High Performance Closed-Channel Cooling System Using Multi-channel Electro-osmotic Flow pumps for 3D-ICs

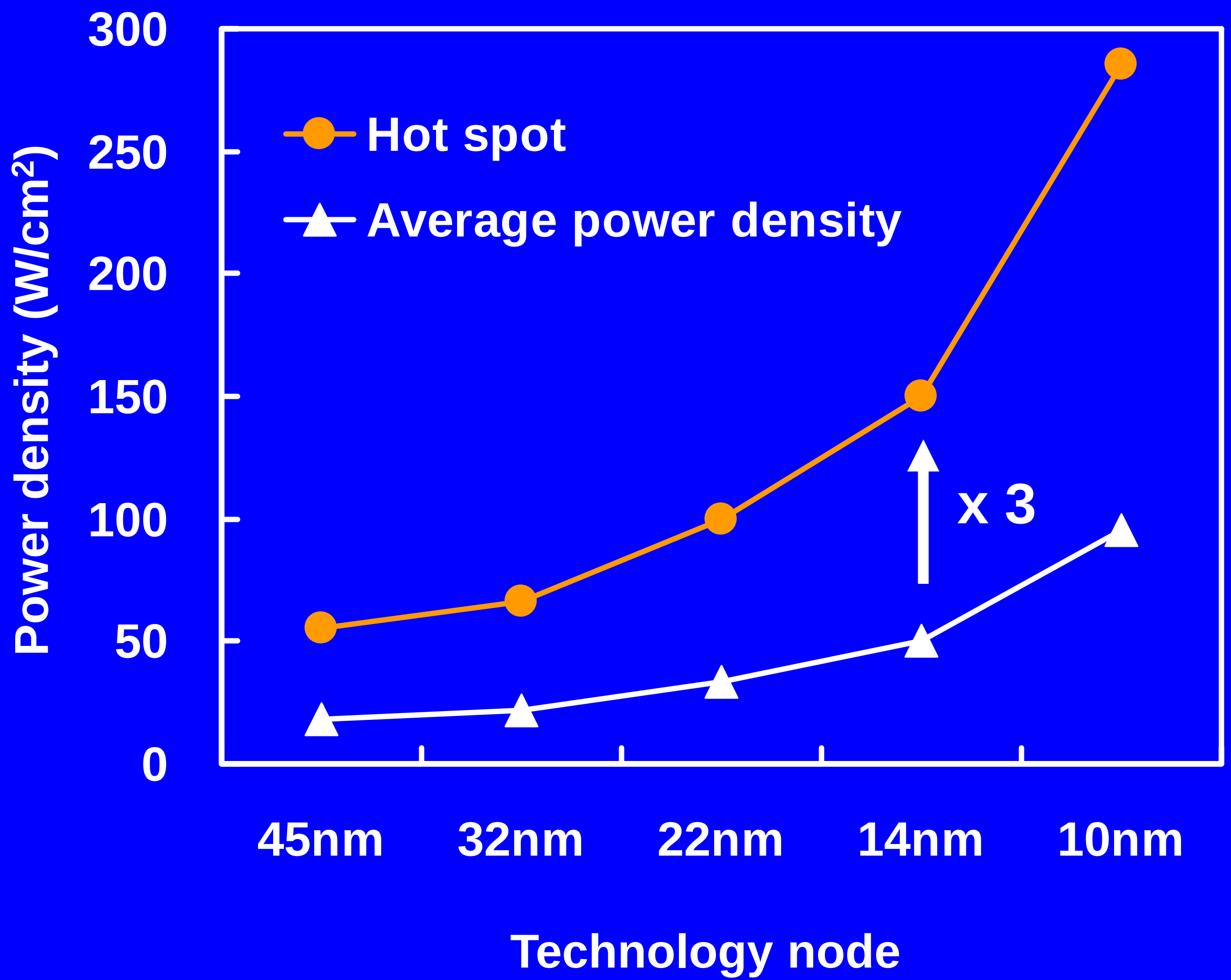
K.Suzuki, H. Kudo, [1]Y. Oguri, [1]J. Nakatsuka, [2]A. Tsukune, [2]Y. S. Kim, [2]H. Kitada, K. Fujimoto, [1]I. Kinefuchi, [1]Y. Matsumoto, and [2]T. Ohba

Dai Nippon Printing Co., Ltd.
[1]University of Tokyo,
[2]Tokyo Institute of Technology

Outline of Presentation

- Closed-channel cooling system
- Multi-channel EOF pumps
- Cooling chip fabrication
- Pumping performance
- Cooling capability

