Pulsatory Mixing of Laminar Flows Using Inertial Micro-pumps

Matthew Rolleston, Brandon Hayes

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Team Introduction

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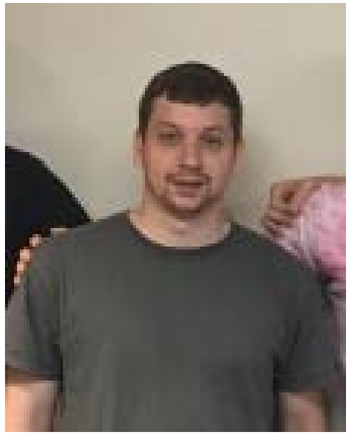

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Overview

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

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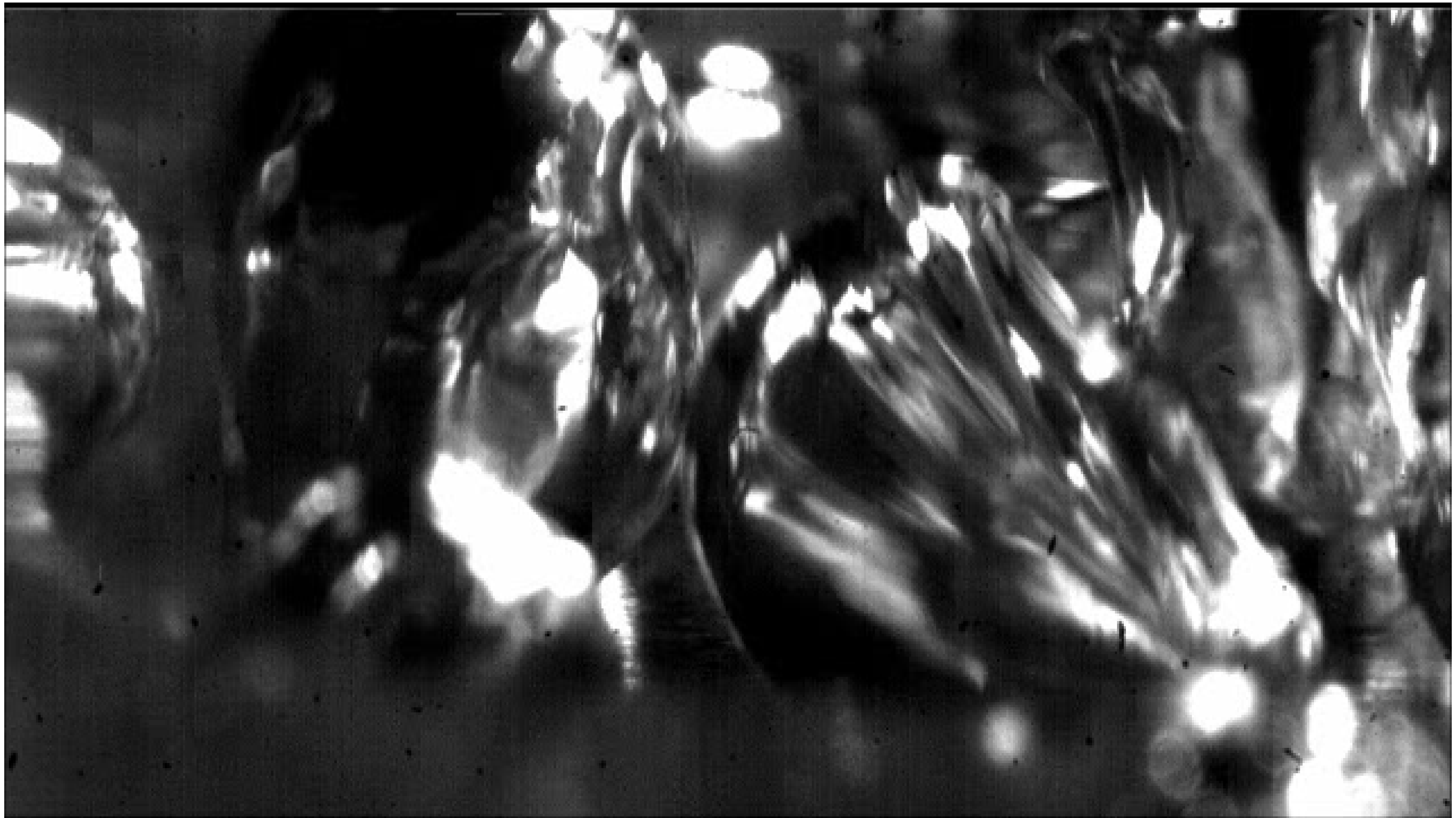
Boiling Background

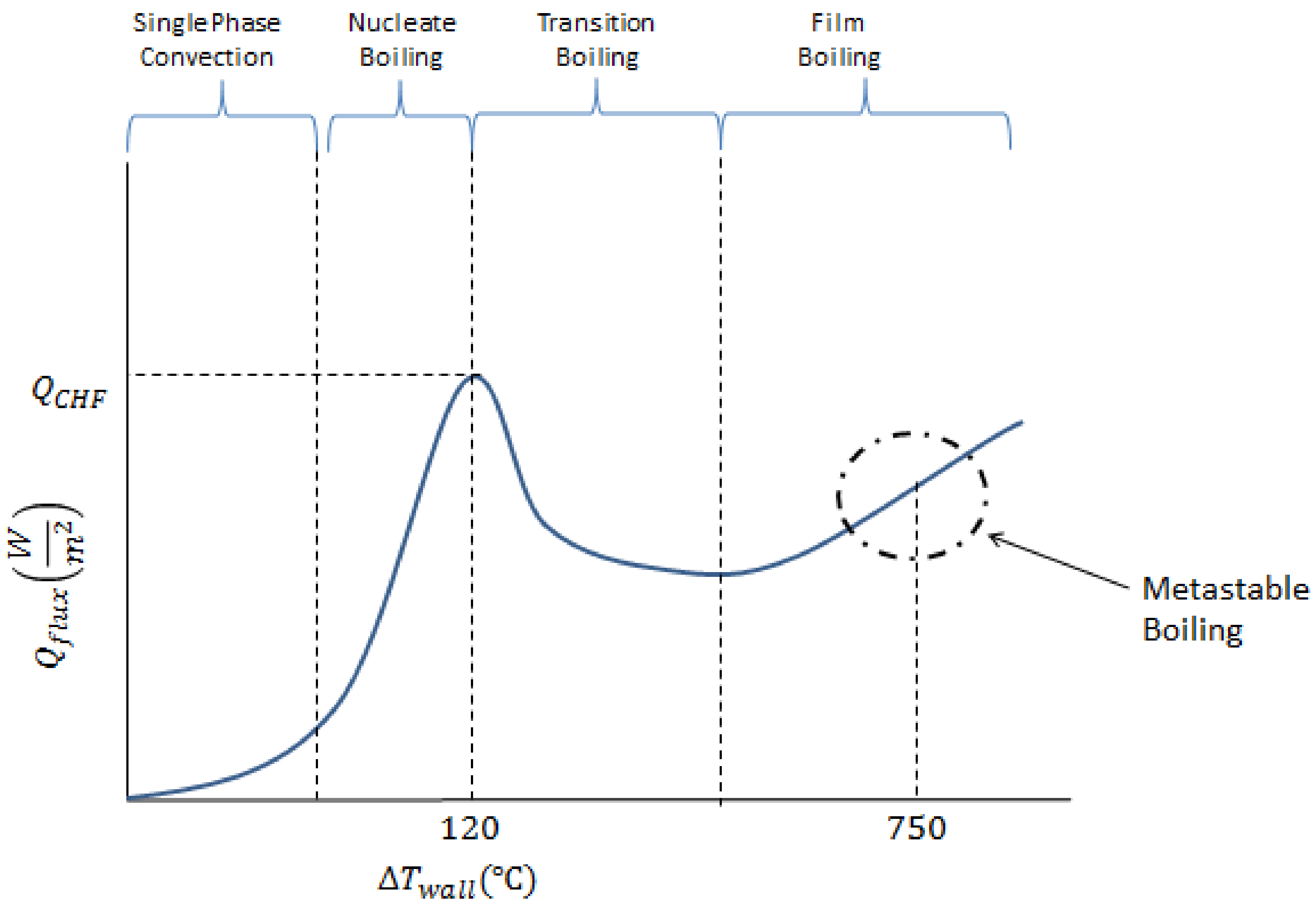
- What is boiling?



Boiling Modes

- Metastable Boiling:

Occurs when you reach film boiling in a subcooled liquid



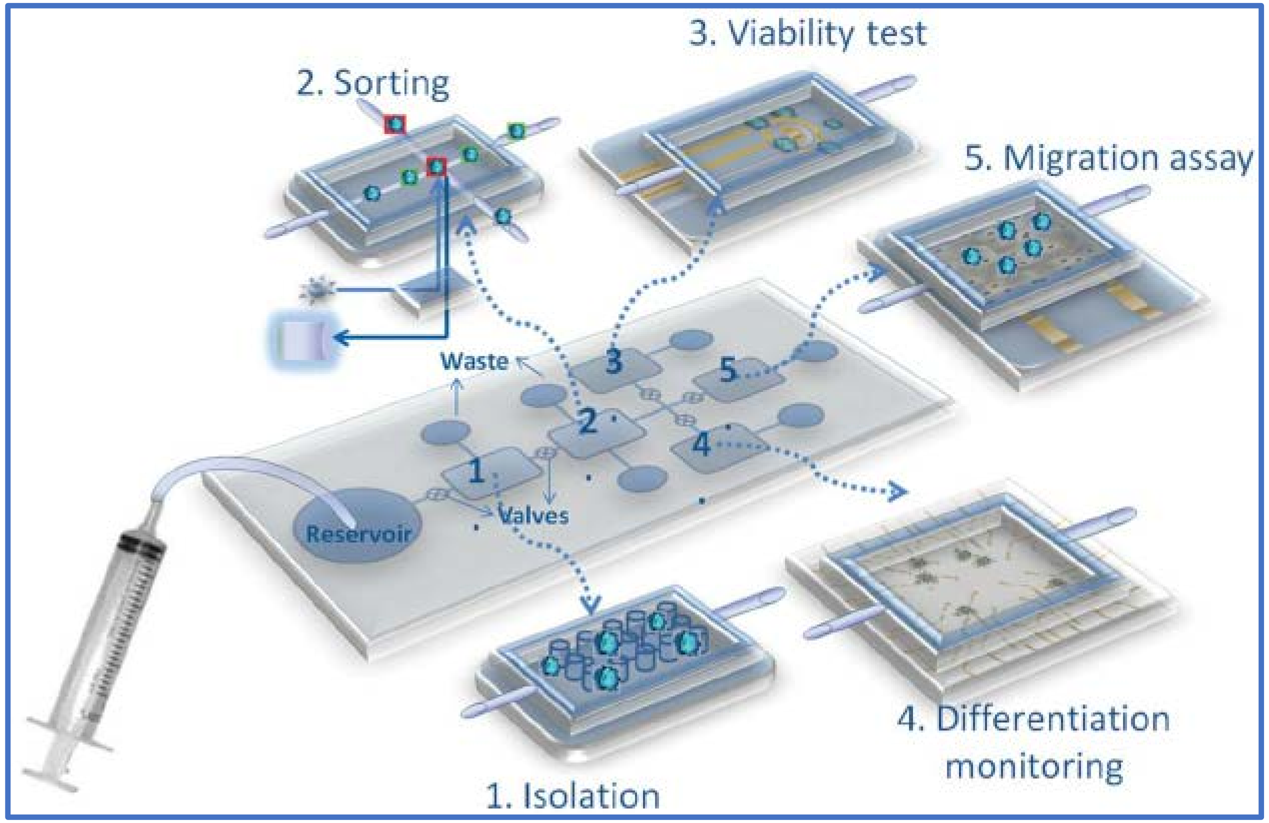
HP Inertial Pump

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.



Primiceri, E., Chiriacò, M., Rinaldi, R. and Maruccio, G. (2018). *Cell chips as new tools for cell biology – results, perspectives and opportunities*.

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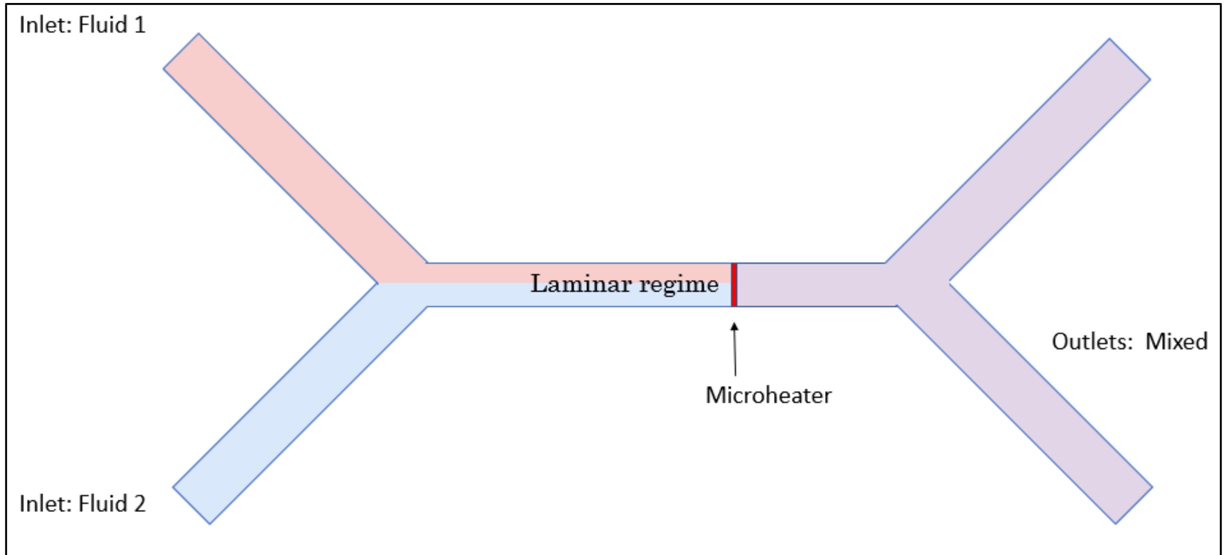
Objective

- 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



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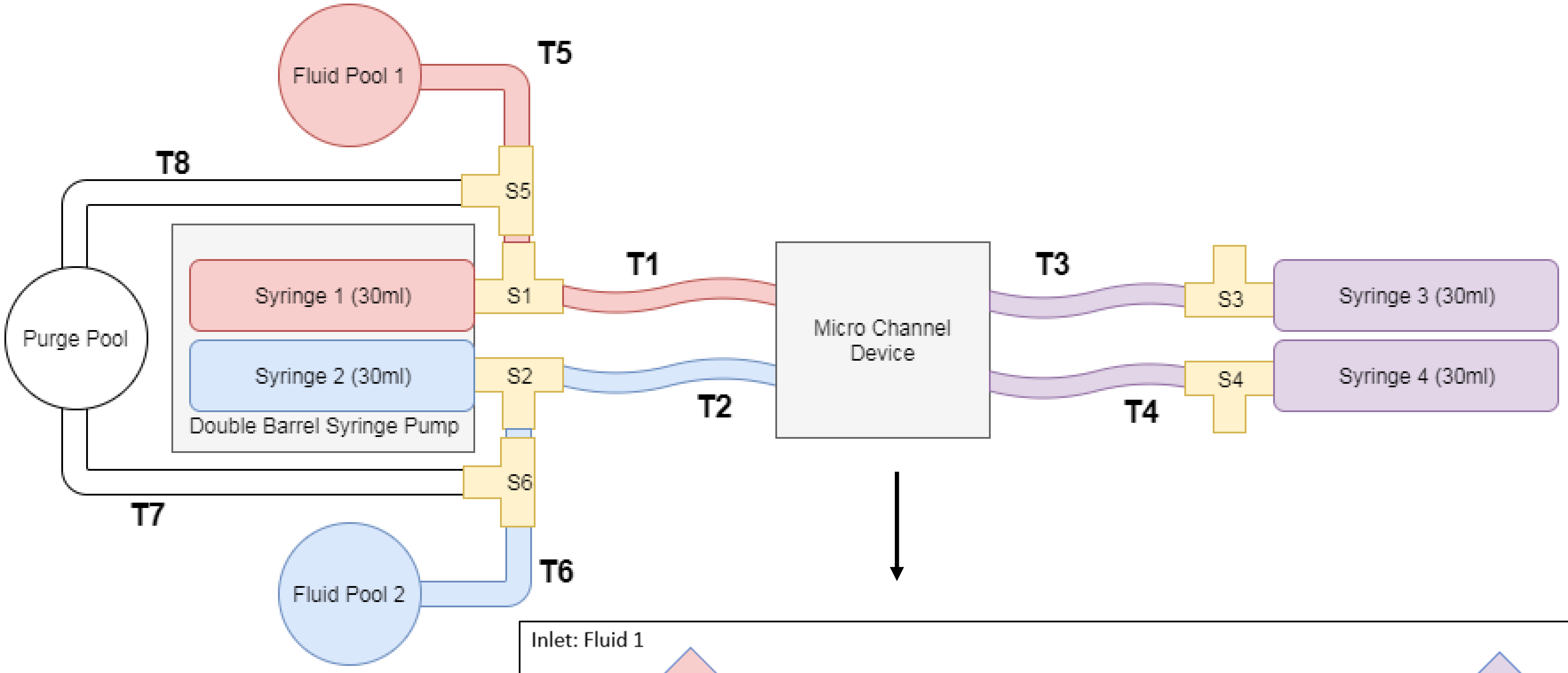
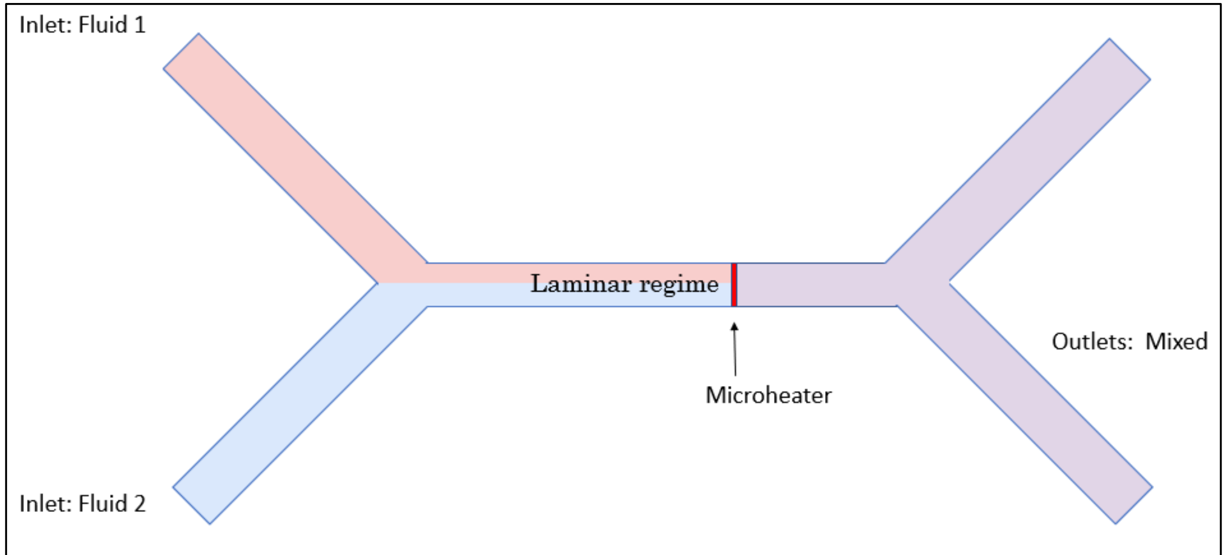
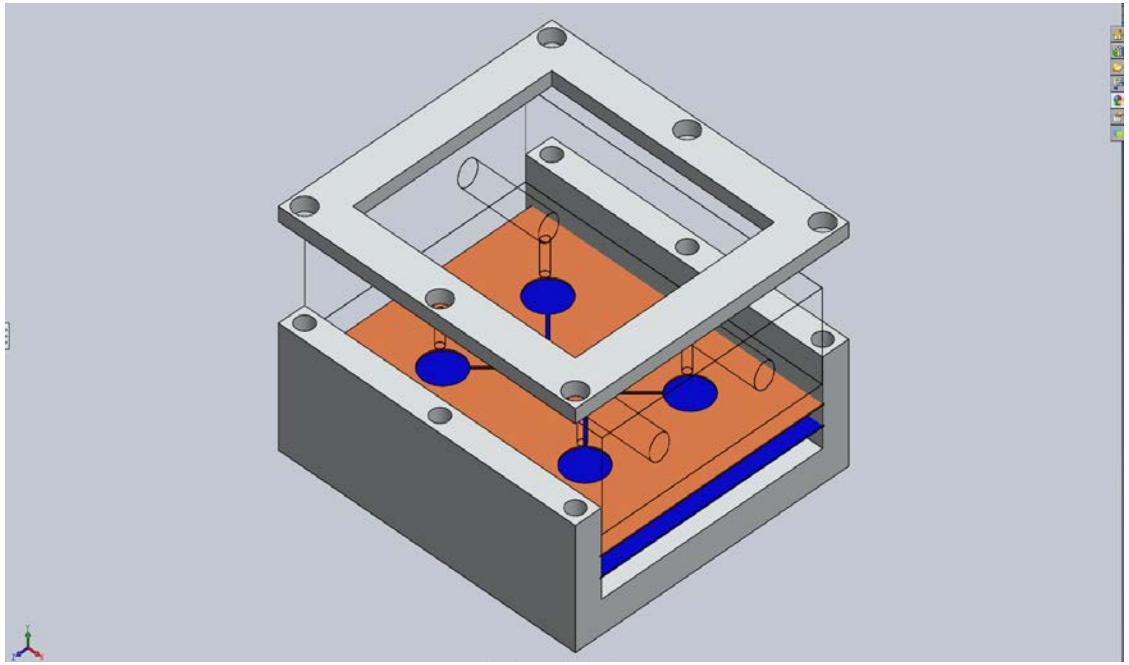
Flow Test Setup

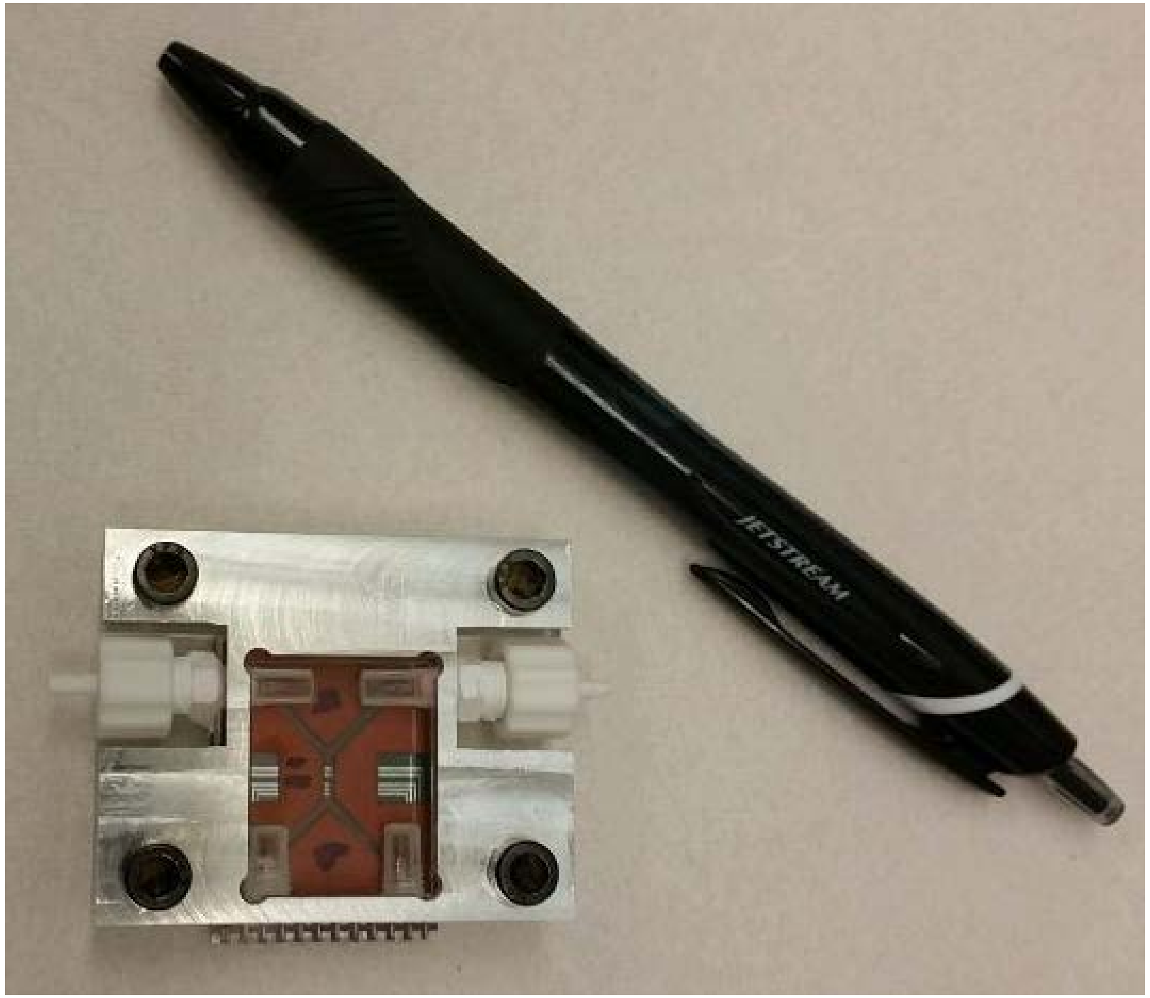




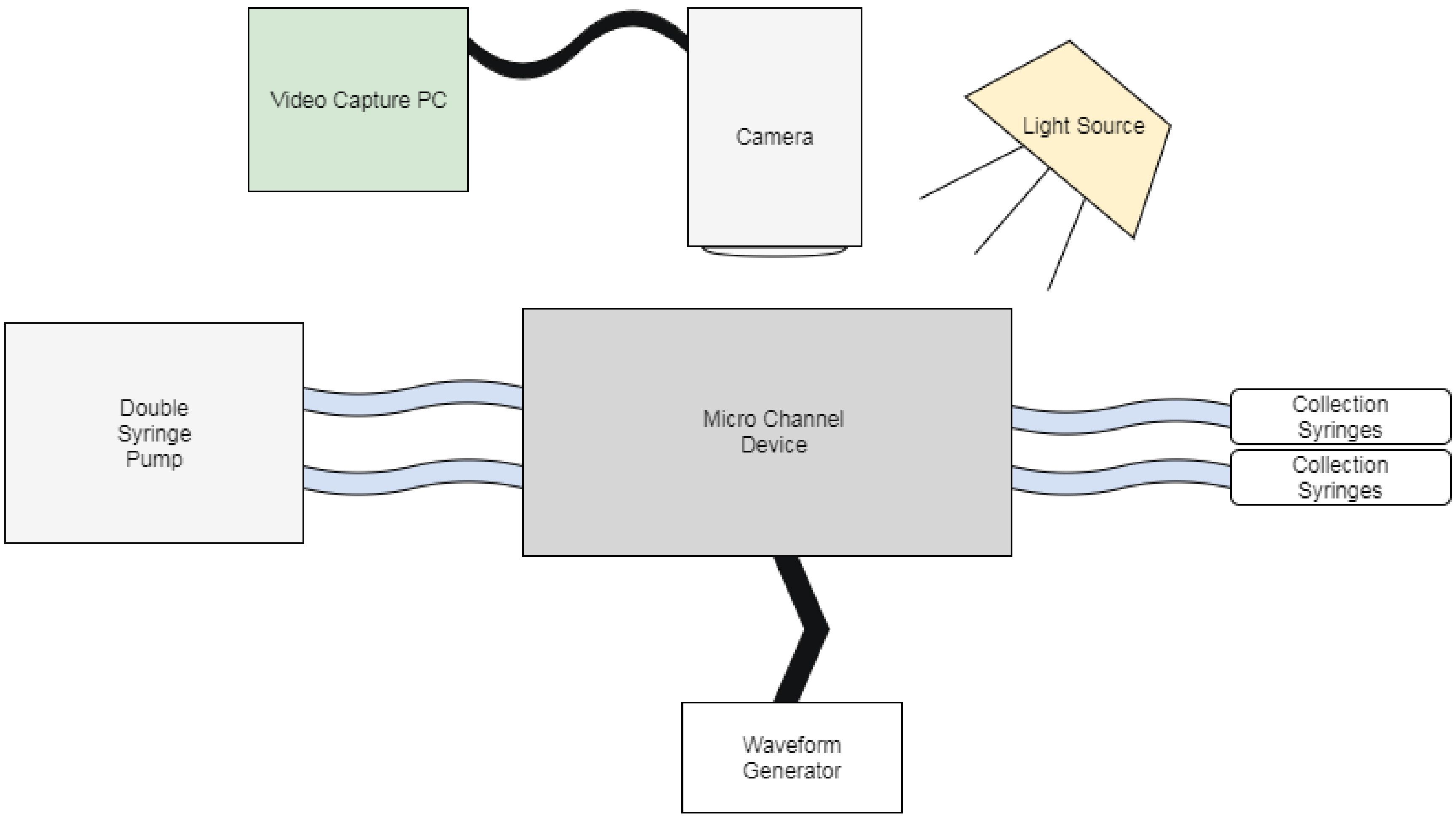
Manifold Setup

- 500 μm rubber gasket seals device and forms channel
- Manifold made to prevent leakage and visualize under microscope systems





Test Setup


Video Capture PC
Camera
Light Source
Double
Syringe
Pump
Micro Channel
Device
Collection
Syringes
Collection
Syringes
Waveform
Generator

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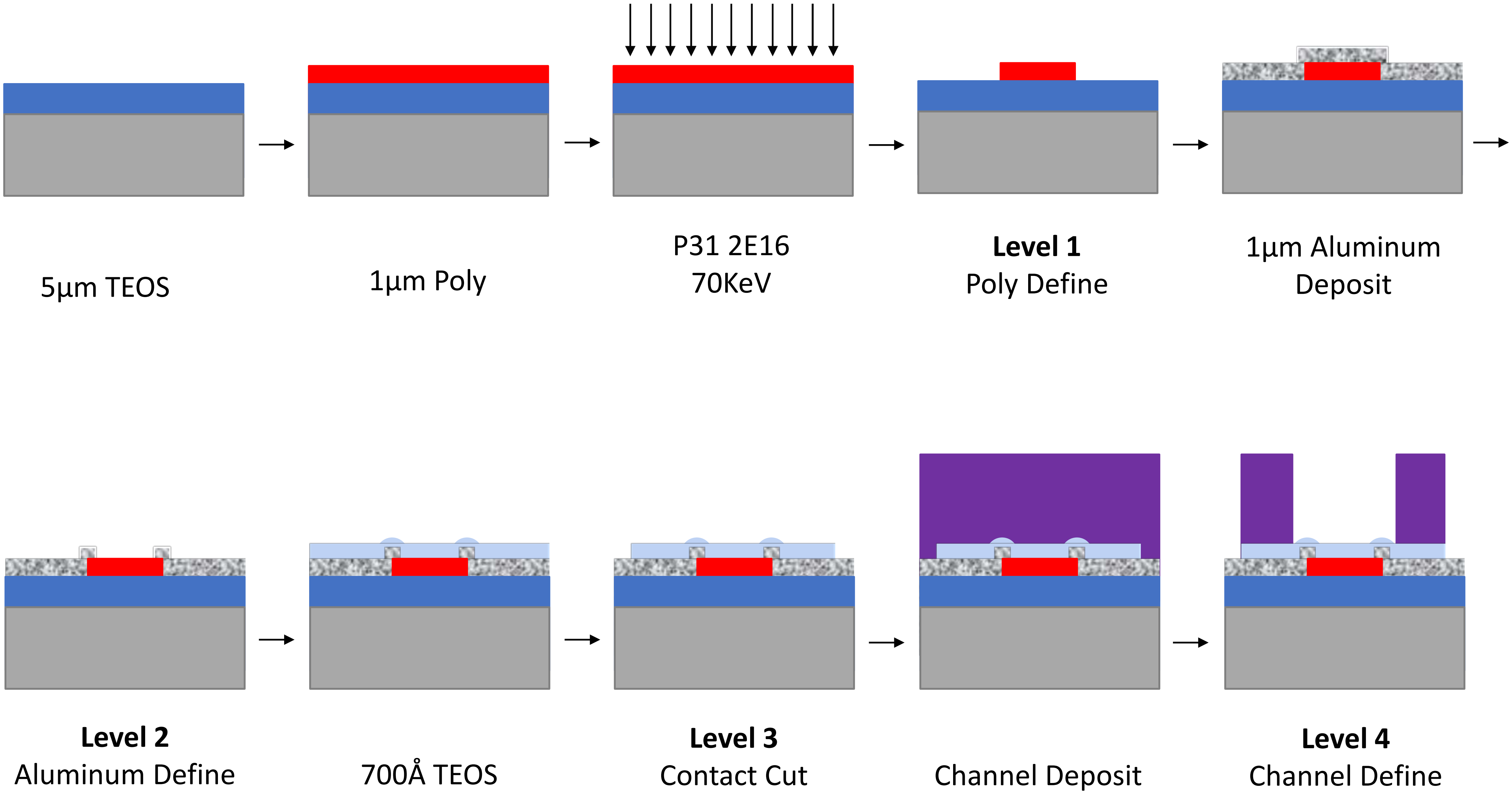
Process Flow

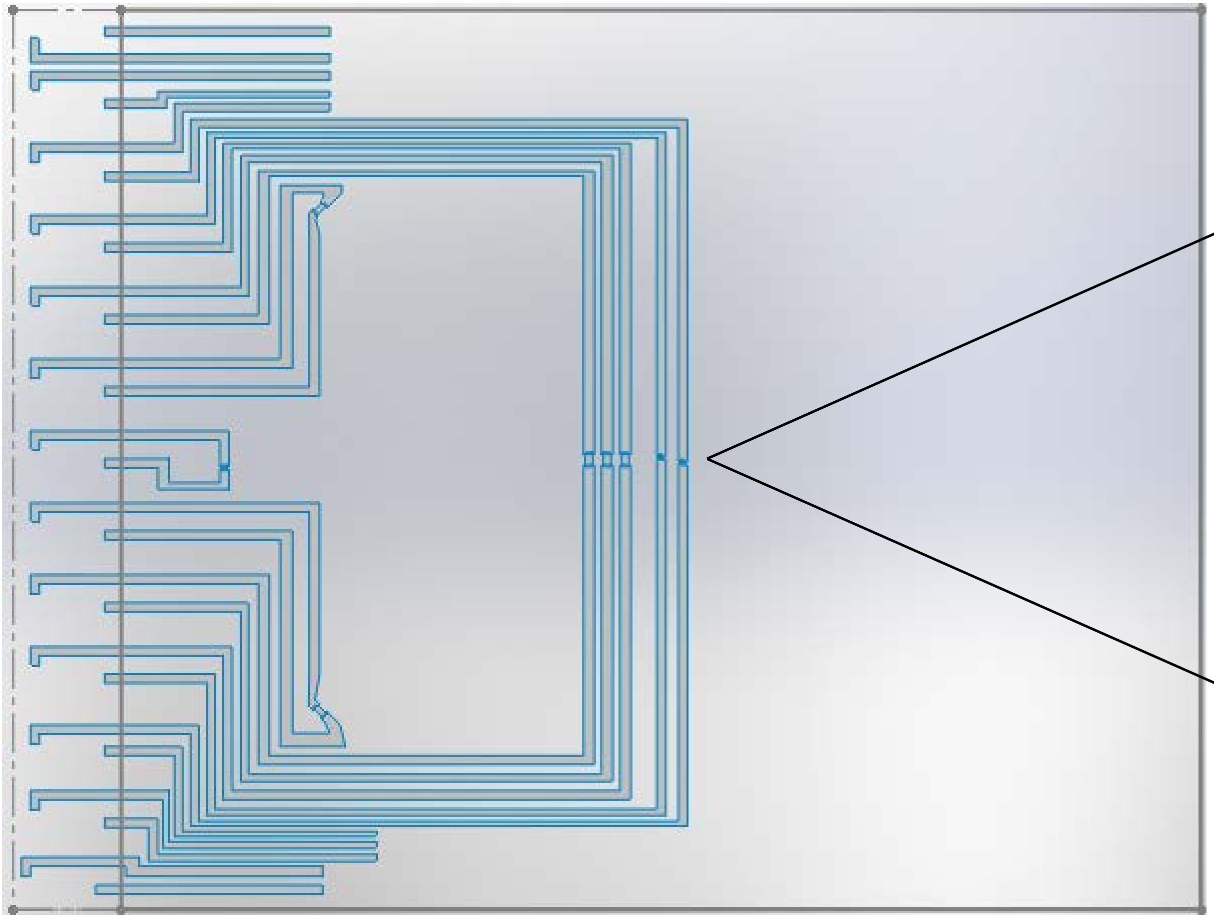


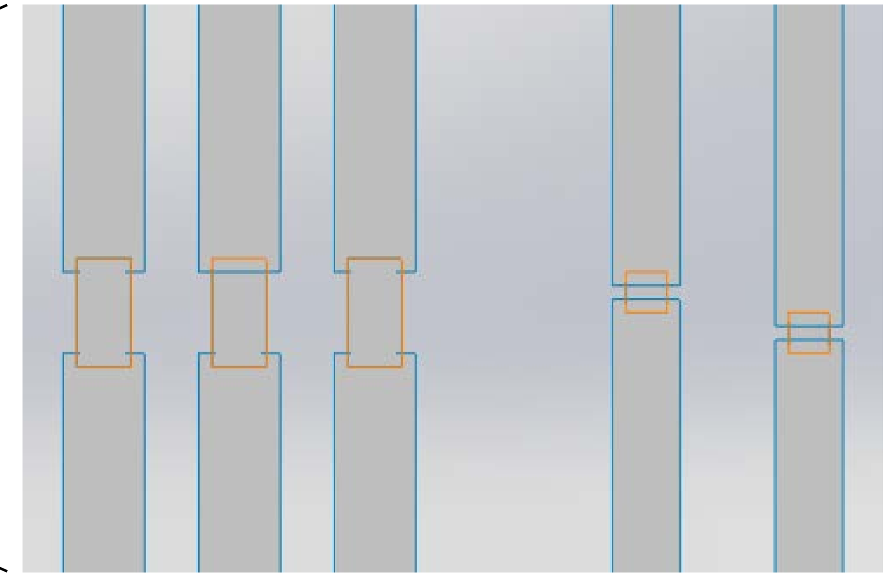
Process Steps

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

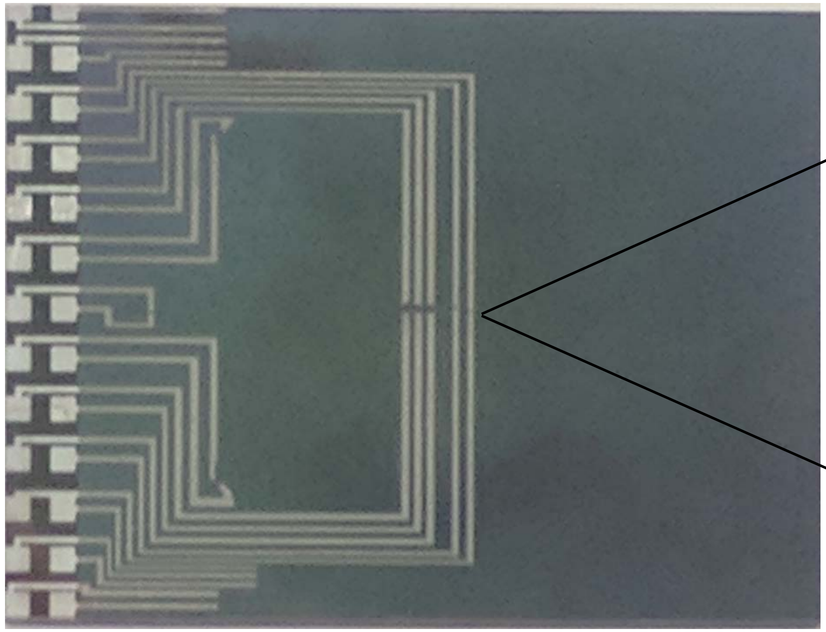
- 3 Levels

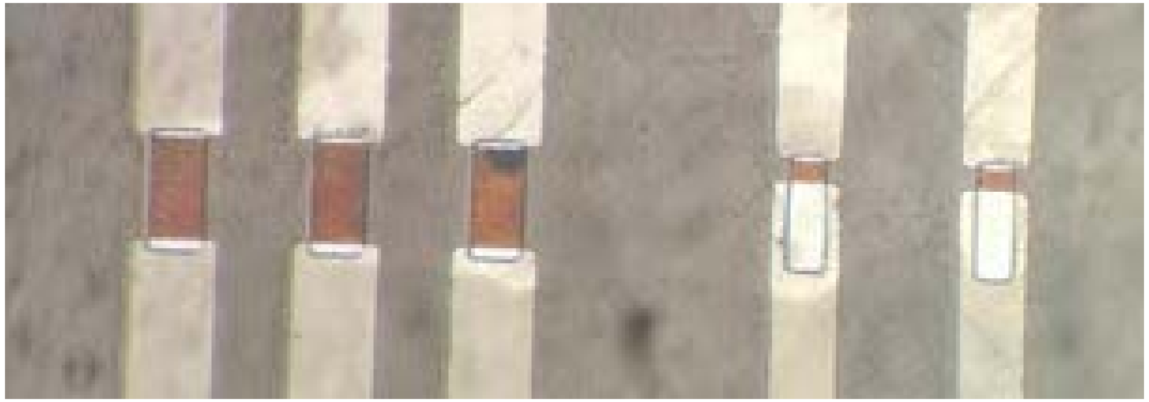




Final Devices

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





Overview

1D Heat Transfer Theory

Fourier's Law for heat transfer was employed to give an estimate of the thermal resistance of a polysilicon heater:

$$R_\theta = \frac{x}{A \times k}$$

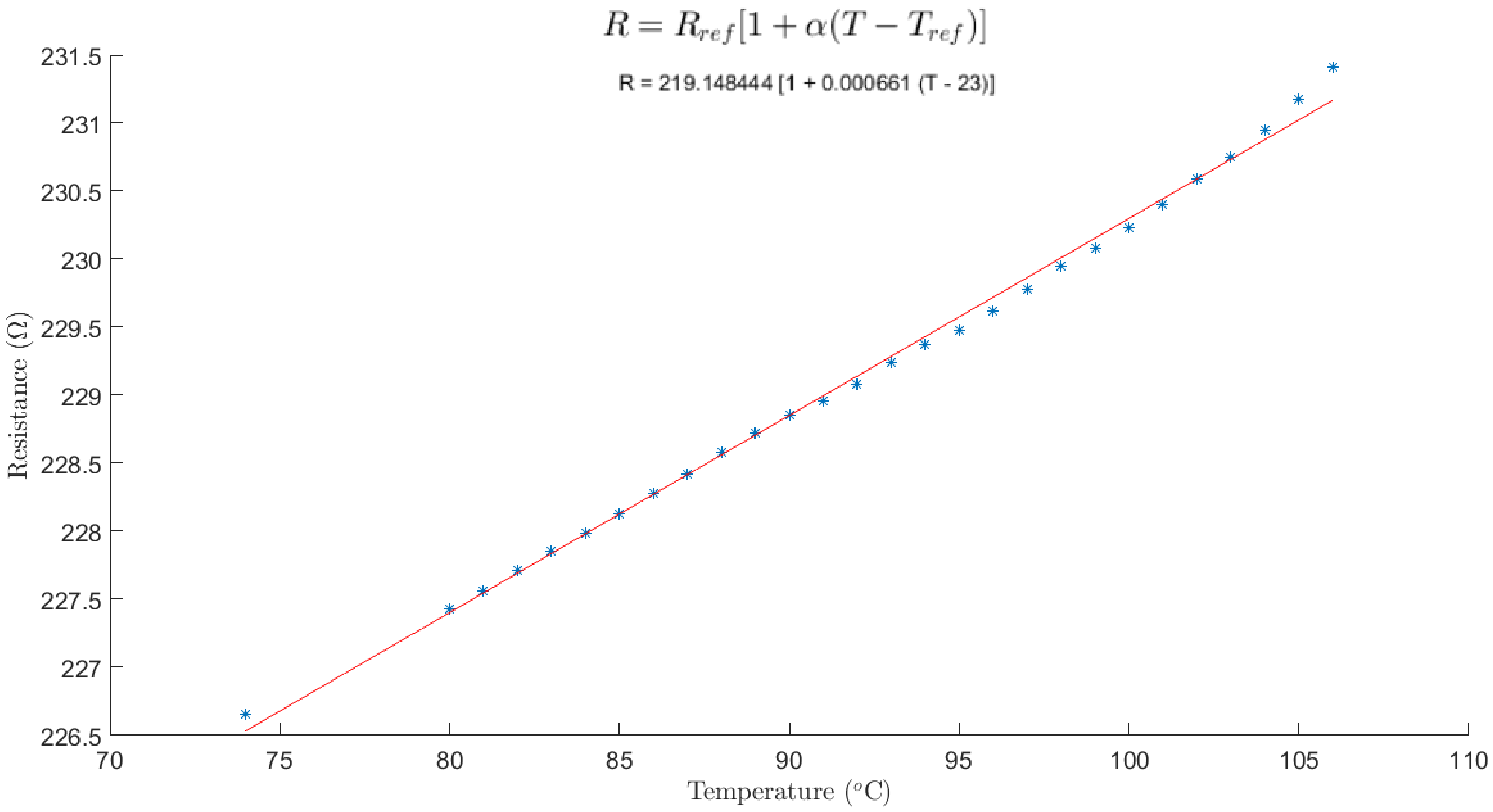
where:
R_θ is the thermal resistance (°C/Watt)
x is the length of the thermal path (m)
A is the cross-sectional area of the polysilicon heater (m^2)
k is the thermal conductivity of SiO_2 (1.4 Watt/m°C)

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

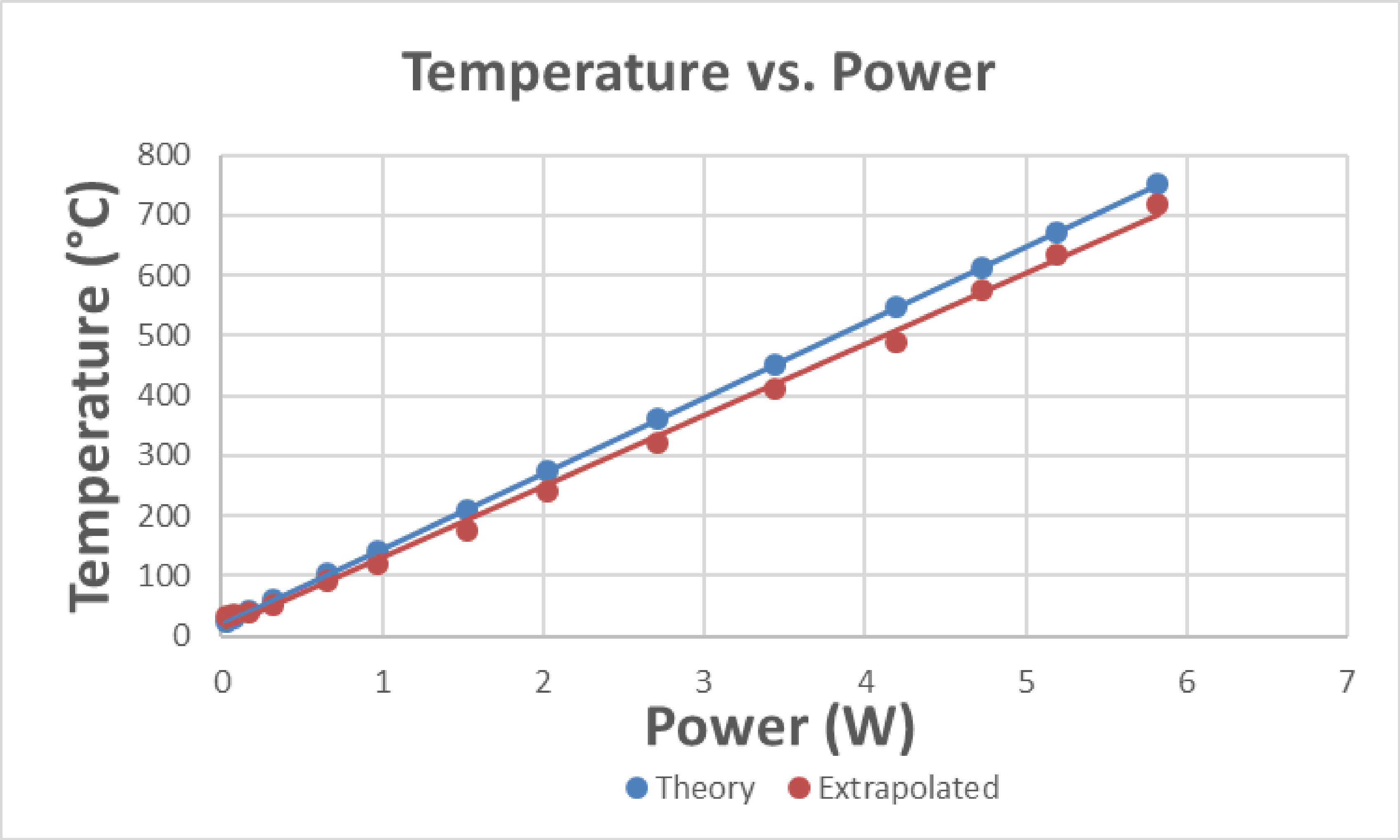
$$V_{app} = \sqrt{\frac{\Delta T \times R}{R_\theta}}$$

where:
ΔT is the desired temperature change of the polysilicon heater (°C)
R is the resistance of the polysilicon heater (Ω)

Resistance Change vs. Temperature



Temperature Change vs. Power



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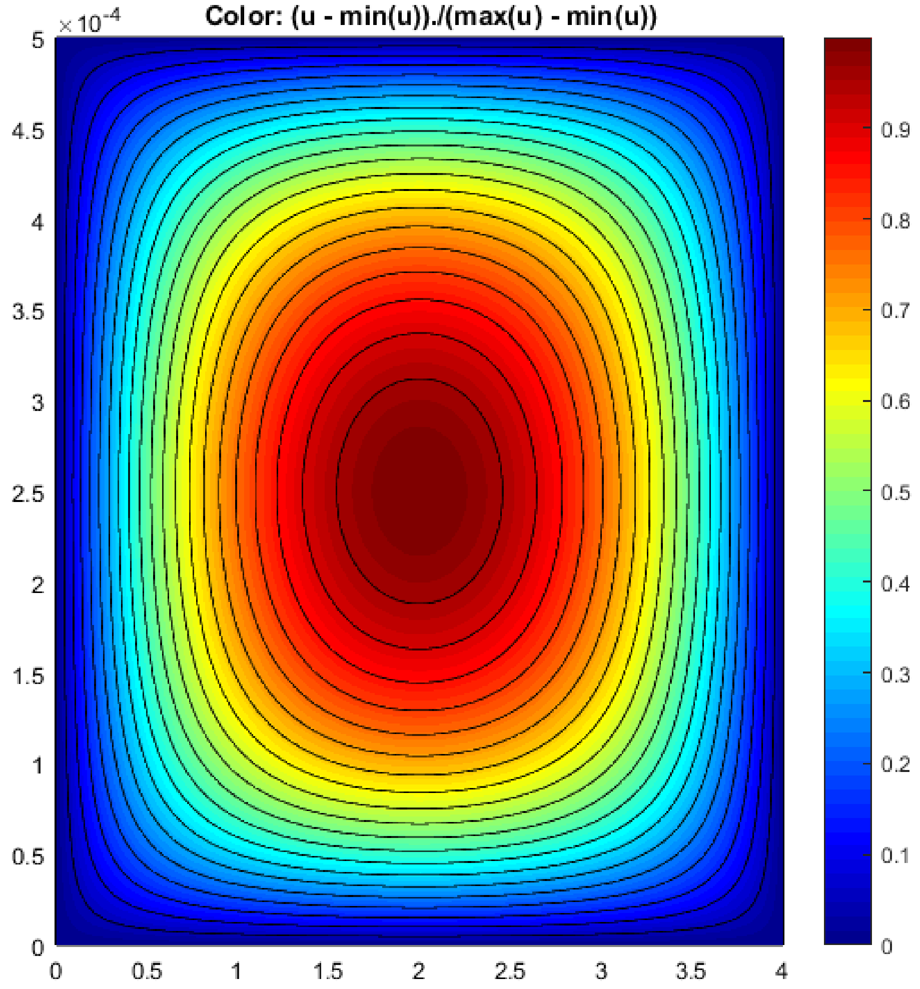
Laminar Flow Theory

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

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

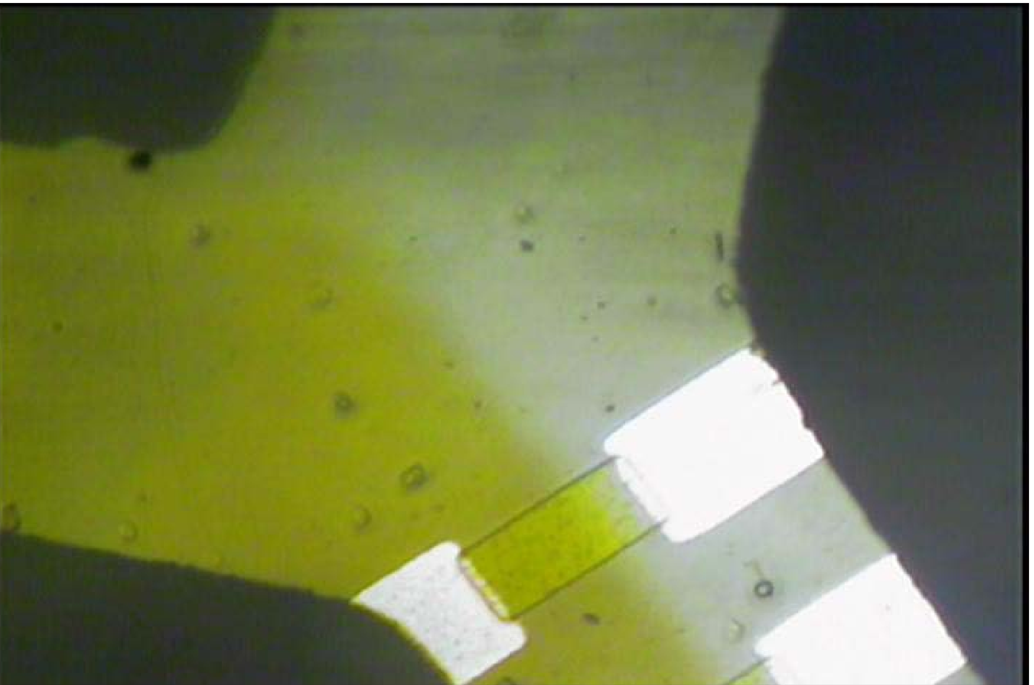
$$V_x(0, z) = 0$$
$$V_x(a, z) = 0$$
$$V_x(y, 0) = 0$$
$$V_x(y, b) = 0$$



Dye Flow Test

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

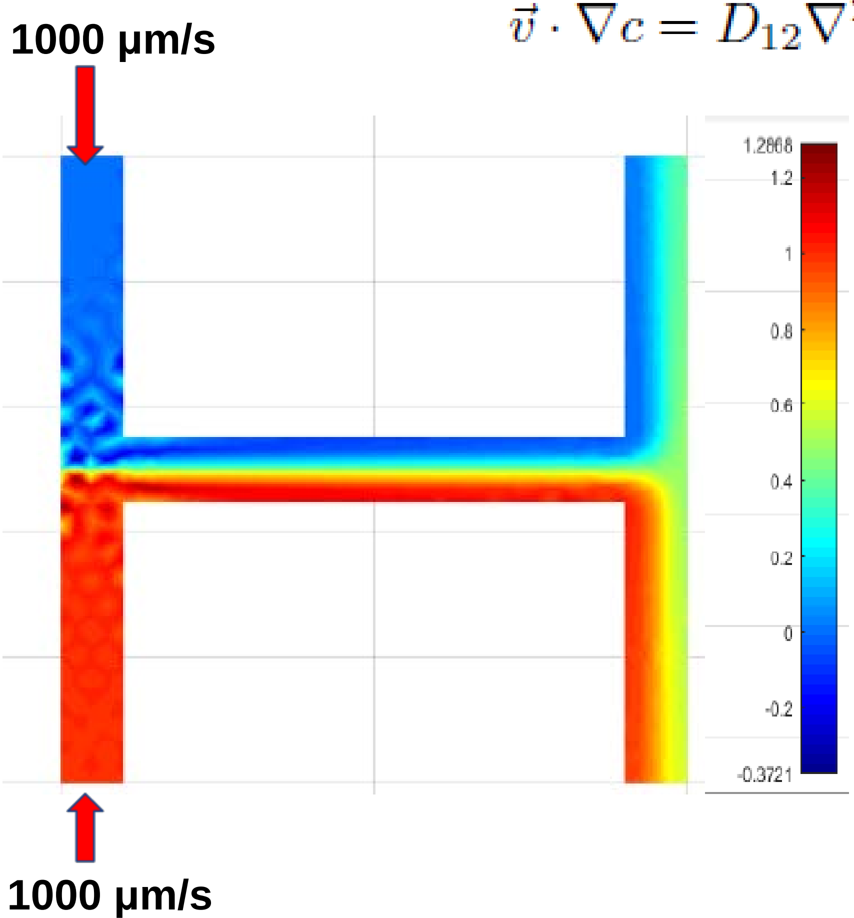
- 0.01 mL/min → 1600 μm/s



$$\rho \vec{v} \cdot \nabla \vec{v} = -\nabla p + \mu \nabla^2 \vec{v}$$

$$\nabla \cdot \vec{v} = 0$$

$$\vec{v} \cdot \nabla c = D_{12} \nabla^2 c$$



$$\vec{v}(walls) = 0$$

$$D_{12} \frac{\partial c}{\partial x}(walls) = 0$$

$$D_{12} \frac{\partial c}{\partial y}(walls) = 0$$

$$Q(inlet\ 1) = Q_1$$

$$Q(inlet\ 2) = Q_2$$

$$c(inlet\ 1) = C_o$$

$$c(inlet\ 2) = 0$$

Image Analysis

- Particle Tracking
  - ➢ Enables quantification and better visualization

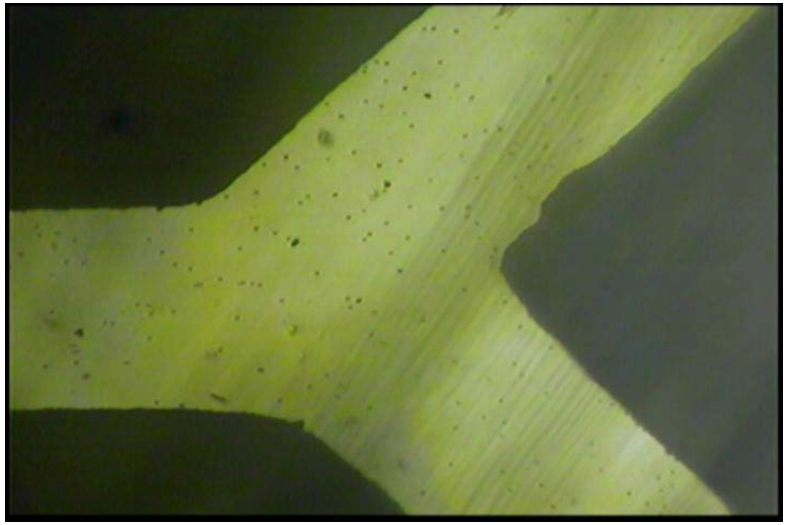
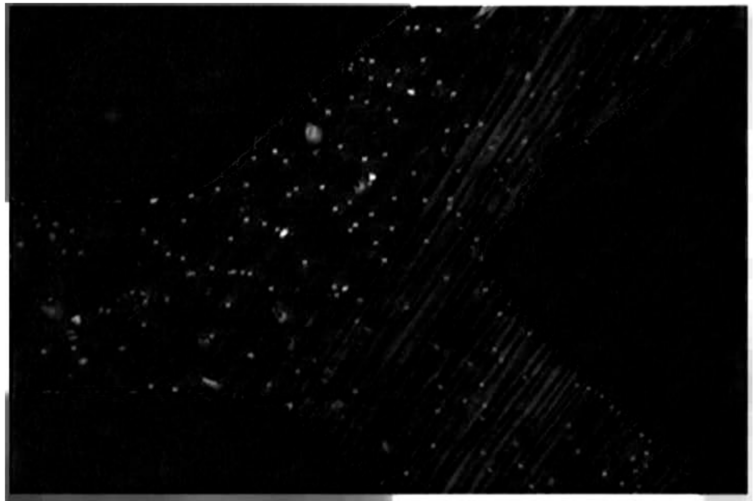
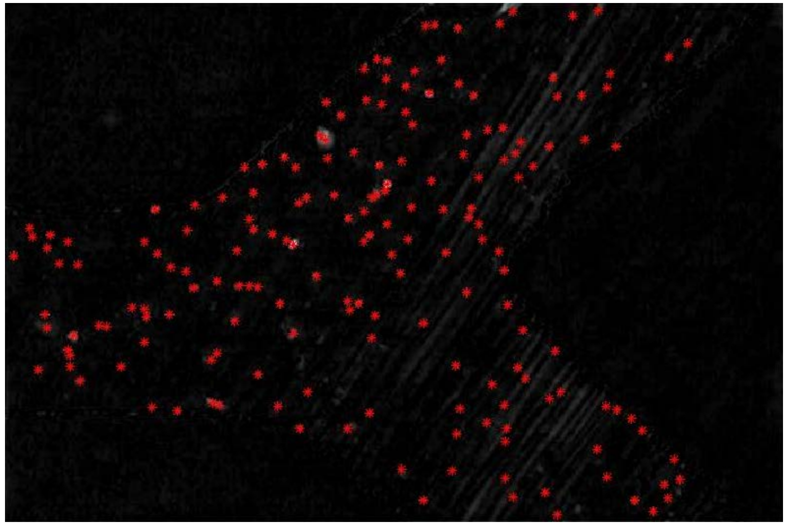


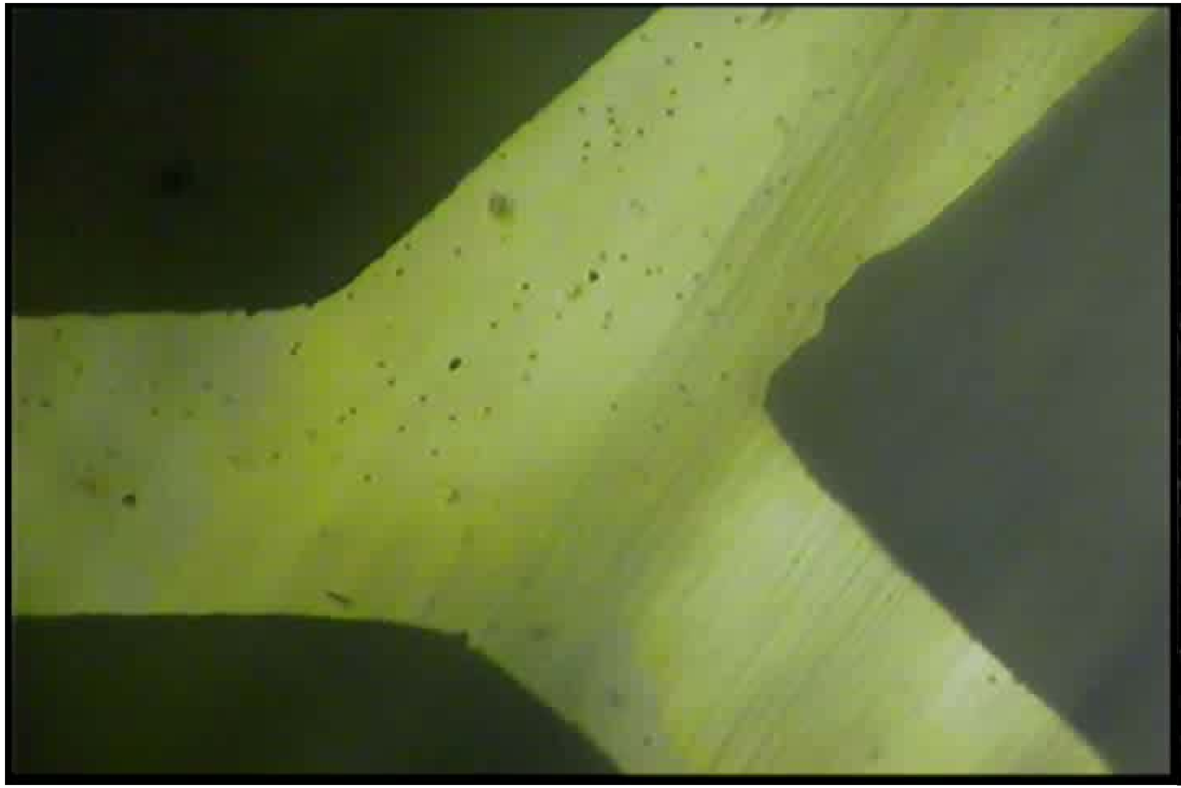
Image Processing



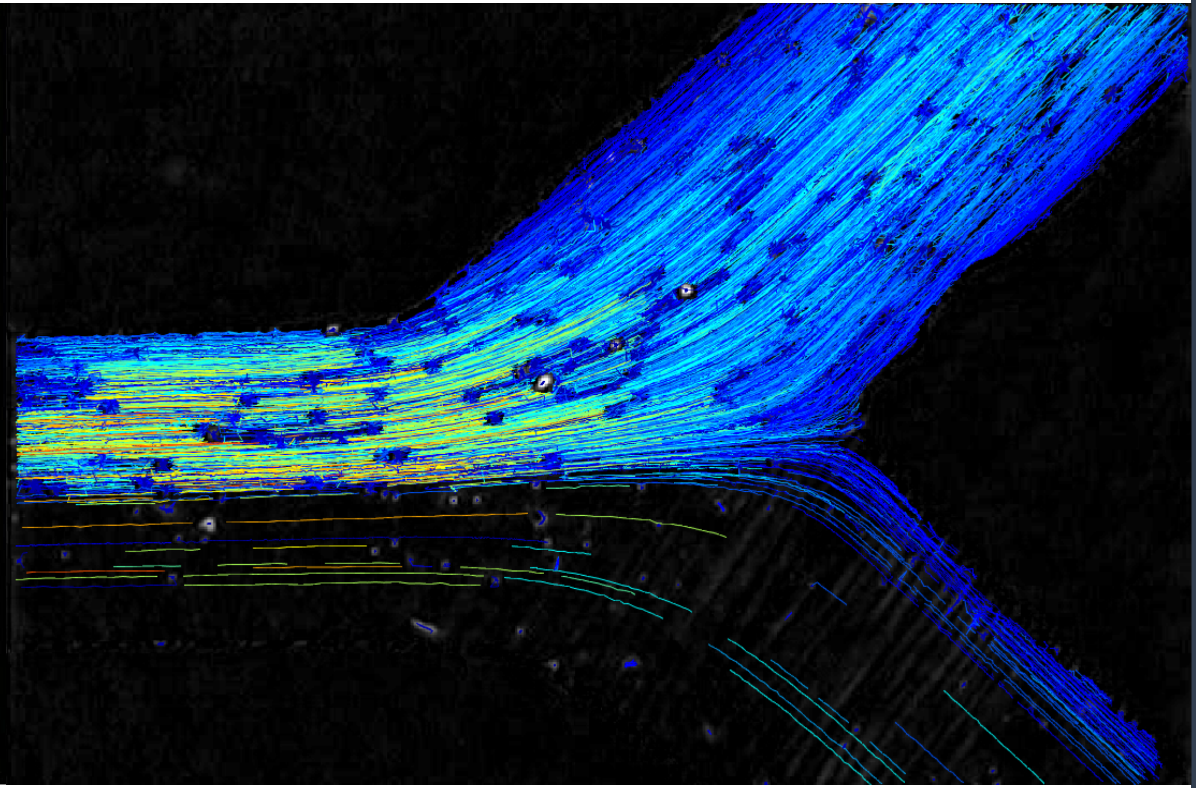
MATLAB Particle Tracking



Particle Flow Test

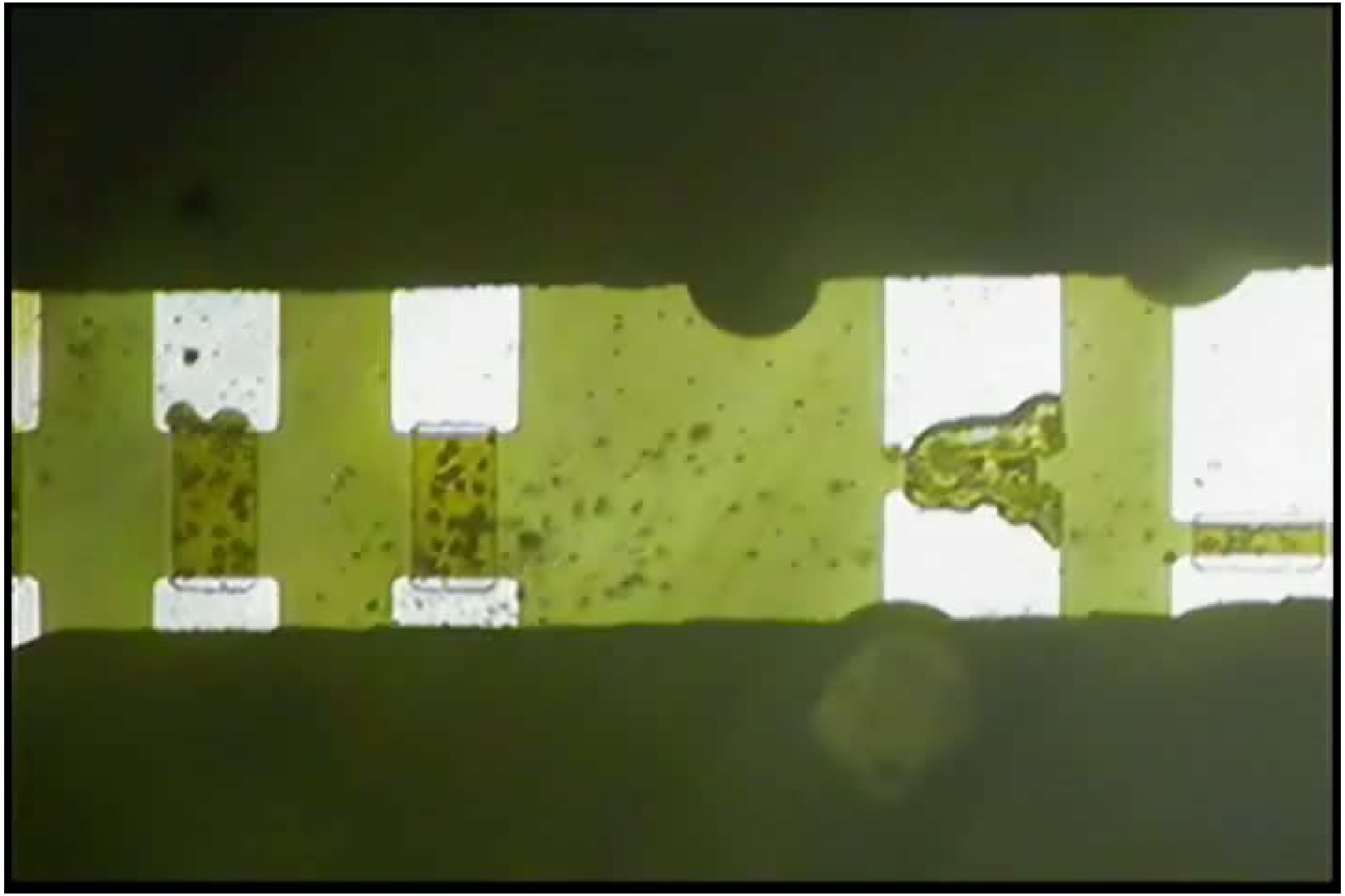


0.01 ml/min flowrate
50 V at 10 μs pulse width
0 Hz firing

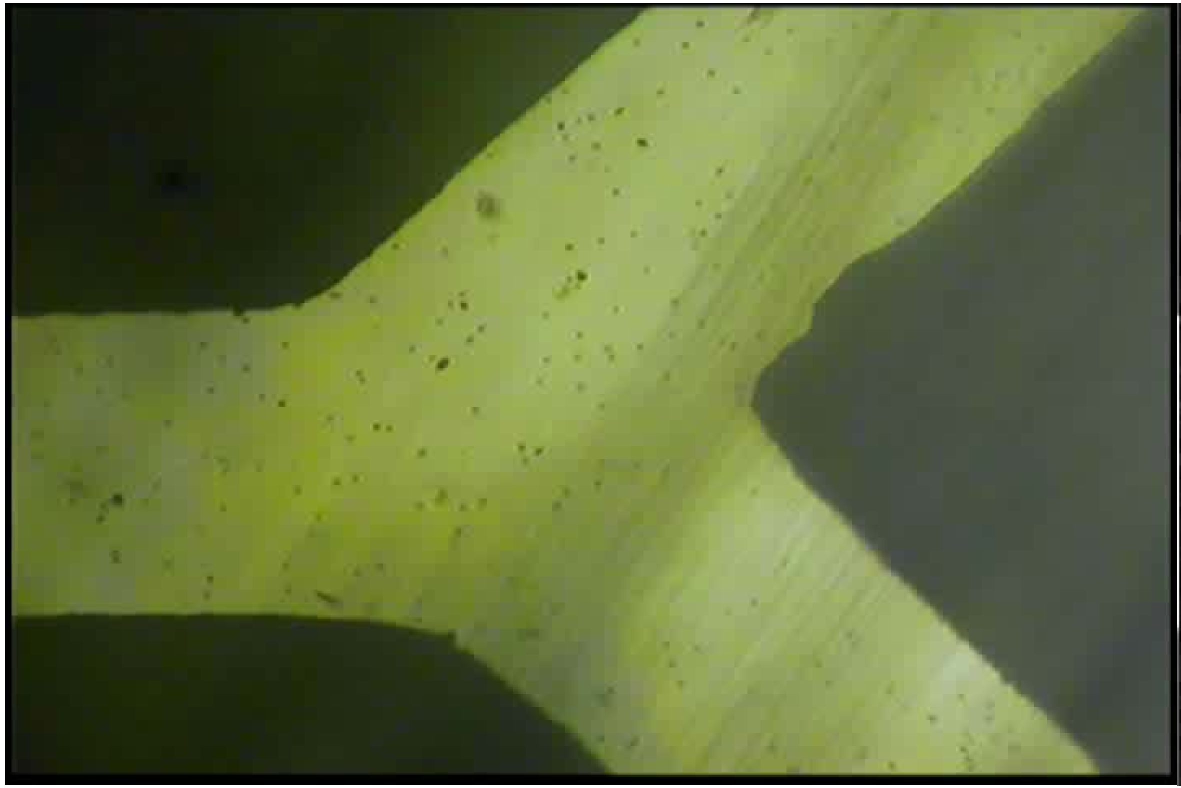


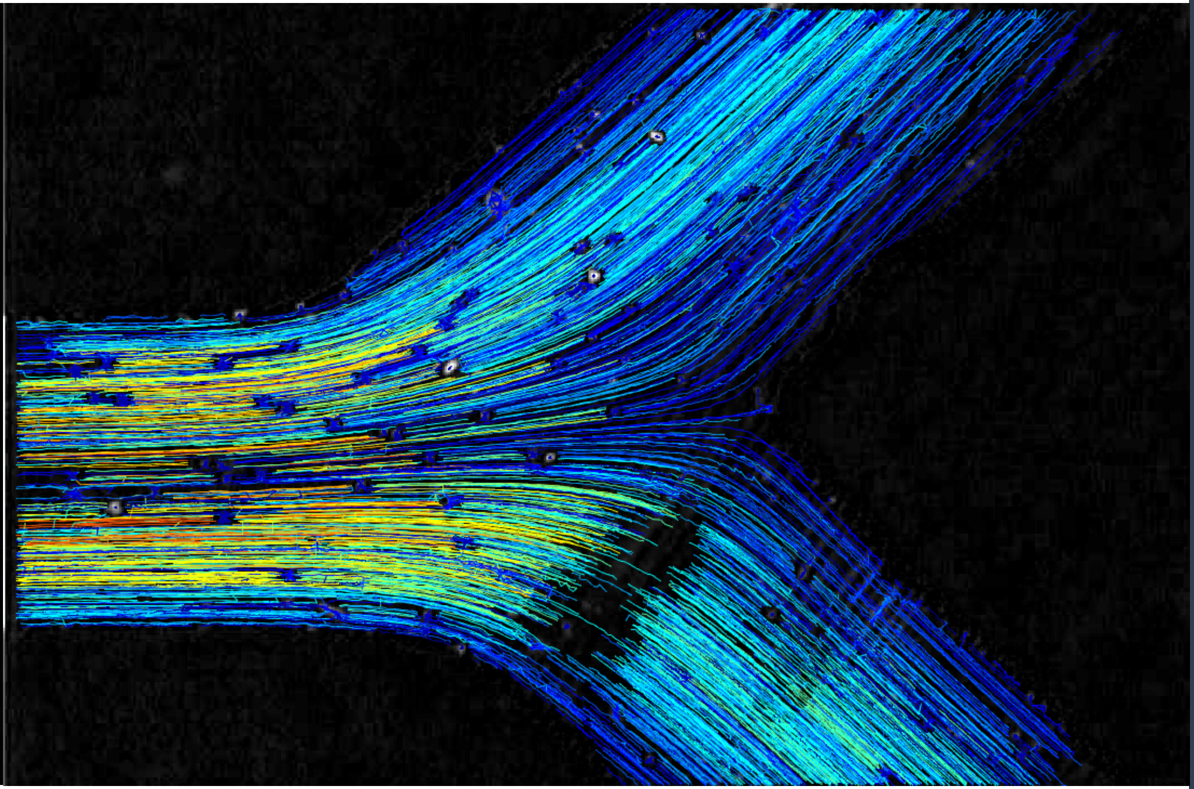
Particle Tracking Streamlines

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

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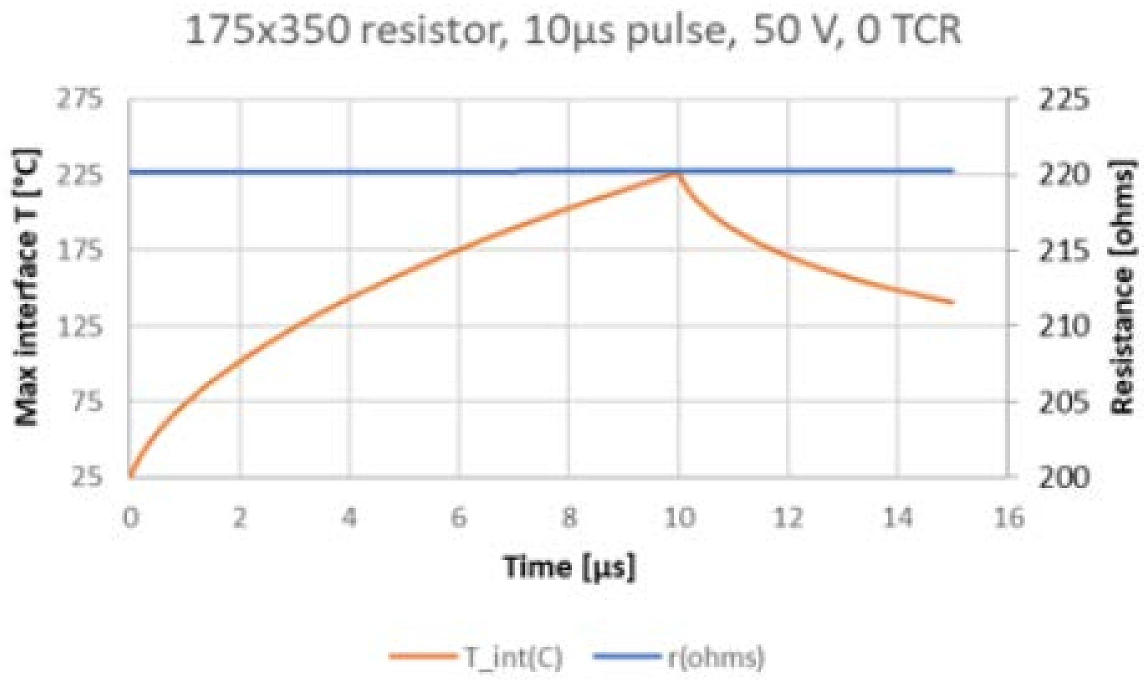
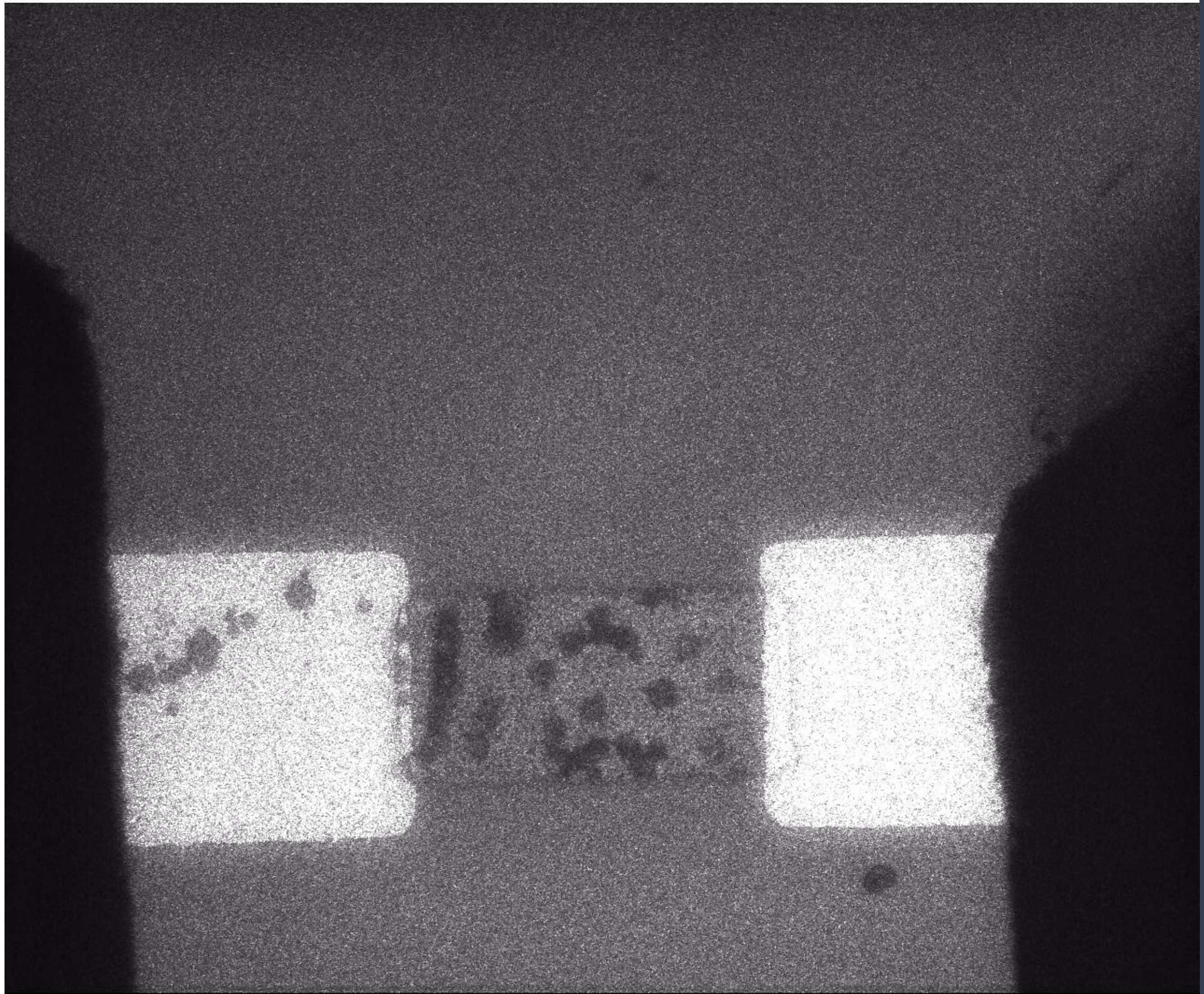
Resistor Firing Conditions

- 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

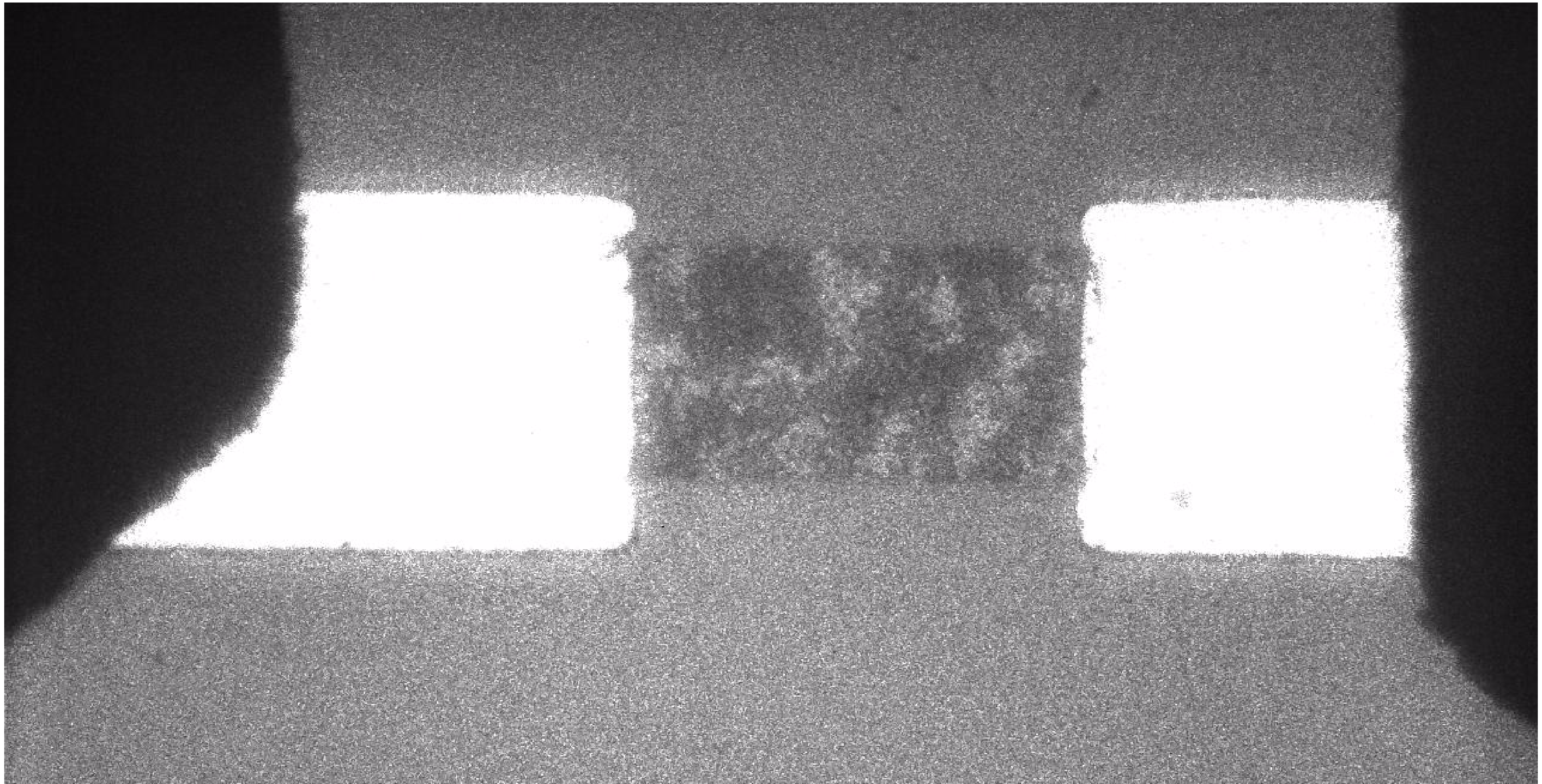
- How do you visualize a 20 μs event?
  - Stroboscopic Effect
  - Laser sends trigger signal to camera sync as well as transistor for resistor sync
  - Camera records at start of resistor firing and laser is delayed
  - Must be a ***REPEATABLE*** event



- 50 V at 10 μs pulse width
  - Nucleate boiling

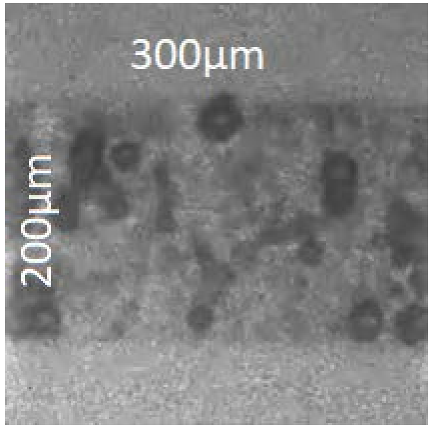
Metastable Boiling

- 65 V at 10 µs pulse width
  - Metastable boiling

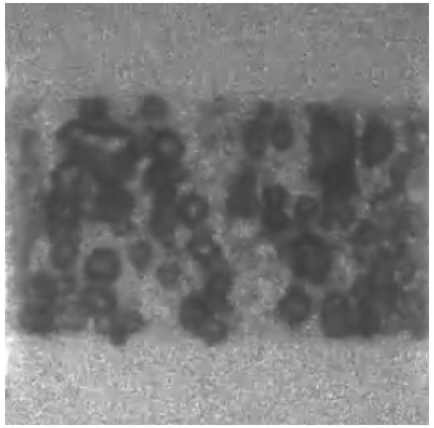


Metastable Boiling

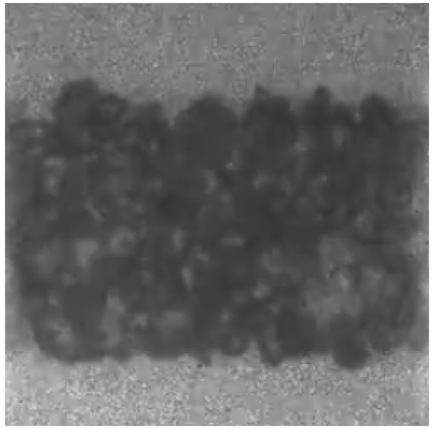
Bubble Formation



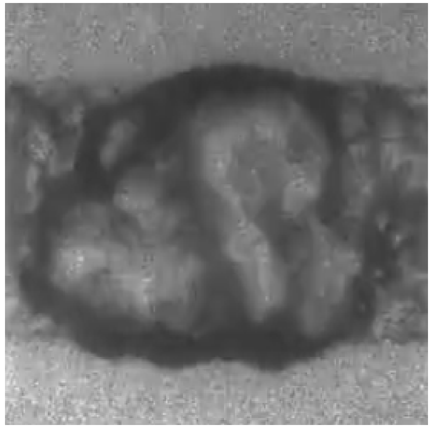
5µs



10µs

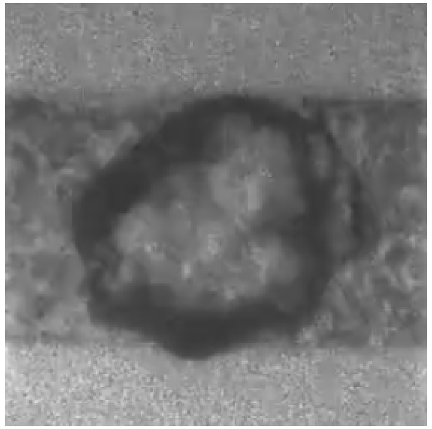


15µs

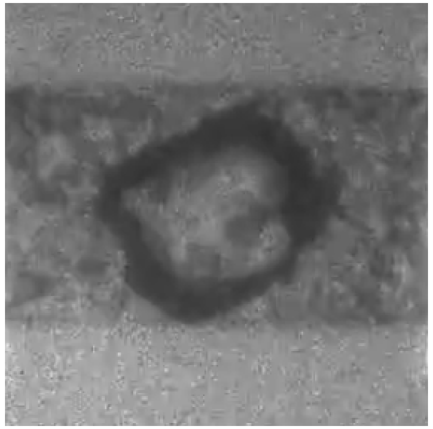


20µs

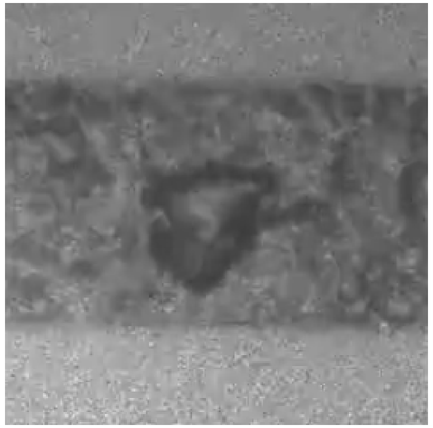
Bubble Collapse



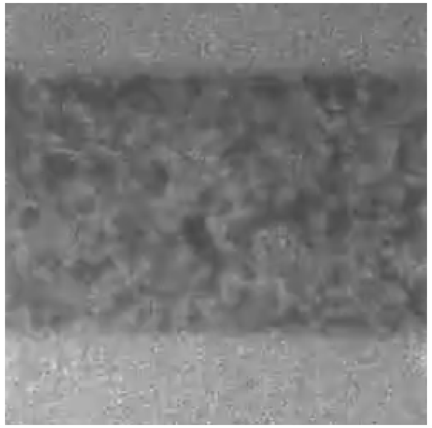
25µs



30µs



35µs

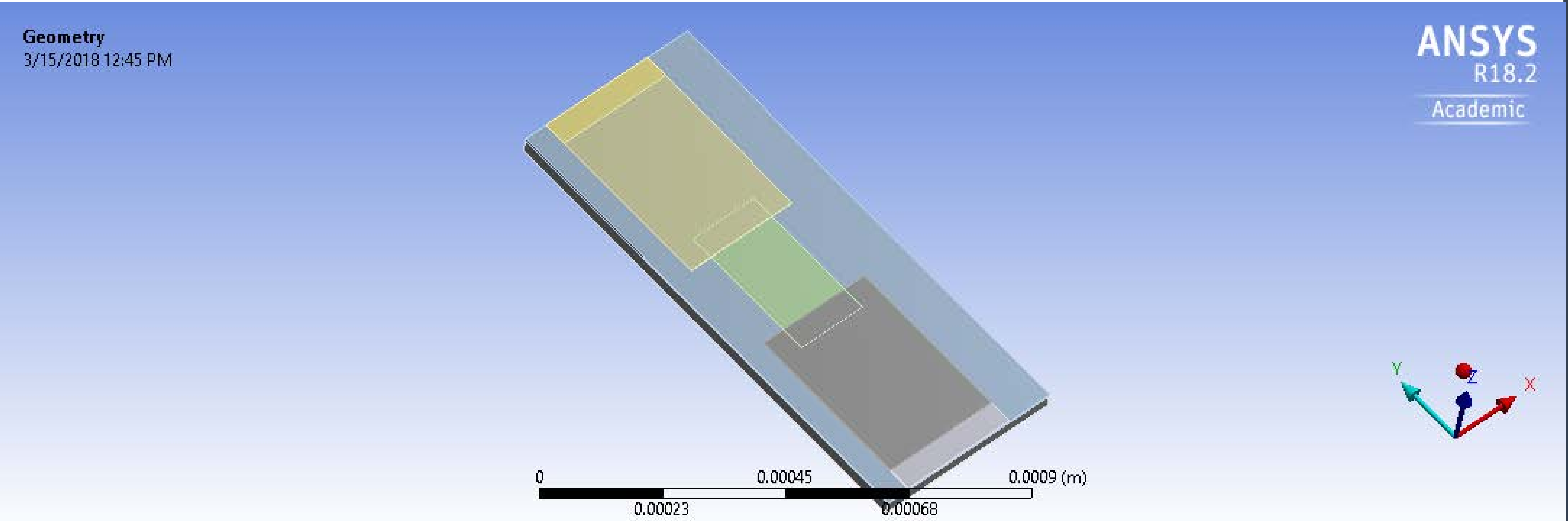


40µs

Overview

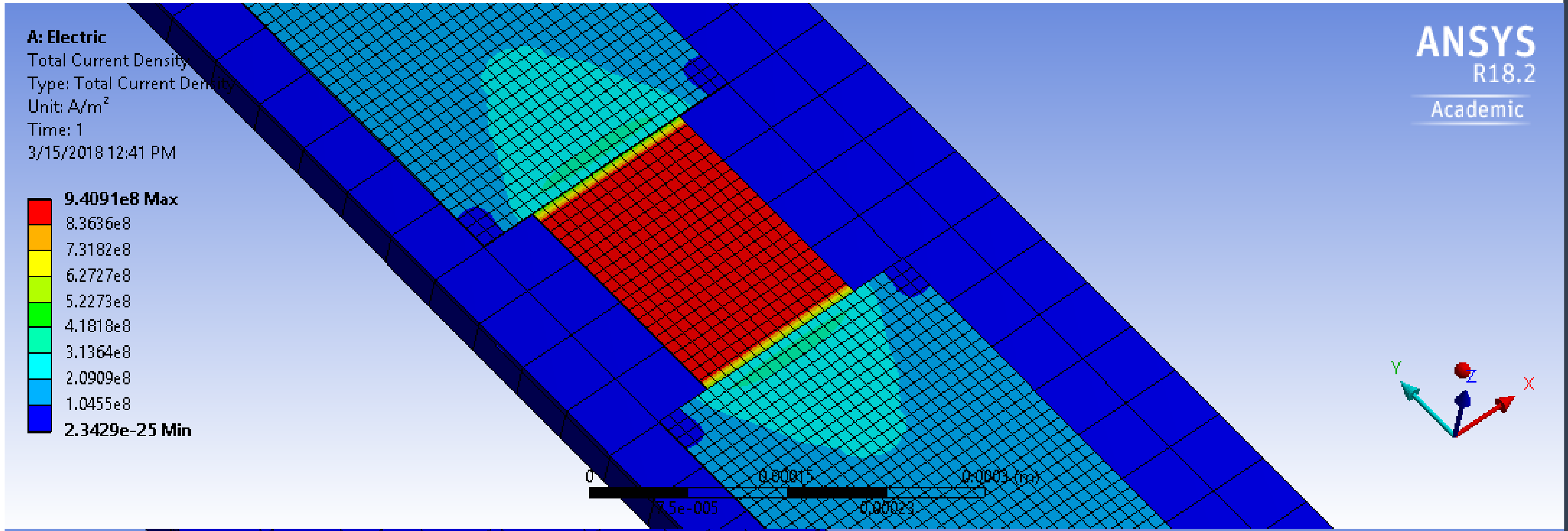
Current Paths

- 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

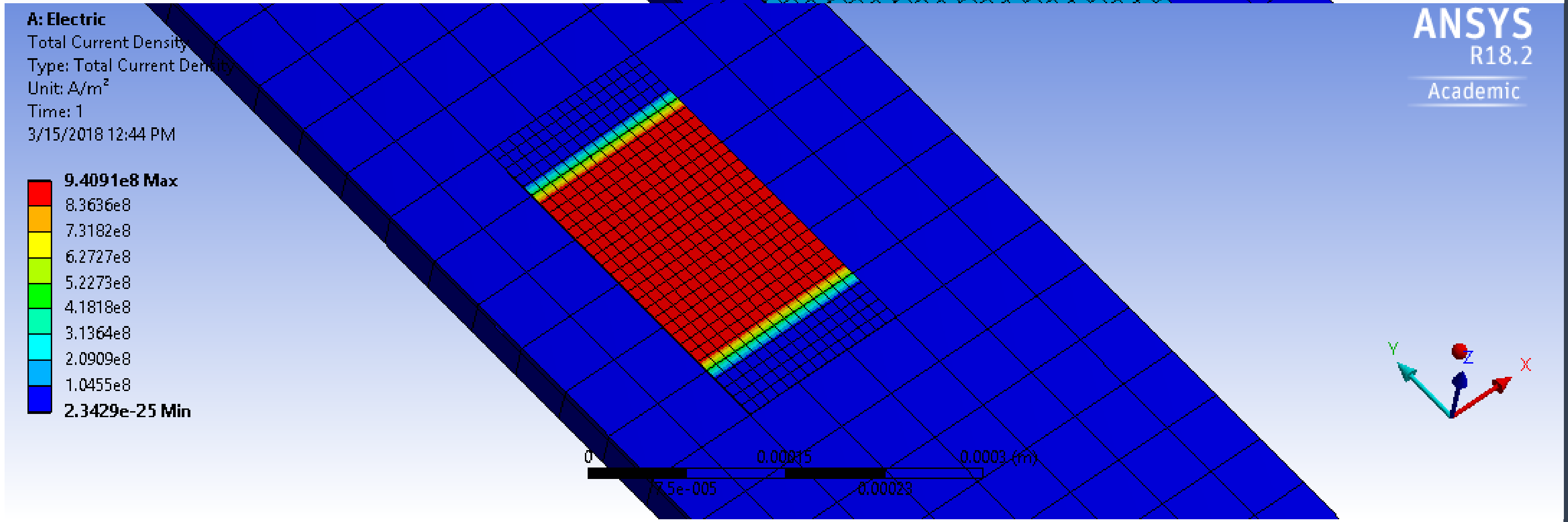


Current Paths

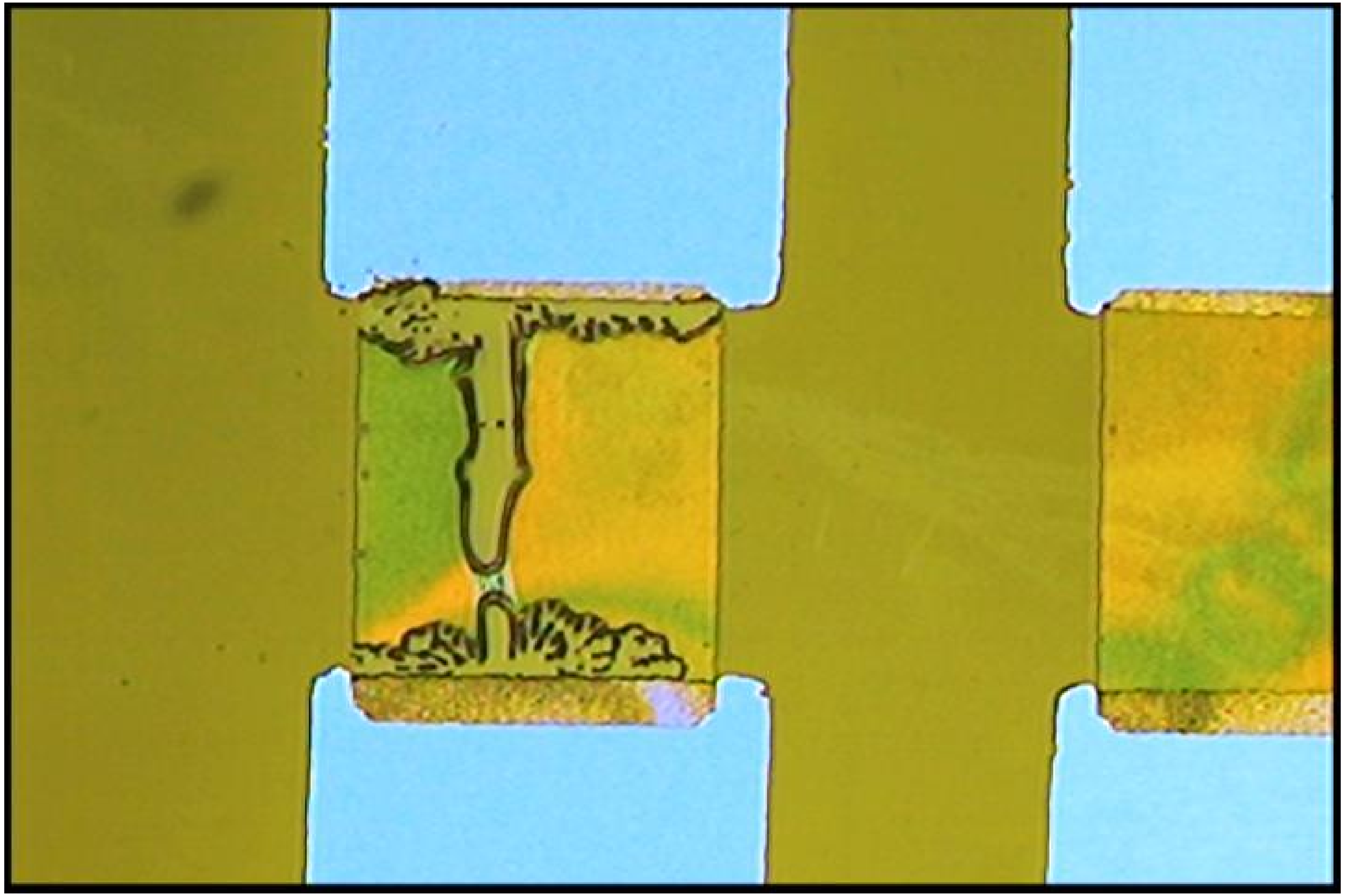
- Current Density Simulation



- Current Density Simulation (not showing Al)

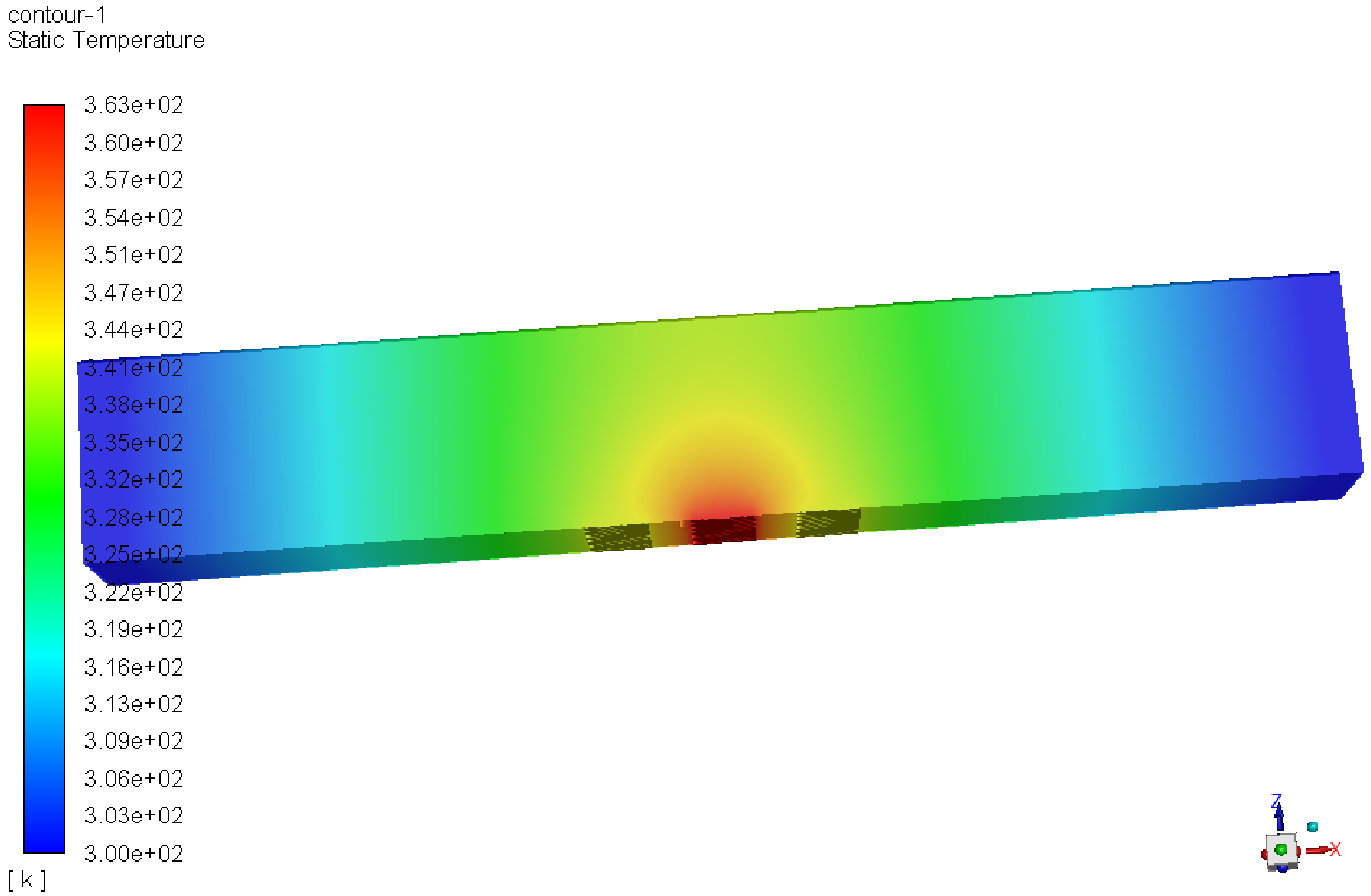


Breakage Path



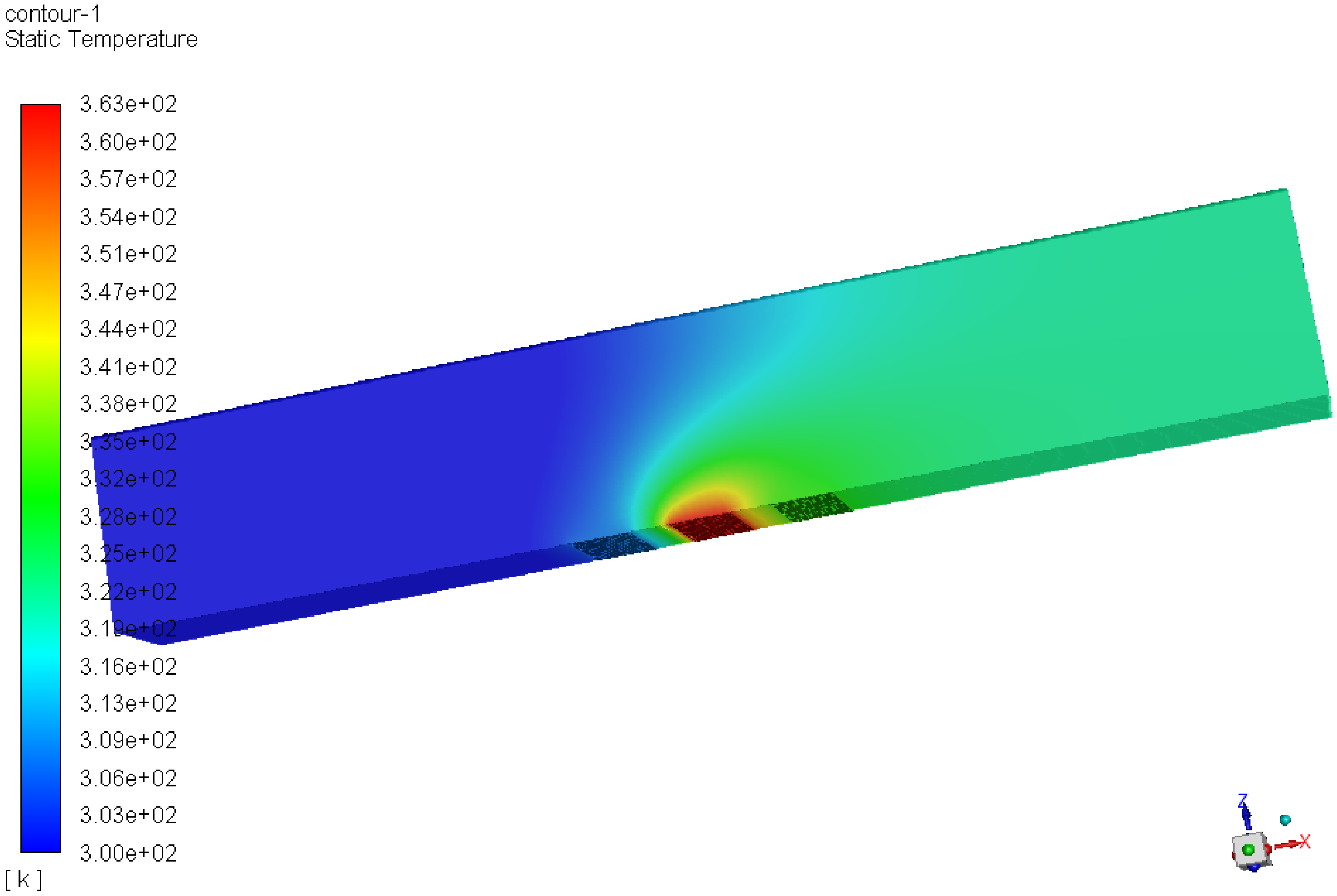
Flow Sensors

- 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

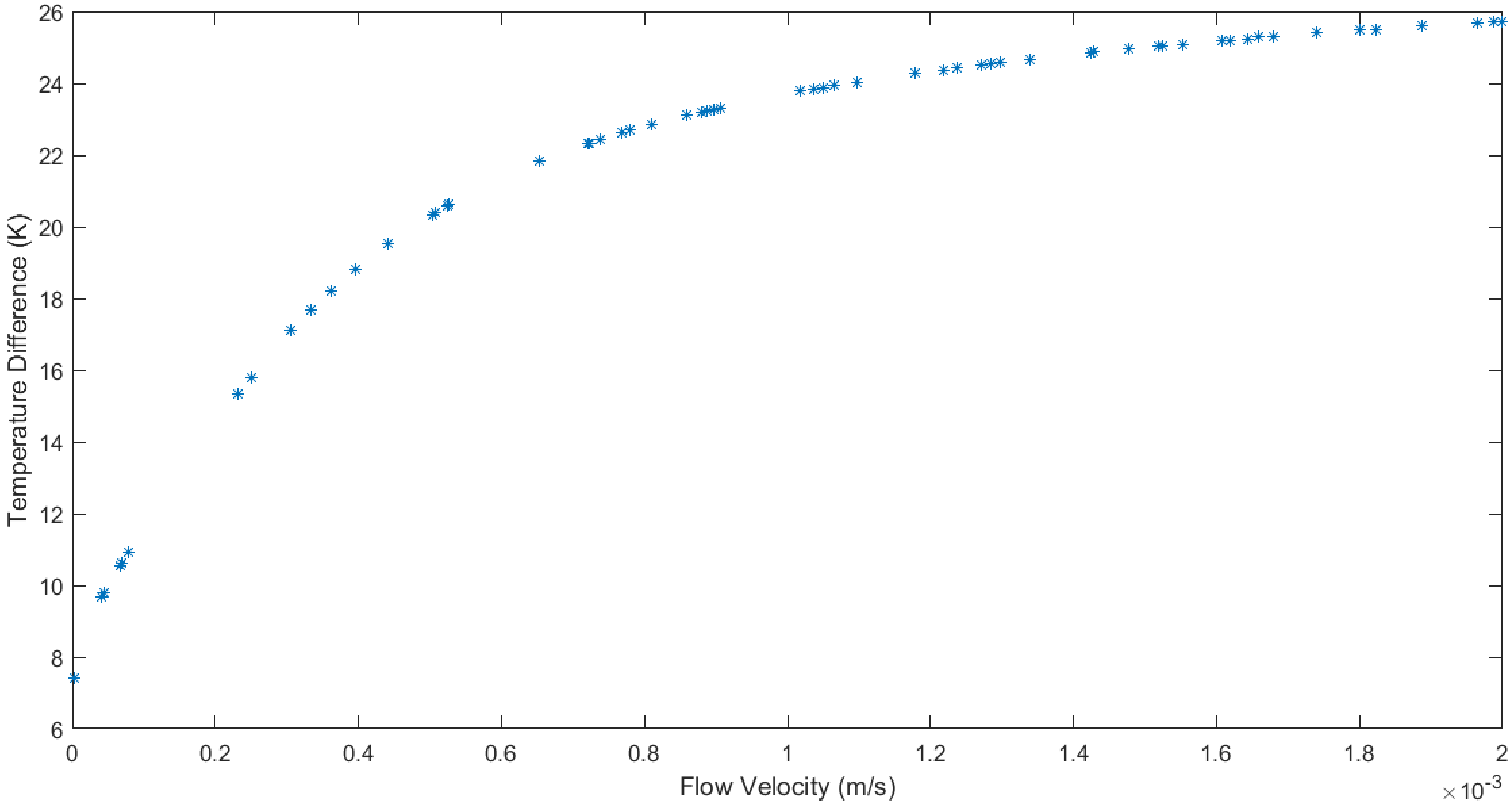


Flow Sensors

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

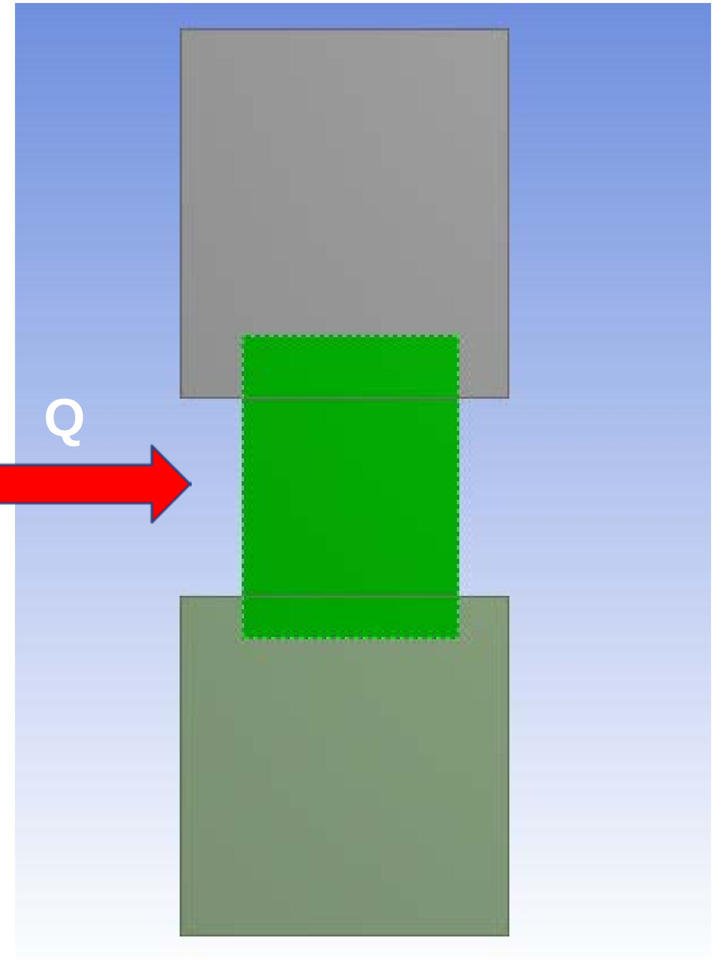


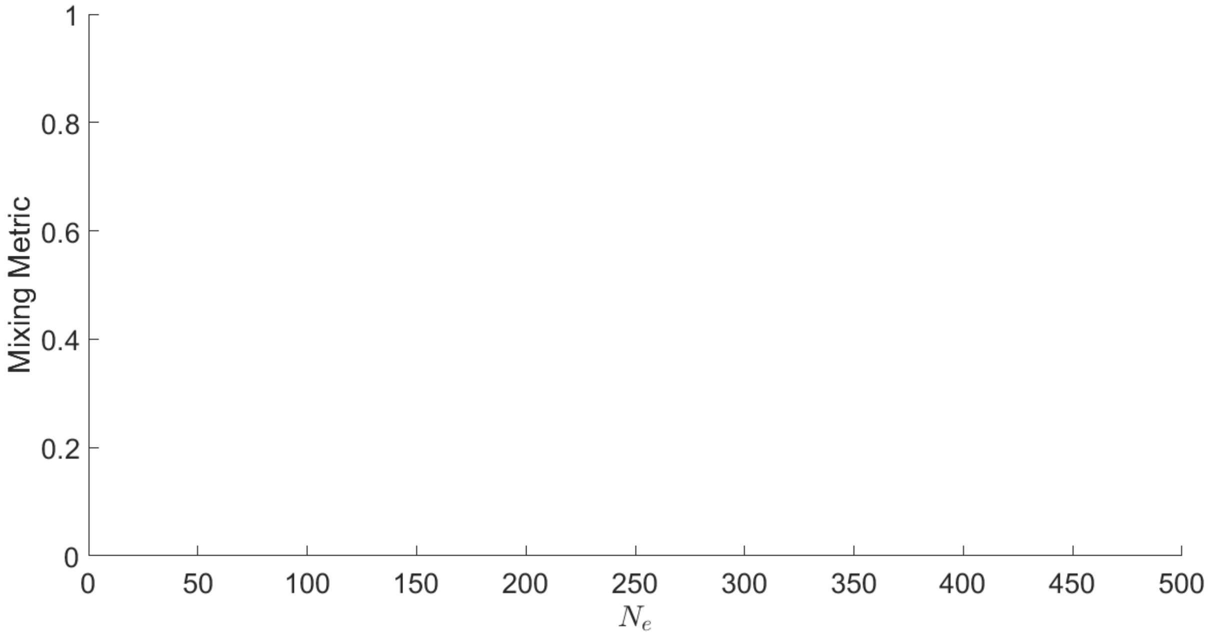
Flow Sensors



Mixing Metric

- How do you quantify mixing with the resistor?





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

$$N_e = f\tau_r$$

A_c $[m^2]$ – cross-sectional area
τ_r [s] – residency time
v_f $[\frac{m}{s}]$ – fluid velocity
Q $[\frac{m^3}{s}]$ – 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: