The Use of COMSOL Multiphysics® for Studying the Fracture Pressure of Rectangular Micro-Channels Embedded in Thin Silicon Substrates

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Abstract

Introduction
The thermal management of silicon detectors and related electronics through micro-structured silicon cooling plates is gaining considerable attention for high precision particle trackers in high energy physics (HEP). Hydraulic micro-circuits are etched in a silicon wafer, which is then coupled to a second wafer to obtain a cooling circuit (Fig. 1).

Typical conflicting requirements that are faced when designing these devices are: obtaining the minimum thickness possible for the least particle tracking disturbance and a strong structural reliability for prolonged time periods at relatively high pressures without maintenance possibilities. This demands careful dimensioning of the channel cross-section and of the total device thickness.

The available literature on the mechanical performances of mono-crystalline silicon that is subject to internal hydraulic pressure is extremely limited and therefore a specific investigation on the structural resistance of rectangular micro-channels embedded in silicon has been launched.

Use of COMSOL Multiphysics®
Samples have been fabricated with one micro-channel connected to a hydraulic inlet with different channel widths and silicon thicknesses to experimentally measure the fracture pressure (Fig. 2).

To simulate fracture pressure samples, COMSOL Multiphysics® has been selected because of its good post-processing tools and for the possibility to easily couple additional multiphysics modules for studying the performance of complex full devices.

Three COMSOL Multiphysics® models have been used based on the samples:
- A full 3D model of the entire pressure sample, on which the maximum stress from increasing pressure has been compared to the limit stress for mono-crystalline silicon (Fig. 3);
- A 2D model of the most critical section, with more refined mesh and detailed edge geometry

of the modeled channel;
- The same 2D model as the above bullet but instead calculating the strain energy release rate by applying the J-Integral theory.

Results
The results from the three models compare well to each other and nicely match the experimental data (Fig. 4).

The results suggest that it is possible to use the 3D model with complex geometrical configurations (not just with one small channel but with a whole fluidic circuit), and a coarser mesh to identify the critical sections. A grid-refined 2D model can then be run for a detailed device dimensioning. Because mono-crystalline silicon is structurally close in characteristics to brittle materials, one can use both the J-integral approach and the concept of fracture toughness to better understand the reliability of these devices even with small defects at the channel bonding edges.

Conclusion
Micro-channel cooling has many other potential applications. Understanding the reliability of these devices is paramount to developing them as extremely efficient thermal solutions in more practical applications. Accurate numerical modeling makes it possible to design the guidelines for safer design and dimensioning of micro-channel silicon cooling plates.

Figures used in the abstract

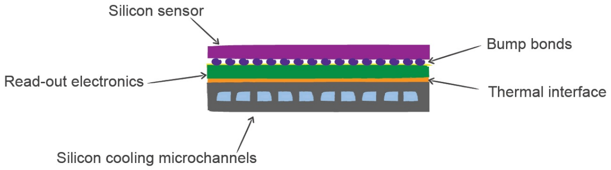

Figure 1: Fig. 1: Micro-channel cooling plate with silicon sensor and electronics.

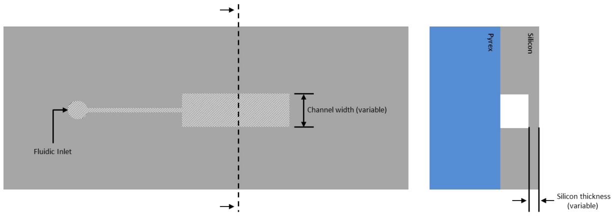

Figure 2: Fig. 2: Test sample with a straight micro-channel.

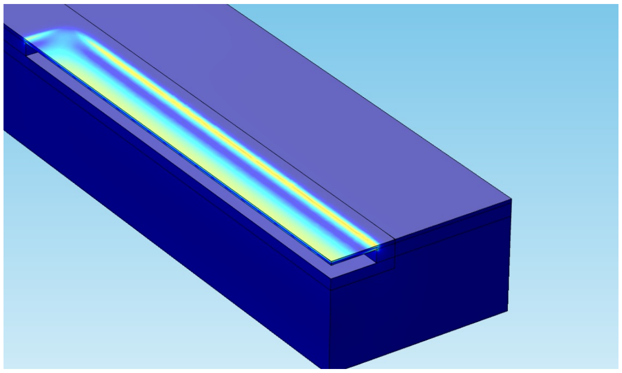

Figure 3: Fig. 3: 3D model

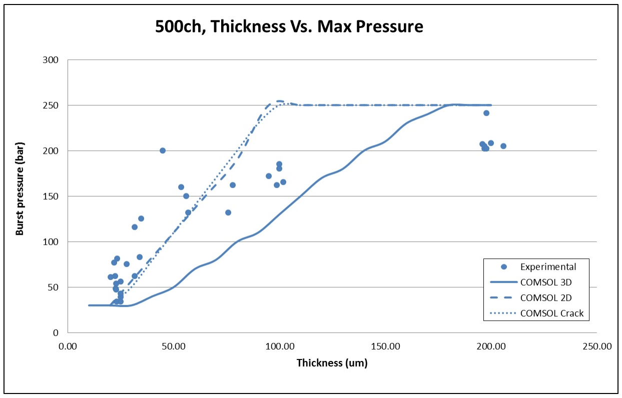

Figure 4: Fig. 4: Comparison between experimental data and COMSOL models for channels 500 µm wide.