Integration and Interfacing Thrust Meeting

10/18/22
Thrust Objective

• Develop interface technologies for system integration across multiple temperature zones and computing technologies

• Evaluate material properties of the interconnect and interface components at cryogenic temperatures

• Apply efficient, fast, and high-throughput active interface technology to transfer data between low temperature circuits to low temperature circuits/multi-chip modules to system components operating at room temperature
Superconducting Flex Cables
Motivation → Superconducting Flex Cables

• Number of required SC transmission lines in cryogenic system will increase with complex architecture needed for future cryogenic systems

• The use of this many coaxial cables would seem to be impractical due to their collective physical size, thermal leakage, and cost

• More densely integrated, scalable and reliable interconnects are needed to improve the performance of cryogenic and quantum systems

• Thin film flexible superconducting transmission line offer very low conductor loss, excellent mechanical flexibility, low thermal leakage, and high density I/O signal compared to commercially available coaxial cables
Research Highlights of Group

- Demonstration of scalable flexible superconducting stripline cables (with low cross-talk)

- Characterization of microwave properties of materials down to below 4 K (specifically materials with exceptionally low loss tangent relevant to flexible superconducting cables)

Plan to Improve Interconnect Design

Dielectric Material

• Photo-definable polyimide like HD-4110 has been used to define micro-vias for stripline cables.

• PI-2611, while not photo-definable, has low stress and CTE compared to HD-4110, which can improve the reliability of long superconducting cables. Laser drilling process can be used to fabricate micro-vias.

Superconducting (SC) vias

• Previous efforts show the use of electroplated Cu vias for stripline cables

• Use of SC material (like SnPb and Sn) for via fabrication can improve the microwave performance of the SC cables.
SC Via - Electroplating and Tc Measurements of Sn and SnPb

Electroplated SnPb sample

- Optical profilometry images of electroplated SnPb pillars

Tc measurement of SnPb, Measured Tc- 6.9 K

Tc measurement of Sn, Measured Tc- 3.5 K
Process Development for Laser Drilled Via

- Femtosecond laser is being used for laser drilling of PI-2611
- Laser drilling works successfully on fused silica substrate
- Damage was observed on Al/Nb/Al layer, when metal layer was exposed to laser
- PI 2611 and Nb has very close laser ablation threshold
- More process development needs to be done

Laser Parameters

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<td>Objective lens</td>
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<td>Power</td>
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<td>Rep rate</td>
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Connector Scheme
Bridging Connector Approach

- Self aligned connector approach to connect multiple flexible superconducting cables using a cable-to-cable connector.

- The test structure comprises multiple components for high-precision micromechanical alignment and to apply uniform pressure on the contact points of cables and the connector.
  - **Bottom and top Al connector bodies** provided precise mechanical alignment and held entire connector assembly together.
  - **Si plate with etched wells** and **polyimide membrane** used to apply uniform localized force on contact location.
  - **Thin-film flexible cables** were placed on top of the membrane with 12 signal line pads (on each cable) facing upwards.
  - **Bridging connector** placed with pads facing down and connecting to the flexible cable traces through Au contact pads provided on the bridging connector and cables.

Bridging Connector Approach: Fabricated and Assembled Components

Laser released flexible thin-film cable:
- 12 parallel Nb signal lines
- Pitch: 300 µm
- HD 4100 used as a protective layer

Bridging connector:
- Stripline structure
- Nb as the conductor
- Cured polyimide HD-4110 as the dielectric

Si plate with wells on bottom Al body:
- Well depth: 20 µm
- Well diameter: 300 µm

Polyimide membrane with Cu pillars:
- Pillar height: 10 µm
- Pillar Diameter: 100 µm

Assembled cables with bridging connector in center and commercial connectors on each end
Bridging Connector Approach: Test Results

- **Initial Coarse Characterization**

  Normalized DC resistances of lines in a fully assembled test structure from 293 K to 4.2 K.

- **Refined Characterization**

  Normalized DC resistances of fully assembled test structure from 30 K to 4.2 K

Critical Current Measurements

Assembled cables with bridging connector in center and commercial connectors on each end
The stripline cables were designed to have a characteristic impedance of 20 Ω. Each cable consisted of 12 parallel Nb signal lines with 300 µm pitch and contact pads on one of the ends to accomplish a direct face-to-face connection. The top alignment Mo piece contained high aspect ratio (HAR) SU-8 pillars to apply uniform pressure. The bottom alignment Mo piece contained 250 µm tall SU-8 features, which were designed to be used as the alignment structures for stripline cables.
Approach

Face-To-Face Connector: Test Results

Resistance vs. current for all signal lines

Tc measurement of signal lines

The plots show the TDR response of 6 superconducting striplines in liquid helium dewar using PNA.
Superconducting MCMs
• Integrating superconducting ICs using microbumps and achieving efficient data transfer among various superconducting/CMOS chips is highly desirable for superconducting computing system

• Superconducting MCMs (S-MCMs) have been demonstrated as promising approach to realize densely integrated and scalable superconducting quantum computing hardware

• Future superconducting systems will need large scale, low resistance-based integration scheme to accommodate numbers of chips on a single MCM substrate, thus reducing cryogenic cooling setup

• Mo as a substrate represent good alternative for S-MCM technology
  • Mo has higher fracture toughness and ductility compared to Si and mechanical strength, which enhances the robustness and reduces the chances of breakage during assembly and fabrication processes
  • From room temperature to ~4 K, total thermal contraction of Mo is closer to Si than most other metals
Mo Substrate for S-MCM

- Initial DC Test Structure for MCM design
  - Assembly comprised of Si chip flip-chip bonded to Mo substrate using In bumps to form snake-and-comb daisy chain interconnects
  - Nb was used for superconducting traces, polyimide dielectric, In bumps for flip-chip bonding
  - Bonded assemblies were found to remain functional over the range of temperatures and cycle numbers
  - Very little to no change in TC after 10 thermal cycles
  - No CTE mismatch related issues observed during number of thermal cycles

• Need high performance interconnect technology with efficient electrical and thermal performance to transfer data between low temperature circuit to MCMs to high temperature system component

• Superconducting material like Nb, NbTi, NbN Sn or SnPb (for vias) can be used for interconnect technology below Tc of Nb. Good normal conductors like Cu or Ag can be a better choice for interconnects operating at high temperature (above Tc)

• EM simulators (i.e ADS, HFSS, Sonnet) will be used for simulation and designing of the interconnects

• Need to incorporate filters and/or attenuators in interconnect design

• Need a good connector scheme to provide impedance match, ground continuities at interface between flexible thin cables

• New S-MCM technologies need to be created to improve system integration, robustness, and reliability