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Simulation Bubble Nucleation and Bubble Growth of a Thermal-Bubble Microejector

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The present study investigates simulation model and droplet ejection performance of a thermal-bubble microejector. This model simulates the bubble nucleation and the bubble growth, to predict the droplet ejection process. Specificity, it is achieved by coupling an electric-thermal model and flow model with bubble dynamics equations. The model is validated by comparing prediction results with experimental data. Moreover, the bubble nucleation mechanisms, nucleation temperature and nucleation rate also are studied. In this paper, this model is solved by the FEM software of COMSOL Multiphysics.

The microejector

The microejector is a bubble pressure driven jet.
The working principle is based on a thermal-bubble inkjet.

- **Each ejection deposits 1' oligonucleotide**
- **Each ejection is individually actuated**

How it works

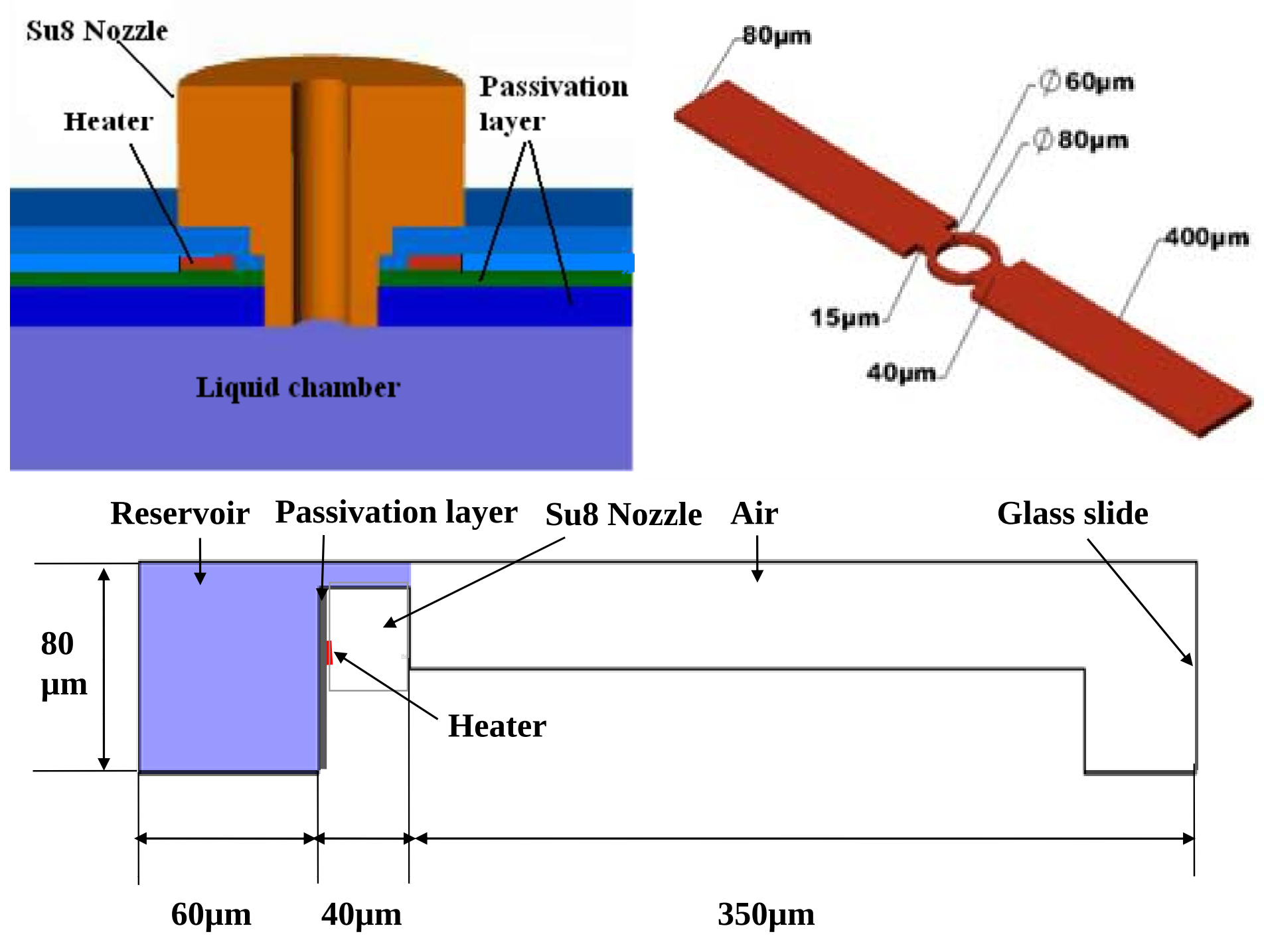
A very short electric pulse is applied to a resistive heater to generate a high heat flux. If the surface temperature of the liquid is higher than the nucleation temperature, a vapor bubble is formed at the surface of the passivation layer. Sudden formation of the vapor bubble generates a pressure impulse, the rapid growth of the bubble expels a small liquid drop from the nozzle exit. After the applied current is removed, the temperature and pressure of the vapor decrease quickly, once the bubble collapses, the nozzle refills due to capillary forces for the next ejecting.

Simulation approaches

Simulation process is divided into two stages by nucleation time point

- ***Before bubble is nucleated,* the temperature distribution of liquid and solid is calculated by the heat transfer equation ($v_{liquid} = 0$).**
- **If the surface temperature of passivation layer is more than nucleation temperature, the nucleation bubble is placed on the surface heater in 0.01µs. *After the bubble is nucleated,* Bubble pressure is calculated by Clapeyron equation. Pressure gradient is inputted to the N-S equations, which is coupled with the heat transfer equation for calculating the velocity of the liquid flow**

Ejector structure to computational model



Bubble growth and governing equations

Heat transfer equation

$$\rho C\frac{\partial T}{\partial t}+\ \rho C(u\cdot\nabla)T=\ Q_{dc}-\nabla\cdot(k\nabla T)$$

Pressure in vapor by Clapeyron equation

$$P_{sat}=P_{amb}exp[\frac{L}{k_B}\left(\frac{1}{T_b}-\frac{1}{T}\right)]$$

$$P_{sat}V=nK_bT$$

Mass flux

$$\dot{m}\ =-\left(\frac{M_w}{\Delta H_{vl}}\right)n\cdot K_v\nabla T_v\approx C\rho_L\frac{(T-T_{sat})}{T_{sat}}$$

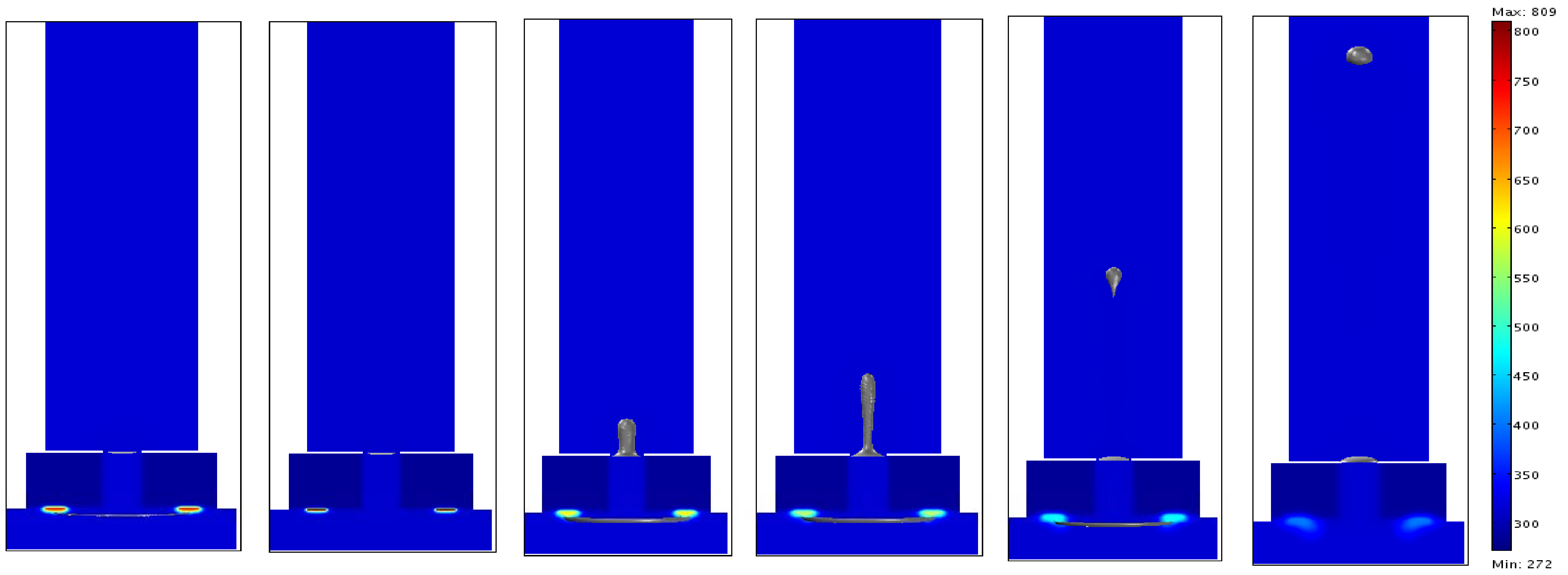
Dynamics interface tracking By Cahn-Hilliard equation

$$\frac{\partial\emptyset}{\partial t}+u\cdot\nabla\emptyset-\dot{m}\delta\left(\frac{V_{f,V}}{\rho_V}+\frac{V_{f,L}}{\rho_L}\right)=\ \nabla\cdot\frac{\gamma\lambda}{\varepsilon^2}\nabla\psi$$

Navier-Stokes equations for incompressible flow

$$\rho\frac{\partial u}{\partial t}+\ \rho u\nabla\cdot(u)=\ \nabla\cdot[-pI+\eta_L(\nabla u+(\nabla u)^T)]+\rho g$$

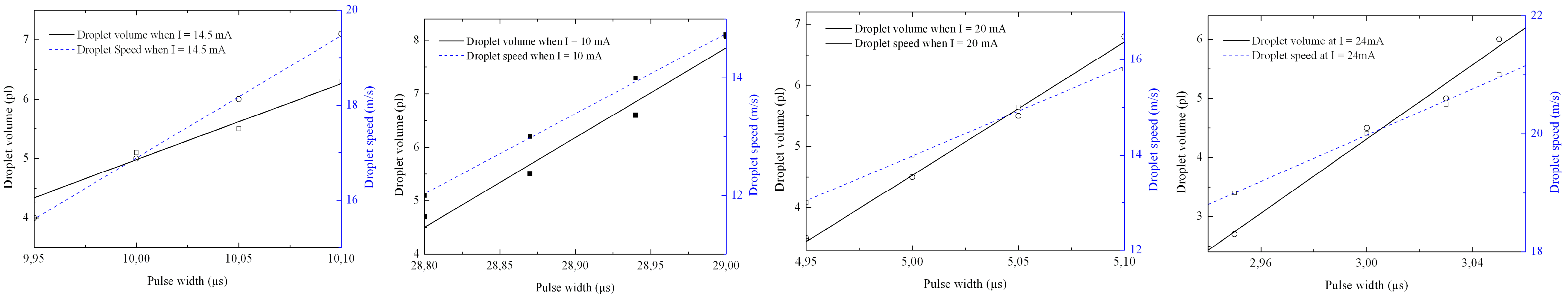
$$\nabla\cdot u=0$$



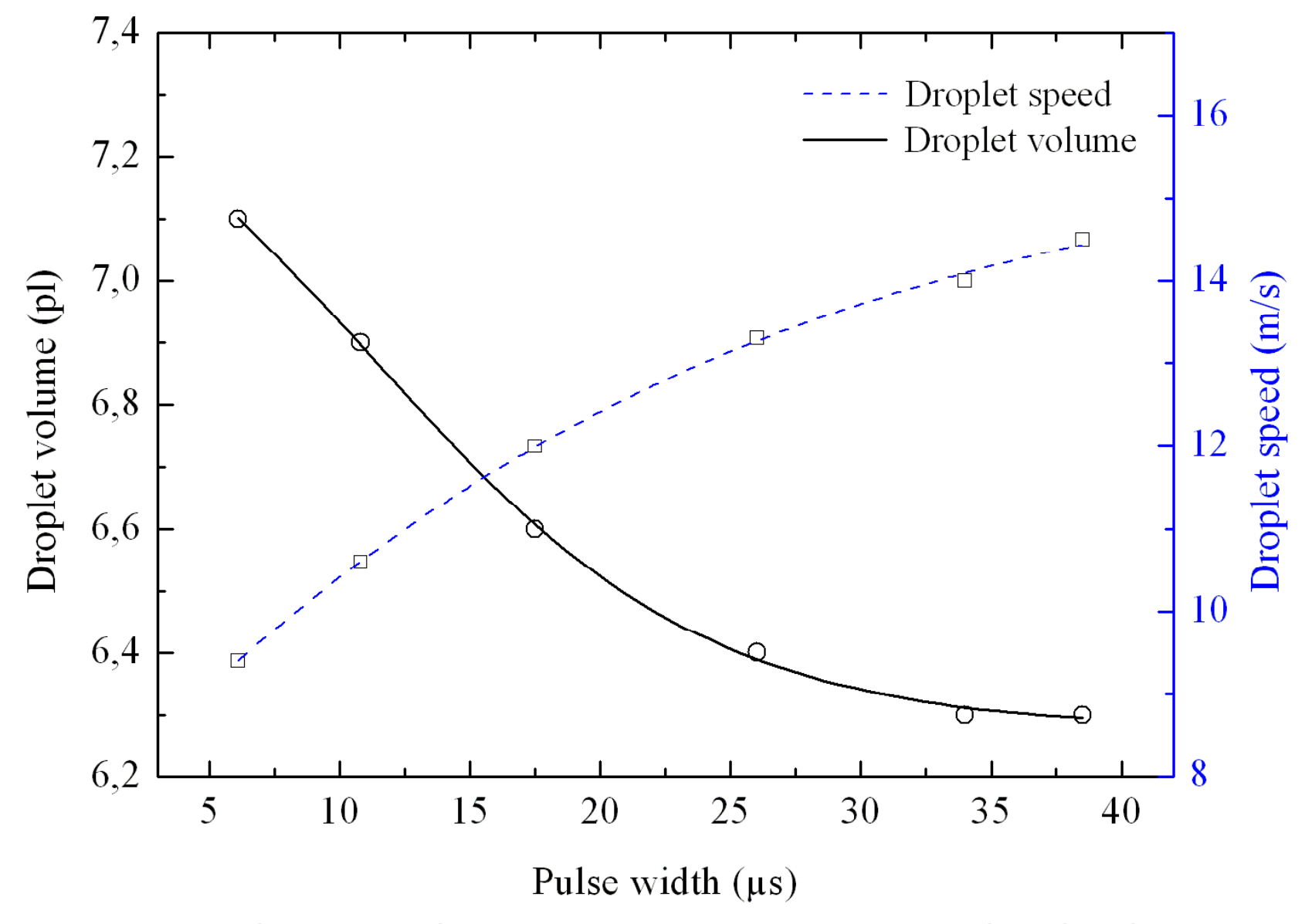
t = 3µs **t = 6µs** **t = 8µs** **t = 9.5µs** **t = 15µs** **t = 30µs**

Evolution of liquid profile with temperature (K) contours inside liquid when I = 20mA, τ = 5µs

