HORIZON 2020

# Self-adaptive microvalve array for energy efficient fluidic cooling in microelectronic systems

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STREAMS

Smart Technologies for eneRgy Efficient Active cooling in Advanced Microelectronic Systems

ITHERM 2017, Orlando, USA.

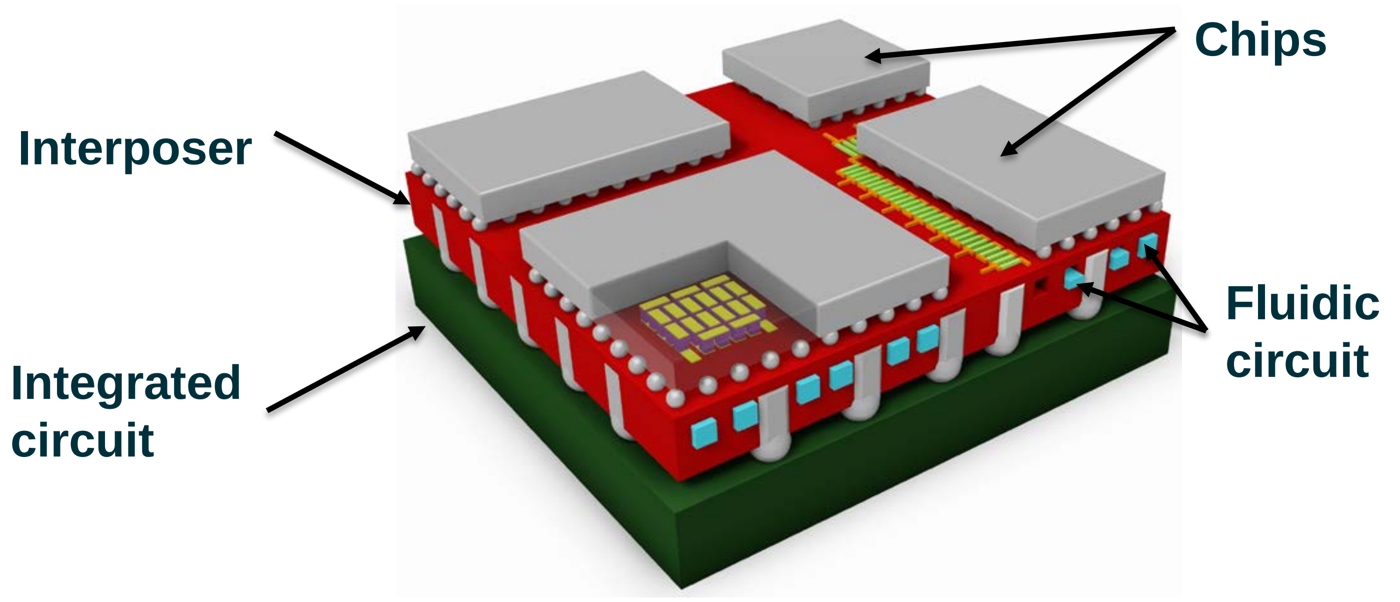
# Introduction and motivations

- To reach higher microelectronic performances, heat management is nowadays a major challenge
- Present microchannel cooling solutions
  - Chip embedment microchannels: best solution, but not always possible or easy (e.g. for expansive and complex chips)
  - Uniform channels/pin fins: non-uniform cooling + extra pumping power
  - Layout specific cooling (hot spot management): requires considerable design resources
- Proposed solution

**"To manage the chip heat from an interposer, by avoiding both layout specific or uniform cooling solutions"**

# STREAMS objectives

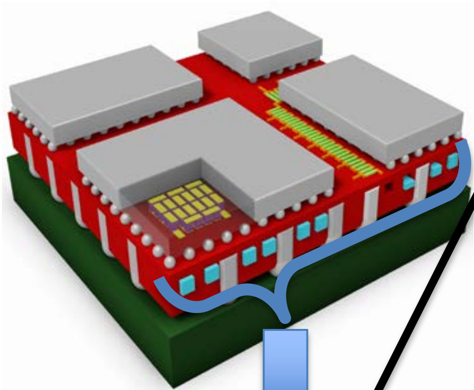
- Global project objective
  - To implement a **self-adaptive** (time and space) microfluidic cooling system
  - To minimize the overall **pumping power** dedicated to coolant
  - To increase the surface **temperature uniformity** of the interposer

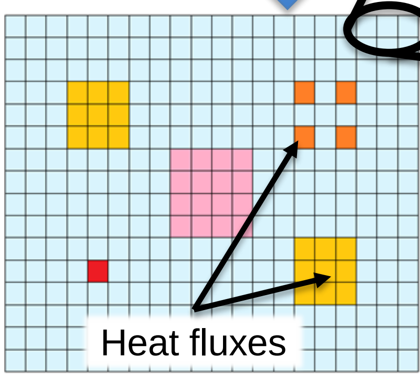



**Requires a smart distribution management**

# Design approach

**The interposer is divided into pixels**

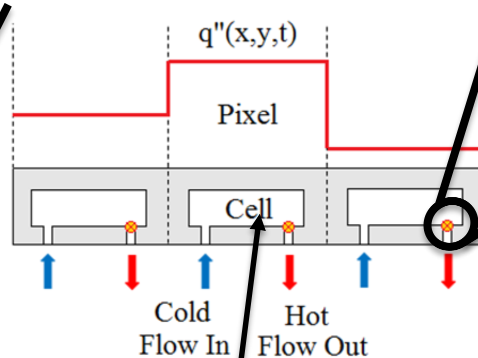





**Pixel array on the interposer with an arbitrary heat flux distribution**

(Pixel dimensions: 1 mm * 1.2 mm)

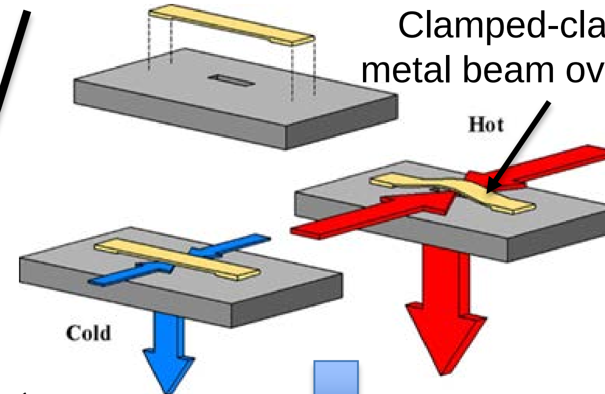
**Each pixel has a heat exchanger (cell) with a single inlet and outlet**




Contains convection enhancing structures

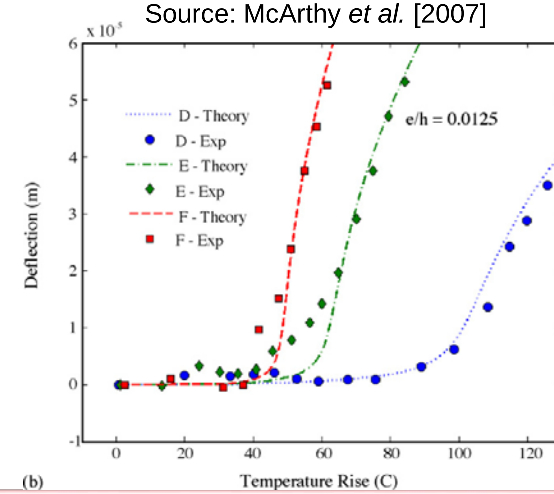
**Thermoactivated microvalves controlling the cell flow rates for temperature regulation**

Clamped-clamped metal beam over a slot




**Valves experimentally tested**

Source: McArthy *et al.* [2007]




**The cooling is managed by an array of thermoregulated valves**

# Advantages

**Flow rate locally controlled based on temperatures**

- Reduces pumping power by limiting the flow rate to the required areas only
- Increases the interposer and chip temperature uniformity

**Short microstructure length**

- The steam only crosses a short length in the cell microstructures: the corresponding pressure drop is significantly lower than with conventional microchannels

**Cold coolant for inlets**

- Each cell is individually feed by a non-heated coolant
- Unlike conventional microchannels, it is independent of the hot spot position along the steam

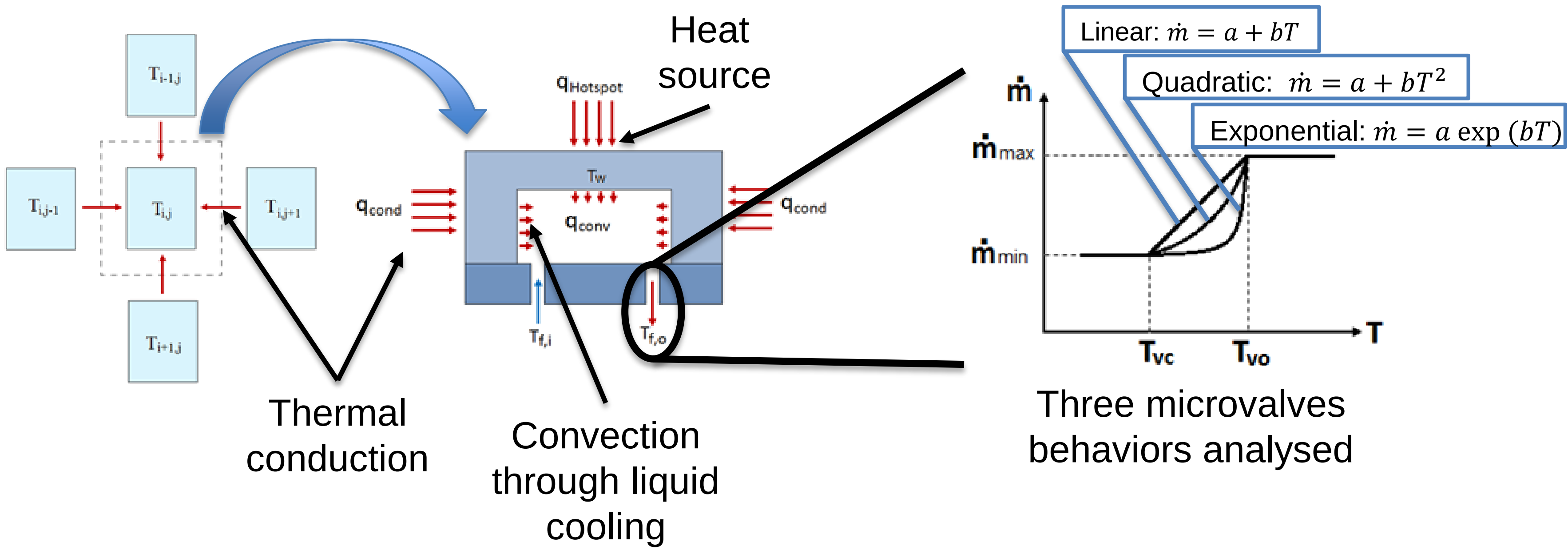
**Compatibility and flexibility**

- Can manage heat layout modification in time and space
- The adaptive property is passive
- No need to design for hot spot layout adaptation

# Modeling

- **Properties**
  - 2D conduction in lateral direction
  - Uniform temperature per cell
  - Flow rates for each cell: function of the cell temperature
- **Model**

**Pixel array modeling** | **Heat fluxes in a pixel** | **Microvalve temperature response**



# Case studies

## Cooling properties

- Pixel array: 16 rows and 20 columns (320 pixels)
- Pixel size: $L_p$=1200 µm, $W_p$=1000 µm, $H_d$=300 µm
- Maximum allowed temperature: 100 °C
- Total heat load 38.8 W

## Heat source scenarios

1) Thermal map with non-uniform hotspots
2) Thermal map with uniform hotspots
3) Uniform heat flux (without hotspots)

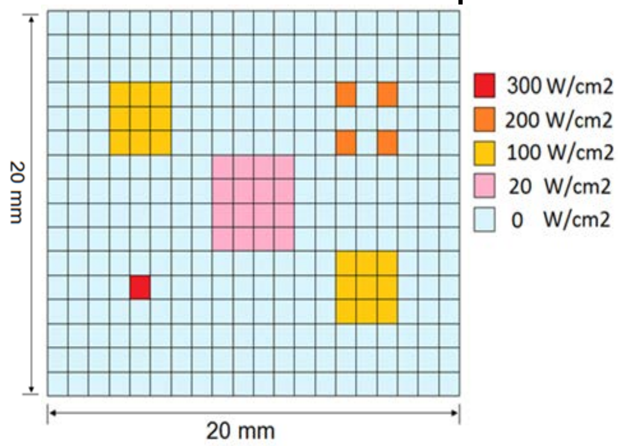
## Considered case studies

1) Without microvalve
2) Single global microvalve
3) A linear microvalve per pixel
4) A quadratic microvalve per pixel
5) An exponential microvalve per pixel

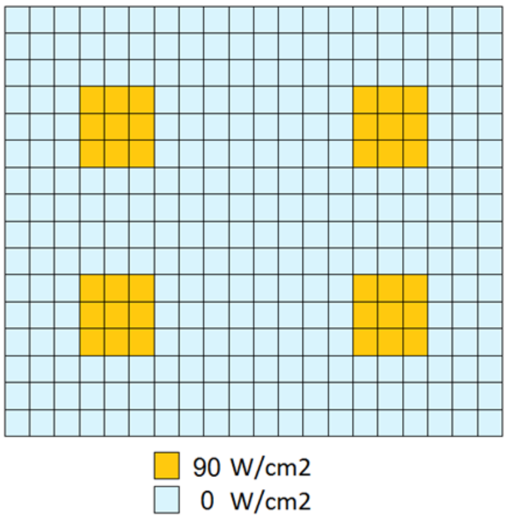
The first studied case: the thermal map with non-uniform hotspots is analysed

## Interposer thermal maps

Non-uniform hotspots

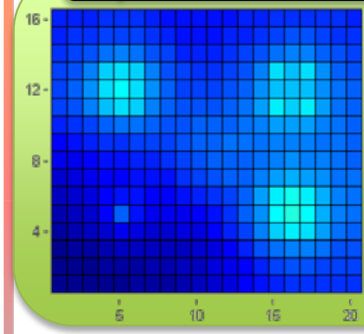



Uniform hotspots



# Temperature distribution for non-uniform hotspots

## 1) Without microvalve

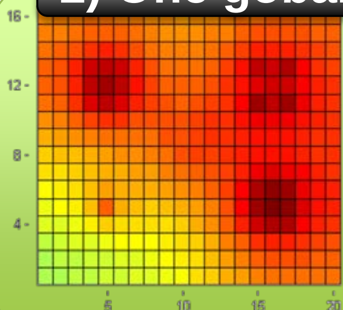



Overcooling ($T_{max}$<<100˚C)

High temperature non-uniformity (~20˚C)

Conclusion: Not efficient

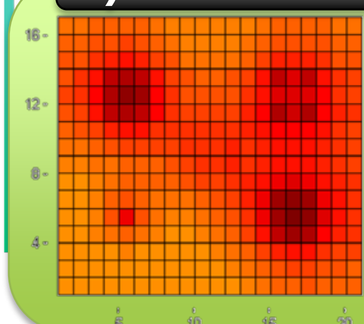
## 2) One gobal microvalve




51% flow rate reduction over case 1

High temperature non-uniformity (>20˚C)

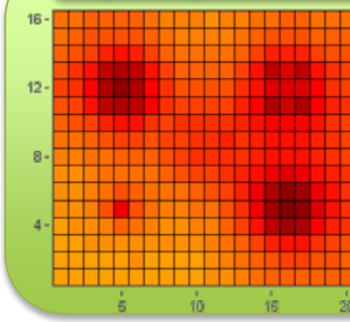
## 3) A linear microvalve per pixel




~39% temperature non-uniformity reduction over case 2

Similar flow rate to case 2

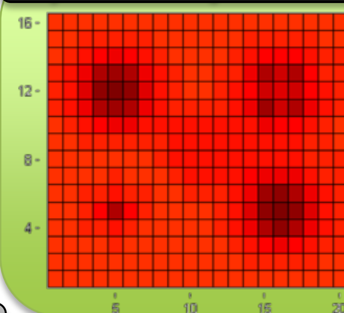
## 4) A quadratic microvalve per pixel




~39% temperature non-uniformity reduction over case 2

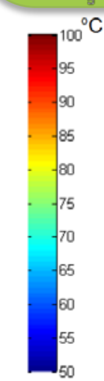
Similar flow rate to case 2

## 5) An exponential microvalve per pixel




The most uniform temperature

Slightly higher flow rate than cases 3 and 4



# Microvalves behavior

| | 1<br>Without microvalve | 2<br>Single microvalve | 3<br>Set of linear microvalves | 4<br>set of quadratic microvalves | 5<br>Set of exponential microvalves |
|---|---|---|---|---|---|
| Total mass flow rate (mg/s) | 320 | 158 | 160 | 160 | 176 |
| Maximum temperature differences (˚C) | 20.1 | 22.8 | 14.2 | 13.8 | 9 |
| Maximum temperature (˚C) | 69.7 | 100 | 100 | 100 | 100 |

## Analysis

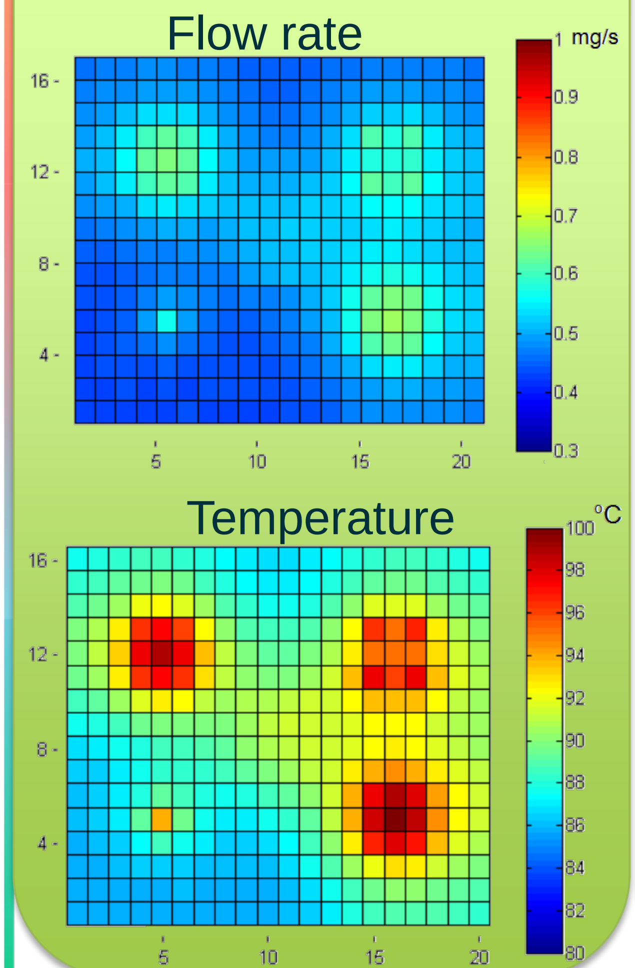
- A regulation valve is required for
  - Proper use of pumping power
  - Having a decent temperature uniformity

- Linear and quadratic valves offers similar performances

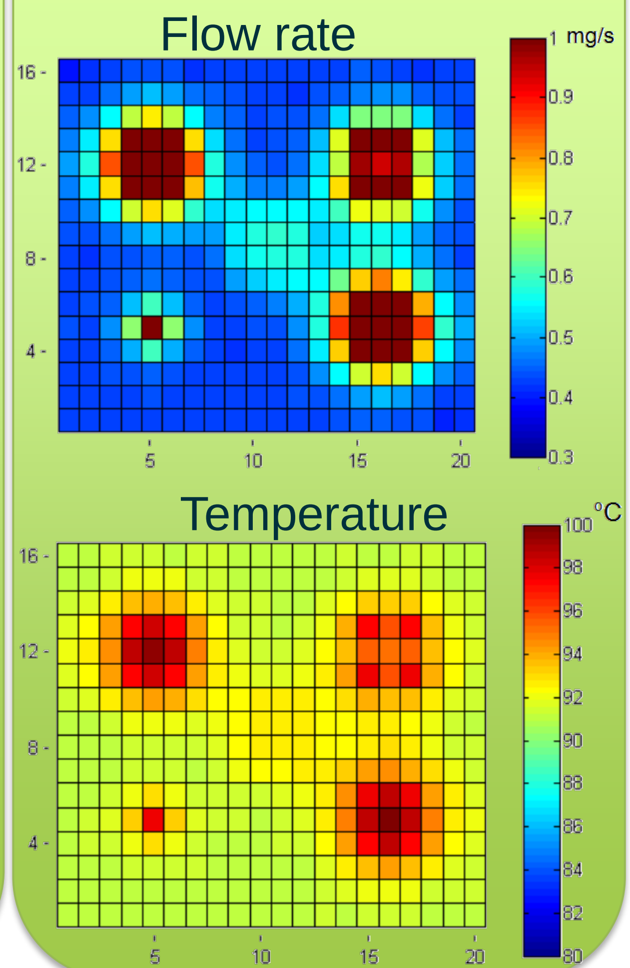
- Compared to a single microvalve, the exponential microvalve reduces the temperature non-uniformity of 60.5 % with an increase of only 11.4 % in flow rate

# Mass flow rate distribution

**Linear microvalve per pixel (similar for quadratic microvalve)**



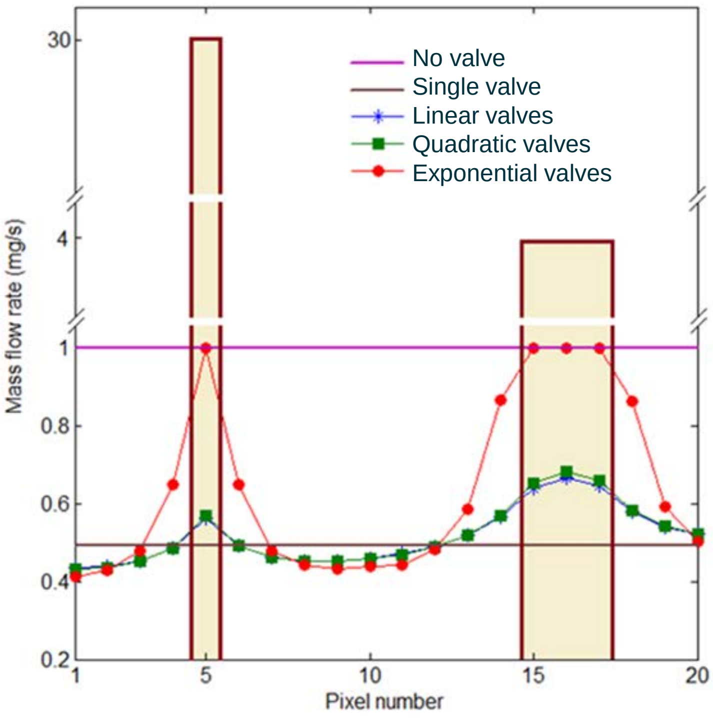

**Exponential microvalve per pixel**



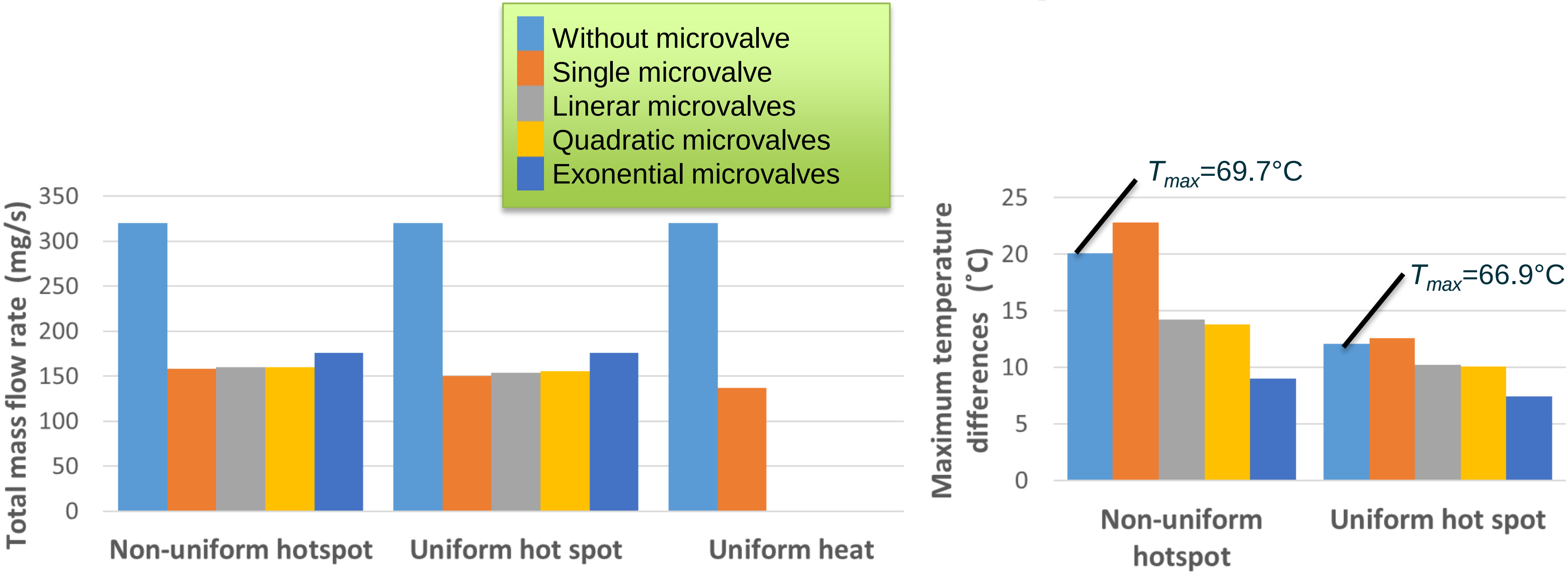

**Microvalves with the highest flow rates variations have the most temperature uniformity**

# Microvalves behavior

- **Investigation**
  - Flow rate distribution is compared in a row of pixels for the different configurations
  - Colored bars represents heat source injections
- **Results**
  - **Lateral thermal conductivity**: limits the thermal spreading
  - **Exponential microvalve arrays:**
    - More temperature sensitive
    - Produces a better temperature uniformity
  - **Single microvalve vs arrays of microvalves**: no significant change the overall flow rate
  - **Microvalve arrays**: increases the temperature uniformity (due to the thermal resistance modulation for each pixel)



# Effect of heat flux map




No temperature difference for uniform heat scenario ($T_{max}$=58.7 °C)

## Uniform hot spots

- Similar flor rates compared to the non-uniform hot spots case (slight decrease)
- Heat source distribution has a significant effect on the chip temperature uniformity

## Uniform heat flux

- Completely uniform interposer temperature (not the case with uniform microchannels)

# Conclusions

**Cell arrays**:
better cooling uniformity with a uniform heat flux

**Global flow rate**:
minimized by using a single microvalve or a set of microvalves

**Temperature-regulated microvalves**:
allow a local control

**The microvalve arrays**:
have significant effect on the chip temperature uniformity

**Exponential microvalve array**:
provides the most uniform chip surface temperature

# Acknowledgments

The research leading to these results has been performed within the STREAMS project (www.project-streams.eu) and received funding from the European Community's Horizon 2020 program under Grant Agreement n° 688564.*

# Thank you for your attention