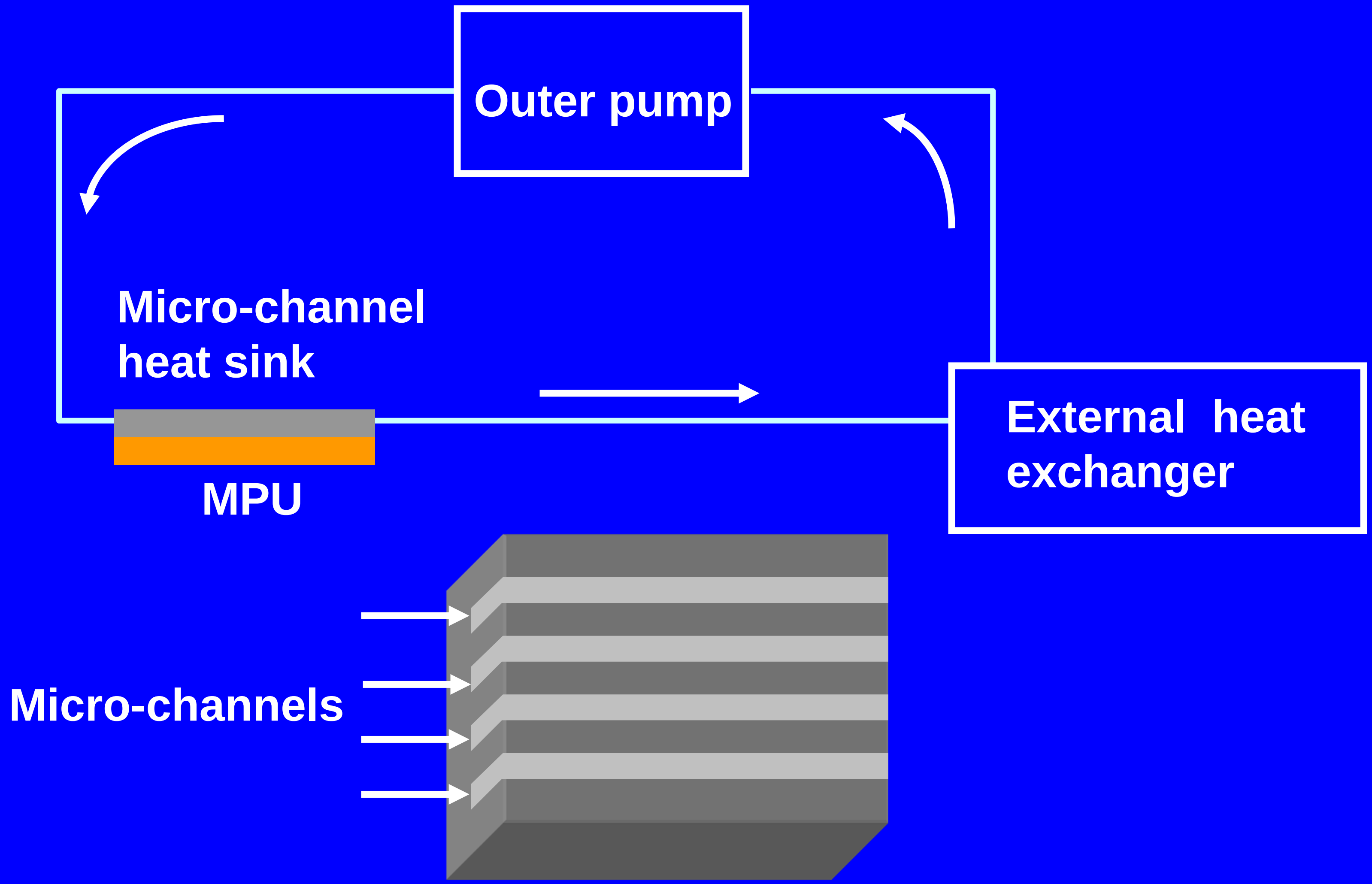
Power Density of MPUs



Hot Spot Issues

- Lowering of speed performance
- Increase in power consumption
- Degradation of functional reliabilities
- Thermal management for 3D-IC integration

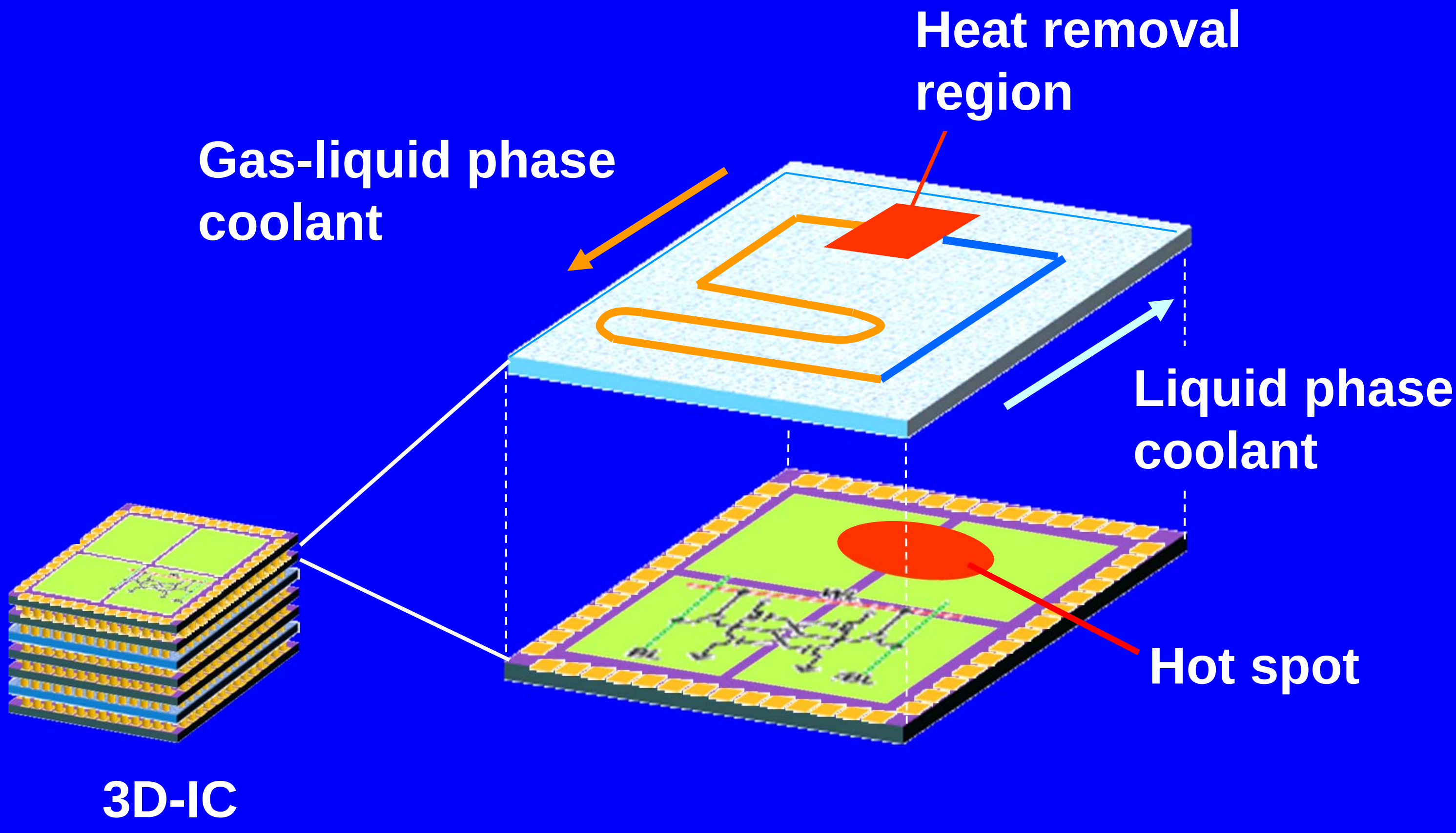
Typical Micro-channel Cooling System



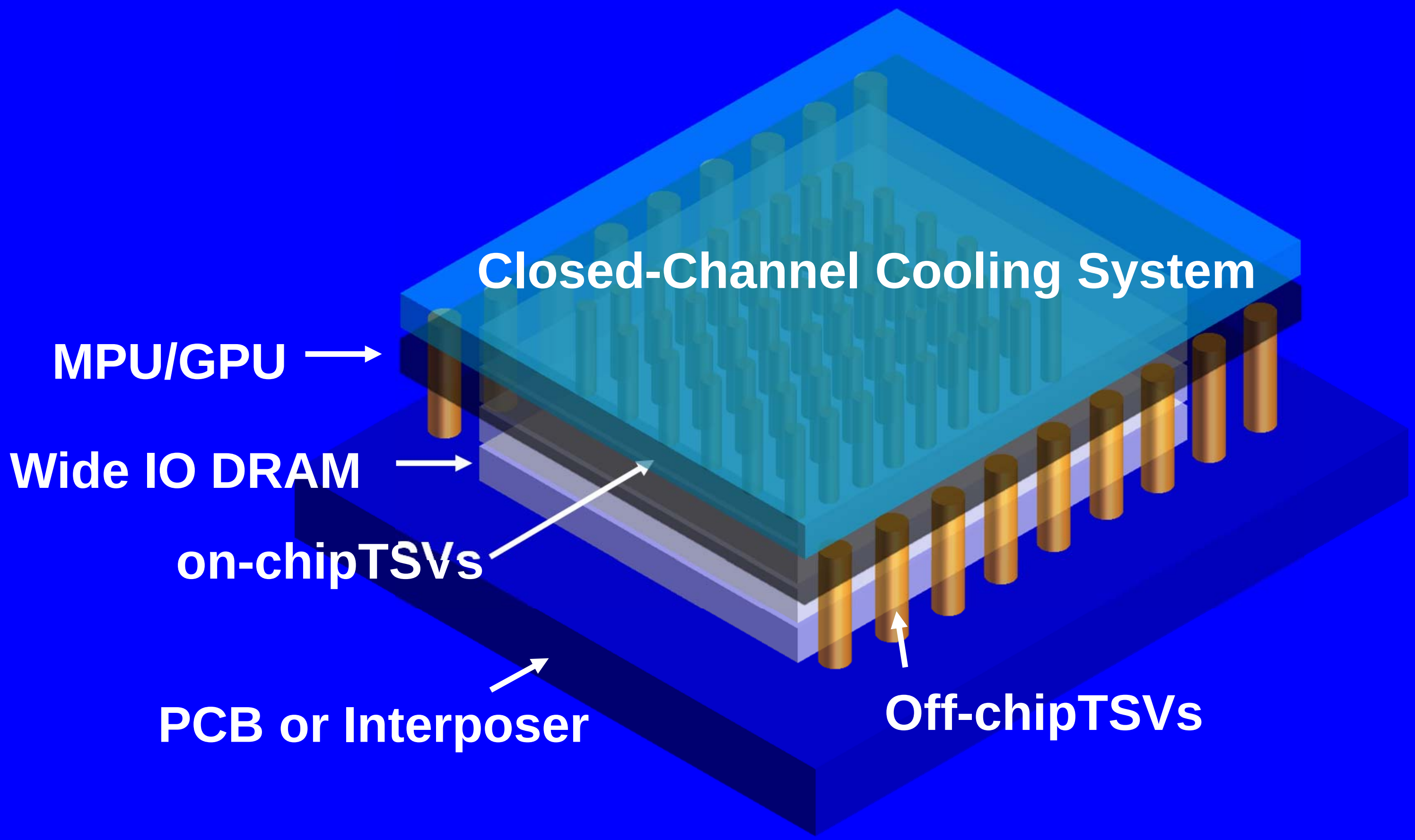
Outline of Presentation

- **Closed-channel cooling system**
- **Multi-channel EOF pumps**
- **Cooling chip fabrication**
- **Pumping performance**
- **Cooling capability**

Closed-channel Cooling System (C^3S)



