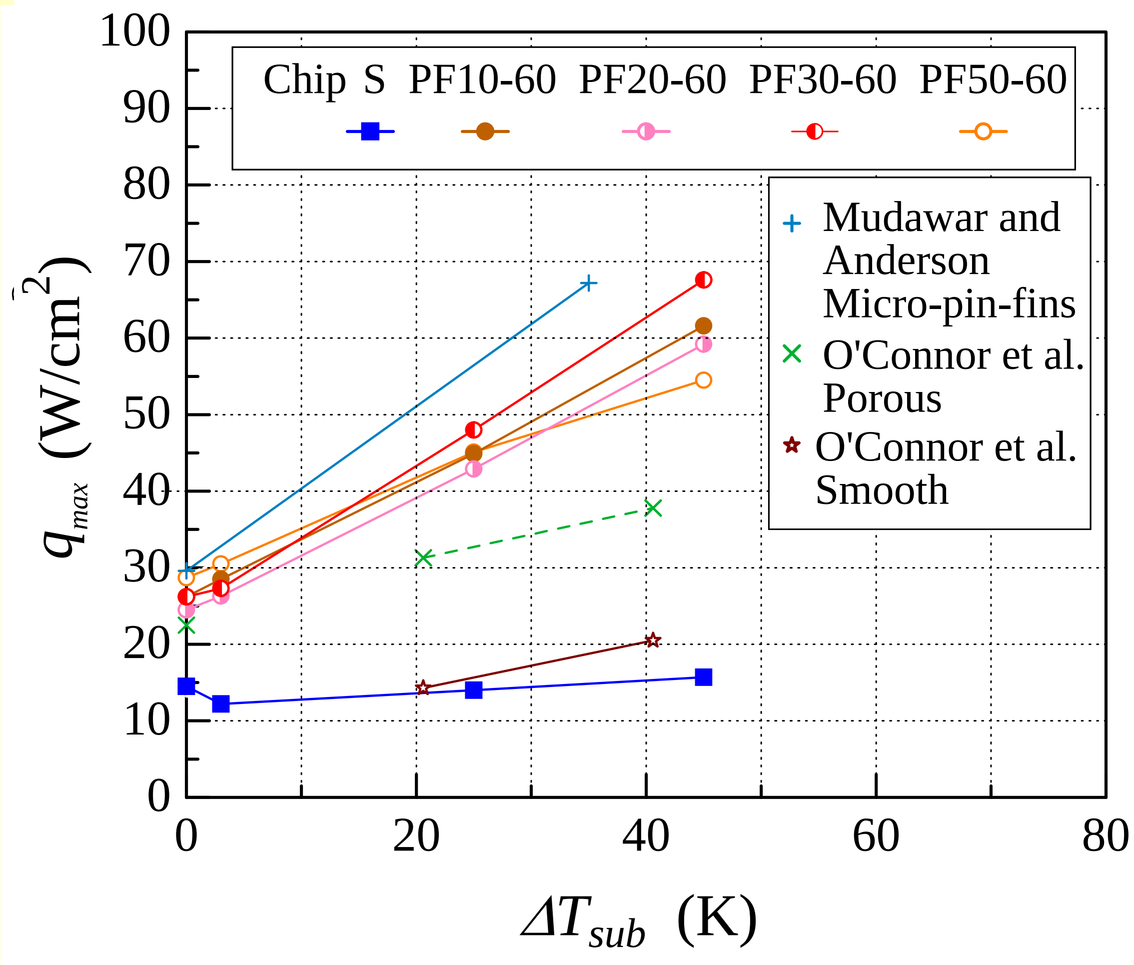
Boiling curves; ΔT_{sub}=45K

CHF: Fin Cross-Sectional Size Effect



Variation of q_{CHF} with $A_t\,/A$. A_t: Total heat transfer area; A: Projected area.

Maximum Heat Flux: Fin Cross-Sectional Size



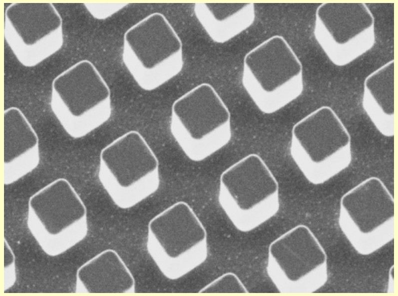
Definition of q_{max}

$$q_{\max} = \begin{cases} q_{CHF} & T_{w,CHF} \le 85^\circ \mathrm{C} \\ q|_{T_w=85^\circ \mathrm{C}} & T_{w,CHF} > 85^\circ \mathrm{C} \end{cases}$$

Variation of q_{max} with ΔT_{sub}

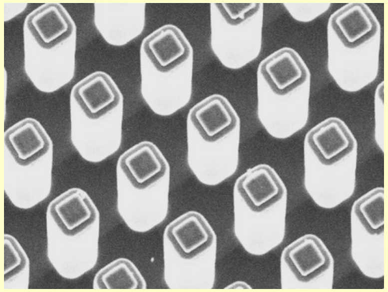
Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin

Effect of Fin Height



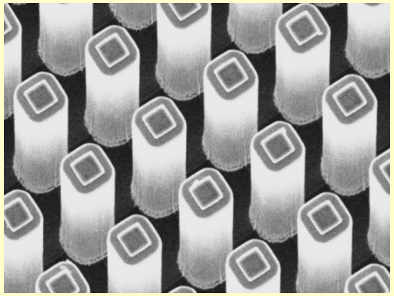
(a) Chip PF30-60

$30 \times 30 \times 60\ \mu m^3$



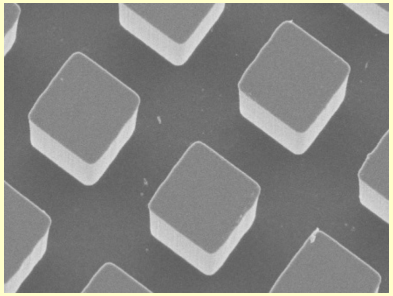
(b) Chip PF30-120

$30 \times 30 \times 120\ \mu m^3$



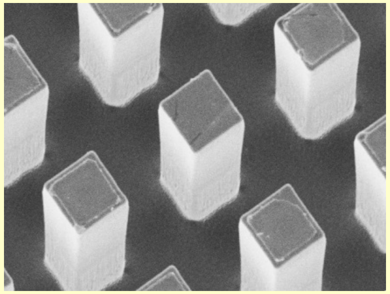
(c) Chip PF30-200

$30 \times 30 \times 200\ \mu m^3$



