Thin Films in Quantum Technology: Demands and Opportunities

A Thesis

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by

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Certificate

This is to certify that this dissertation entitled "Thin Films in Quantum Technology: Demands and Opportunities" submitted towards the partial fulfilment of the Master of Science in Quantum Technology represents study/work carried out by Nived Murali from Indian Institute of Science Education and Research Pune under the supervision of Dr. Vidur Raj (CEO, Quanastra Pvt. Ltd.) during the academic year 2025–2026.

Signature of Supervisor (Dr. Vidur Raj) Date: 21-04-2026

Signature of Advisory Member (Prof. Umakant D. Rapol) Date: 18 May, 2026

Declaration

I hereby declare that the matter embodied in the report entitled “Thin Films in Quantum Technology: Demands and Opportunities” are the results of the work carried out by me at the Quanastra Pvt. Ltd. under the supervision of Dr. Vidur Raj (CEO, Quanastra Pvt. Ltd.) and the same has not been submitted elsewhere for any other degree.

Signature of the Author (Nived Murali) Date: 24\04\2026

Abstract

As quantum technologies transition from fundamental theory to industrial applications, the quality and accessibility of high-end thin films have emerged as a primary determinant of hardware performance. To highlight the critical role of high-end thin films in current and emerging quantum technologies and prepare the future Indian quantum technology ecosystem to be ready and capable, this research identifies different applications where thin films are currently used at lab scale. This will allow us to make future proof technological readiness level, which will drive the thin-film industry when quantum technology is adopted at large scale.

To achieve this, we identified 700+ leading experimental quantum technology researchers and groups across 34 countries and reached out to them for their inputs on the research that involves the use of thin films. This report maps the global demand, technical requirements(like thickness, roughness and materials) and systemic bottlenecks (including equipment reliability, supply chain latency, human capital, etc.) within the thin film landscape, based on the 59 expert inputs received. Through these inputs, we showcase the dependency of quantum technologies on high-end thin films and provide actionable insights for policymakers, industry and research institutions to align the Indian thin film ecosystem for the upcoming quantum age.

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നന്ദി!

This thesis is dedicated to:

My beloved Mother who always believed in me.

സമർപ്പണം:

എന്റെ കഴിവുകളിൽ എന്നേക്കാളേറെ വിശ്വാസമർപ്പിച്ച എന്റെ പ്രിയപ്പെട്ട അമ്മയ്ക്ക്...

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Chapter 1

Introduction

Quantum technology uses the fundamentals of quantum physics to push the boundaries of computation, communication, and sensing. Technologies such as lasers, modern transistors, and electron microscopes are all examples enabled by quantum physics. However, these are often referred to as first generation quantum technologies, where quantum effects are used collectively, without directly controlling individual quantum states.

More recent or the second generation quantum technologies are different. They are based on three foundational principles of quantum mechanics: superposition, entanglement, and quantum interference. While the older quantum technologies relied on the combined behavior of quantum systems, today's quantum technologies directly exploit these fundamental principles, enabling performance levels that were once thought to be impossible. The second quantum revolution has opened doors to materialization of many new technologies based on the laws of quantum physics. This includes quantum computers, quantum enabled secure communication and quantum sensors with unprecedented measurement capabilities.

The whole world is racing to be the first to have the quantum advantage. Industries, and government researchers around the world are all a part of this. The quantum industry is expected to grow from a 6-7 billion dollar industry to approximately 97 billion dollar industry by 2035 according to Quantum Technology Monitor 2025, McKinsey [1]. That is a 14x growth factor in 10 years.

Many countries have recognized the potential of quantum technology and are investing in it to develop computing, communication, and sensing capabilities. This includes both government and private sector research investments. The Indian government also launched the National Quantum Mission (NQM) in 2023 to ensure India's progress in the field of quantum technology. However, realizing quantum technologies from quantum computing and sensing to secure communication demands bridging theoretical promise with practical viability. Key challenges include decoherence (loss of quantum superposition due to environmental interactions), noise (fluctuations in qubit states) and scalability. The first two can be often traced to atomic scale imperfections and thin film defects like grain boundaries or pinholes [2]. This makes high end thin films an important player in quantum technologies. The ability of thin films to manipulate dimensionality, transforming bulk materials into 2D systems and allowing for the fine tuning of density of states and quantum confinement effects is what makes it suitable to be applicable in quantum technologies. Atomically smooth thin films with minimal defects are proven to be enhancing coherence times in thin-film Josephson junctions [3]. They enable hybrid platforms like oxide heterostructures for Majorana fermions [4], solid state quantum memory /emitter platforms [5] and many more.

As quantum tech matures, thin films will remain indispensable. This demands a detailed study on the thin films used in quantum technologies. From academic research papers published recently, we identified over 90 thin films used in the different domains of quantum technologies including quantum computing, quantum communication and quantum sensing. This by no way is a comprehensive list, but it does show the importance of thin film for the future of quantum technologies. They have been tabulated along with their respective references.

To understand more about the trends in thin film used in quantum technologies, expert inputs from leading quantum technology researchers around the globe were collected. We were able to identify major thin film materials used, distribution of thickness and roughness tolerance of the thin films required by the researchers, major bottlenecks faced, etc. This information can be used to know about the future trends in the thin films used in quantum technology and help us achieve future proof technological readiness level, which will drive the thin film industry when quantum technology is adopted at large scale.

Chapter 2

Background / Literature Review

2.1 Introduction to Quantum Technologies

Quantum technology utilizes the fundamentals of quantum physics to perform tasks that are beyond the capabilities of classical systems. It can enable new and better capabilities in computation, communication, and measurement systems by leveraging principles of quantum mechanics like superposition, entanglement, and quantum interference.

Superposition is the ability of a quantum particle or system of being in multiple states simultaneously. For example, particles like electrons do not exist in one single spot. Instead, they behave like waves. They exist in a cloud of probability, occupying every possible position and state simultaneously. This weird ability fuels the quantum computers to achieve exponential algorithmic speedup [6].

Entanglement is the phenomenon where the state of two or more quantum particles become correlated or codependent regardless of their spatial separation. In quantum technology, this property of quantum particles is used for secure communications and powerful quantum computing operations [6].

If superposition is about having many options and entanglement is about how options connect, quantum interference is how we can manipulate these options. Quantum interference is what happens when the probability waves of a particle interact with each other. We can use this to our advantage for amplifying the correct answers and suppress the incorrect one by increasing or decreasing the probability of quantum states by constructively or destructively interfering the probability waves of quantum states.

Other than these, phenomena like quantum tunnelling, where quantum particles can “tunnel” through barriers that would be impenetrable in the classical world are also used in many quantum technologies [7].

These above discussed principles act as the pillars which support the various kinds of quantum technologies. Even though there are many subfields, quantum technology encompasses mainly three verticals. That is, quantum computing, quantum communication and quantum sensing [1]. Some of the other subfields of quantum technologies are quantum devices, software&algorithms, optics and photonics [8, 9]. Below we discuss some of these.

2.1.1 Quantum Computing

The idea of quantum computing was originally put forward by Feynman in a talk in 1981 [10] where he proposed building a new computer using quantum principles to simulate nature accurately. In 1994, a mathematician named Peter Shor published a paper [11] that instantly garnered attention to the security consequences of a quantum computer. It showed that the Rivest-Shamir-Adleman (RSA) encryption [12] that encrypts much of our data can be decrypted by using quantum algorithms in a very short time. Currently, our data is secured because the multiplication of large prime numbers is very easy to do but factoring it is extremely difficult. Shor's paper showed that a quantum algorithm could quickly factor large prime numbers, potentially putting much of the world's encrypted information at risk. Quantum computing has also been proven to have an advantage in solving many complicated optimization problems that are currently impossible for classical computers [13].

Quantum computers use quantum bits, or qubits. Unlike classical bits which can be either 0 or 1, a qubit can be in either a state, or a superposition of both. And also the quantum states of individual qubits can be entangled with each other [6]. These properties of qubits are what makes quantum computing superior to classical computing. But, these qubits are very fragile. Material/fabrication impurities or a stray electric/magnetic field or even a temperature fluctuation can accelerate decoherence, where qubits lose their quantum state prematurely [14]. A solution is to create error corrected qubits that can fix qubit errors. And for this error correction, we need to scale up the number of reliable qubits very much.

Industry, universities, and government researchers around the globe are racing to make more reliable and stable qubits and build electronics and laser systems supporting it. And they are experimenting with many types of qubits [6], out of which some popular qubit types and notable players in those fields are listed below.

Table 2.1: Overview of Leading Qubit Platforms

Qubit type	Description	Notable Players
Superconducting [15]	Artificial atoms made from superconducting circuits using Josephson junction. Quantum states are manipulated using microwave rf pulses. Allows for many different qubit designs (transmon, fluxonium, etc.)	IBM, Google, Rigetti
Trapped ion [16]	Electrically charged atoms are trapped using electric or magnetic fields. Qubits are controlled and measured with laser lights and electromagnetic fields. They have longest coherence times, and allow for high precision/fidelity.	IonQ, Quantinuum
Neutral atom [17]	Uncharged atoms are held together using optical tweezers (lasers). Quantum states are controlled and measured with laser lights and electromagnetic fields. Highly scalable to thousands of qubits and allows for flexible geometry.	QuEra, Pasqal
Semiconducting [18]	Electron charge or spin is trapped in a semiconductor nano structure like quantum dots. Quantum states can be controlled and measured using electrical gates or electromagnetic fields. Leverages existing chip factories.	Intel, Diraq
Photonic [19]	Particles of light (photons) are used to encode quantum information in their polarization, time of arrival, number of photons, or wavelength. Devices like beamsplitters and single photon detectors are used to measure and control the encoded quantum states.	PsiQuantum, Xanadu
Topological [20]	Exotic quasiparticles called Majorana fermions are example of topological qubits. Encodes quantum information by braiding quasiparticles, helping to protect them from outside disturbances. The states would be controlled and measured using magnetic and electric fields.	Microsoft

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Table 2.1 – continued from previous page		
Qubit type	Description	Notable Players
Colour Centers [21]	A Nitrogen atom replaces a Carbon atom in a diamond lattice, creating a vacancy with a trapped electron (N-V Center). Information is encoded in the electronic spin. States are controlled with light and microwaves.	Quantum Diamond Tech, Element Six

Many variants of each of the qubit types discussed above are currently under investigation and researchers around the world are still trying to figure out the best one, and which could become a fully scalable useful quantum computer. Some of these qubit variants that are being researched are listed below.

Table 2.2: Qubit Types and Specifications

Qubit Category	**Specific Qubit Type**	**Specification**
Superconducting	Transmon [22]	A charge based qubit that uses a large shunt capacitor to become significantly less sensitive to electrical noise [23].
	Xmon [24]	A variant of the Transmon with a cross-shaped geometry that allows for easy coupling to multiple neighbours in a 2D grid [24].
	3D Transmon [25]	A Transmon qubit placed inside a large 3D microwave cavity to shield it from the environment and dramatically extend its coherence or lifespan.
	Gatemon [26]	A Transmon where the junction is made of a semiconductor nanowire, allowing you to tune the qubit frequency with a voltage gate instead of magnetic flux.
	Inductively Shunted Transmon (IST) [27]	A design that adds an inductor to a Transmon circuit to suppress noise while maintaining a simple, scalable structure.

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Qubit Category	Specific Qubit Type	Specification
	3-JJ flux qubit [28]	A loop with three Josephson junctions that uses the direction of circulating current to store information, offering high anharmonicity for fast operations.
	C-shunt flux qubit [29]	A flux qubit with an added capacitor that reduces its sensitivity to magnetic noise without losing its high performance.
	Fluxonium [30]	A qubit that shunts a junction with a very high-inductance (superinductor), resulting in exceptionally high coherence and clear state separation.
	0-Π Qubit [31]	A complex circuit designed so that the 0 and 1 states never overlap, theoretically making the qubit immune to almost all local noise.
	Unimon [32]	A newer design that uses a single Josephson junction in a specific grounded loop to achieve high anharmonicity and high fidelity across a wide frequency range.
	Blochnium [33]	Uses an extremely high-inductance shunt (a superinductor) to protect against flux noise in a way that allows it to exploit Bloch oscillations.
Trapped ion	Hyperfine [34, 35]	Uses two ground-state hyperfine levels of an ion with non-zero nuclear spin.
	Optical [36]	Use narrow optical transitions; they are faster to control but slightly more fragile than hyperfine.
Neutral atom	Rydberg qubits [37]	Atoms excited to high-energy states where they puff up, allowing for massive interactions.
	Dual-species arrays [38]	Using two different atoms (e.g., Rubidium and Cesium) so one can be a "data qubit" and the other a "helper" that doesn't disturb the data.

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Qubit Category	**Specific Qubit Type**	**Specification**
	Alkaline-earth qubits [39]	Uses clock transitions for extreme stability.
Semiconducting	Single-spin qubit [40]	Information is encoded in the spin of an electron trapped in a quantum dot.
	Donor spin qubit [41]	Uses valence electrons of atoms in substrate as qubits. Eg: P-31 in silicon.
	Hole spin qubits [42, 43]	Uses the “absence” of an electron (a hole) to encode information.
	Singlet-triplet spin qubit [44]	Information is encoded using two electrons in a double quantum dot in their spin orientations.
	Exchange-only spin qubit [45]	Uses three electrons to perform gate operations with exchange interactions.
	Andreev Spin [46]	A hybrid qubit where we use Andreev bound state to trap a single electron spin formed at the junction between a superconductor and a semiconductor.
Topological	Majorana [20]	Encodes quantum information by braiding quasiparticles exotic quasiparticles called Majorana fermions.
Photonic	Dual-rail (Path) qubit [47]	Encodes information by the presence of a single photon in one of two separate spatial paths or waveguides.
	Polarization qubit [47]	Information is encoded in the polarization (oscillation direction of the light wave) state of the light.
	Cat qubits [48]	Qubits that encode information in special ”Schrödinger’s cat” states within a cavity, providing built-in protection against bit-flip errors.
	GKP qubits [47]	Qubit is encoded in a grid-like state of a light field that can automatically correct for small errors in phase and amplitude.

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Qubit Category	**Specific Qubit Type**	**Specification**
	Squeezed State qubit [47]	Uses squeezed light to reduce noise in one variable (like position) to near zero, forming the basic resource for Gaussian quantum computation.
	Cluster state qubits [47]	Network of entangled photons where the computation is performed by measuring the photons one by one.
Colour centers	Nitrogen-Vacancy (NV) Center [21]	A Nitrogen atom replaces a Carbon atom in a diamond lattice, creating a vacancy with a trapped electron (N-V Center). Information is encoded in the electronic spin.
	hBN Color Centers [49]	Defects in hexagonal Boron Nitride (like a missing Boron atom) act as artificial atoms that can emit single photons at room temperature.
	Silicon-Vacancy (SiV) Center [50]	A silicon atom is split between two empty carbon sites in the diamond lattice.
	Tin-Vacancy (SnV) [51]	A single tin (Sn) atom replaces two carbon atoms in the diamond lattice.
	Silicon Carbide (SiC) Divacancy [52]	A missing silicon atom next to a missing carbon atom in a SiC crystal.
Molecular	Rare-Earth Molecular Qubits [53]	Molecules featuring ions like Erbium or Ytterbium that can emit light at telecom-band frequencies.
	Transition-Metal [54]	Uses ions like Vanadium V^4+ or Copper Cu^{2+} surrounded by organic ligands that act as a protective cage, allowing for high-speed microwave control.
Others	Graphene spin [55]	Uses the spin of an electron trapped in a graphene quantum dot.

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Qubit Category	Specific Qubit Type	Specification
	Twistronics [56]	By stacking two layers of 2D materials and twisting them at a "magic angle," a giant "Moiré" interference pattern is created. This pattern acts as a natural array of thousands of tiny quantum dots.
	TMDC valley [57]	Materials like MoS_2 have unique valleys (momentum states) that can store quantum information.
	Acoustic (Phononic) qubits [58]	Uses sound or vibrations to encode the quantum information.
	Skyrmion qubit [59, 60]	Information is stored in the quantum degree of helicity. The logical states can be adjusted by electric and magnetic fields, offering a rich operation regime with high anharmonicity.

Although still in early development, quantum computers are already demonstrating promise in areas such as cryptography [61], drug discovery [62], optimization by solving problems in logistics, finance and supply chains [63] as well as artificial intelligence and machine learning [64].

2.1.2 Quantum Communication

Quantum communication encodes information into qubits, usually photons in the form of polarization, phase or arrival time, which will provide better security and network capabilities beyond classical communication. It began with the publication of the BB84 protocol for quantum key exchange by Bennet and Brassard [65], followed by Ekert, who introduced the use of entangled qubits into quantum key distribution (E91 protocol) [66]. In quantum communication, the presence of an eavesdropper is easy to detect since whenever an eavesdropper tries to intercept and read, it would cause the qubit to lose its initial state. In addition, the no-cloning theorem [67] makes it impossible to create an independent and identical copy of an arbitrary unknown quantum state ensuring that no one can copy this information without disturbing the qubit state. This provides one with secure communication in the quantum way.

Quantum communication is not only just about the qubits themselves. It requires specialized hardware stacks to realize and control them physically. Devices such as single photon sources, entangled photon pair generators, quantum grade fibre optics, free space optical links, single photon detectors etc. are all essential components for a practical quantum communication system [68].

Quantum communication can be used to distribute encryption keys securely between classical devices or to enable secure access to remote quantum computers. It can also be employed to interconnect quantum sensors, allowing correlated measurements and enhanced sensitivity over large areas (for example, synchronizing clocks within a communication network [69]). An extension of quantum communication is quantum network where it is envisioned that quantum communication may be used to network quantum computers so they can efficiently exchange data and pool computational power [70]. An extended quantum network leads to a quantum internet, which in addition requires quantum repeaters since qubits can be lost in the fiber optic cables over a long distance [71]. Quantum repeaters do not work like classical repeaters due to the no-cloning theorem. They use entanglement swapping and distillation and need to store qubits in quantum memory units.

Several countries have advanced quantum communication systems. China has already implemented carrier-grade quantum communication networks over 10000 km called the China Quantum Communication Network (CN-QCN) [72] and Europe is building a continent wide quantum secure infrastructure integrating terrestrial and satellite segments through a programme called European Quantum Communication Infrastructure (EuroQCI) [73]. In India, DRDO & IIT Delhi has demonstrated a quantum entanglement based free space quantum secure communication over more than 1 km distance [74]. The United States [75], South Korea [76] and many other countries also have advanced national or regional QKD and quantum safe network testbeds, making them also key players in this field.

2.1.3 Quantum Sensing

Quantum sensing makes use of quantum particles such as photons or atoms as sensing elements. They are used as devices which can detect extraordinarily small changes in physical quantities such as magnetic fields, time, temperature, rotation, gravity, electromagnetic spectra, etc.

One of the well known examples for quantum sensing is atomic clocks [77], which have been around for a long time. They use characteristic transition frequency in the electromagnetic spectrum of atoms as a standard. Other quantum sensing devices include atom interferometry based gravimeters and gyroscopes [78]. Magnetic field sensors based on Nitrogen Vacancy (NV) centers in diamonds [79], superconducting quantum interference device(SQUID) sensors [80], optically pumped magnetometers (OPMs) [81] which are sensitive enough to detect changes in single nerve cells, Electric field sensors using Rydberg atoms in highly excited state(super atoms) [82], superconducting nanowire single photon detector(SNSPD) [83], quantum radio frequency (RF) sensors [84], etc. Many measurement standards have been also redefined using quantum enabled high precision measurement like Josephson junctions (using quantum tunneling), which provide highly stable voltage standards and the quantum hall effect (QHE) defining resistance standards [85].

The current research integrates quantum sensing into fields such as healthcare for more sensitive and high resolution medical imaging [86], GPS free navigation using quantum inertial sensors [87], mapping underground resources or structures using quantum gravimeters [88] and for many defense purposes like detecting stealth submarines, quantum radar for stealth detection, and many more [89].

2.2 National Quantum Mission (NQM)

The whole world is racing to be ready when the 'Q-day' arrives. The day when quantum systems break classical encryption and unlock utility-scale applications. Quantum Technology is expected to grow to a 97 billion dollar market within 10 years [1]. As a part of this, the Government of India launched the National Quantum Mission as an initiative to foster quantum technologies related scientific and industrial research and development. The Union Cabinet, approved the National Quantum Mission (NQM) on 19th April 2023 with a budget of Rs.6003.65 crore from 2023-24 to 2030-31. The mission aims to seed, nurture and scale up scientific and industrial R&D while creating a vibrant and innovative ecosystem in Quantum Technology. This will accelerate a quantum technology led economic growth, strengthen the national ecosystem, and position India as one of the leading nations in quantum technologies and applications. The Mission objectives include [90],

- Developing intermediate-scale quantum computers with 50-1000 physical qubits in 8 years in various platforms like superconducting and photonic technology.
- Satellite-based secure quantum communications between ground stations over a range of 2000km within India.
- Long-distance secure quantum communications with other countries.
- Quantum key distribution between cities over 2000km.
- Multi-node quantum networks with quantum memories.
- Developing magnetometers with high sensitivity in atomic systems, atomic clocks, single photon sources/detectors, and entangled photon sources.

- Supporting the design and synthesis of quantum materials such as superconductors, novel semiconductor structures, and topological materials for the fabrication of quantum devices [90].

NQM has established four thematic hubs across the country, each focusing on a key area of quantum technology research providing activities including technology development, human resource development, entrepreneurship development & industry collaboration and international collaborations. The Defense Research and Development Organization (DRDO) and Indian Institute of Technology (IIT), Delhi have demonstrated quantum entanglement based free space secure communication over 1km distance at IIT Delhi campus [91].

Also state-of-the-art fabrication and central facilities are being established at premier institutions like IISc Banglore, IIT Kanpur, IIT Bombay, and IIT Delhi for indigenous quantum hardware development which will focus on providing access to researchers from academia, startups, industry and strategic sectors under defined governance and utilization frameworks coordinated through the Mission and the respective host institutions [91].

Chapter 3

Thin Films in Quantum Technologies

Thin films, layers of materials just nanometer thick, show extraordinary physical properties which could be useful for a vast array of technological applications. From highly reflective optical mirrors and solar cells to microelectronics, we cannot even think about modern life without them. Their tunable optical, electrical, and magnetic behaviours also drive fundamental research in condensed matter physics. The ability of thin films to manipulate dimensionality, transforming bulk materials into 2D systems and allowing for the fine tuning of density of states and quantum confinement effects is what makes it suitable to be applicable in quantum technologies. Thin films can be said to be one of the absolute necessities in most quantum technologies. Many varieties of materials are used as thin films in every technology by researchers around the globe to achieve better capabilities. In this chapter we will see the applications of thin films in the many different types of quantum technologies that are currently going on.

3.1 Quantum Computing

3.1.1 Superconductor based Quantum Computing

Superconducting qubits are electronic circuits comprising lithographically defined Josephson tunnel junctions, inductors, capacitors, and interconnects [92]. Superconducting thin films, such as those made from Niobium, Aluminium, Tantalum, etc., form the basis for the qubit circuit. Josephson junction, the nonlinear inductor at the heart of the qubits are fabricated using ultra thin superconducting films separated by a tunnel barrier. Thin films capping layers are used to prevent native oxide formation which otherwise causes dielectric losses and decoherence. High-quality thin films minimize defects, impurities, and surface oxides that cause decoherence, improving coherence times (T1) by reducing two level system (TLS) losses and flux noise [93].

Table 3.1: Thin-Film Materials for Superconducting Qubit Components

Qubit Component	**Thin Film Material**	**Research Reference**
Ground Plane / Capacitor	Tantalum (Ta)	[94, 95]
	Aluminum (Al)	[96]
	Niobium (Nb)	[97]
Josephson Junction	TiN / AlN / TiN	[98]
	NbN/AlN/NbN	[99]
	$Al/AlO_x/Al$	[100]
Weak Link (SIT)	Niobium Nitride (NbN)	[101]
	Niobium titanium nitride (NbTiN)	[102]
	InGaAs/InAs 2DEG	[103]
Superinductance	Tungsten Silicide (WSi)	[104]
	NbTiN	[105]
	Granular aluminium (grAl)	[106]
Resonator	Tantalum (Ta)	[107]
	TiN	[98]
	NbTi	[108]
	Al	[109]
	Nb	[110]
Hybrid Capacitor	$NbSe_2$ / hBN	[103]
Surface Protection	Magnesium (Mg)	[111]
	Ruthenium (Ru)	[112]

3.1.2 Ion Traps based Quantum Computing

Thin films play a very critical role in trapped ion qubits by forming the multilayer electrodes, dielectric insulators, and integrated photonic structures in microfabricated surface ion traps. The uniformity of thickness of thin metal film plays a crucial role in the ion confinement by generating precise electric fields.

Table 3.2: Thin-Film Materials for Ion Trap Components

Trap Component	Thin Film Material	Research Reference
RF/DC Electrodes	Au/Ti	[113, 114]
	AlCu/TiN	[113, 114]
Dielectrics	SiO_2, SiN_x	[115]
Sacrificial Layer	Copper (Cu)	[115]
Transparent Electrodes	ITO, $LiNbO_3$	[116, 117]

3.1.3 Neutral Atoms based Quantum Computing

In neutral atom quantum computing, thin films are primarily used in photonic and electro-optic components for optical tweezer arrays and laser control. High end thin films like silicon nitride (Si3N4) enables the precise handling of the atoms and reduces losses.

Table 3.3: Thin-Film Materials for Neutral Atom Tweezer Array Components

Component	Thin Film Material	Research Reference
Tweezer Array	Silicon nitride (Si_3N_4)	[118]
	Titanium dioxide (TiO_2)	[119]
Optical Mask	Gold (Au) / Germanium (Ge)	[120]

3.1.4 Semiconductor based Quantum Computing

Semiconductor qubits, such as those based on silicon quantum dots or donor spins, rely on thin films for precise heterostructure formation, gate dielectrics, electrodes, and passivation to enable spin or charge qubit operations. The quantum well which traps the qubits are made by precise heterostructure formation of thin films, enabling valley splitting and longer coherence time while reducing the nuclear spin noise. The ultra thin dielectric layer enables the tunable quantum dot while minimizing charge traps and the protective cap layer prevents oxidation and interface defects.

Table 3.4: Thin-Film Materials for Semiconductor Spin Qubit Components

Layer / Component	**Thin Film Material**	**Research Reference**
Qubit Host	Si/SiGe	[121, 122]
	Zinc Oxide (ZnO)	[123]
Gate Oxide Stack / Dielectric	HfO_2/SiO_2	[121, 122]
	AlO_x	[123]
Gate Metal	Titanium Nitride (TiN)	[122]
	Ti/Au	[123]
Cap Layer	Amorphous Si-rich	[121]

3.1.5 Topological Qubits

Thin films are vital in topological qubits, which leverage Majorana zero modes (MZMs) for fault-tolerant quantum computing, as they enable epitaxial heterostructures of topological insulators, semimetals, or semiconductors proximitized by superconductors to host non-Abelian anyons at engineered defects or edges.

Thin films of topological insulators like Bi2Se3 proximitized by Al s-wave superconductors induce p-wave-like pairing at interfaces, opening topological gaps for MZMs in vortices or wire ends. At the same time, the semiconductor thin films with spin-orbit coupling, magnetic insulators, and superconductors form hybrid stacks mimicking Kitaev chains [124].

Table 3.5: Thin-Film Materials for Topological Qubit Components (Majorana Platform)

Component / Material	**Thin Film Material**	**Research Reference**
Topologically Protected Surface States	Bi_2Se_3 (bismuth selenide)	[125]
Superconducting Nanowire Strip	Aluminium (Al)	[20]
Semiconductor 2DEG / Interfacial Layer	Indium Arsenide (InAs)	[20]

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Table 3.5 – continued from previous page		
Component / Material	**Thin Film Material**	**Research Reference**
Gate Dielectrics	HfO_2 or Al_2O_3	[20]
Normal Contacts	Ti/Au	[20]

3.1.6 Skyrmion Qubits

Skyrmion qubits are part of the emerging field of spintronics. To create a skyrmion, you need a very specific magnetic interaction called the Dzyaloshinskii-Moriya Interaction (DMI). This force "tilts" magnetic spins rather than letting them point in the same direction. Thin films are crucial for skyrmion qubits, as DMI occurs at the interface between a ferromagnetic thin film (like Cobalt) and a heavy metal thin film (like Platinum or Tungsten) [59].

Table 3.6: Thin-Film Materials for Skyrmion Qubits and Magnonic Interconnects

Technology Type	**Thin Film Material(s)**	**Reference / Research Basis**
Skyrmion Qubit	Pd/Fe/Ir	[126]
	Co/Pt	[127]
	Mn_4N on MgO	[128]
	W/CoFeB/MgO	[129]
Magnonic Interconnect	Yttrium iron garnet (YIG)	[130]

Thin films are extensively used in many qubit technologies other than that have been listed above like in photonic qubits and NV center based qubits etc. They are discussed in coming parts since the same technologies are used in other areas of quantum technologies like quantum communication, sensing, etc.

3.2 Quantum Communication/Photonics

Quantum photonics on chips are emerging as a new transformative technology. Various photonic components like waveguides, beam splitters, detectors, etc. are integrated onto a single platform. This integrated platform promises unprecedented capabilities over a wide range of applications like building compact and scalable quantum processors for photonic quantum computing, for ultra-secure quantum networks through quantum key distribution in communication and in sensing applications for high precision measurements [131].

Thin film material like Lithium niobate (LiNbO3) is used in integrated photonics, High Performance Electro-Optic Devices, Nonlinear and Quantum Photonics, Acousto-Optic Devices, etc. as waveguides, single-photon source, modulators, frequency converters, and for many other applications. Other than thin film lithium niobate (TFLN), other materials like silicon nitride, amorphous silicon carbide thin films are also used for photonic integrated circuits [131].

Thin films also serve as scalable hosts for single photon emitters (SPEs) in quantum technologies, enabling deterministic emission control via strain, defects, and integration with photonic circuits for on-chip quantum networks [132]. Materials like hBN and WSe2 thin films provide room-temperature, high-purity single photons essential for quantum computing, key distribution and communication [133].

We have already talked about photon sources and components that are used to manipulate these photons. But for a scalable quantum network, we will have to store fragile quantum states, which are photons in this case. This is similar to cache memory in a classical computer's central processing unit, that is as the short-term memory used to increase the speed of the CPU. The device that can take a fragile quantum state, a quantum state encoded onto a single photon and preserve it in time is called quantum memory [134].

Without quantum memory, a quantum network is inefficient. This essential device is physically realized through compact, integrable rare earth ion (REI)-doped thin film platforms like Er/Yb-doped Y2O3, Er-doped TiO2, thin film diamonds carrying defect centers etc. which are compatible with photonic chips for scalable quantum networks.

Components and thin film materials used in quantum communication and photonics related technologies are listed in table below along with their references.

Table 3.7: Thin-Film Materials for Photonic Quantum Components

Component	**Thin Film Material**	**Research Reference**
Photonic PICs	Lithium niobate ($LiNbO_3$)	[135, 136]
	Silicon nitride (SiN/Si_3N_4)	[137, 138]
	Amorphous silicon carbide (a-SiC)	[139]

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Table 3.7 – continued from previous page		
Component	**Thin Film Material**	**Research Reference**
Single Photon Source / Host	WSe_2	[132]
	hBN	[140]
	InGaAs/GaAs	[136]
	$MoTe_2$	[140]
	Tantalum thin film	[141]
	CeO_2	[142]
Superconducting Thin-Film Resonators	Ta, Nb, Al	[143]
Quantum Memory	Diamond Thin Film	[144]
	Er/Yb-doped Y_2O_3	[145, 146]
	Er-doped TiO_2	[147]
	Er-doped CeO_2	[148]
	RE-doped Y_2SiO_5 (YSO)	[149]
	Tm-doped $CaZrO_3$	[150]
	Lithium Niobate	[151]
	YAG	[152]

These Thin film materials are the building blocks of scalable quantum repeaters, photonic chips, and secure networks.

3.3 Quantum Sensing

Thin film superconductors have found critical applications in various advanced technologies. In quantum sensing, they are essential in the fabrication of devices such as superconducting quantum interference devices (SQUIDs), Superconducting Nanowire Single Photon Detectors (SNSPDs), etc.

Superconducting quantum interference devices (SQUIDs), which are used in highly sensitive magnetometers, works using josephson junction, which is fabricated with superconducting thin film material, which is also the heart of superconducting qubits. High-quality superconducting thin films are also important for reproducible critical currents, sharp transitions, and low excess noise, all of which are crucial for reliable SQUID operation [80].

Superconducting Nanowire Single Photon Detectors (SNSPDs) are used for the detection of single photons. Different kinds of superconducting thin films based on nitrides, silicides, excited, rare earth cuprates, etc., are used in the fabrication of SNSPDs [83].

Sensors based on colour centers or defects like NV center in diamonds and Colour Centers in hBN, are sensitive enough to detect the weak magnetic fields generated by human brain (in femtoTesla range) functions by taking advantage of Optically detected magnetic resonance (ODMR). The materials hosting these colour centers are used in thin film form by researchers for improving sensitivity, compatibility with devices, and nanoscale resolution.

Another major type of sensors in quantum sensing are those based on trapped ions which offer atomic precision and entanglement enhanced sensitivity for measuring. They majorly use high end thin films in trap surfaces for generating precise fields for ion manipulation, similar to ion trapped qubits.

Other than all these, thin film materials like Au, Cr, Si are also used as a capping or protection layer for almost all of these sensing devices to protect them from surface oxidation, contamination, and unwanted phase formation in near-surface regions of sensitive materials.

Quantum sensors and varieties of thin film materials used in their fabrication along with references are listed below.

Table 3.8: Thin-Film Materials for Quantum Sensors (NV Centers, SNSPD, SQUID, TES)

Technology Type	**Thin Film Material(s)**	**Reference / Research Basis**
NV Sensor	Diamond Thin Film	[79]
	Quantum sensor-doped polymer films (PVP for FNDs)	[153]
	Silver (Ag)	[153]
Colour Centers in hBN	hBN	[154]
	Quantum sensor-doped polymer films (PMMA for hBN)	[153]
SNSPD	Niobium Nitride (NbN)	[83]
	Niobium Titanium Nitride	[83]

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Table 3.8 – continued from previous page

Technology Type	**Thin Film Material(s)**	**Reference / Research Basis**
	Tantalum nitride	[83]
	Molybdenum nitride	[83]
	Vanadium nitride	[83]
	Tungsten Silicide (WSi)	[83]
	MoSi	[155]
	NbSi	[156]
	MoGe	[157]
	MgB_2	[158]
	NbReN	[159]
	Silicon	[160]
SQUID Magnetometer	Nb/NbN	[161]
	YBCO	[162]
	HfTi	[163]
	Al/AlO_x	[164]
	Pb	[165]
	MgB_2	[166]
	Cr/Au	[166]
TES Bolometer	Aluminum (Al) / Bismuth	[167]
	Mo/Au	[168]
Atomic Vapor Cells	Al_2O_3	[169]
	Cr/Au	[170]
Iontronic Electrode	Gold (Au)	[171]

The analysis of all these emerging quantum technologies confirms that thin film technology is indispensable for a future with better computing, communication, and sensing devices. Whether in the form of superconducting tantalum for long coherence qubits, thin film lithium niobate for high speed photonics, or rare-earth-doped oxides for integrated memories, thin films provide a versatile platform where quantum properties can be engineered with unprecedented precision. By synthesizing quantum materials in thin film form, we not only gain compatibility with established fabrication techniques but also unlock the ability to tune dimensionality and exploit heterogeneous interfaces, paving a clear way for the future quantum technologies.

Chapter 4

Methods

4.1 Searching and identifying researchers

To highlight the critical role of high-end thin films in current and emerging quantum technologies, we planned to reach out to leading experimental quantum technology researchers around the globe and get their inputs about usage of thin films in their ongoing research.

As the process of identifying experimental quantum technology researchers, countries which are leading in different verticals of quantum technology like 'quantum computing, quantum communication and cryptography, quantum materials and devices, quantum sensing and metrology' are identified using the the International Technology Engagement Strategy for Quantum (ITES-Q) [8] strategic framework released by India's Office of the Principal Scientific Adviser on April 14, 2025. We identified 34 such countries including India who are currently frontiers in quantum technology research. Then major institutions from these countries where experimental quantum technology research is identified from websites of quantum technology research hubs in each country or with the help of AI powered search engines.

Then leading experimentalists in quantum technology research were identified and documented along with their affiliation, country, email and research interest. We listed 700 experimental quantum technology researchers which consist of principle investigators, scientists, postdocs working in major quantum technology research groups from 34 countries around the globe.

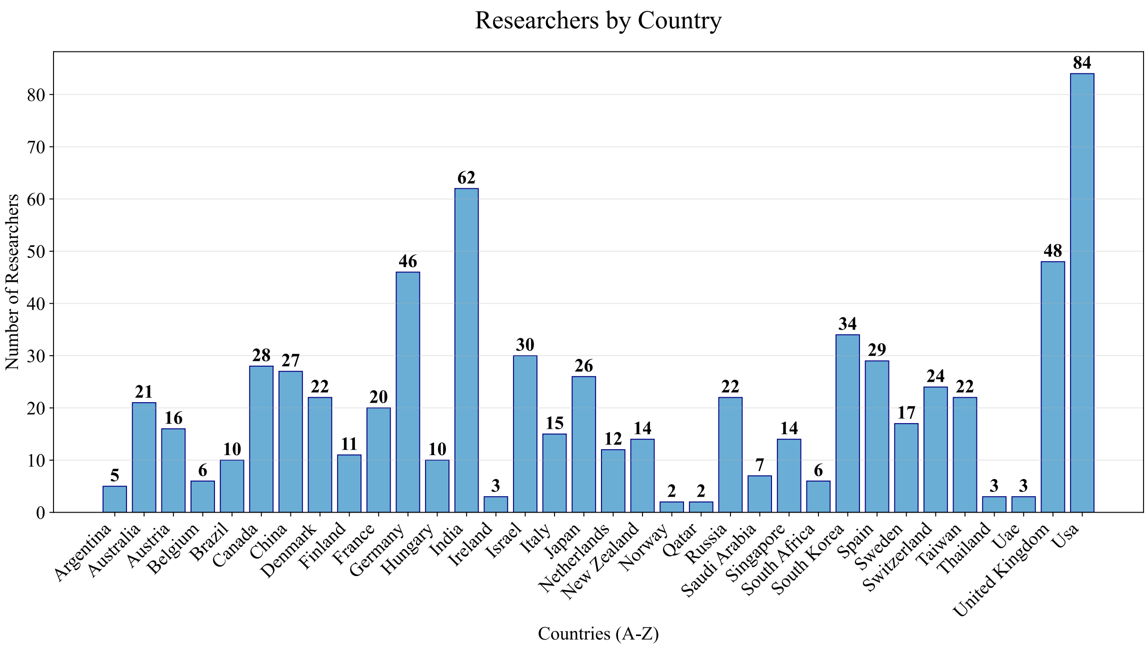

Figure 4.1: Comparison of researchers identified and mailed from each countries

4.2 Collecting inputs from the researchers

The researchers were contacted via email stating the goal and providing them with a google form survey link with the questions. The questions asked in the survey form are listed below;

1. In which area of quantum technology is your research focused?
a) Quantum computing
b) Quantum communication
c) Quantum sensing
d) Quantum materials and devices
e) Other:

2. How necessary are thin films to your research?
a) Absolutely essential
b) Moderately
c) Not at all

3. Which materials do you use for thin film deposition? (Please name any four

most important materials):

4. Film thickness needed:
a) <10 nm
b) 10-100 nm
c) >100 nm

5. Roughness tolerance:
a) <1%
b) 1-5%
c) 5-10%
d) 10-30%

6. What is the ultimate device that comes out of your lab?

7. Where are your thin film deposition processes primarily carried out?
a) In my own lab, using in-house deposition equipment
b) In a shared central facility within my institution
c) At an external commercial facility/service provider
d) I do not perform thin film deposition
e) Other:

8. What are the bottlenecks you face in sourcing or accessing high quality thin films? (cost/technical expertise/delivery time/equipment related, etc.)

The emails were sent to 10-15 recipients every day starting from January first week. This action was also noted in the documents with the details about researchers along with the date of action. The survey responses were frequently checked and the researchers who participated were labelled as replied in the document as well as in the mails.

A short follow up mail was sent to all the researchers who did not respond after a week of the initial mail. An email containing all the questions from the survey form was also sent later to all recipients, since some of the researchers raised security concerns over clicking on an unknown link. This enabled researchers to submit their responses directly through email.

By the end of January, it was noticed that ninety percent of the responses were received either on weekends or holidays according to the timestamps of the responses. Inferring from this information, from that point on, all emails were scheduled to be sent on weekends. This proved to be more effective than before by the number of responses received. All researchers had been contacted by the third week of March. The inputs received through the google form survey form and through emails were compiled.

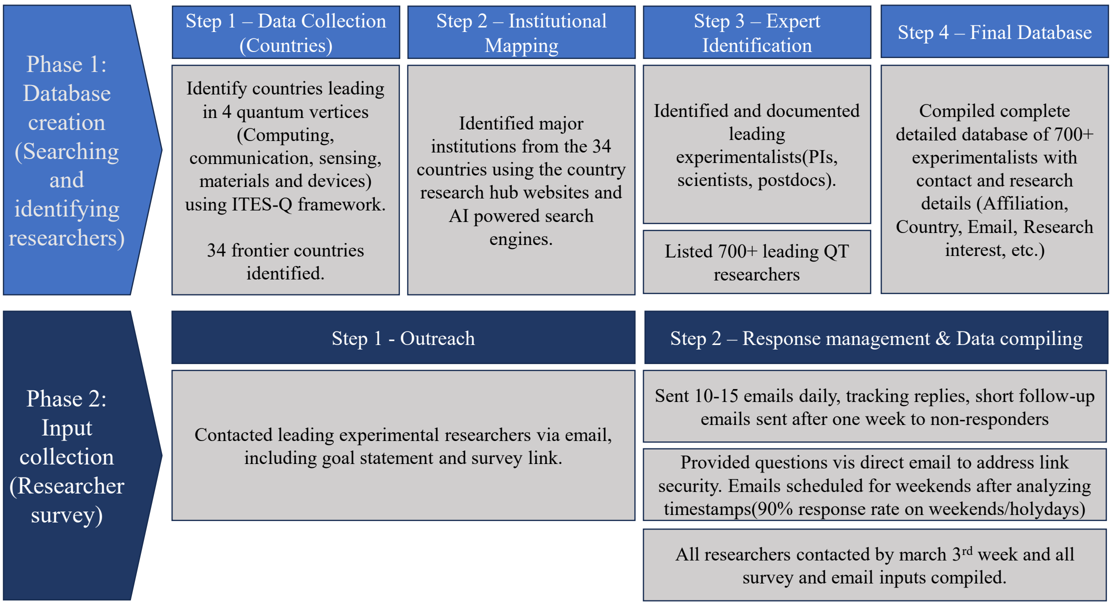

Figure 4.2: Methodology used for identifying, reaching out and collecting data from the researchers worldwide

Chapter 5

Results

5.1 Survey result

5.1.1 Responses from Researchers

A total of 78 researchers around the world responded out of which, 59 researchers participated in the survey regarding the use of thin films in their ongoing quantum technology research from the list of 700 researchers belonging to 34 different countries.

Most responses came from European countries, including the UK, Spain, Germany, Denmark and others. Researchers from countries outside Europe such as India, Australia, Japan, Taiwan and others also made significant contributions to the survey.

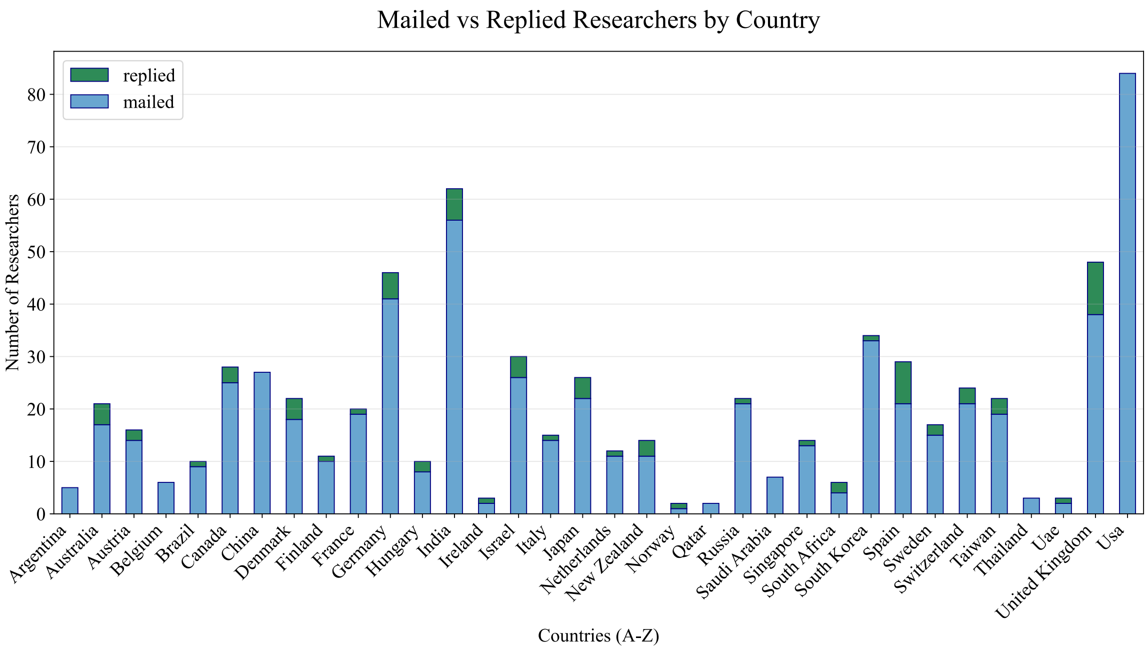

Figure 5.1: Comparison of researchers reached out to and responded with their countries.

Despite reaching out to a large number of researchers, we received no responses from the USA and China, two countries at the forefront of quantum technology research. The reason for this could be due to the researchers receiving a large volume of collaboration and survey requests, and they may selectively respond only to requests that align closely with funding priorities, institutional policies or immediate research interests. It is also notable that most of their quantum technology research is driven largely by state linked institutions with a strong emphasis on strategic priorities and national security. This structure and associated sensitivities around international data sharing and collaboration might have limited researcher's willingness or ability to respond to external outreach.

The researchers who participated in the survey belonged to different verticals of quantum technology like quantum computing, quantum communication, quantum sensing, quantum materials and devices etc. For some researchers their work is spanned to more than one of these verticals. These domains of quantum technology which the respondents belong to are compared with the help of figure, using a pie chart. Our dataset reflects a balanced representation across all the four major quantum technology domains, with each sector contributing at least 17.3% of the total pool. This ensures that our insights are not dominated by a single field but are representative of the broader quantum ecosystem. Figure 5.2 shows this clearly.

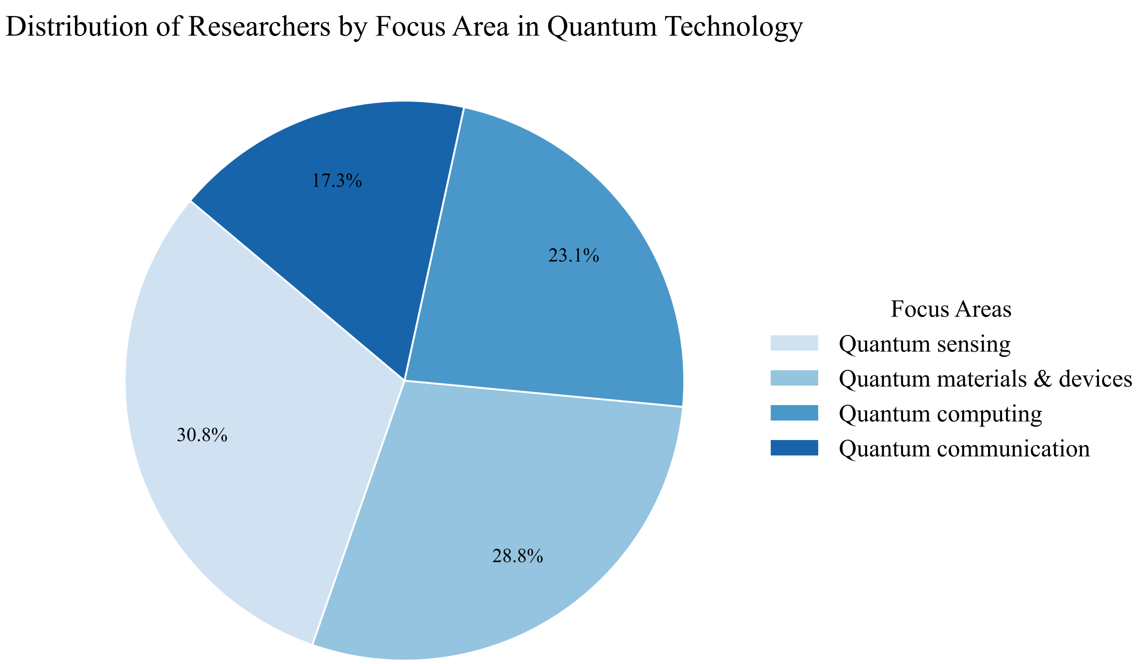

Figure 5.2: Distribution of researchers by focus area in quantum technology.