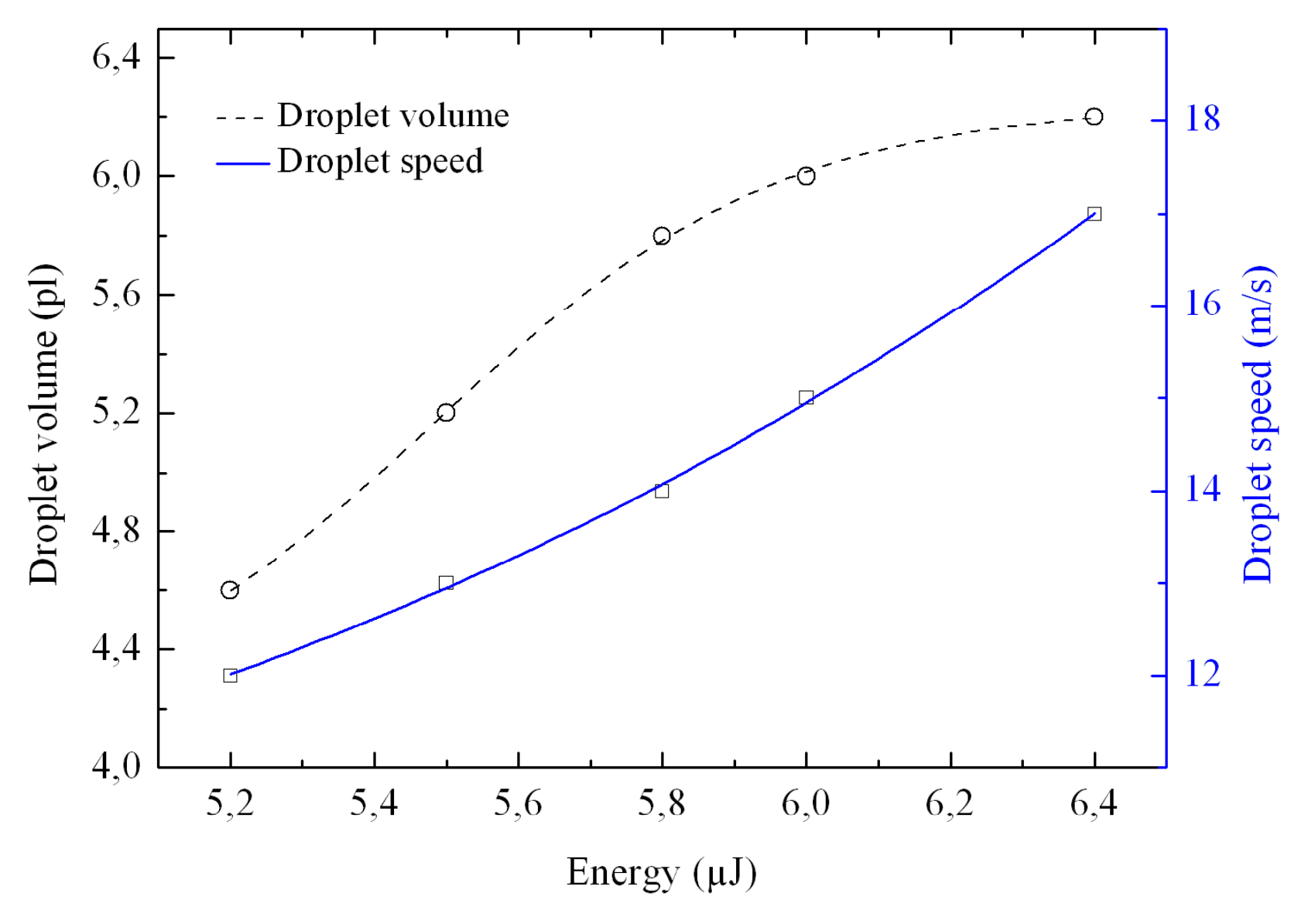
Effects of energy and geometry on droplet volume and speed



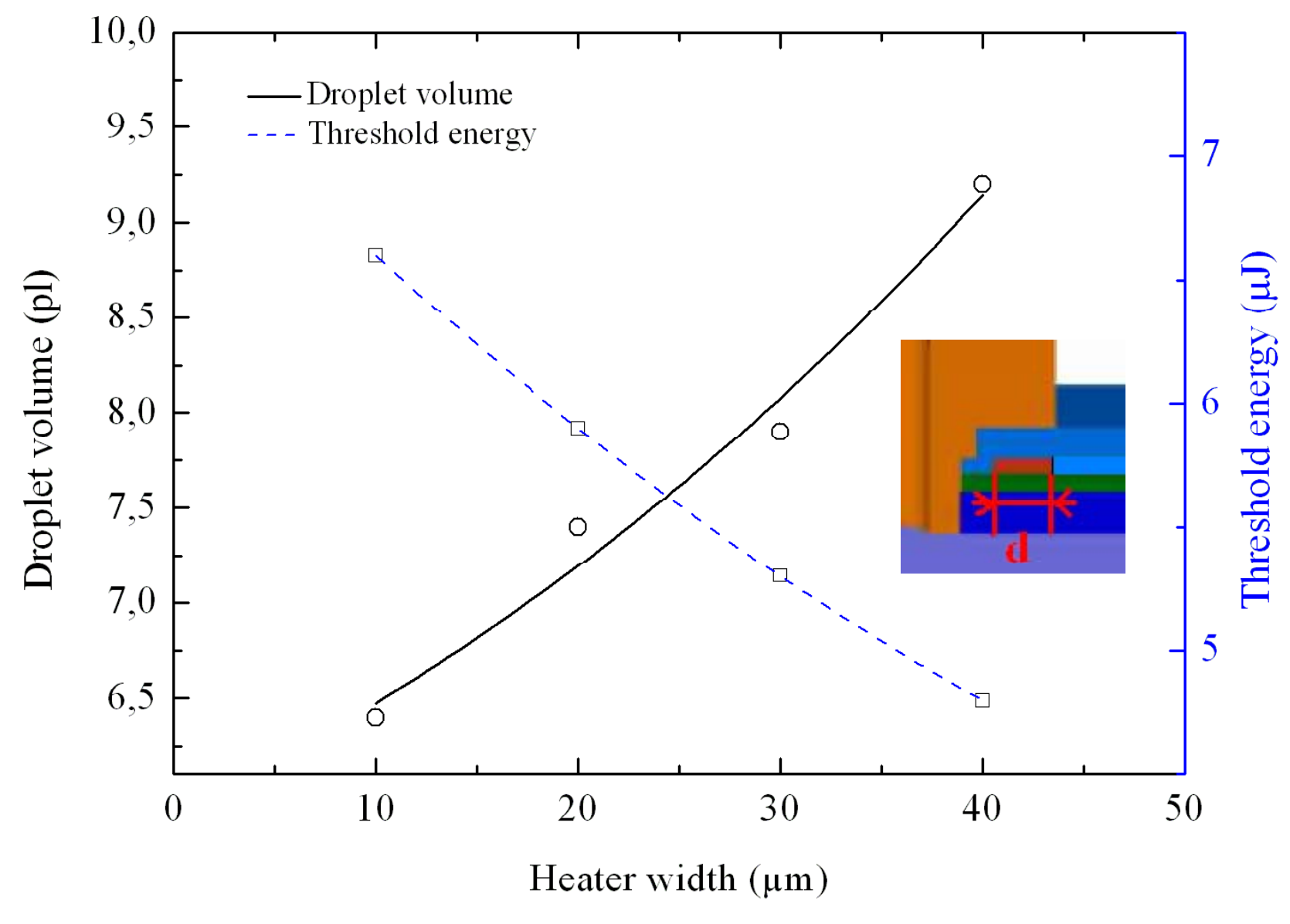
•In forming a droplet, the ejection volume increases linearly with the pulse width (the thermal energy)
•The variation range of the pulse width is within ~0.2 µs for forming a droplet



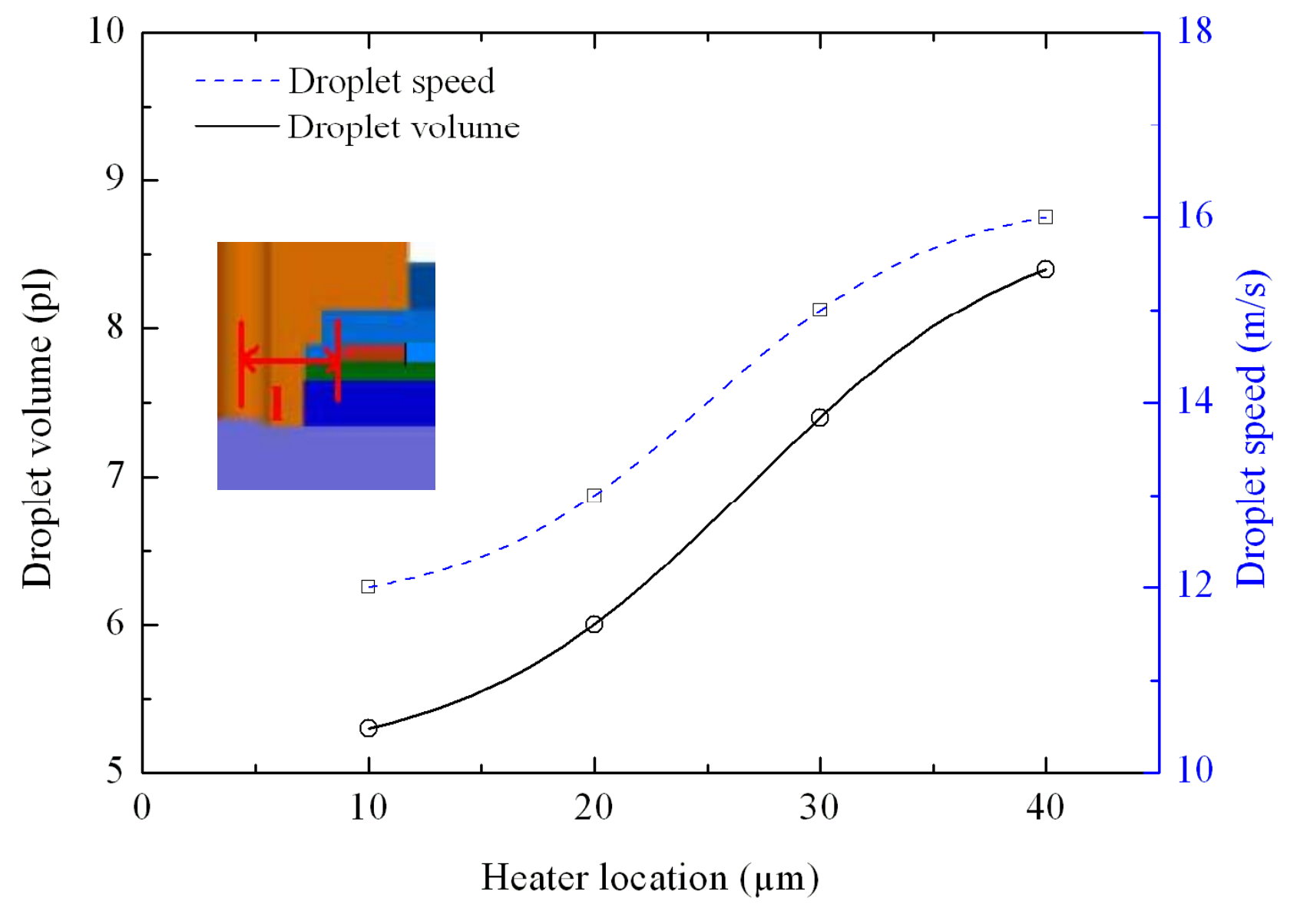
•Droplet volume decreases slightly as pulse width increases in same thermal energy, but droplet speed increases



•Droplet volume and speed increase as thermal energy increases



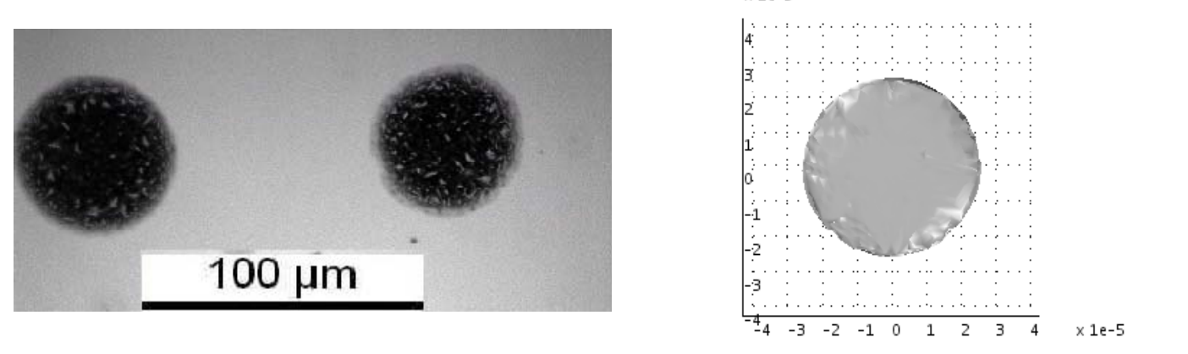
•Droplet volume increases with the heater width increases



•Droplet volume and speed increases as the heater location increases

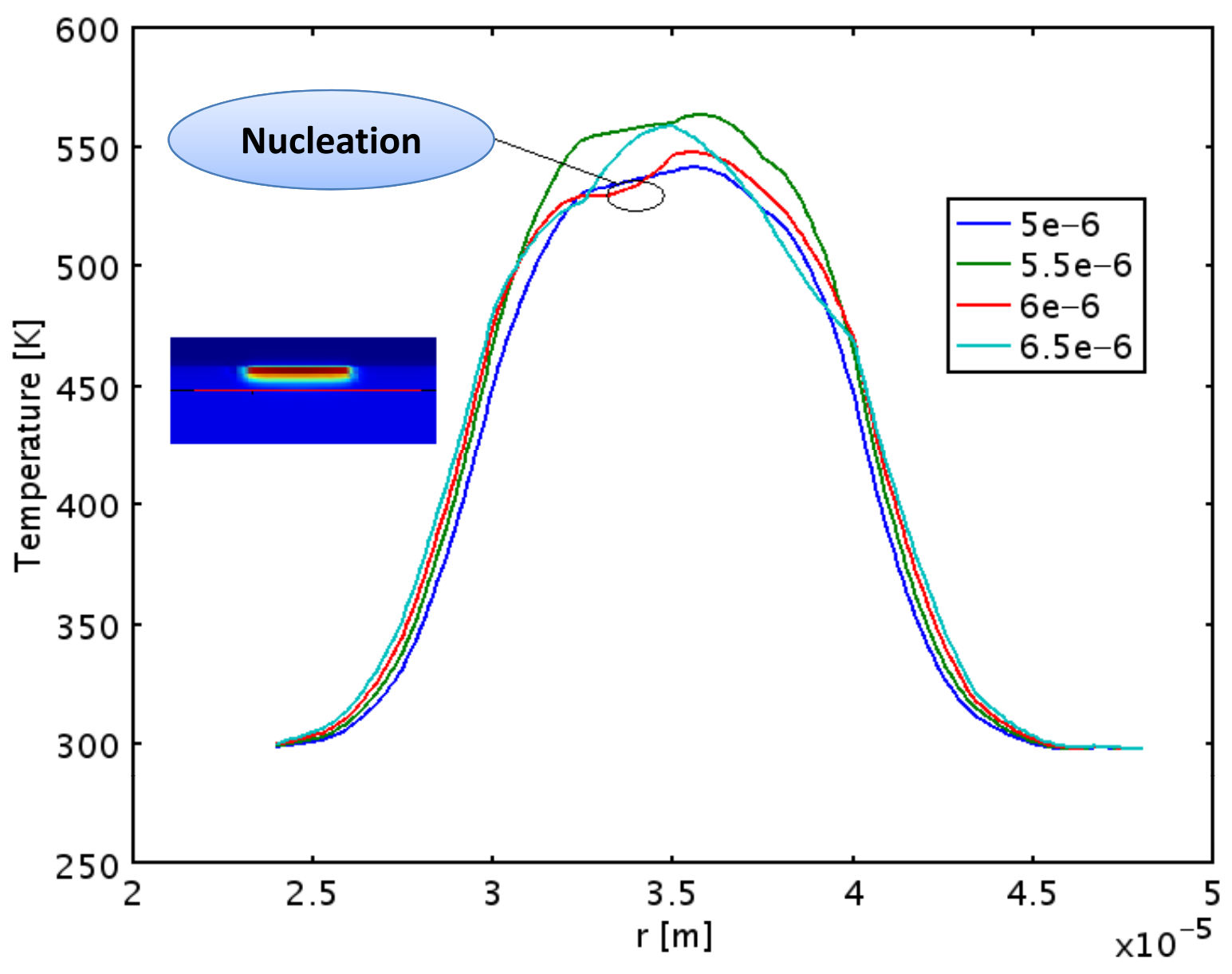
The microejector chip and experimental setup

Comparing with experimental and simulation results of droplet ejection



a) r= 24.5µm
I = 3mA, τ = 5ms

b) r= 25.5µm
I = 3mA, τ = 4.5ms



Why boils at 270 °C?

•The liquid in microejector starts to nucleate only when it is heated close to the superheat temperature of 270°C.
•Because the liquid is heated extreme quickly, and the heat flux as high as ~4.6×10⁸ W m⁻², while τ is extreme short, ~5µs

Conclusions

- **Homogeneous nucleation, nucleation temperature (270°C), and nucleation probability (0.01µs)**
- **This model was achieved by coupling electric-thermal and flow model with bubble dynamics equations for simulation bubble growth and collapse of the microejector.**
- **This model was used to study the droplet ejection performance and predict the droplet ejection process. The effects of current and pulse width , geometry on droplet volume and speed, satellite droplet generation were studied.**
- **In forming one droplet, the results show that ejection volume increases linearly with thermal energy. The variation range of the pulse width is within ~0.2 µs. Droplet volume: 1 pL – 11 pL (ng), power consumption: 45 mW – 0.4 W**
- **Thinner thickness of the chamber, bigger surface area of the heater and appropriate current with pulse width can help to eliminate the satellite droplets**
- **This model was used to understand, help to design and verify the operation of the microejector, can optimize ejector design and droplet ejection performance**