Heterogeneous Integration Technologies for Scaled Quantum Information Processing Systems

Michael Hamilton (*) and Luu Nguyen (**)

(*) Auburn University; Director, Alabama Micro/Nano Science and Technology Center
(**) PsiQuantum; Co-Chair, IEEE Quantum

Quantum information processing (QIP) can be performed using any multi-state quantum system that is sufficiently isolated from its surrounding thermal and dissipative environment while also being sufficiently controllable and addressable. These systems function as quantum bits (qubits) and quantum-limited sensors that are used for information-processing tasks such as computing and sensing. Leveraging the incredible technology and related infrastructure developed for integrated solid-state systems, such as CMOS, is expected to yield efficient routes to realize densely integrated QIP systems with many more qubits, which is much more computationally powerful than demonstrated systems (with qubit numbers of order 100).

This scaling-up will only occur with advancements in packaging technologies that take the quantum nature of the information into account and will be strongly impacted by advancements in heterogeneous integration technologies (HIT). Furthermore, to enhance isolation and reduce the impact of the thermal environment, many of these quantum systems will reside at cryogenic temperatures below or well below 4 K, which requires extreme environment considerations (e.g., impactfully large dimensional changes due to CTE mismatches, lack of knowledge of materials properties over wide temperature ranges, thermal cycle reliability, non-standard testing infrastructure, etc.). While we highlight the connection between quantum packaging and HIT in this article, readers are directed to an excellent review of materials challenges for quantum hardware as discussed in [1].

Multiple physical quantum system types are currently being investigated due to their combination of ease of physical realization, ability to integrate large numbers of sufficiently uniform qubits, degree of quantum state/interaction control, coherence times, and number of quantum operations per coherence time. Promising examples include:

Trapped ions: Where the quantum information is stored in the electronic states of groups of isolated ions (such as Sr, Ca, etc.) that exist in a vacuum above a solid-state microfabricated electromagnetic trap, controlled by laser pulses and read out by imaging and spectroscopy approaches. Scaling-up of these systems is expected to happen through the realization of larger, more precise (2D and 3D) integrated traps, packaged vacuum spaces, and integrated precision laser/photonic systems constructed through leveraging CMOS fabrication technologies as well as MEMS and MOEMS approaches [2].

Superconducting (SC) qubits: Where the quantum information is stored in artificial atoms formed using microscale superconducting electronic circuitry including capacitors, inductors, resonators, and Josephson junctions. These qubits are cooled to ~ 10 mK in a dilution refrigerator and are controlled and read out by microwave pulses. Scaling-up of these systems will happen through advancements in understanding loss mechanisms in the materials and architecture of densely integrated arrays of SC qubits and in the surrounding packaging and interconnect structures [3]. Critical to these systems are energy (information) loss mechanisms that are termed two-level systems, which are generally associated with lingering amorphous oxides. Reducing the volume of these loss mechanisms and realizing more highly integrated and scaled-up systems is a necessary and challenging undertaking that will rely heavily on HIT.

Electrostatic quantum dots (QDs): Where quantum information is stored in the spin states of electrons (or holes) within the embedded dopants or quantum dots. These QD systems rely on mature semiconductor heterostructure technologies (e.g., GaAs/AlGaAs or Si/SiGe) technologies and can leverage CMOS scaling approaches [4].

Color centers: Where quantum information is stored in long strings of "color centers" (nitrogen-vacancy centers) qubits in a diamond lattice irradiated by high-energy heavy ions. The crystal lattice can protect the coherence of the electron and nuclear spins of the nitrogen-vacancy centers and allow for potential usage in non-cryogenic environments. However, color-center strings can only be formed with beams from large particle accelerators. More compact laser-plasma accelerators are required for any future research [5].

Photonics approaches: Where quantum information is stored in photons - an appealing approach since they are almost free of decoherence. High scalability can be achieved as the stringent environmental conditions (e.g., ultra-low vacuum and mK temperatures) required by the other qubit technologies are no longer required. Current challenges are in developing high-efficiency single photon sources and detectors that can be integrated into photonic circuits [6].

The key to advancing all these approaches to a useful level of integration is the importance and impact of packaging and integration technologies that provide means to connect a growing number of qubits, while also minimizing noise sources and energy loss paths that can lead to decoherence. The Heterogeneous Integration Roadmap (HIR) has thus far only peripherally addressed quantum computing and quantum technologies (https://eps.ieee.org/technology/heterogeneous-integration-roadmap.html). Concerted efforts in the future will need to bring together multidisciplinary subject matter experts to map out the commonalities and challenges to drive a HIT industry roadmap for quantum.

References

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