3D ceramic packagings, the armors for quantum technology warriors

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Quantum technologies at extreme cold.

Recent advancements in science and technology have ushered in the second era of quantum technology. While Moore's Law has been under debate in recent years due to technical challenges hindering the miniaturization and performance enhancement of microelectronic devices, the emergence of Quantum 2.0 offers new possibilities. This next phase enables information processing at atomic and quantum-particle scales, leveraging pure quantum phenomena such as state superposition and entanglement. These advancements bring renewed hope for technologists seeking to meet the growing demand for high-performance information processing units, even though their current applications are perceived as complementary to conventional computers. Since the early 2010s, advanced technology nations and states have prioritized this domain, attracting billions of dollars from both public and private sectors. It is now evident that quantum technology is as strategically significant as the internet or nuclear energy were in past decades, proving to be a game-changer in empowering its owners with economical, scientific, and political supremacies.

This has resulted in a battleground at the frontiers of science and technology, where various research and industrial units employ diverse approaches to gain an edge over their competitors. Notably, in the absence of a definitive solution, approaches span a wide range of technologies, from cold atoms and trapped ions to Rydberg atoms, Josephson Junction circuits, quantum wells, and spin defects and impurities. Each corporation has chosen its unique arm to tackle the challenge, while states closely monitor progress to determine budget allocations. Remarkably, though we are still years away from achieving sufficiently performing, cost-effective, and user-friendly quantum machines for implementation even in specialized tasks, the technology has already formed a global market evaluated several tens of billion dollars[1]. Currently, this market is primarily defined by enabling technologies that provide the necessary devices and components for fabricating quantum computing and communication prototypes.

However, the present common points of all evolved approaches are cryogenic conditions requirements and the use of photons as flying qubits. The reason is straightforward: quantum states are vulnerable to environmental perturbations[2]. Among various applicable quantum particles, photons are the least affected by major environmental perturbations such as electromagnetic fields or crosstalk[3]. In the realm of communication, they are the fastest means and can propagate in various media from metals to vacuum. Even in the case of Josephson junctions (JJs), the application of photons for information writing, fast communication, and readout has been proposed[4]. However, to utilize photons, one needs to capture, control, and secure their sources from thermal fluctuations. This is where the battle of light sabers unfolds in the frozen lands of cryogenic temperatures (<4K), albeit at a significant cost!

The current state of cryogenic technology involves the use of liquid helium (He3 and He4 depending on the target temperature) within sophisticated isolated chambers. These chambers consist of large-volume, multilayer structures, where only a small fraction of space is suitable for device integration. The setup fabrication cost is significant, ranging in the hundreds of thousands of euros for a simple laboratory-sized setup that can only accommodate a centimeter-long sample. Additionally, one must consider the expense of the cryogenic gas required for cooling the system, the electricity needed for cycling and re-liquefaction, and ongoing maintenance costs[5].

Currently, IBM is developing its Goldeneye[6] cryogenic chamber, which offers 1.7m^3 of experimentally available space and can accommodate only 1000 qubits, a modest number for deploying a quantum correction protocol. However, achieving a viable quantum computer necessitates a minimum of 100,000 qubits[7]. In the current state of the art, this would require 200,000 liters of space, and one can imagine the significant amount of liquid needed to cool

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[1] https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing

[2] Zurek, W. H. (2003). Decoherence, einselection, and the quantum origins of the classical. Reviews of Modern Physics, 75(3), 715. doi:10.1103/RevModPhys.75.715

[3] Gisin, N., Ribordy, G., Tittel, W., & Zbinden, H. (2002). Quantum cryptography. Reviews of Modern Physics, 74(1), 145. doi:10.1103/RevModPhys.74.145

[4] Schoelkopf, R. J., & Girvin, S. M. (2008). *Wiring up quantum systems*. Nature, 451(7179), 664-669. doi:10.1038/451664a

[5] Blais, A., Grimsmo, A. L., Girvin, S. M., & Wallraff, A. (2021). *Circuit quantum electrodynamics*. Reviews of Modern Physics, 93(2), 025005. doi:10.1103/RevModPhys.93.025005

[6] IBM Quantum Blog. "IBM cools down world's largest quantum-ready cryostat." IBM Quantum Computing Blog, 2023. https://www.ibm.com.

[7] IBM Quantum Computing Blog. "Charting the Course to 100,000 Qubits." IBM, 21 May 2023. Available at IBM Quantum.

such a vast space. To realize such a system, two approaches are being pursued. Firstly, there is an urgent need to optimize cryogenic technology. Secondly, there is a vital need to further miniaturize quantum devices and circuits to reduce the required space and the corresponding energy and cost. This is where the demand for creative and innovative device integration becomes pronounced.

Moreover, such setups pose challenges in terms of accessibility for frequent device maintenance and part replacement. Therefore, the robustness and reliability of the devices are paramount, especially considering that one defective device could disrupt all sensitive quantum operations. Cryogenic temperatures, coupled with the ultra-high vacuum atmosphere required by these systems, are both considered harsh environmental conditions.

Thermomechanical shocks and stress, primarily stemming from the expansion coefficient mismatch between different components, are the primary reasons for the failure of circuits and devices in the optoelectronic realm. Not all materials can endure such thermomechanical shocks, leading to fatigue and eventual failure. Similarly, electrical contacts (such as solders and wire bonds) are prone to failure due to these effects.

In addition, these systems primarily consist of optoelectronic or photonic components and achieving robust and reliable integration solutions for coupling between optical and electronic elements at low temperatures is essential. In this context, various designs and solutions for efficient packing of photonic integrated circuits and microelectronic interconnect circuits have been proposed and demonstrated. Generalizing the technical challenges, they can be categorized into two main subjects:

- Optical-Electronic Integration:
  It's customary to reduce the thermal load on the cooling system by maintaining the controlling optical and electronic units outside the cryogenic chambers. Communication between these units is facilitated through electric cables and optical fibers[8]. The alignment and fixation of multiple optical fibers to circuits containing optoelectronic components (such as photon detectors and rapid single flux quantum circuits) are crucial. Typically, metallic housings, ferrules, and alignment sleeves adhered to semiconducting circuits are used, albeit bulky solutions. Moreover, fiber optics adhered inside v-grooved substrates via low-temperature epoxies, resins, or conventional soldering solutions between metallic components and circuits are proposed for efficient multi-fiber integration[9]. It's important to note that in such systems, components are made from different materials (metals, polymers, epoxies) with differing expansion coefficients. This mismatch can lead to alignment deviations, both in angle and distance, resulting in reduced coupling efficiency and information loss due to dispersive effects.
- Interconnection of Optoelectronic Components:
  Various optoelectronic components such as photodiodes, superconducting circuits, single-photon detectors, emitters, and integrated electronic control units often require interconnection solutions between multiple chip modules. These solutions may involve

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[8] Joshi, S., & Moazeni, S. (2022). Scaling up Superconducting Quantum Computers with Cryogenic RF-photonics. arXiv preprint. https://doi.org/10.48550/arXiv.2210.15756;

[9] Lin, B., Witt, D., Young, J. F., & Chrostowski, L. (2021). *Cryogenic Optical Packaging Using Photonic Wire Bonds*. APL Photonics, 6(6), 066102. https://doi.org/10.1063/5.0045249

conventional wire-bonding, flip-chip bonding, direct adhesion, etc. In low-temperature applications, the thermal expansion mismatch between modules and adhesion/solder materials can induce significant mechanical stresses on components, leading to the formation of microcracks and defects[10]. Additionally, such mismatches can result in misalignment failures, such as gaps between waveguides and detectors, leading to increased dispersive effects[11]. A more robust alternative is the fabrication of single on-chip modules, such as silicon photonic integrated circuits. While this approach satisfies both the miniaturization and robustness requirements of devices, its application is limited to structures that can be deposited directly over each other (i.e. multilayer deposition process).

Another problem arises from heat accumulation in high-speed circuits. Components such as polymer-based PCB interconnect circuits, adhesion epoxies, and resin materials are insulators prone to accumulating heat. This, alongside perturbations of device functionalities, leads to local heat accumulation, thermomechanical strains, and the formation of failure points.

As a result, further progress in components, interconnect boards, and bonding materials suitable for extreme low-temperature applications is imperative. These materials must possess properties such as effective heat sinking, strain resistance, and matching expansion coefficients. Additionally, given the rapid advancement of technology, there is an urgent need for new, and perhaps more sophisticated designs for device integration and interconnection structures. These designs should be resilient to thermally induced alignment and functionality failures while facilitating further miniaturization of systems.

Advanced ceramics; the survivors!

In quantum technology, man is challenging the nature to its extreme limits. We are on the brink of entering an era forbidden by nature for macroscopic bodies, yet we are nearly there, compelling quantum particles to bend to our will. In this ongoing battle, our "Madalorian knights" require their own version of Beskar to emerge victorious. These materials must withstand extreme temperatures, remain resilient to thermomechanical shocks, offer shielding against electromagnetic perturbations, enable high-precision fabrication and processing, facilitate heat sinking, allow for photon guidance, provide engineerable electrical isolation, and be cost-effective.

Advanced ceramics represent a distinct category of materials distinguished by their exceptional properties, facilitating a myriad of applications across multiple industries. This class encompasses a broad spectrum, including technical glasses, quartz, diamond, metal oxides, nitrides, and carbides, among others. Noteworthy attributes of these ceramics include

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[10] https://www.idc-online.com/technical_references/pdfs/electronic_engineering/Electronics_Materials_Stress_Caused_by_Thermal_Mismatch.pdf?utm_source=chatgpt.com; Guo, X., Zuo, X., He, H., Xiao, H., Liu, J., Tian, R., & Liu, Y. (2023). Microstructural Evolution and Deterioration of Shear Properties of Sn3.0Ag0.5Cu/Cu Solder Joints after Long-Term Storage at Cryogenic Temperatures. *Crystals*, 13(4), 586. https://doi.org/10.xxxx/crystals1340586.

[11] M. Huang, "Analytical solutions for thermal stresses in buried channel waveguides," in *IEEE Journal of Quantum Electronics*, vol. 40, no. 11, pp. 1562-1568, Nov. 2004, doi: 10.1109/JQE.2004.835716; Dieter Opielka and Dieter Rittich, "Transmission loss caused by an angular misalignment between two multimode fibers with arbitrary profile exponents," Appl. Opt. 22, 991-994 (1983)

unparalleled hardness, resilience to extreme temperatures, chemical resistance, wear resistance, and superior electrical properties[12]. Consequently, advanced ceramics find utility in demanding scenarios ranging from furnaces, jet engines, and cutting tools to cutting-edge applications in MEMS, aerospace, telecom, photonics, medical devices, and electronic components. Their utilization spans diverse sectors such as medical technology, mobility (including e-mobility), cutting tools, electrical engineering, electronics, and industry, owing to their exceptional performance and longevity.

Advanced ceramics such as Al2O3, AlN, TiO2, SiC, and diamond play crucial roles not only in the fabrication of structures for cryogenic and ultra-high vacuum environments but also directly in optoelectronic device structures. While being ceramic materials, they offer the advantages of large bandgap semiconductors, with their electrical, optical, and thermal properties being tunable through conventional materials engineering techniques like doping, polytype and crystallinity controls, and external electronic and mechanical adjustments.

These exceptional properties make them ideal for various applications, including waveguides, gate dielectrics, reflectors, power diodes, and LEDs. Furthermore, they can be fabricated using a range of processes, from powder processing and compaction to layer deposition techniques such as PVD, ALD, MBE, etc. Each method offers different controls over crystallinity, thickness, engineering, and fabrication time/cost efficiencies. Moreover, their material compatibility allows for the fabrication of hybrid structures by combining different techniques. For instance, thin ceramic layers can be grown over highly polished[13] ceramic plane blocks and sheets using PVD techniques. These layers can then be processed to form structures such as waveguides or electronic components. Additionally, these structures can incorporate multimaterial layers, including metallic, semiconductor, dielectric, and superconductor layers grown directly through layer deposition, enabling the fabrication of complex devices. These layers can be strongly adhered to ceramic base structures to form on-chip multicomponent devices.

One well-known example of such structures is an interconnect circuit, widely used for device integration. While conventional microelectronics and optoelectronics typically use organic polymeric materials (in the form of PCBs) for such circuits, their low mechanical durability makes them unsuitable for certain applications[14]. Hence, ceramic-based interconnect circuits have been utilized since the 1960s, particularly in harsh environment applications such as aerospace systems.

In the realm of quantum technologies, ceramic-based materials play crucial roles. Aside from their traditional applications in cryogenic setups as thermal and electrical insulators, support and mounting points for delicate components, seals and gaskets, sensors and detector structures, valves, and supports for superconducting magnets, ceramics are directly integrated into devices themselves. For instance, ceramics like SiC, diamond, and technical glass form the matrices hosting qubits, while also serving as single photon waveguides. These applications highlight

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[12] Ćurković, L., & Žmak, I. (2024). Mechanical Properties and Applications of Advanced Ceramics. Materials, 17(13), 3143. https://doi.org/10.3390/ma17133143

[13] with the possibility of achieving ultra-low roughness levels

[14] Li, J., Duan, H., Yu, K., & Wang, S. (2010). Interfacial and Mechanical Property Analysis of Waste Printed Circuit Boards Subject to Thermal Shock. Journal of the Air & Waste Management Association, 60(2), 229–236. https://doi.org/10.3155/1047-3289.60.2.229

the adaptability of ceramic materials between quantum devices and their enabling components, emphasizing their importance as technology-enabling elements. They play a key role in realizing the full potential and performance of quantum devices and in adapting them to their required operating environment.

These amazing materials are the magic Beskar that while protecting the qubits can be used to form the whole on-chip armor. Next is how our warriors are going to use them, and this is where appropriate designs for devices and components become crucial.

Arming the devices with 3D optelectronic packaging

The compatibility of advanced ceramics with various device structures and layer deposition processes, along with their potential for precise machining and patterning, has facilitated the fabrication of practical structures with complex forms, such as interconnect devices. These devices not only exhibit high performance but are also suitable for harsh environment applications. In the realm of quantum technologies at cryogenic temperatures, advanced ceramics-based structures offer solutions to numerous technical challenges:

- *High-density device integration:* While planar ceramic interconnect devices are commonly used for integrating devices in cryogenic conditions, more sophisticated structures are needed to achieve high density integration. One potential solution is the use of technologies like flip-chip bonding of multiple planar structures. However, this approach has limitations, particularly concerning the spatial arrangement, connection, or alignment of devices, especially in situations where lateral space is limited and efficient use of volume is essential. For such scenarios, the application of 3D interconnect devices (CI3D) has shown promise[15]. CI3D enables optimized spatial arrangement of devices, reduces the need for less reliable contacts by allowing intricate geometrical forms and arrangements, and facilitates ultra-precise alignment (with angular tolerances in the order of 0.5°) of sensors and detectors along desired directions in space. With pitches achieving 20µm, these structures achieve an extremely high degree of integration density.
- *Complex optoelectronic devices/multi-chip interconnection:* Further application of 3D ceramic packaging can be extended to address interconnection reliability issues. These structures offer all the advantages of traditional PCBs in terms of interconnection traces and multi-chip contacts, supporting various packaging methods such as DIP, BGA, wire bonding, Flip chip, etc., for device and chip integration. This, opens up the possibility of creating intricate structures comprising multiple devices and interconnected components, which are connected in a highly customizable manner. Such capabilities are crucial for quantum optoelectronic systems, for instance, where direct coupling of photon detectors to waveguides, or connecting superconducting single photon detectors to single flux quantum chips are essential. The use of CI3D technology in this context provides a dual benefit. Firstly, it allows for the definition of complex traces in a 3D configuration, reducing the reliance on methods like wire bonding that can be unreliable

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[15] KHAZEN, KHASHAYAR. "3D Ceramic Packaging a Solution to High Density Device Integration at Harsh Environnements." IMAPS NORDIC 2024, 2024.

and unstable, especially in cryogenic conditions with thermomechanical stresses. Secondly, ceramic materials enable ceramic welding solutions to address challenges related to precise alignment. As mentioned earlier, achieving precise alignment is a significant technical challenge in optoelectronic and photonic device packaging at cryogenic temperatures due to differences in thermal expansion coefficients between binders and solder materials leading to misalignments and potential packaging failures caused by strains and thermomechanical stresses. Utilizing ultra-short pulse laser welding[16] enables direct bonding of these components, enhancing their structural integrity and maintaining alignment through various thermal cycles. Previous studies have demonstrated the feasibility of welding different types of ceramics and glasses using femtosecond lasers, which are also employed for micropatterning and fabricating these intricate structures.

- *Optical fiber integration and coupling:* For the case of single fiber coupling the v-grooves can be easily achived by machining of the ceramic. Using the laser ablation and drilling one can define these structures in 3D configuration to micron precision, enabling the precise coupling of the optical fibers to the detection or control devices integrated over the packing parts. One the other hand, one can also consider introducing multi passage sleeves through the ceramic parts for multi-fiber packaging. In practice, optical fibers can be utilized without protective coatings in the coupling section to facilitate direct light transmission and interaction with other optical components or devices. This approach is common in scenarios where the focus is on maximizing light coupling efficiency and increasing the packaging density. The compatibility of the optical fiber shell materials (cladding, primary coat) which are usually made from glass, silicon and silica, enables using reliable welding solution (via UPS laser welding) to bond the fibers together and to the interconnect ceramic packaging structure.

Where are you standing?

In the quest to conquer the realm of Quantum Technology, whether you're a titan in the industry or a new-born startup, success demands bold strategies and innovative system architectures. But let's face it—bringing these groundbreaking designs to life requires more than imagination; it demands chip carriers, submounts, and packages built to endure harsh environments while delivering intricate spatial configurations for tailored interconnections.

Here is the challenge: ceramics are a double-edged sword. Their hardness, brittleness, and chemical resistance make them indispensable for advanced applications, but these same qualities turn precision fabrication into a high-stakes game. Unlike metals, ceramics do not play nice when it comes to high-precision machining and structuring. Add to that the need to integrate metallic elements like traces, waveguides, or signal carriers into the mix, and you are looking at a technological puzzle with no easy solutions. And do not forget the fast-paced nature of quantum tech—scientists and engineers need rapid prototyping to test and refine multiple

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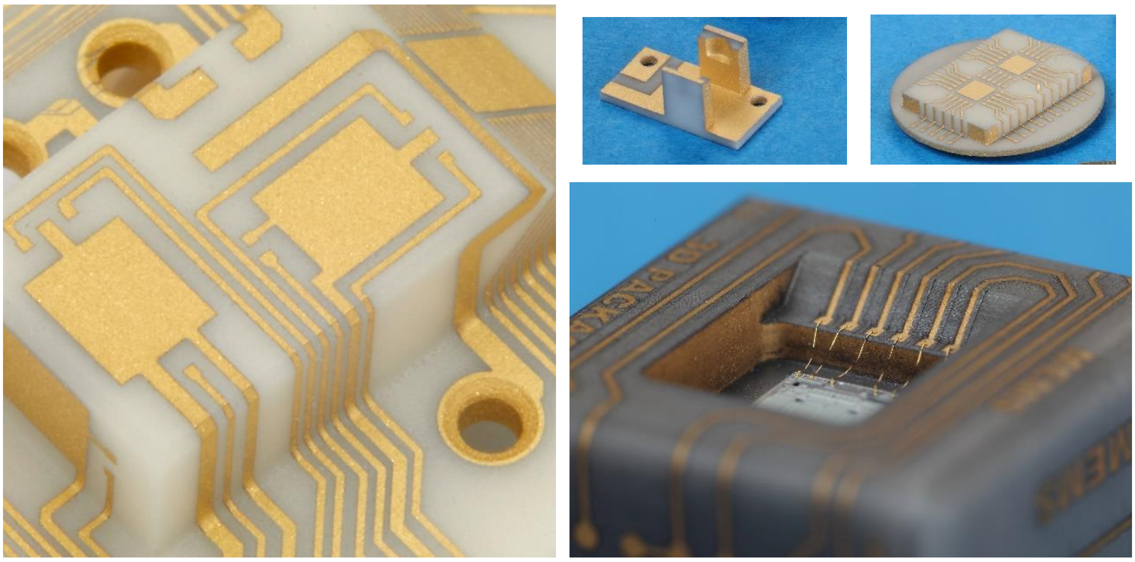
[16] Penilla, E. H., Devia-Cruz, L. F., Wieg, A. T., Martinez-Torres, P., Cuando-Espitia, N., Sellappan, P., Kodera, Y., Aguilar, G., & Garay, J. E. (2019). Ultrafast laser welding of ceramics. Science, 365(6455), 803–808. https://doi.org/10.1126/science.aaw6695

designs. Conventional fabrication methods simply cannot keep up with the demands of this ambitious field.

At Microcertec, we have stepped up to meet these challenges head-on with our unique CI3D fabrication technology. This innovative fabrication process allows us to create fully customized 3D hybrid ceramic-metal devices, including interconnects, antennas, and photonic chips, using any type of advanced ceramic or metal material. Our state-of-the-art production line combines traditional techniques like rectification with cutting-edge tools such as layer deposition, ultrasonic micromachining, pulsed laser ablation, and even ceramic 3D printing. With over 50 years of experience, we have delivered micron-scale precision solutions for industries working in ultra-high vacuum and extreme low-temperature environments.



From compact, high-density device integration to precise alignment of optoelectronic and microelectronic systems, we have been the innovation partner for startups and global players alike. As quantum technologies continue to evolve, so does our role as a trusted ally, accelerating progress and shaping the future.

So, while you're out there crafting the “Darksaber” of quantum innovation, rest assured that we're the “Armorer”, forging the ceramic armor that shields your vision and makes it reality.