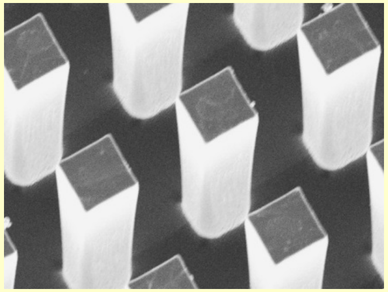
(d) Chip PF50-60

$50 \times 50 \times 60\ \mu m^3$



(e) Chip PF50-200

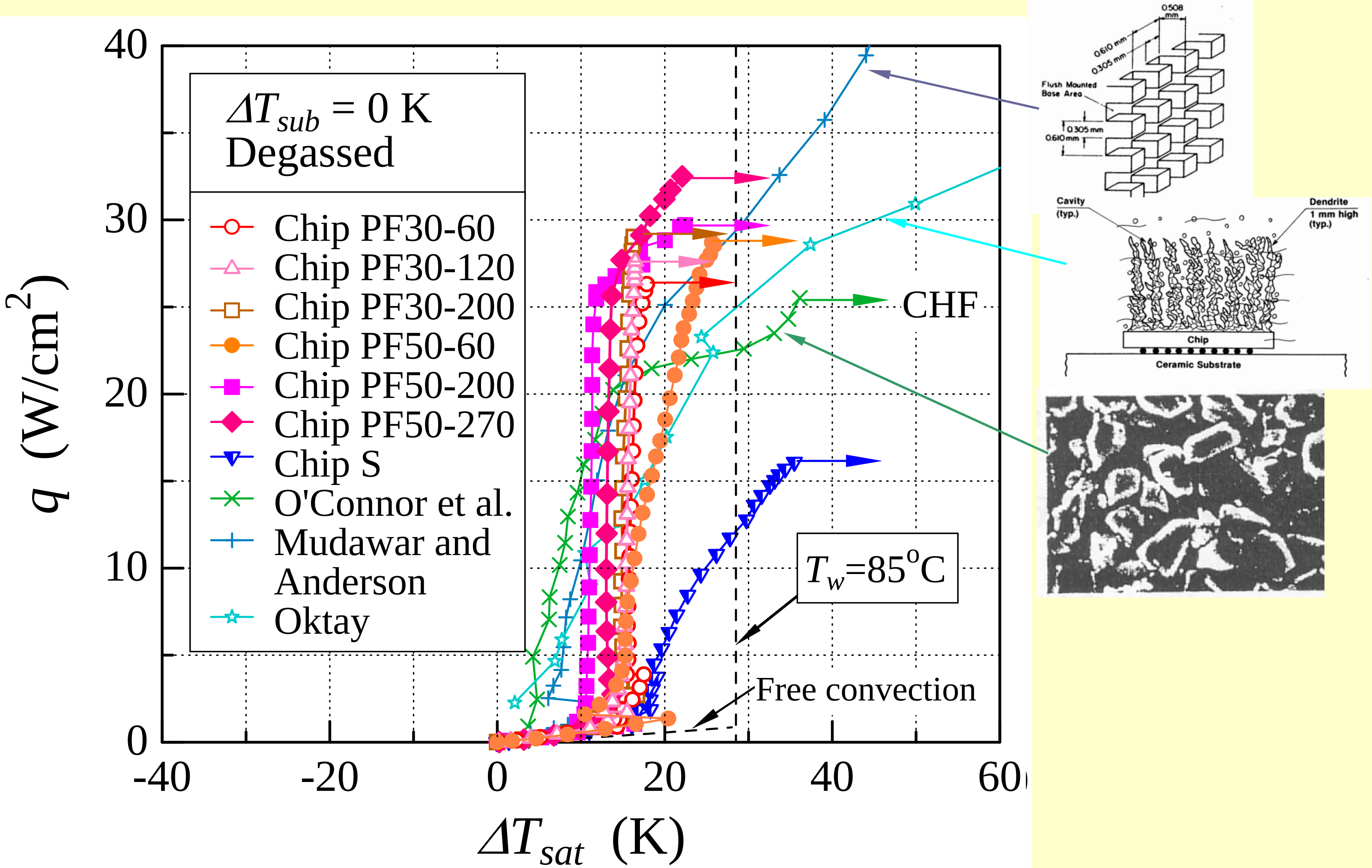
$50 \times 50 \times 200\ \mu m^3$



(f) Chip PF50-270

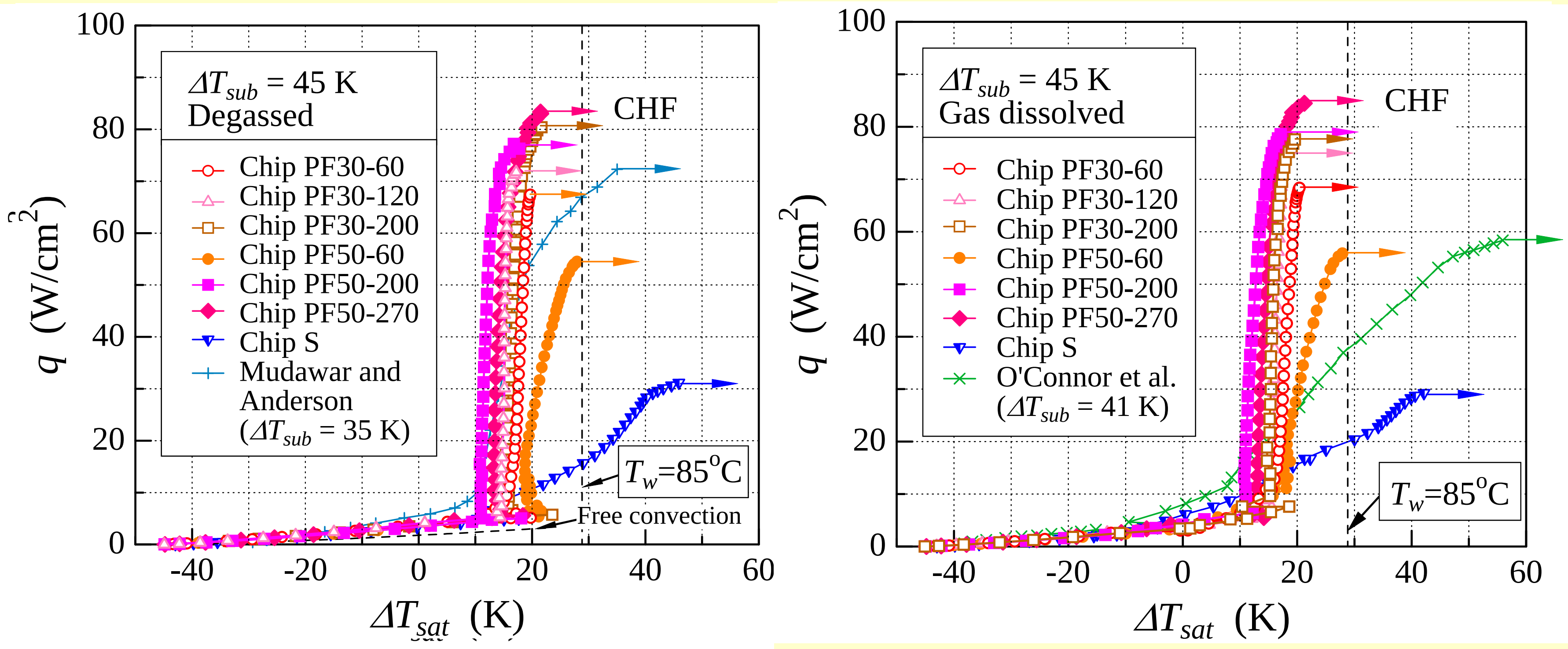
$50 \times 50 \times 270\ \mu m^3$

Boiling Curves:Effect of Fin Height



