Pulsatory Mixing of Laminar Flows Using Inertial Micro-pumps

Matthew Rolleston, Brandon Hayes
Team Introduction

Austin Hayes
Co-Lead Engineering
MECE
ach6895@rit.edu

Brandon Hayes
Co-Lead Engineering
BME/MicroE
bsh4263@rit.edu

James Krishe
Project Manager
MECE
jak9660@rit.edu

Matt Rolleston
FAB Specialist
MicroE
mxr9040@rit.edu

Alexander Borghetti Ferreira
Facilitator
MECE
abf9454@rit.edu
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
What is boiling?
Boiling Modes

• Metastable Boiling:

Occurs when you reach film boiling in a subcooled liquid
HP Inertial Pump
Laminar Flow

Microfluidics → Low Reynolds Number → Laminar Flow
Difficult to mix laminar flows
Motivation

• The precise manipulation of fluids can be applied anywhere from healthcare in medical diagnostics to pharmaceutical companies miniaturizing reactions to reduce reagent consumption.

• Current Lab-on-a-chip technologies employ basic unit operations such as mixing and dilution before more complex functions are performed.

• Inertial micropump technology can be used to mix, dilute, and displace fluids.

Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
Objective

• Research Question:
  ➢ Can we mix laminar flow modeling off of HP’s thermal inkjet bubble technology and to what extent does this mixing occur?

• Project Decomposition
  1. Design and fabricate a microheater element modeled off of inkjet technology
  2. Build external flow setup
  3. Perform mixing tests
  4. Verify correct boiling mode of resistors
  5. Quantify a mixing metric for analysis
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
Flow Test Setup

Diagram showing flow test setup with various components including fluid pools, syringes, a microchannel device, and outlets. The diagram illustrates the flow paths and connections between these components.
Manifold Setup

• 500 μm rubber gasket seals device and forms channel

• Manifold made to prevent leakage and visualize under microscope systems
Test Setup
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
Process Flow

- **Level 1**: Poly Define
  - 1µm Poly
  - P31 2E16 70KeV
  - 1µm Aluminum Deposit

- **Level 2**: Aluminum Define
  - 5µm TEOS
  - 1µm Poly

- **Level 3**: Contact Cut
  - 700Å TEOS

- **Level 4**: Channel Define
  - Channel Deposit
Process Steps

1. Starting Wafer
2. CL01 - RCA Clean
3. OX07 – Deposit 5µm TEOS
4. CV01 – LPCVD Poly 1µm
5. SD01 – Spin on Dopant
6. OX04 – Anneal
7. PH03 – Level 1 Poly
8. ET08 – Poly Etch
9. ET07 - Resist Strip
10. CL01 - RCA Clean, HF Dip
11. ME01 - Metal Deposition - Al
12. PH03 - level 2 Metal
13. ET55 - Metal Etch
14. ET07 - Resist Strip
15. OX04 – Al Sinter
16. CV03 - TEOS - 700Å
17. PH03 - Level 3 Contact Cut
18. ET06 - TEOS Etch
Mask Design

• 3 Levels
Final Devices

- Die Dimensions: 33mm x 25mm
- Device Dimensions: 200μm x 300μm
  150μm x 50μm
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
Fourier’s Law for heat transfer was employed to give an estimate of the thermal resistance of a polysilicon heater:

\[ R_\theta = \frac{x}{A \times k} \]

where:
- \( R_\theta \) is the thermal resistance (°C/Watt)
- \( x \) is the length of the thermal path (m)
- \( A \) is the cross-sectional area of the polysilicon heater (m^2)
- \( k \) is the thermal conductivity of SiO_2 (1.4 Watt/m°C)

The voltage needed to heat the polysilicon to a given temperature is represented as:

\[ V_{app} = \sqrt{\frac{\Delta T \times R}{R_\theta}} \]

where:
- \( \Delta T \) is the desired temperature change of the polysilicon heater (°C)
- \( R \) is the resistance of the polysilicon heater (Ω)
Resistance Change vs. Temperature

\[ R = R_{ref} \left[ 1 + \alpha (T - T_{ref}) \right] \]

\[ R = 219.148444 \left[ 1 + 0.000661 (T - 23) \right] \]
Temperature Change vs. Power

![Graph showing temperature change vs. power with two lines representing theory and extrapolated data.](image-url)
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
Laminar Flow Theory

• Mixing Analysis – particles or dyes?
  ➢ Particles follow flow field
  ➢ Dyes will naturally diffuse

\[
\frac{\partial^2 V_x}{\partial y^2} + \frac{\partial^2 V_x}{\partial z^2} = -\frac{\Delta P}{\mu L}
\]

\[
V_x(0, z) = 0 \\
V_x(a, z) = 0 \\
V_x(y, 0) = 0 \\
V_x(y, b) = 0
\]
Dye Flow Test

• Convective-Diffusion Analysis
  ➢ With fluorescein, requires 1000 µm/s to prevent diffusion

• 0.01 mL/min $\rightarrow$ 1600 µm/s
Image Analysis

• Particle Tracking
  ➢ Enables quantification and better visualization

Image Processing

MATLAB Particle Tracking
Particle Flow Test

0.01 ml/min flowrate
50 V at 10 μs pulse width
0 Hz firing

Particle Tracking Streamlines
Particles at 50V 10us 100Hz
Particle Flow Test

0.01 ml/min flowrate
50 V at 10 μs pulse width
100 Hz firing

Particle Tracking Streamlines
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
Resistor Firing Conditions

- Resistor must operate in metastable boiling
- HP internal simulations on film stack
- Want to push from nucleate boiling into metastable regime by increasing the resistor surface temperature
Bubble Nucleation

- How do you visualize a 20 μs event?
  - Stroboscopic Effect
  - Laser sends trigger signal to camera sync as well as transistor for resistor sync
  - Camera records at start of resistor firing and laser is delayed
  - Must be a **REPEATABLE** event

- 50 V at 10 μs pulse width
  - Nucleate boiling
Metastable Boiling

- 65 V at 10 μs pulse width
  - Metastable boiling
Metastable Boiling

Bubble Formation

Bubble Collapse

5 μs  10 μs  15 μs  20 μs

25 μs  30 μs  35 μs  40 μs
Overview

1. Background
2. Project Goal
3. Mechanical Design and Fabrication
4. Resistor Design and Fabrication
5. Heat Transfer Theory and Temperature Measurements
6. Flow Theory and Mixing Test
7. Bubble Nucleation and Dynamics
8. Future Work and Conclusions
• With overlap connection areas, will the current go into the polysilicon?
  - Likely should follow the path of least resistance
  - Should not count the resistor overlap in its number of squares
Current Paths

- **Current Density Simulation**

- **Current Density Simulation (not showing Al)**
Breakage Path
Flow Sensors

- Require an integrated feedback loop to adjust mixing resistors

- Three resistors
  - Heat middle and temperature difference in other two act as measureme

- Steady-State Heat Transfer at 0 μm/s
Flow Sensors

- Steady-State Heat Transfer at 1000 μm/s
  - Temperature profile “bends” with flow due to convective heat transfer
Flow Sensors
Mixing Metric

• How do you quantify mixing with the resistor?

\[ \tau_r = \frac{L_r}{v_f} = \frac{L_R}{Q/A_c} = \frac{L_RA_c}{Q} \quad [s] \]

\[ N_e = f \tau_r \]

- \( A_c \ [m^2] \) — cross-sectional area
- \( \tau_r \ [s] \) — residency time
- \( v_f \ [m/s] \) — fluid velocity
- \( Q \ [m^3/s] \) — flow rate
- \( f \ [Hz] \) — electrical resistor firing frequency
- \( N_e \) — number of pump events per unit fluid element over the resistor
Conclusions

• A microheater was designed and fabricated modeled off HP’s inkjet technology.

• Confirmed that this technology can be used as a micromixer for both nucleate boiling and metastable boiling regimes.

• Provided evidence that the mixing mechanism was bubble-driven.

Future Work:

• Incorporate a graded boundary from the metal layer to the polysilicon heater to allow the device to withstand a higher current density

• Integrate calibrated flow sensors to allow for a feedback loop to control pulse frequency depending on flow rate.
This work was made possible by: