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

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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
Background

Trend of sing-chip packaging technology

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2010</th>
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<tbody>
<tr>
<td><strong>Performance</strong></td>
<td>3.19 GH</td>
<td>9.54 GH</td>
</tr>
<tr>
<td><strong>Integration</strong></td>
<td>0.2 billion transistors</td>
<td>1 billion transistors</td>
</tr>
<tr>
<td><strong>DRAM ½ pitch</strong></td>
<td>80 nm</td>
<td>45 nm</td>
</tr>
<tr>
<td><strong>Power density</strong></td>
<td>70W/cm²</td>
<td>85 W/cm²</td>
</tr>
<tr>
<td><strong>Junction temp</strong></td>
<td>85 °C</td>
<td>85 °C</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>Increases by 10°C</td>
<td></td>
</tr>
<tr>
<td><strong>Fault probability</strong></td>
<td>Increases by 50%</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>CPU型号</th>
<th>设计功率</th>
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<tbody>
<tr>
<td>Athlon 64 FX-55 (Clawhammer)</td>
<td>105W</td>
</tr>
<tr>
<td>Pentium 4 E 3.4GHz (Prescott)</td>
<td>100W</td>
</tr>
<tr>
<td>Pentium 4 E 2.8GHz (Prescott)</td>
<td>89W</td>
</tr>
<tr>
<td>Pentium 4 2.4GHz (Northwood)</td>
<td>66.2W</td>
</tr>
<tr>
<td>Athlon 64 3000+ (Winchester)</td>
<td>63W</td>
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</table>
Air cooling technology

Finned heat pipe radiator

- 1 toward large volume and weight
- 2 nose increasing
- 3 Limited heat dissipation ability
Liquid cooling technology

**Merit**
1. high efficiency
2. low noise

**Demerit**
- Poor security and reliability

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

(2) Critical heat flux occurs at $T > 85 \, ^\circ\text{C}$
Objectives

To develop a new surface microstructure for effective boiling heat transfer

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

\[ \Delta T_{\text{sat}} \]

\[ q \]

\[ \text{CHF} \]

\[ T = 85 \, ^\circ C \]

\[ \text{ONB} \]

\[ \text{smooth} \]

\[ \Delta T_{\text{sat}} \]
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
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
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

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

Experimental Apparatus
Micro-Pin-Finned Chips

SEM images of micro-pin-fins

Experimental Apparatus
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 Apparatus
Experimental Conditions

<table>
<thead>
<tr>
<th>Test chips(12)</th>
<th>8 micro-pin-finned surfaces</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2 roughed surfaces</td>
</tr>
<tr>
<td></td>
<td>1 roughed micro-pin-finned surface</td>
</tr>
<tr>
<td>Chip orientation</td>
<td>Horizontal and vertical</td>
</tr>
<tr>
<td>Working fluid</td>
<td>FC-72(Saturation temp. 56°C)</td>
</tr>
<tr>
<td>Liquid subcooling</td>
<td>45K (Liquid temp. 11°C)</td>
</tr>
<tr>
<td></td>
<td>25K (Liquid temp. 31°C)</td>
</tr>
<tr>
<td></td>
<td>3K  (Liquid temp. 53°C)</td>
</tr>
<tr>
<td></td>
<td>0K  (Liquid temp. 56°C)</td>
</tr>
<tr>
<td>Air concentration</td>
<td>3-6 Vol. % (Degassed)</td>
</tr>
<tr>
<td></td>
<td>36-40 Vol. % (Gas dissolved)</td>
</tr>
</tbody>
</table>
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Effects of Micro-Pin-Fins and Submicron-Scale Roughness

- 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) $q = 2.71 \text{W/cm}^2$

(b) $q = 5.98 \text{W/cm}^2$

(c) $q = 11.8 \text{W/cm}^2$

Chip C

(d) $q = 4.72 \text{W/cm}^2$

(e) $q = 12.2 \text{W/cm}^2$

(f) $q = 30.8 \text{W/cm}^2$

Chip EPF50-60

(g) $q = 4.83 \text{W/cm}^2$

(h) $q = 15.8 \text{W/cm}^2$

(i) $q = 39.6 \text{W/cm}^2$

$\Delta T_{sat} \approx 4.0 \text{K}$

$\Delta T_{sat} \approx 11.0 \text{K}$

$\Delta T_{sat} \approx 19.0 \text{K}$

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

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

Boiling curves; $\Delta T_{sub} = 0$ K, degassed

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

Boiling curves; \( \Delta T_{sub} = 25 \text{ K} \)

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

(a) Degassed  
(b) Gas dissolved
Boiling Curves

(a) Degassed
(b) Gas dissolved

Boiling curves; $\Delta T_{sub} = 45$ K

Effects of Micro-Pin-Fins and Submicron-Scale Roughness
Boiling Phenomena: Effect of Subcooling

(a) \( q = 2.055 \text{ W/cm}^2 \)
\[ T_w = 69.9 \, ^\circ \text{C} \]
\[ \Delta T_{sub} = 3 \, \text{K} \]

(b) \( q = 5.102 \text{ W/cm}^2 \)
\[ T_w = 73.8 \, ^\circ \text{C} \]

(c) \( q = 30.53 \text{ W/cm}^2 \)
\[ T_w = 81.0 \, ^\circ \text{C} \]

(d) \( q = 2.724 \text{ W/cm}^2 \)
\[ T_w = 66.1 \, ^\circ \text{C} \]

(e) \( q = 6.641 \text{ W/cm}^2 \)
\[ T_w = 76.1 \, ^\circ \text{C} \]
\[ \Delta T_{sub} = 25 \, \text{K} \]

(f) \( q = 44.46 \text{ W/cm}^2 \)
\[ T_w = 81.1 \, ^\circ \text{C} \]

Boiling phenomena; Chip PF50-60

Effects of Micro-Pin-Fins and Submicron-Scale Roughness
Boiling Phenomena: Dissolved Gas Effect

Degassed

Chip PF30-60

(a) $q = 3.60 \text{W/cm}^2$
$T_w = 71.2 \, ^\circ \text{C}$

(b) $q = 16.8 \text{W/cm}^2$
$T_w = 73.0 \, ^\circ \text{C}$

(c) $q = 47.5 \text{W/cm}^2$
$T_w = 74.0 \, ^\circ \text{C}$

Gas-dissolved

(d) $q = 2.84 \text{W/cm}^2$
$T_w = 66.6 \, ^\circ \text{C}$

(e) $q = 16.6 \text{W/cm}^2$
$T_w = 71.6 \, ^\circ \text{C}$

(f) $q = 47.5 \text{W/cm}^2$
$T_w = 75.6 \, ^\circ \text{C}$

Effects of Micro-Pin-Fins and Submicron-Scale Roughness
### Critical Heat Flux

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

<table>
<thead>
<tr>
<th></th>
<th>Chip</th>
<th>S</th>
<th>E</th>
<th>C</th>
<th>PF</th>
<th>EPF</th>
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<tr>
<td>Gas dissolved</td>
<td>▲</td>
<td>▪</td>
<td>□</td>
<td>▲</td>
<td>▼</td>
<td>▼</td>
</tr>
<tr>
<td>Degassed</td>
<td>▼</td>
<td>▲</td>
<td>□</td>
<td>▲</td>
<td>▼</td>
<td>▼</td>
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</table>

**Variation of $q_{\text{CHF}}$ with $\Delta T_{\text{sub}}$**

- Mudawar and Anderson Micro-pin-fins
- O'Connor et al. Porous
- O'Connor et al. Smooth

$q_{85^\circ C}$
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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

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

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
Boiling Curves: Orientation Effect

Comparison of boiling curves for vertically and horizontally mounted chips

(a) Chip PF50-200
(b) Chip PF30-200

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

(a) Chip PF10-60  (b) Chip PF20-60  (c) Chip PF30-60  (d) Chip PF50-60
10×10×60 μm³  20×20×60 μm³  30×30×60 μm³  50×50×60 μm³

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

Boiling curves; $\Delta T_{sub} = 0K$, degassed

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

(a) Degassed
(b) Gas dissolved

Boiling curves; $\Delta T_{sub} = 45K$

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
Variation of $q_{CHF}$ with $A_t/A$. $A_t$: Total heat transfer area; $A$: Projected area.

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
Maximum Heat Flux: Fin Cross-Sectional Size

Variation of $q_{\text{max}}$ with $\Delta T_{\text{sub}}$

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

Definition of $q_{\text{max}}$

$$q_{\text{max}} = \begin{cases} q_{\text{CHF}} & T_{w,\text{CHF}} \leq 85^\circ \text{C} \\ q_{T_e=85^\circ \text{C}} & T_{w,\text{CHF}} > 85^\circ \text{C} \end{cases}$$
Effect of Fin Height

(a) Chip PF30-60  (b) Chip PF30-120  (c) Chip PF30-200
30 × 30 × 60 μm³  30 × 30 × 120 μm³  30 × 30 × 200 μm³

(d) Chip PF50-60  (e) Chip PF50-200  (f) Chip PF50-270
50 × 50 × 60 μm³  50 × 50 × 200 μm³  50 × 50 × 270 μm³

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
Boiling Curves: Effect of Fin Height

Boiling curves; $\Delta T_{sub} = 0$ K, degassed

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
Boiling Curves: Effect of Fin Height

(a) Degassed

Boiling curves; $\Delta T_{sub} = 45K$

(b) Gas-dissolved

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

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

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
Maximum Heat Flux: Effect of Fin Height

Variation of $q_{\text{max}}$ with $\Delta T_{\text{sub}}$

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
\[ \eta = \frac{Q_t}{Q_\infty} = \frac{\tanh[m(h + t/2)]}{m(h + t/2)} \]

\[ m = \sqrt{\frac{4\alpha}{k}} \]

\[ \alpha = \frac{qA}{\Delta T_{sat}A_t} \]

Variation of \( \eta \) with \( q \)

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
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Heat Transfer Process in Micro-Pin-Fins

(a) FC-72

(b) Micro-pin-fin

Evaporation of thin liquid film

(c) Bubble

Pumping action of bubble growing

Micro-convection by capillary force

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

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

Effects of the Cross-Sectional Size and Height of Micro-Pin-Fin
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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 $\Delta T_{sub}$. 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!