Boiling curves; ΔT_{sub}=0K, degassed

Boiling Curves:Effect of Fin Height

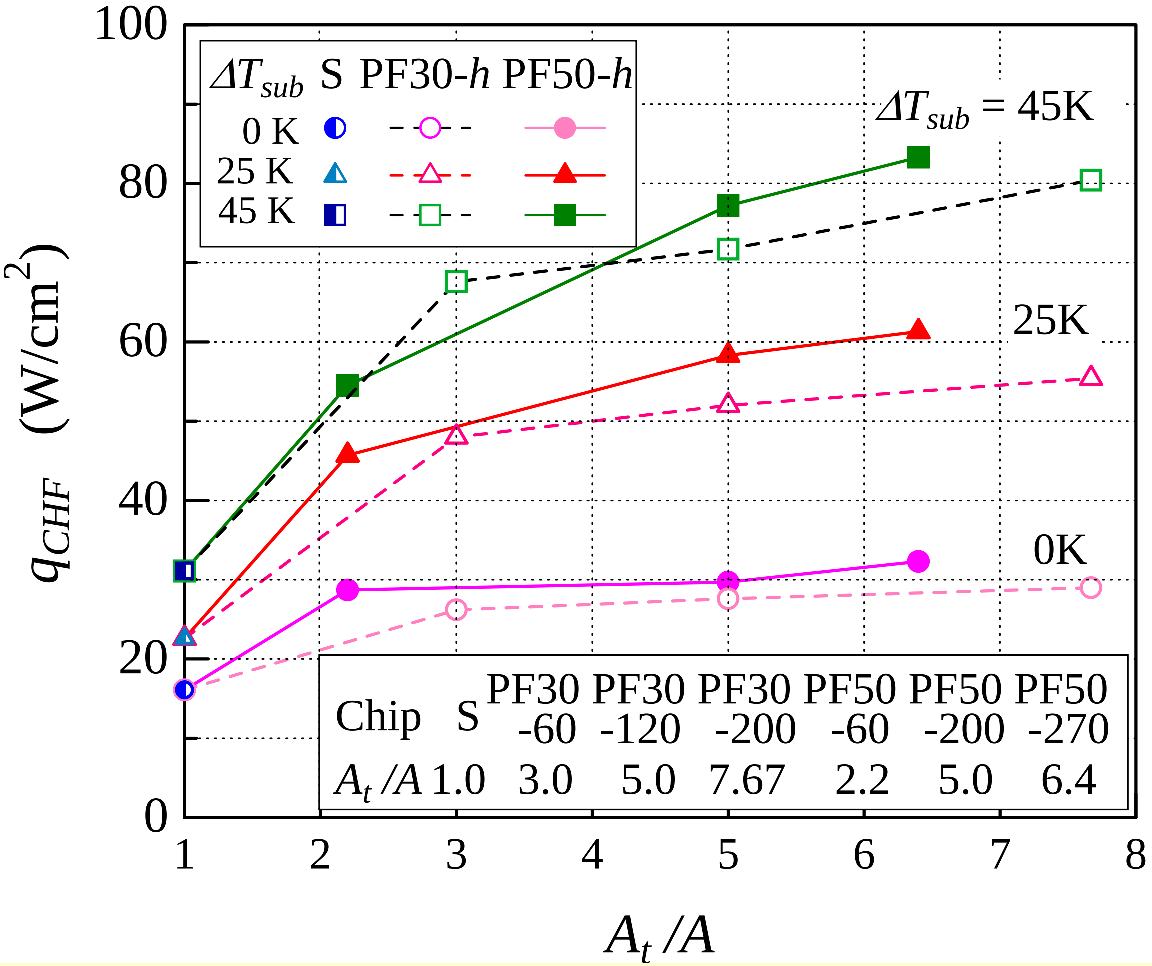


(a) Degassed

(b) Gas-dissolved

Boiling curves; ΔT_{sub}=45K

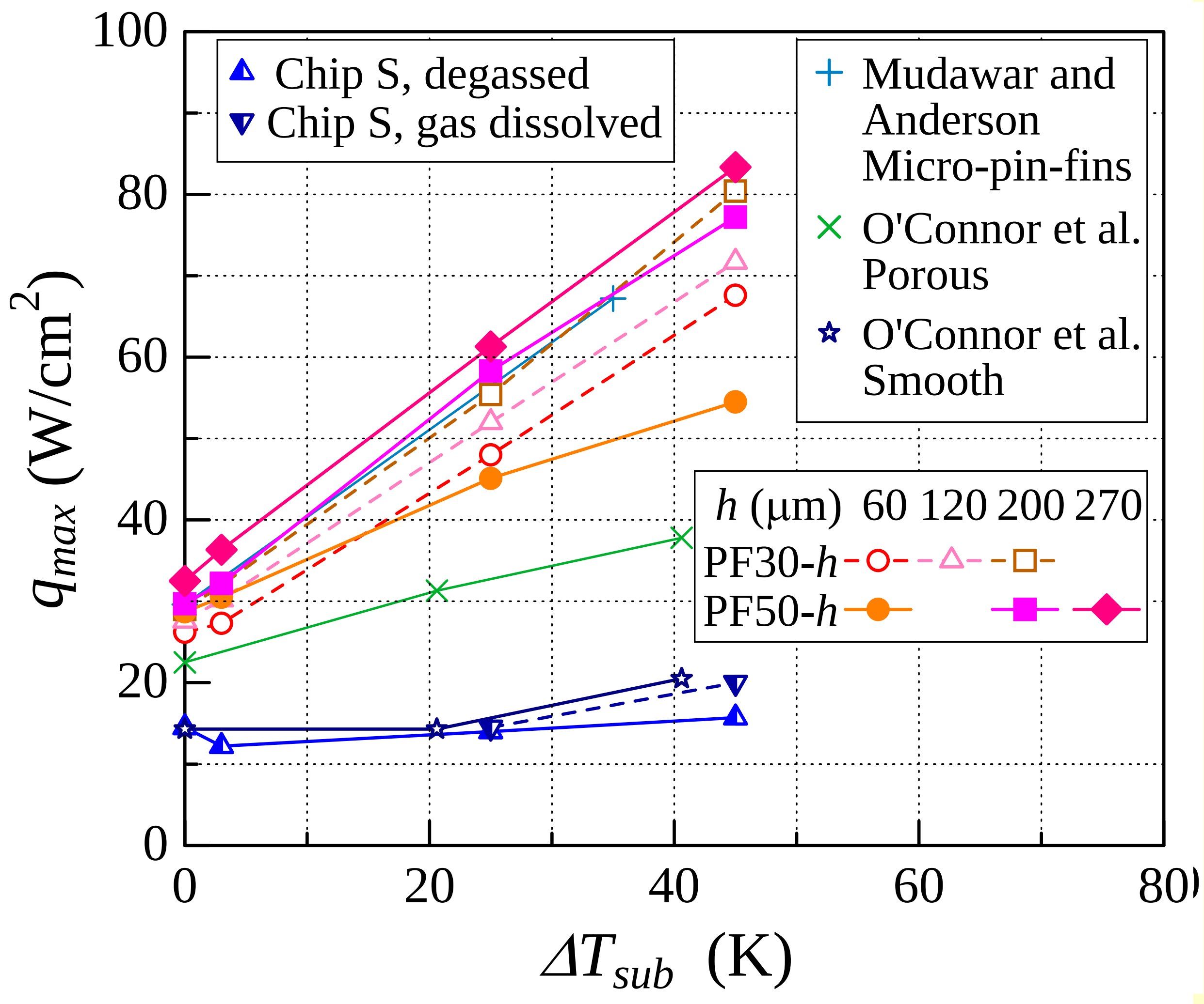
CHF: Effect of Fin Height



Chip	S	PF30 -60	PF30 -120	PF30 -200	PF50 -60	PF50 -200	PF50 -270
A_t/A	1.0	3.0	5.0	7.67	2.2	5.0	6.4

Variation of q_{CHF} with A_t/A. A_t: Total heat transfer area; A: Projected area.

Maximum Heat Flux: Effect of Fin Height



Variation of q_{max} with ΔT_{sub}

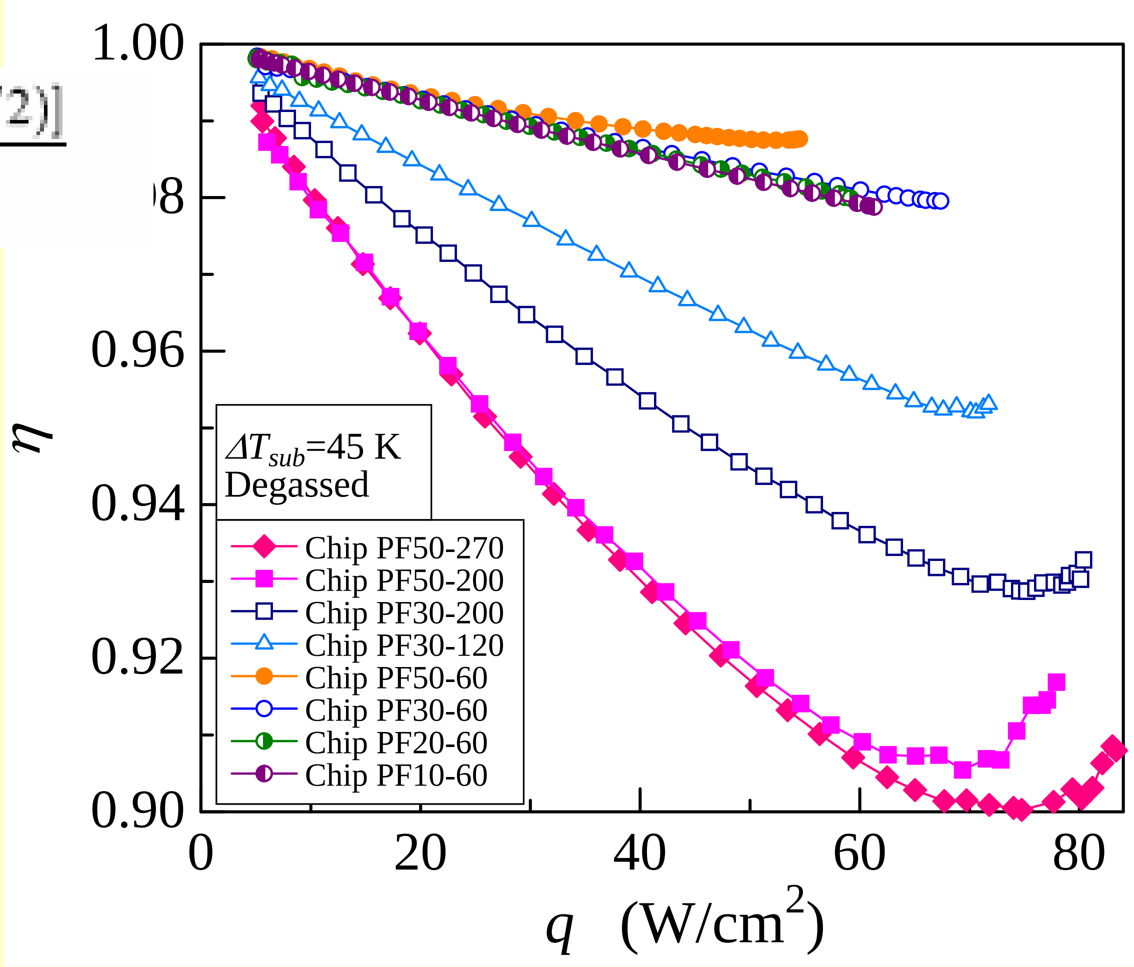
Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin

Fin Efficiency

$$\eta = \frac{Q_f}{Q_\infty} = \frac{\tanh[m(h+t/2)]}{m(h+t/2)}$$

$$m = \sqrt{\frac{4\alpha}{k}}$$

$$\alpha = \frac{qA}{\Delta T_{sat} A_t}$$



Variation of η with q

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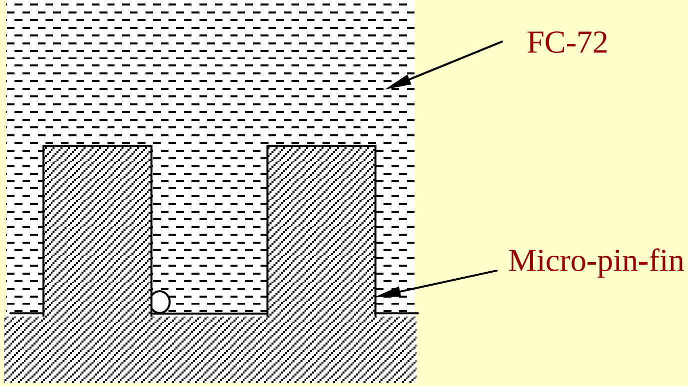
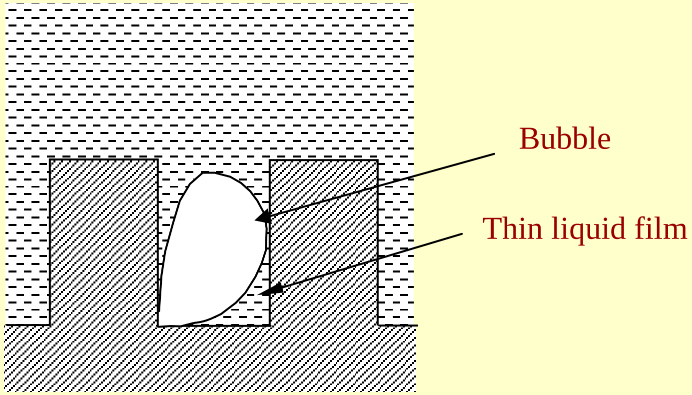
Heat Transfer Process in Micro-Pin-Fins

(a)

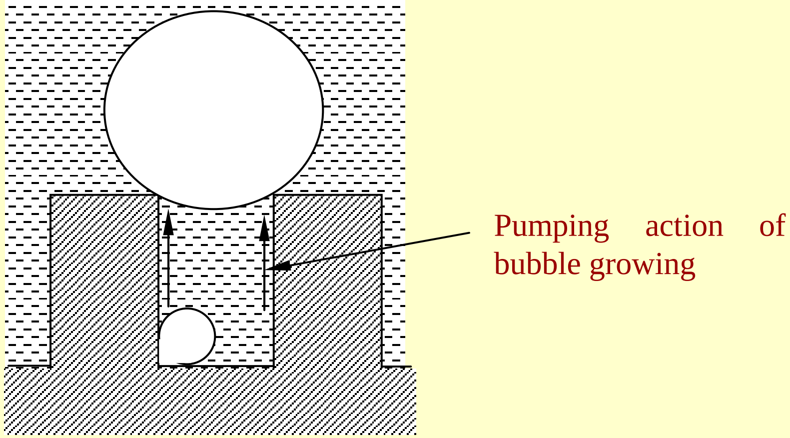


(b)



Evaporation of thin liquid film

(c)

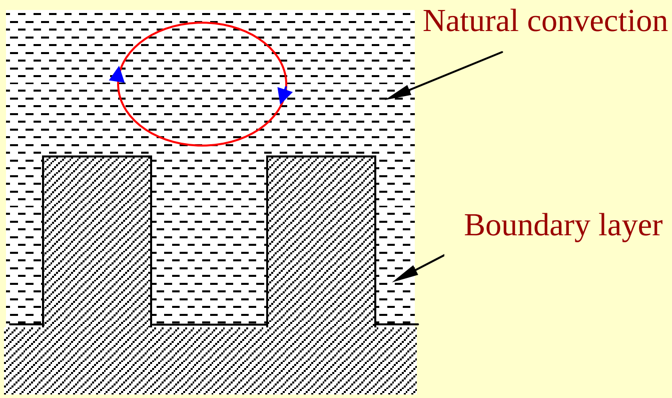


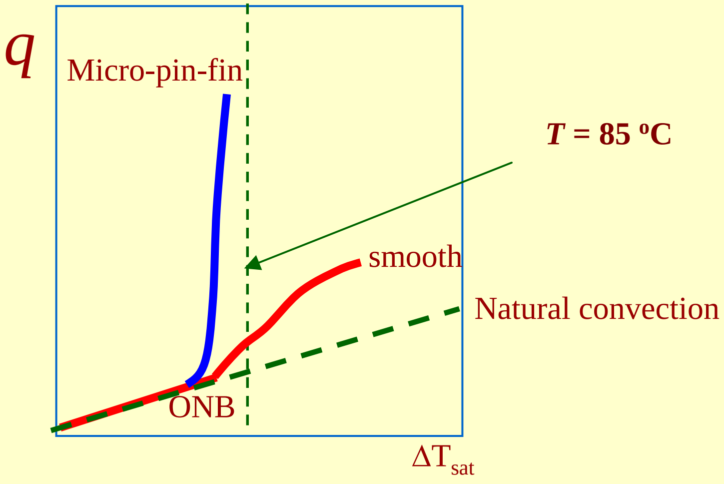
Micro-convection by capillary force

Heat Transfer Process in Micro-Pin-Fins

※ No natural convection heat transfer enhancement ---

All micro-pin-fins are immersed in a boundary layer so that the fin side surfaces will not participate natural convection heat transfer, indicating fin side surfaces are not effective for non-boiling heat transfer enhancement.

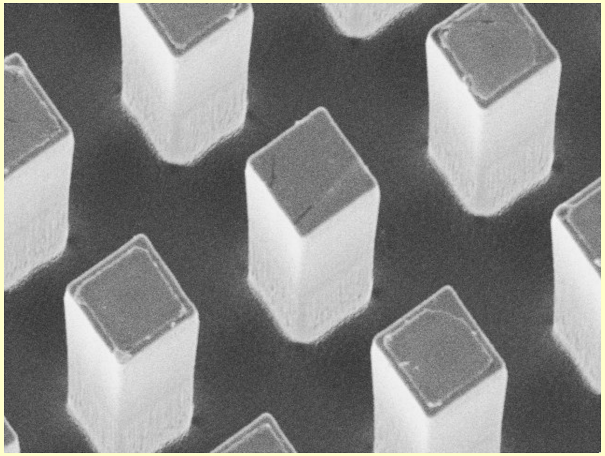


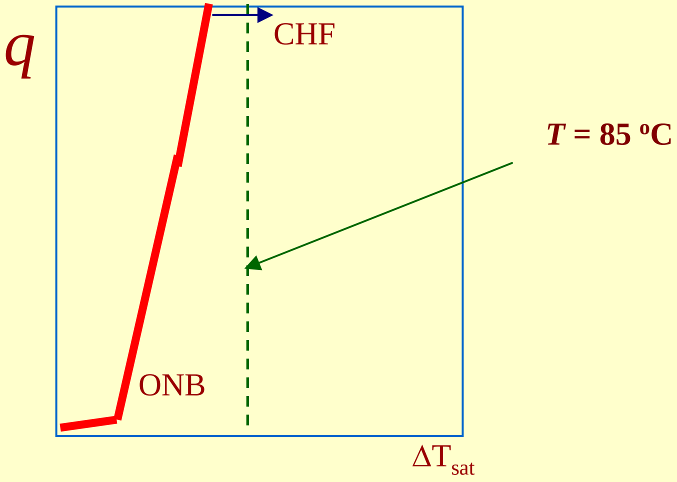


Heat Transfer Process in Micro-Pin-Fins

※ Steep boiling curve -------

Almost simultaneous burn out of many bubbles on the pin fin side surfaces due to nearly the same surface conditions by fabrication with a small increase in wall temperature, resulting in an fast increase of effective boiling heat transfer surface area

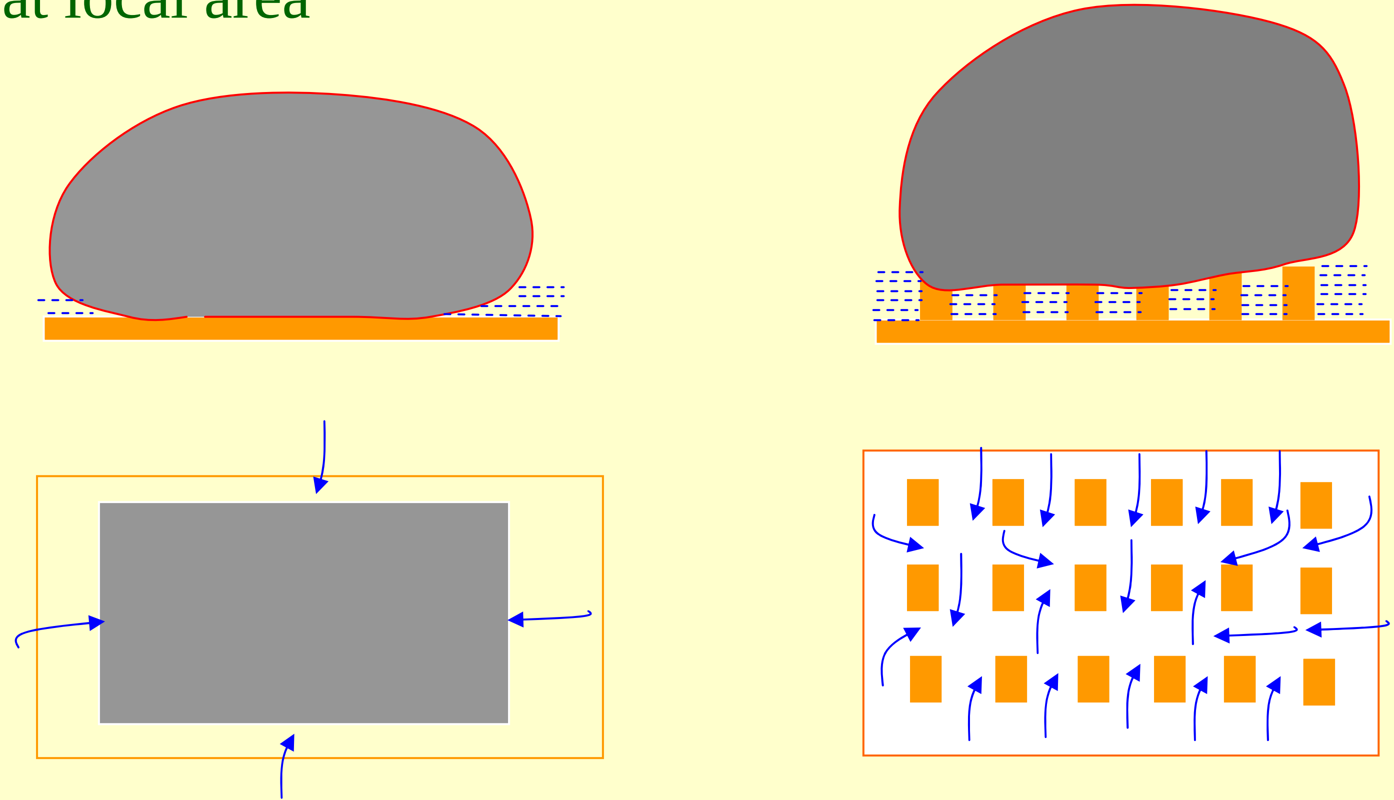




Heat Transfer Process in Micro-Pin-Fins

※ No obvious deterioration at high heat flux ---

Enough fresh bulk fluid supply through the inter-connect channels formed by micro-pin-fins, preventing the burnout at local area



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Conclusions

(I) Submicron-scale rough surface and micro-pin-finned surface

(1) Submicron-scale roughness and micro-pin-fins were effective in enhancing heat transfer in the nucleate boiling region and increasing the CHF. The boiling curve of the micro-pin-finned chip was characterized by a very small increase in wall superheat with increasing heat flux. While the micro-pin-finned chip showed a lower heat transfer performance than the chip with submicron-scale roughness in the low-heat-flux region, it showed a higher heat transfer performance than the latter in the high-heat-flux region. The roughened micro-pin-finned chip showed higher heat transfer performance than a corresponding single rough surface or micro-pin-finned surface.

(2) The high boiling heat transfer performance was considered to be relevant to the micro-convection and evaporation of superheated liquid within the confined gaps between fins and the micro-convection caused by the suction of a bubble hovering on the top of micro-pin-fins.

Conclusions

(II) Effect of chip orientation

(3) For the smooth surface and rough surface, vertical orientation provides better heat transfer in the nucleate boiling regime with a very small decrease of CHF value, whereas for the micro-pin-finned surface, nucleate boiling superheats was independent of orientation but the CHF value was about 20% lower for the vertical orientation than that for the horizontal.

(III) Effect of liquid subcooling

(4) q_{CHF} increased almost linearly with increasing ΔT_{sub}. Liquid subcooling was very effective in elevating CHF for all the micro-pin-finned chips as compared to the smooth surface and other treated surfaces.

(IV) Effect of dissolved gas in FC-72

(5)The gas-dissolved FC-72 showed a marked decrease in the boiling incipience temperature. As a result, the heat transfer performance in the low-heat-flux region was higher than the case of degassed FC-72. However, the heat transfer performance in the high-heat-flux region was close to each other.

Thanks for your attention!