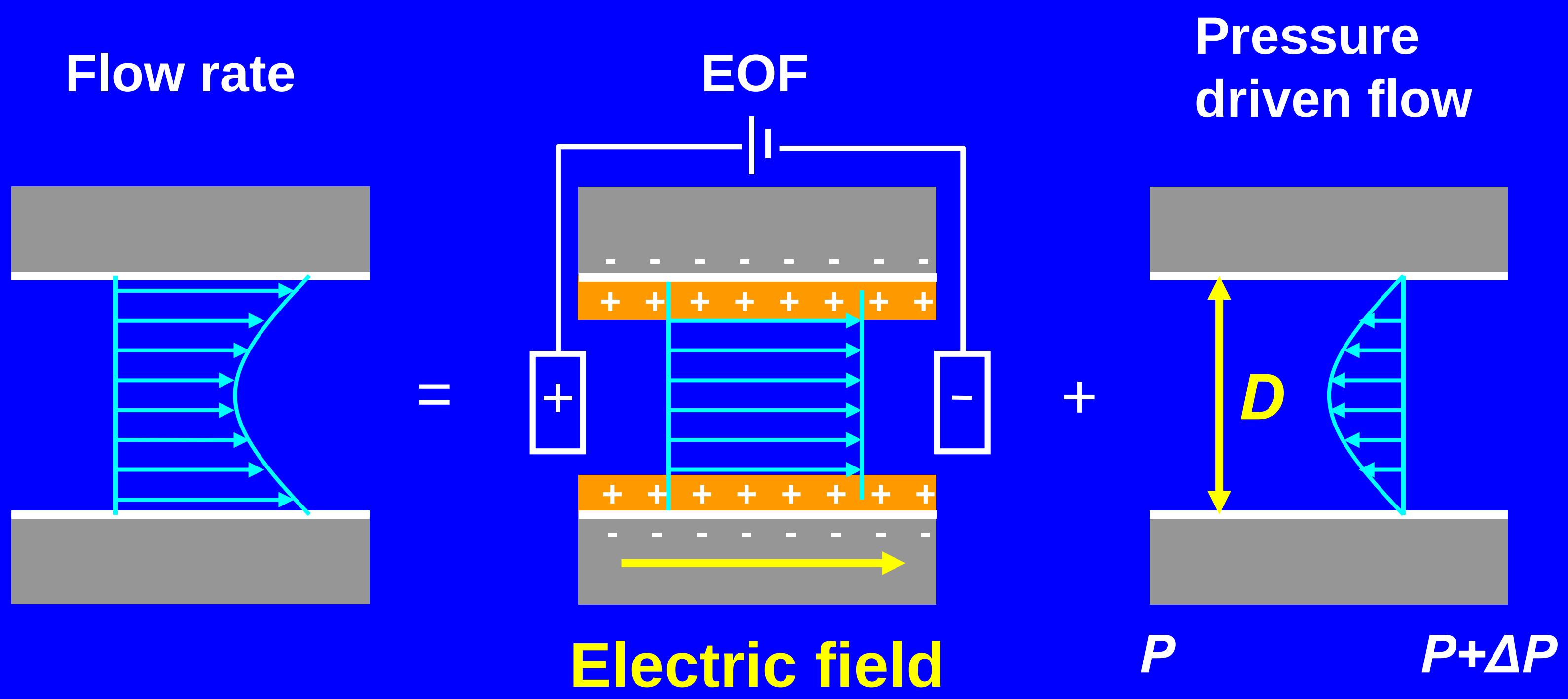
Application of C^{3}S to 3D-IC



Outline of Presentation

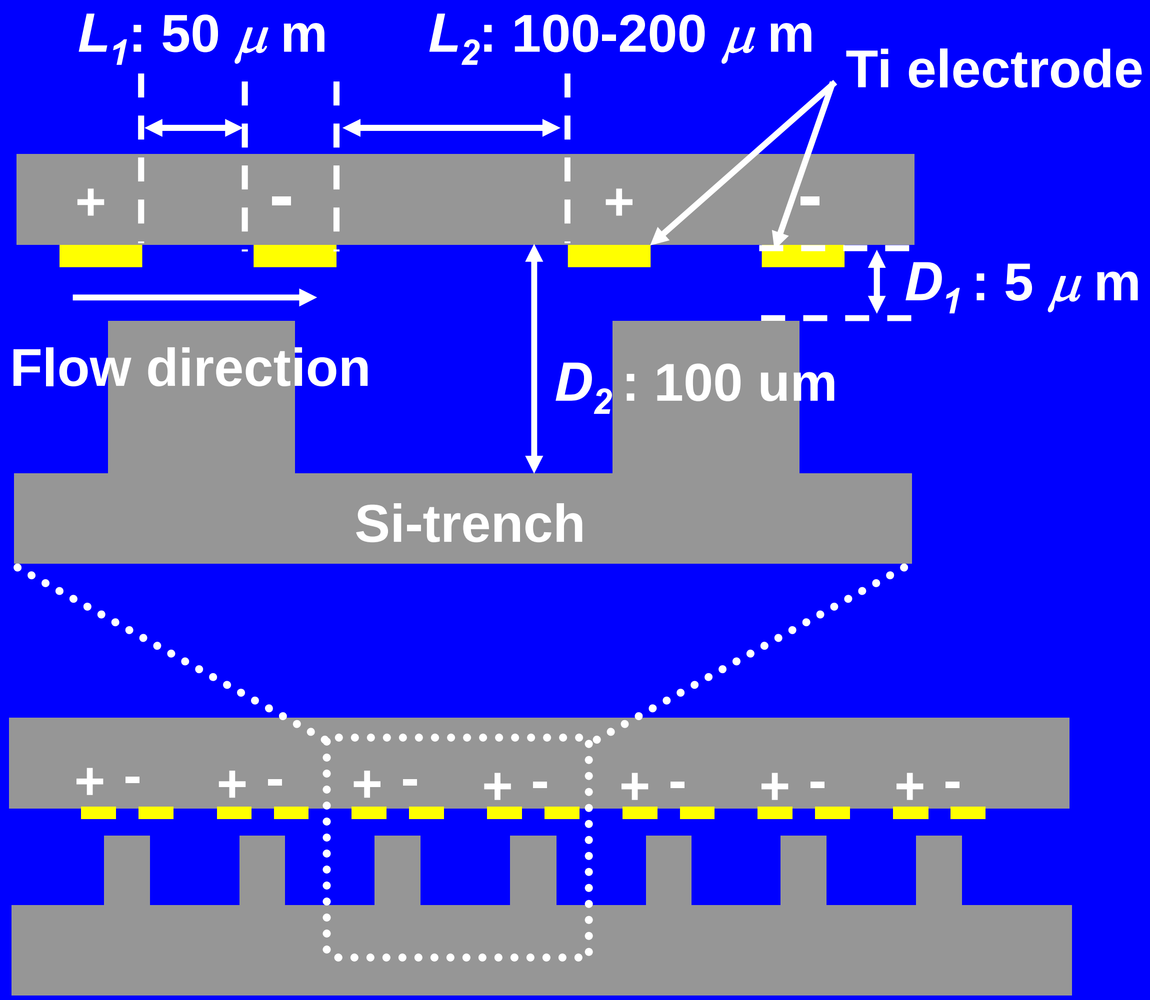
- Closed-channel cooling system
- **Multi-channel EOF pumps**
- Cooling chip fabrication
- Pumping performance
- Cooling capability

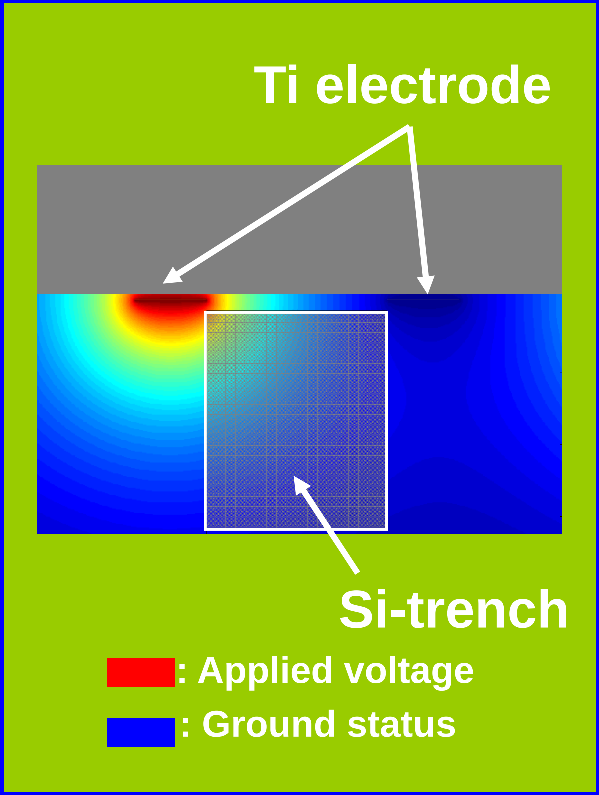
Electro-osmotic Flow (EOF) Mechanism



$$\textit{Flow rate} = -\frac{\varepsilon\,\zeta\,w\,D}{\mu}E - \frac{w\,D^3}{12\mu}\frac{\Delta P}{L}$$

Multi-channel EOF pumps





Dimensions of EOF pump

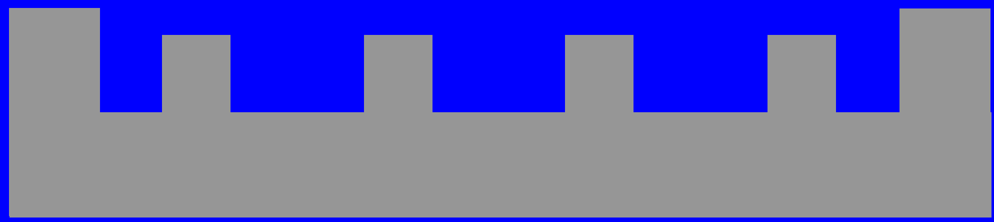
Chip	Channel-A	Channel-B	Channel-C
D_1 (μm)	5	5	5
D_2 (μm)	100	100	100
L_1 (μm)	50	50	50
L_2 (μm)	100	200	200
Channel (EOF unit) number	91	55	46

Outline of Presentation

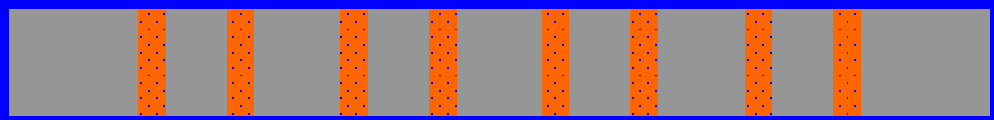
- Closed-channel cooling system
- Multi-channel EOF pumps
- Cooling chip fabrication
- Pumping performance
- Cooling capability

Fabrication Process of Cooling Chip

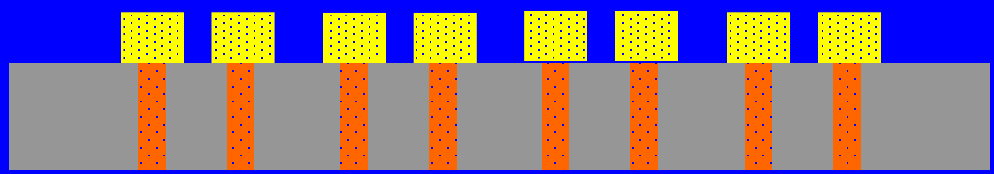
(a) Si trench formation



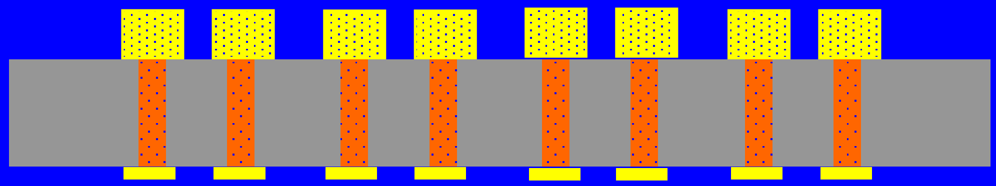
(b) Formation of through Si via (TSV) filled with electro-plated Cu



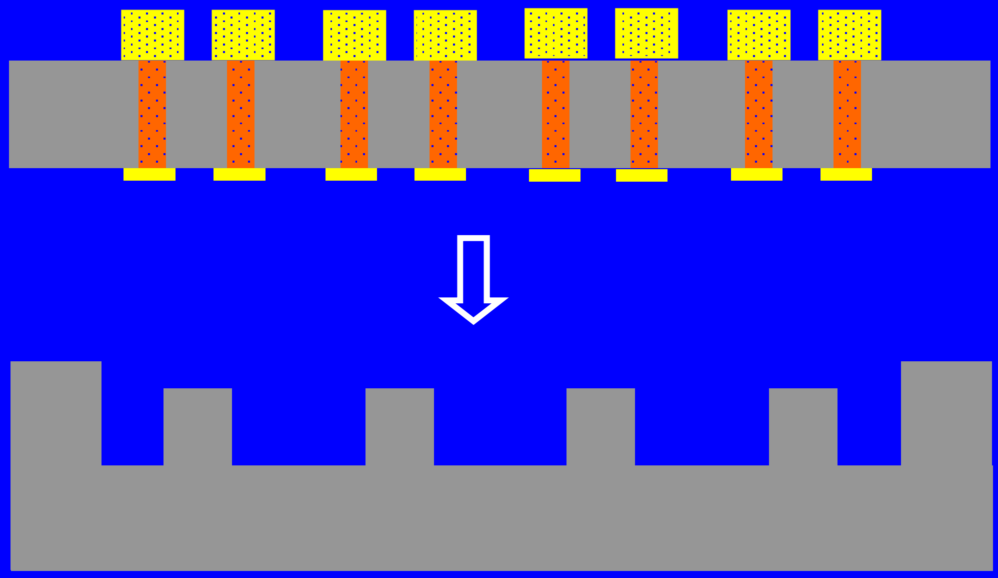
(c) Patterning Al line for applying voltage



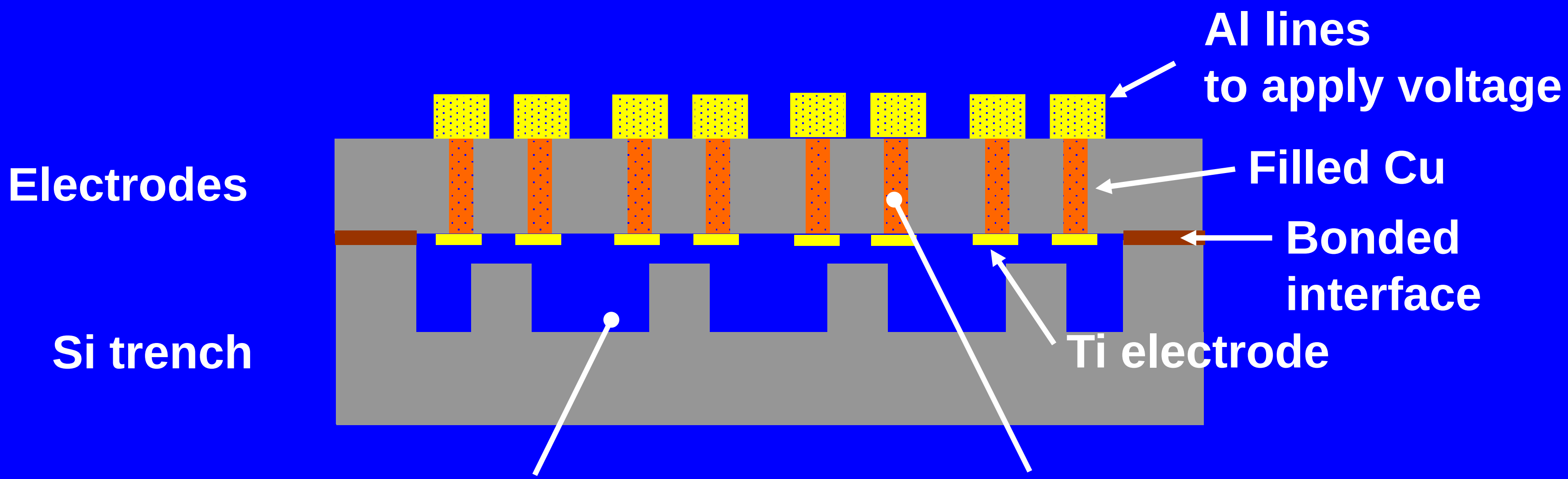
(d) Pattering of Ti electrode for EOF pumps

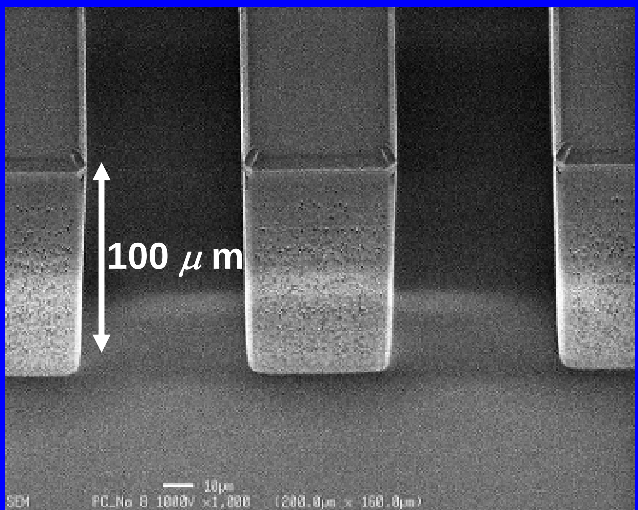


(e) Surface activated bonding (SAB)

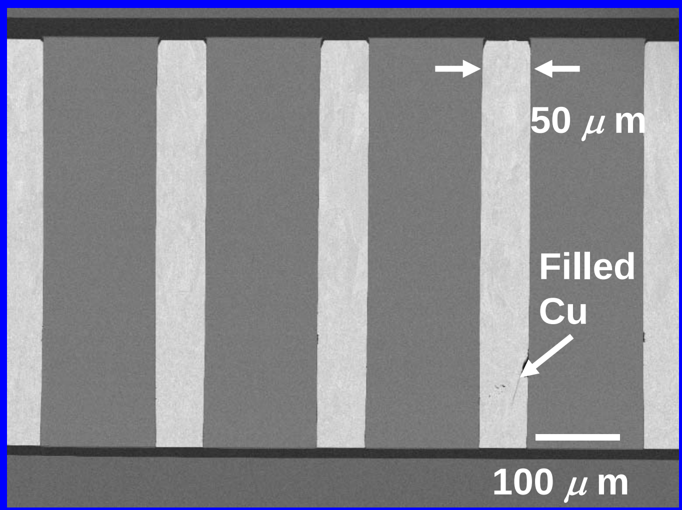


In-process SEM photos



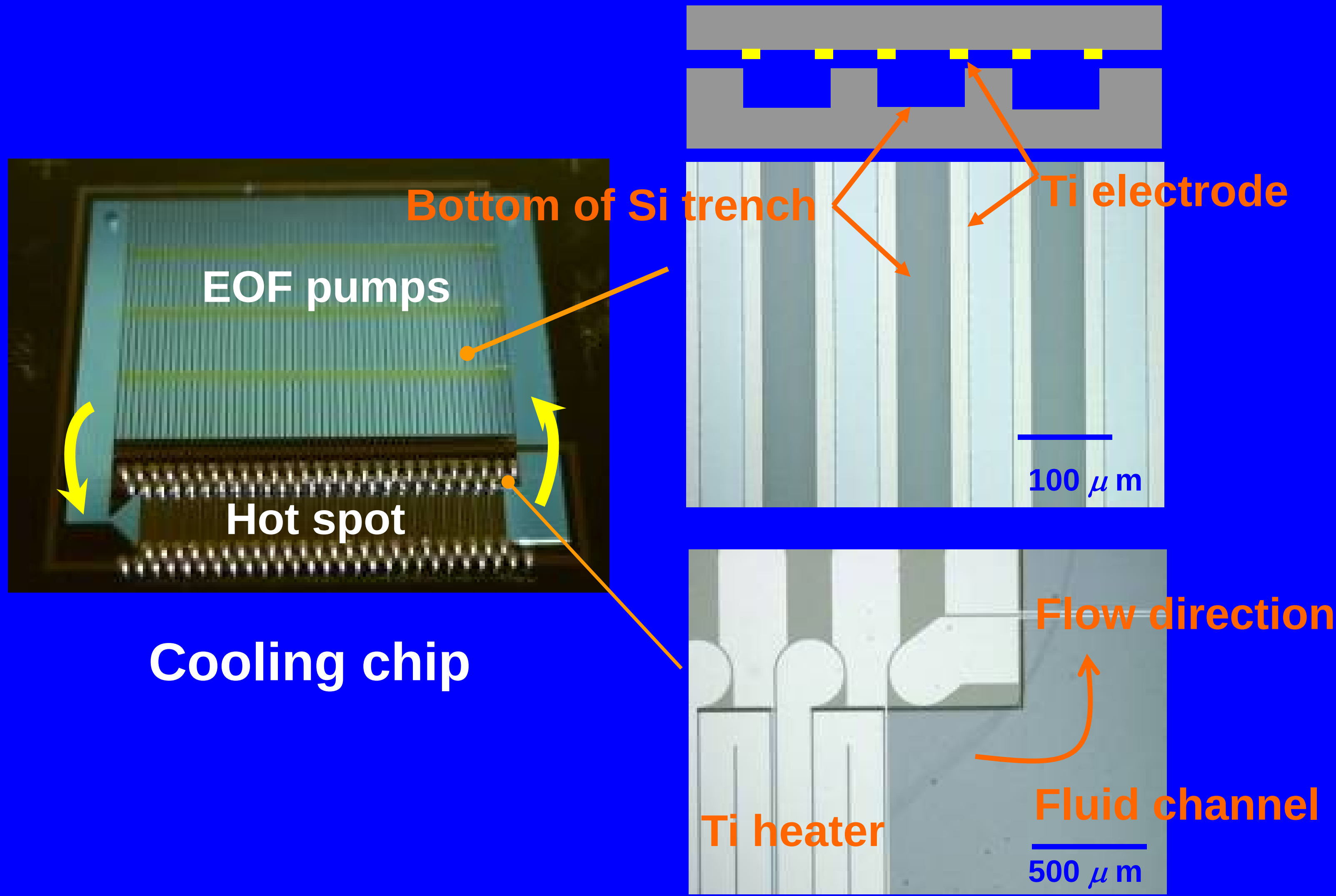


Si trench from tilt angle



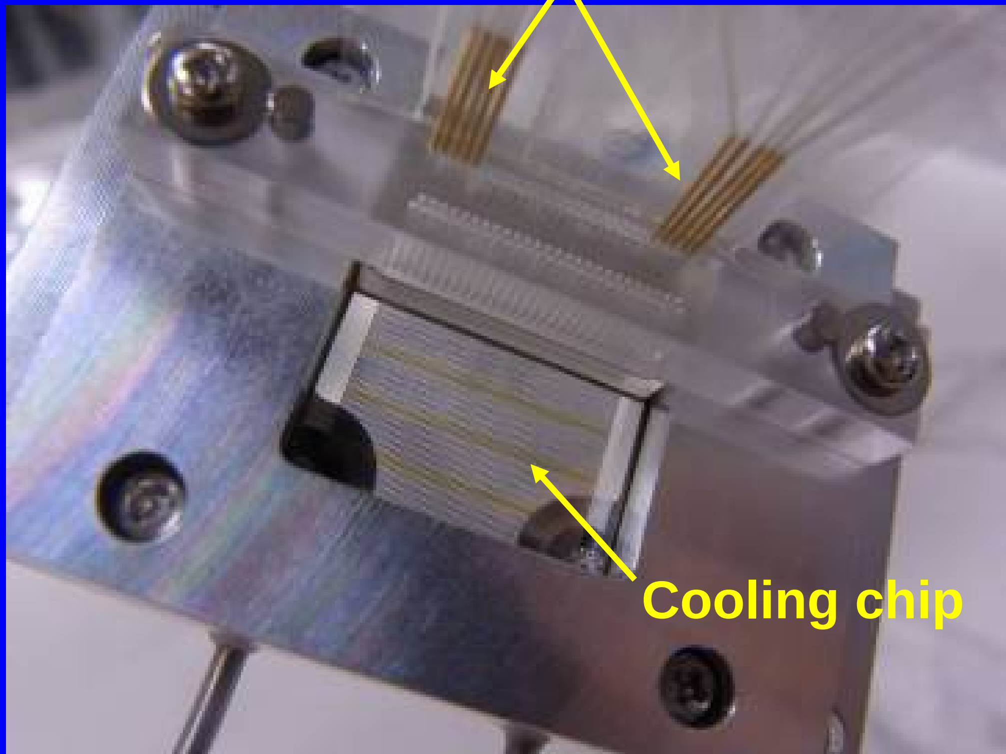
TSV filled with electro-plated Cu

Close-up Images of EOF pumps and Hot Spot



Cooling Chip Mounted to Measurement Jig

Wires for applying voltage



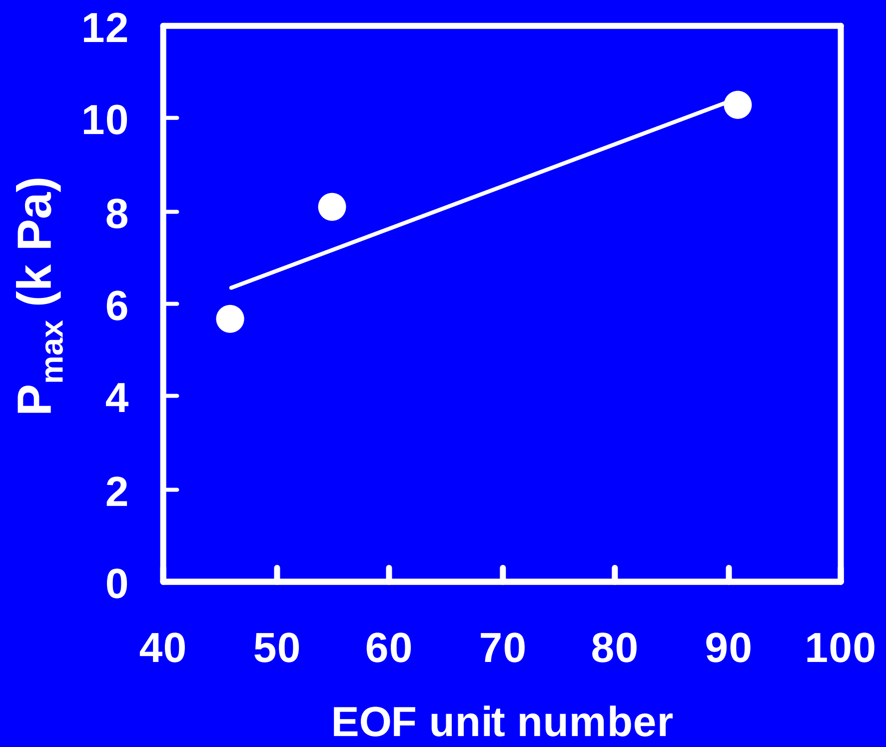
Inlet **Outlet**

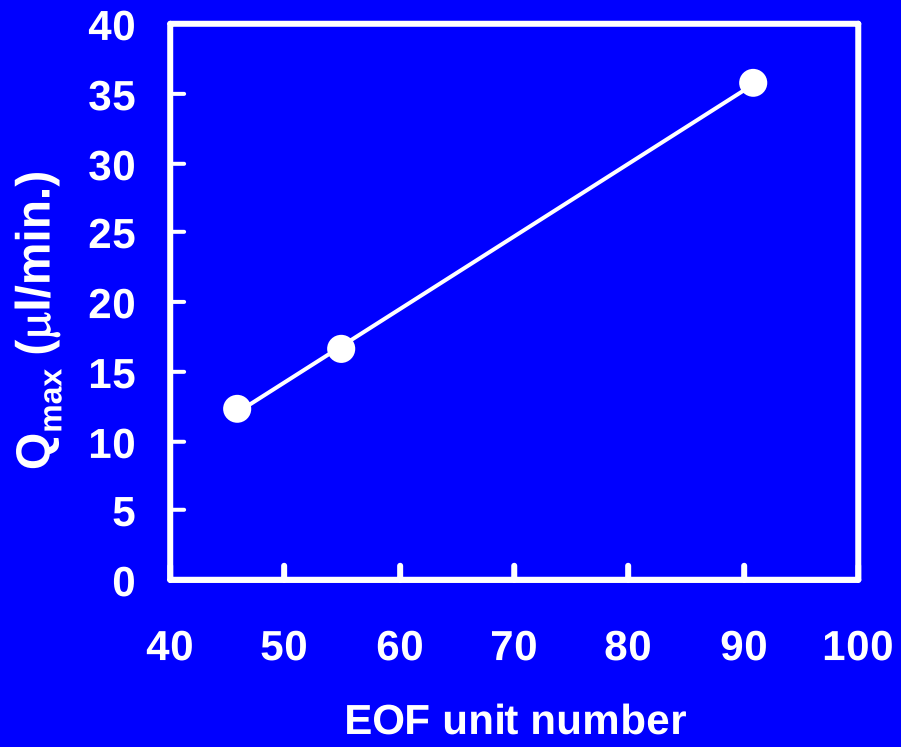
Coolant: Isopropyl alcohol (IPA)

Outline of Presentation

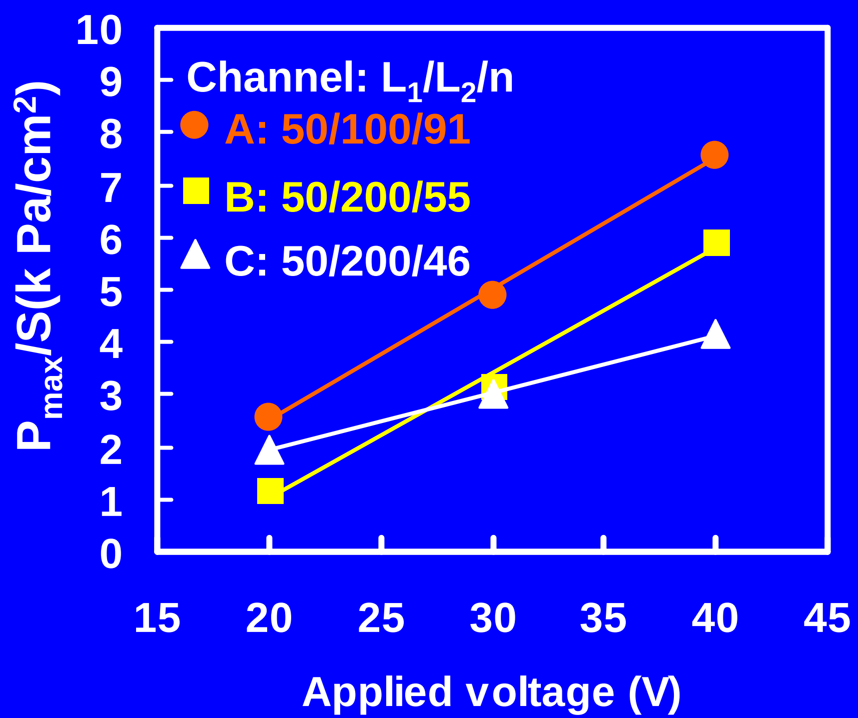
- Closed-channel cooling system
- Multi-channel EOF pumps
- Cooling chip fabrication
- Pumping performance
- Cooling capability

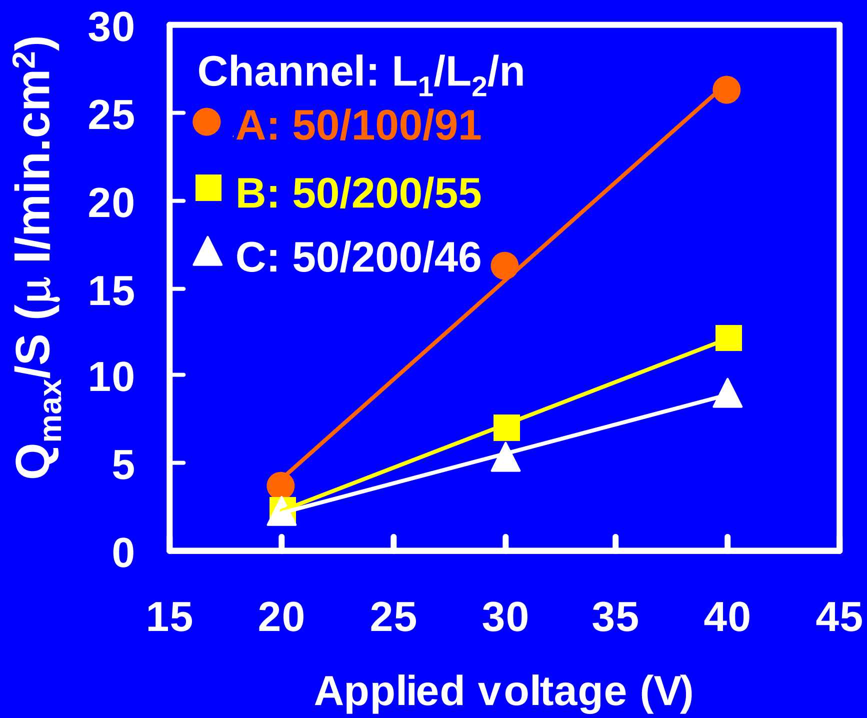
P_{max} and Q_{max} as a Function of Number of EOF Unit at 40 V





Normalized P_{max} and Q_{max} by Total Channel Area

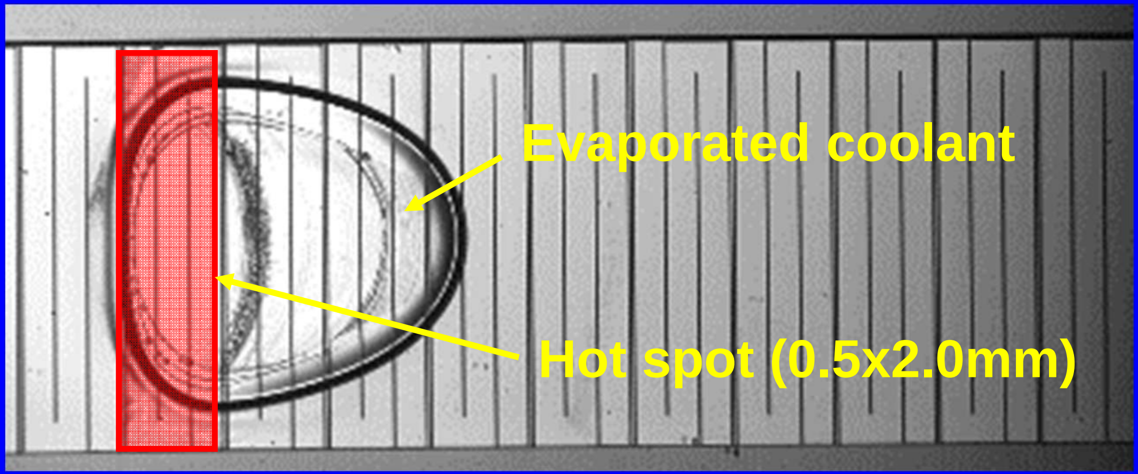




Outline of Presentation

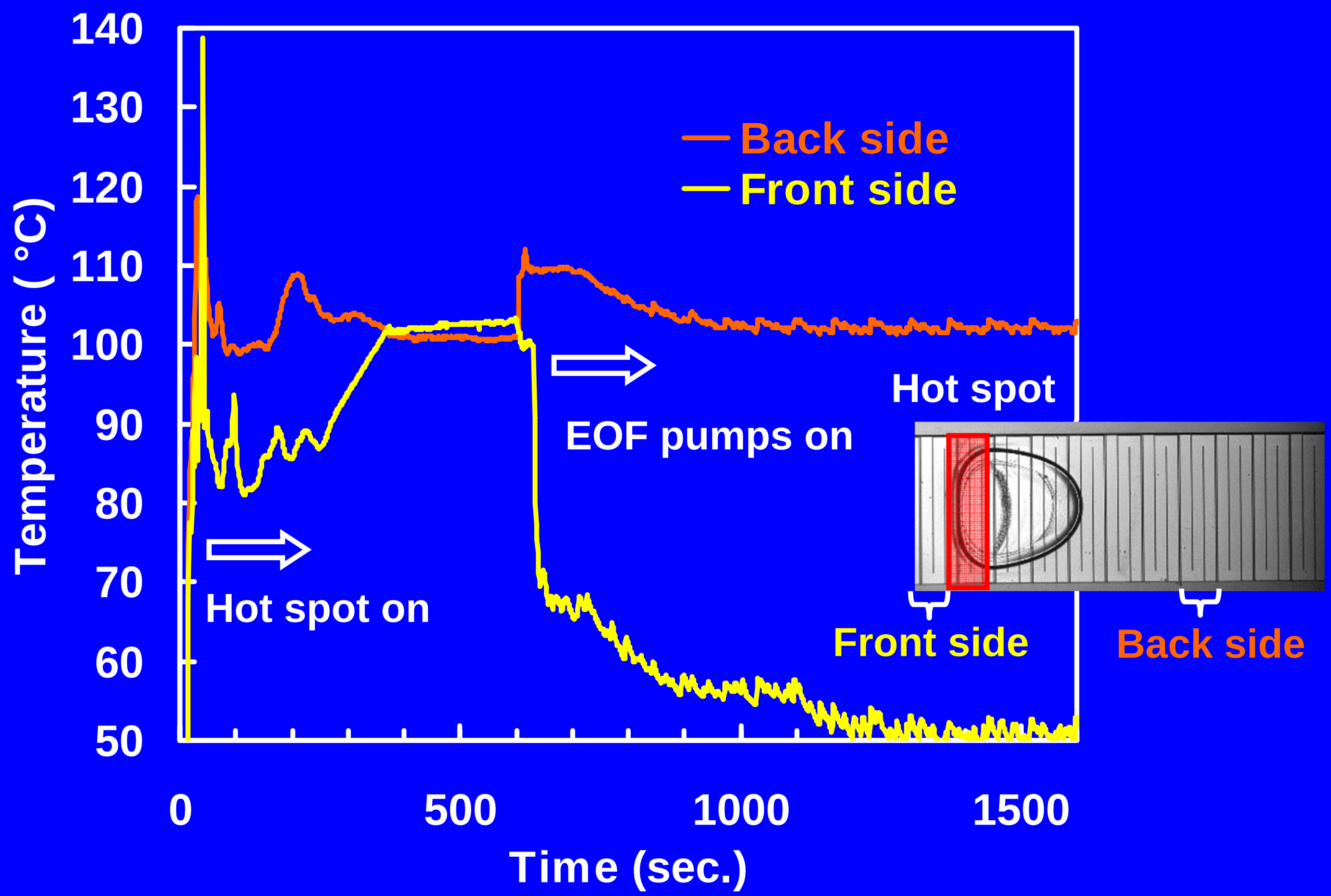
- Closed-channel cooling system
- Multi-channel EOF pumps
- Cooling chip fabrication
- Pumping performance
- **Cooling capability**

Fluid Behavior of Coolant on Hot Spot



Flow direction

Change in Coolant Temperature at Back and Front Sides of Hot Spot



Summary

- We have successfully fabricated a cooling chip equipped with C^3S with multi-channel EOF pumps.
- Operating the EOF pumps with a very low applied voltage of 40 V.
- High pumping capability: P_{max}= 10 kPa, Q_{max}= 38 µl/min.
- Cooling capability was as high as 140 W/cm^2.
- C^3S with the EOF pumps enable us to meet the requirements of 3D-ICs.

Acknowledgements

This study was carried out based on the three-dimensional integration development program of the WOW Alliance and the authors thank the more than 20 alliance members.