We have a notably diverse distribution of researchers across domains, ranging from 17.3% to 30.8%. This level of participation across all categories provides a statistically robust analysis.

5.1.2 Necessity of thin films in the quantum technology research

One of the most important questions that the researchers were asked was how necessary thin films are for their research. About two third of the researchers responded that thin films are absolutely essential for their research, one by fifth said thin films are moderately needed for their research and the rest, not at all. This data is plotted as a pie chart in figure 5.3.

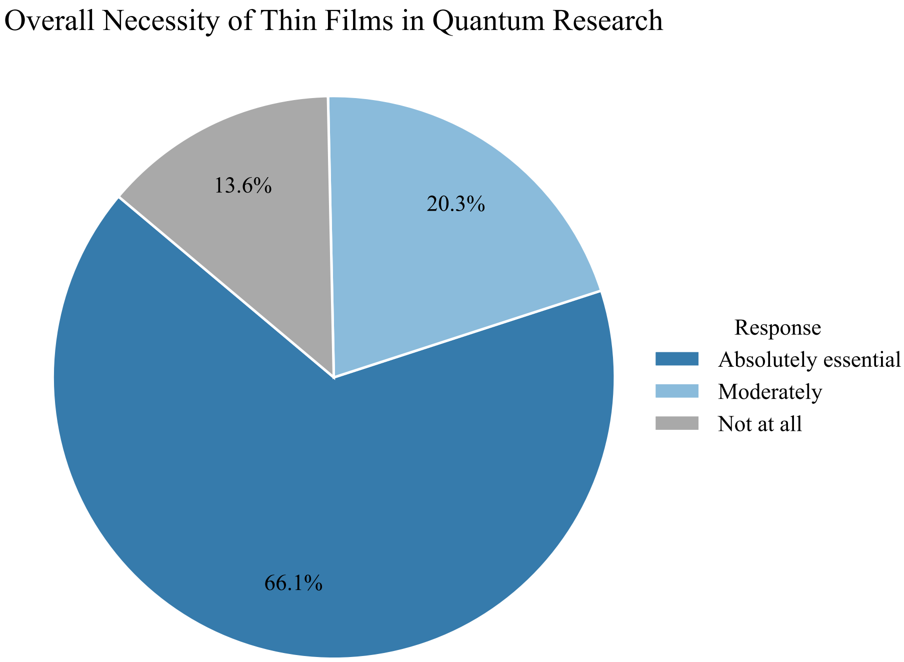

Figure 5.3: Necessity of thin films in quantum technology research: reported by researchers.

We also compared how much the necessity of thin films is for different domains of quantum technology. For this the necessity of thin films is plotted for each of the quantum technology domains as a bar plot and compared in figure 5.4.

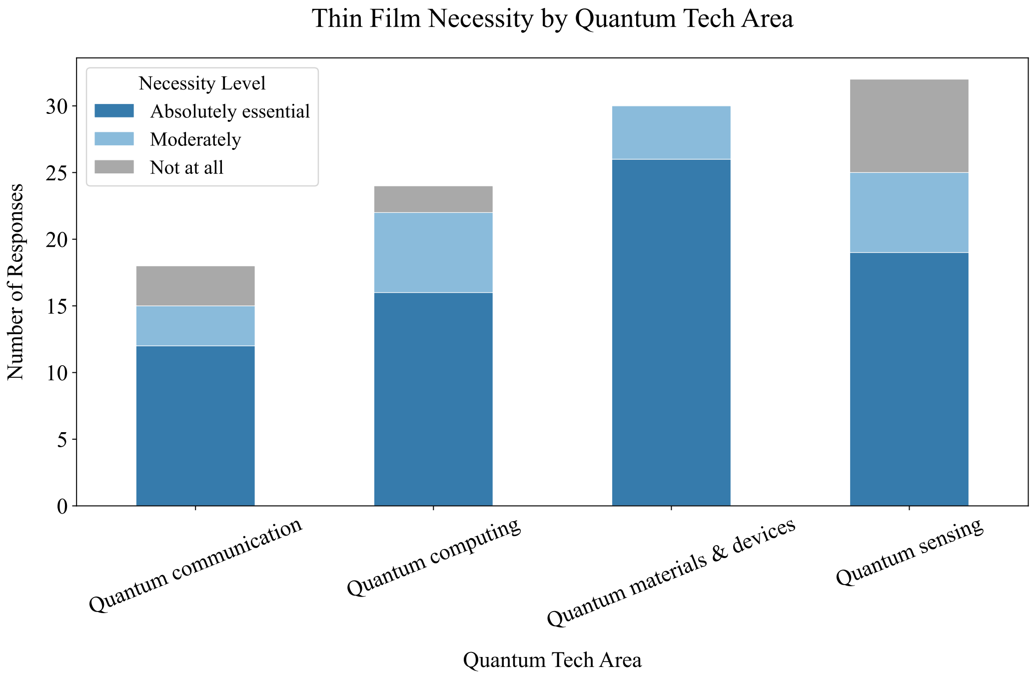

Figure 5.4: Thin film necessity by quantum technology domain.

From figure 5.4, we can see that more than half of all the responses from all of the domains indicate thin films are absolutely essential for them. Whereas in the domain of quantum materials and devices all the responses said they need thin films for their research. The domain which recorded the most responses saying that thin films are not needed for their research at all is quantum sensing. Most of these researchers are noticed to be working related to cold gases, atomic clocks etc.

5.1.3 Required Thin film specifications

We have clustered the specifications about the thin films used by researchers in quantum technology, which consists of information such as required thickness, roughness and materials used for thin films.

The recorded dataset shows that the thin film thickness in the range of 10-100 nanometre is what 47.1% of the experimentalists needed and 27.1% was recorded as need of thin films with less than 10 nanometer thickness.

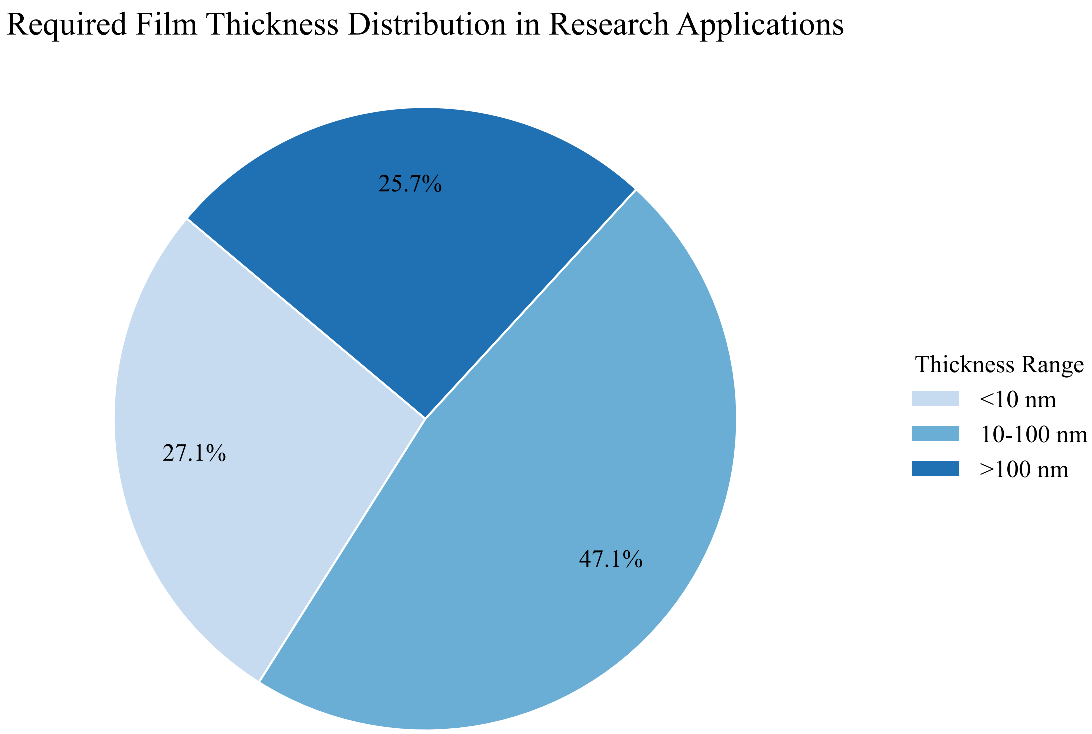

Figure 5.5: Required film thickness distribution in quantum tech research application.

The thin film roughness tolerance or uniformity plays a critical role in quantum technology applications. Thin films with very less roughness tolerance will let you have stable, better and precise control over quantum systems. This is one of the main challenges faced by many experimentalists. Collected data from the researchers are shown in the figure 5.6. We can see that more than one third of the responders (35.1 percent) said that their research includes thin films with less than one percentage of roughness tolerance. This means that the root mean square (RMS) roughness is under 1% of the film's total thickness. That is, if you have a thin film that is 100 nm thick, a 1% tolerance means the surface deviations cannot exceed 1 nm.

43.9% of researchers said that they require a roughness tolerance between 1-5% and almost one by fifth (19.3%) reported a roughness tolerance in the range of 5-10%.

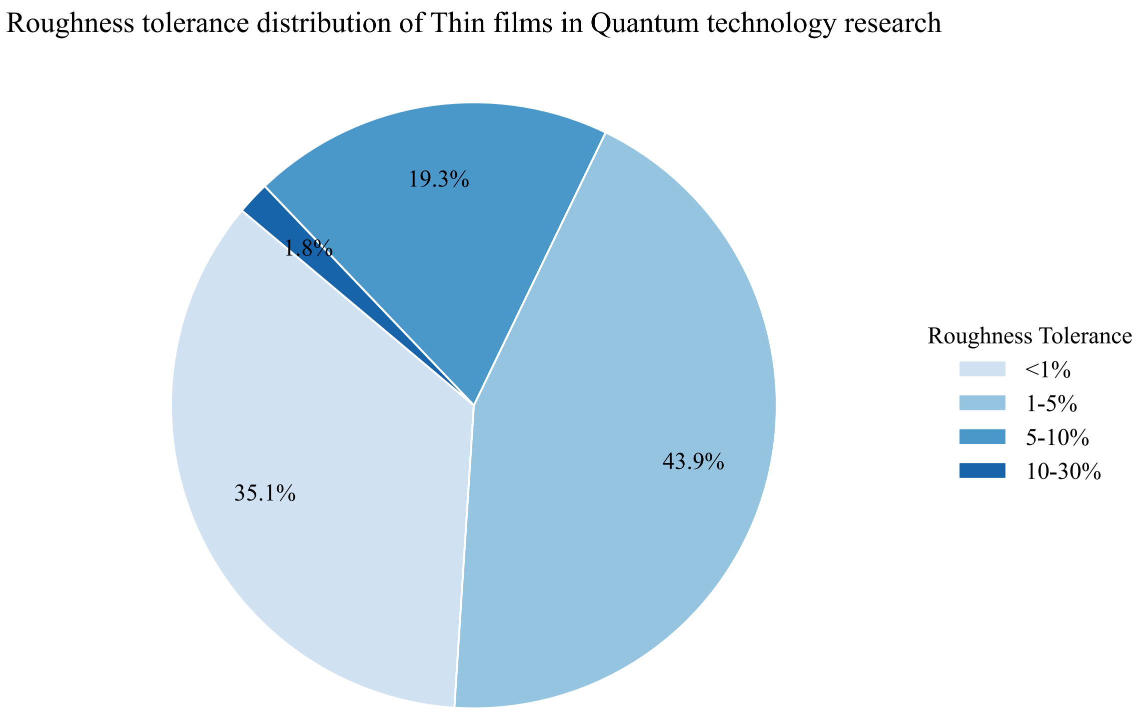

Figure 5.6: Required film-surface roughness tolerence distribution in quantum tech research application.

A comparison heatmap between the thickness and the roughness tolerance distribution is plotted in figure 5.7 below. The bottom left region (low thickness, low roughness tolerance) denotes the high performance thin film regime and the upper-right corner, (high thickness, high tolerance regime) represents the low performance thin film zone, which is rarely used for quantum technology applications.

From figure 5.7, we can see that about more than 39.5% of the researchers require an atomically smooth surface, that is roughness less than 1 nm. Thin films with a roughness of less than 5 nm is required by more than 70.4% of the researchers. This atomic scale smoothness is critical for high performance applications like quantum devices, preventing scattering losses and defects.

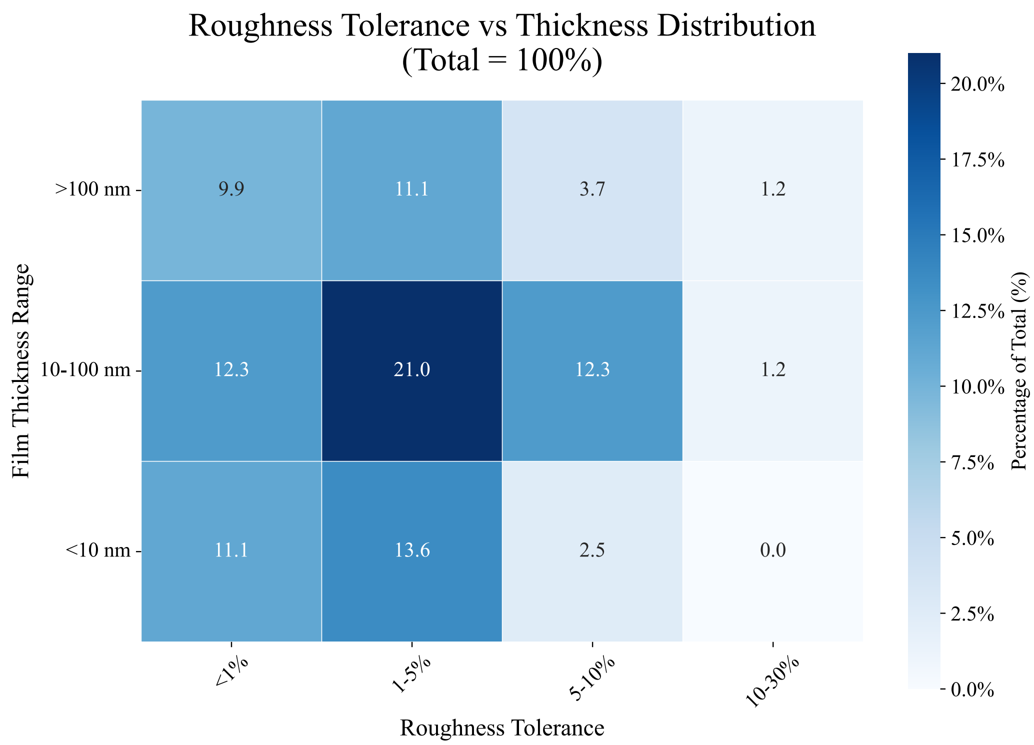

Figure 5.7: Correlation Heatmap of Film Thickness vs. Roughness Tolerance.

We have also plotted the thickness and roughness tolerance distribution along different domains as normalized stacked bar plots in the figure 5.8 and figure 5.9. We can infer that the distribution of film thickness and the roughness tolerance is almost equal in all four domains of quantum technology.

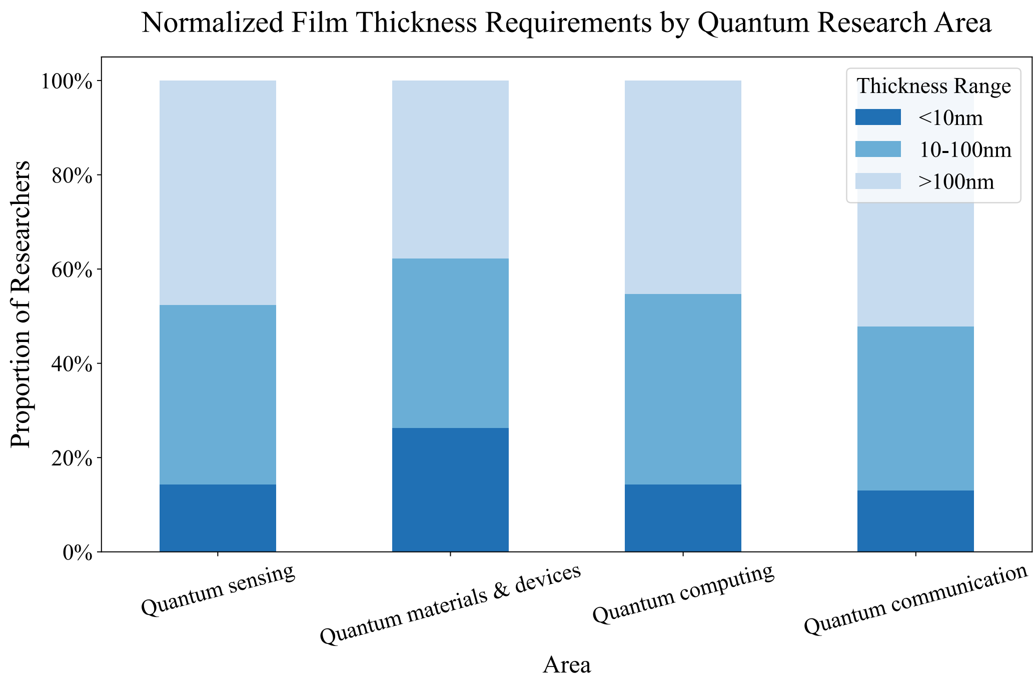

Figure 5.8: Thin film thickness distribution by quantum research area.

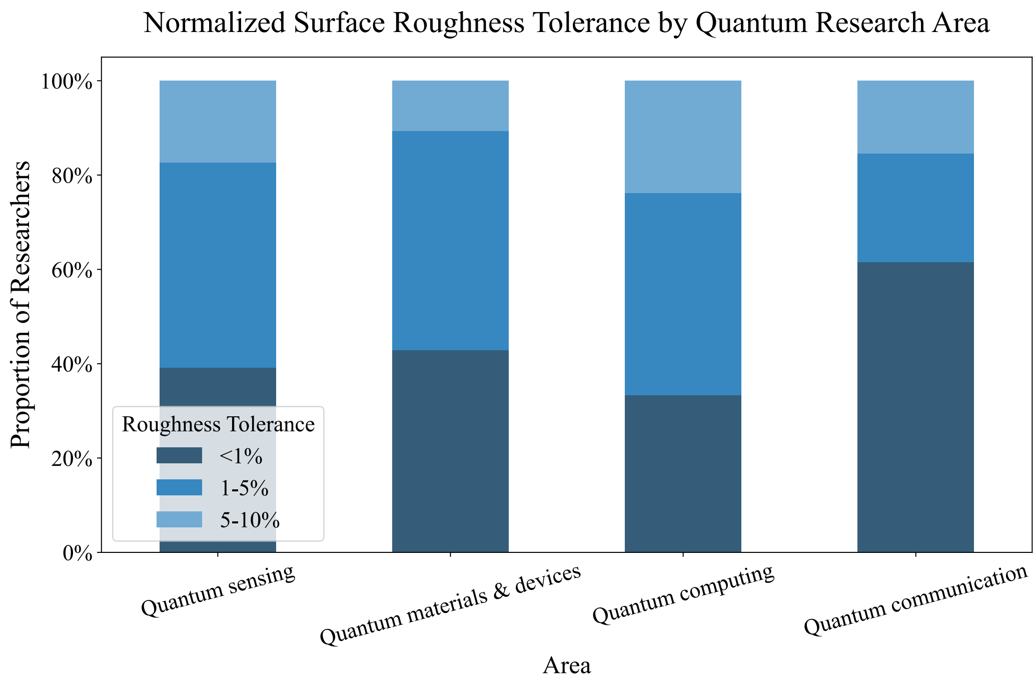

Figure 5.9: Thin film roughness tolerance distribution by quantum research area.

5.1.4 Thin film materials used in quantum technology

Apart from the materials we have already listed in chapter 3, we collected the thin film materials used by the researchers through the survey. We were able to identify more than 50 thin film materials that are currently used by researchers for quantum technologies this way. The whole list of materials recorded along with their frequency is given in the table 5.1.

Major thin film materials consist of metals like Aluminium (Al), Gold (Au), etc., and superconductors such as Niobium (Nb), Niobium Nitride (NbN), Titanium Nitride (TiN), etc. We can also see many semiconducting materials (Silicon (Si), Gallium Arsenide (GaAs), etc.) and dielectric/insulators (Silicon Nitride (SiN), Silicon Dioxide (SiO2), Alumina (Al2O3), etc.) in the list. Some materials like Aluminum (Al) and Titanium Nitride (TiN) are metals at room temperature but are also used as superconductors in low temperature thin film form (e.g., in quantum circuits).

Figure 5.10 illustrates the distribution of thin film materials across various functional categories, based on data collected from researchers. This provides valuable insight into the dominant material types currently used in quantum technology.

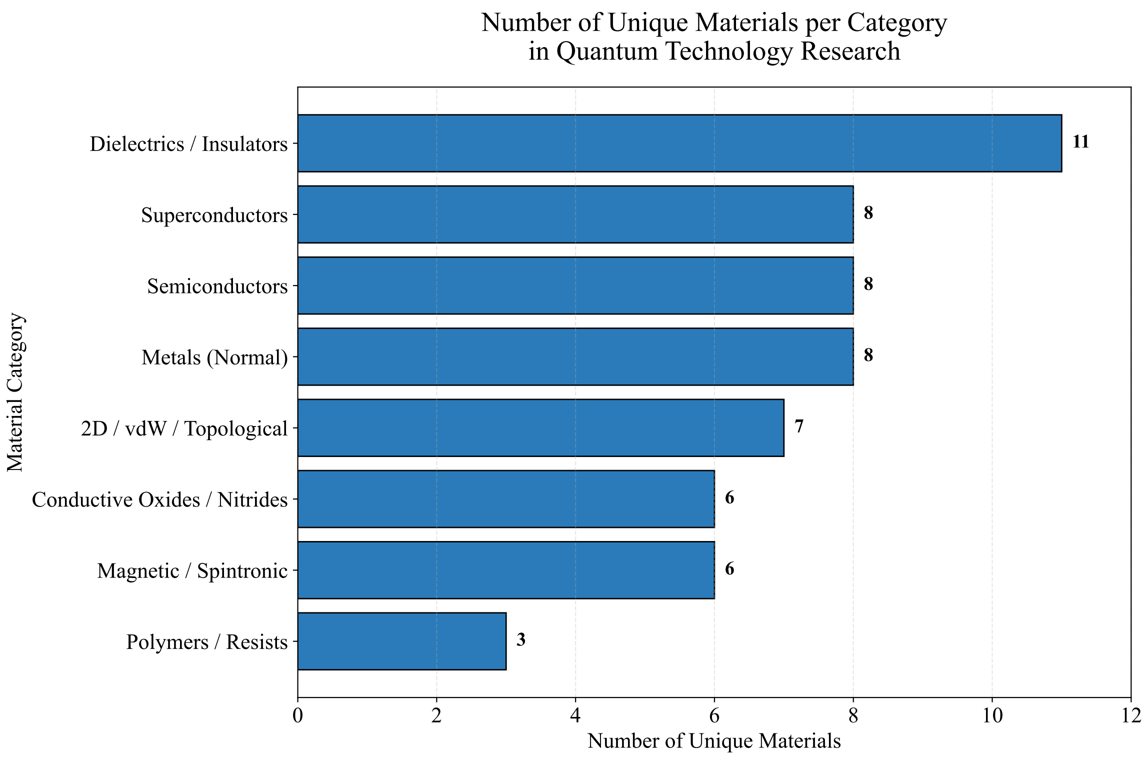

Figure 5.10: Number of Unique Materials per Category in Quantum Technology Research.

Table 5.1: Material Frequency in Quantum Thin Film

Material	Frequency
Aluminum (Al)	13
Niobium (Nb)	11
Gold (Au)	9
Silicon Nitride (SiN)	6
Silicon Dioxide (SiO_2)	6
Niobium Nitride (NbN)	5
Silicon (Si)	4
Alumina (Al_2O_3)	3
Titanium Nitride (TiN)	3
Niobium Titanium Nitride (NbTiN)	3
Graphene	3
Aluminum Nitride (AlN)	2
Gallium Arsenide (GaAs)	2
Aluminum Oxide (AlO_x)	2
Lithium Niobate ($LiNbO_3$)	2
Titanium (Ti)	2

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Table 5.1 – continued from previous page

Material	Frequency
Platinum (Pt)	2
Tantalum (Ta)	2
YBCO	2
Titanium Dioxide (TiO_2)	2
$PbTiO_3$, $BaTiO_3$, CrN, Mn_3CuN, InAs, GaSb, SiC, YIG, W, ITO, hBN, SU8, Pd, Permalloy, Cu, InP, Diamond, LiF, Ag, Cr, Cadmium-based, MoS_2, MoTe, BSCCO, MgB_2, GdN, $LaTiO_3$, $SrVO_3$, $LaAlO_3$, $SrIrO_3$, PMMA, Bismuth (Bi), Antimony (Sb), Tellurium (Te)	1 (each)

5.1.5 Infrastructure Distribution: Primary Venues for Thin Film Deposition

The researchers were asked where their thin film deposition is carried out and the responses are given as a pie chart in the figure 5.11 below. 40.8% carries out thin film deposition in their own lab, using an in-house thin film deposition system, 28.6% uses a shared facility in their institution and 16.3% of the researchers depend on an external commercial facility for the thin film deposition. The rest of them carry out thin film deposition through collaborations, etc.

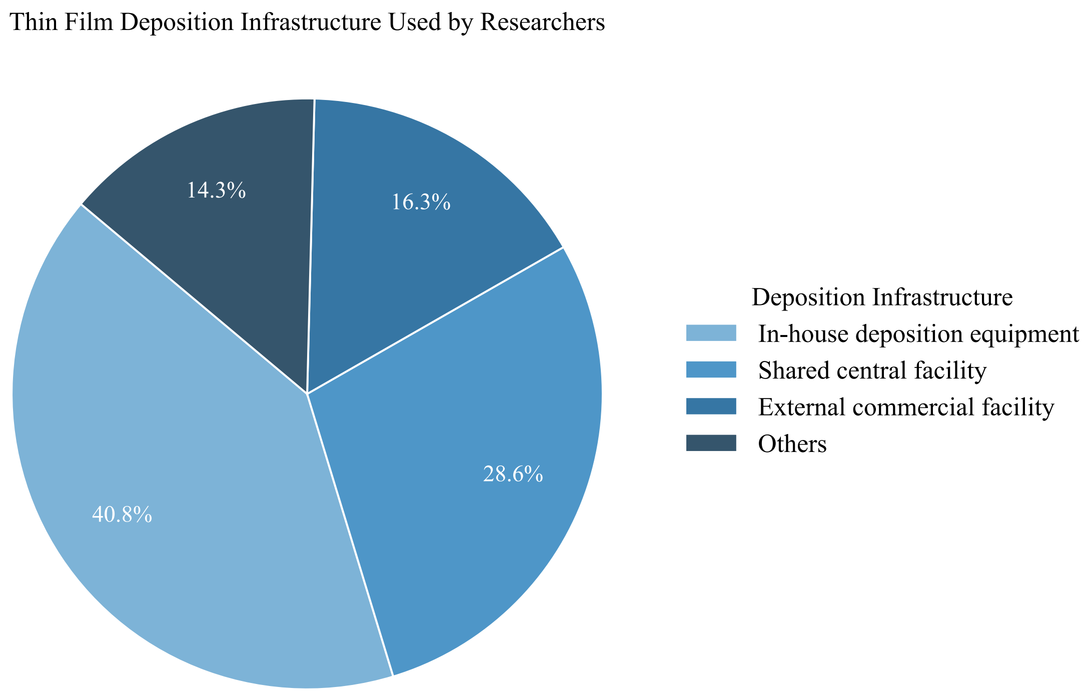

Figure 5.11: Thin film deposition infrastructure used by researchers.

5.1.6 Bottlenecks faced by the experimentalists

Based on the feedback received, we have been able to map out some of the major bottlenecks faced by the researchers while working with thin film deposition. The most cited issue has been equipment reliability and maintenance. Researchers have pointed out that their machine is getting old, servicing the components is taking a long time since the manufacturers are from overseas, issues with reliability and downtime with the equipment, etc. After this, the most pointed out issue is regarding the funding and capital costs. Not enough funding from agencies and cost to purchase and maintain equipment is mentioned by many researchers. Also a lack of technical expertise, lack of resources for certain materials, purity and reproducibility of the high end thin films, lead time, supply chain issues etc. are mentioned by many. Major bottlenecks mentioned by the researchers are categorized and tabulated in the table below.

Table 5.2: Key Bottlenecks in Thin-Film Deposition for Quantum Devices (Researcher Feedback)

Category	**Key Bottlenecks Cited by Researchers**
Infrastructure & Equipment Reliability	Ageing of equipment; equipment reliability concerns; frequent equipment downtime; inadequate support for maintenance, servicing, and replacement; servicing by overseas vendors results in long lead times
Financial & Capital Constraints	Limited funding from research agencies; high costs associated with purchasing, operating, and maintaining deposition equipment; difficulty procuring equipment tailored to specific research objectives; equipment sharing among multiple users to distribute costs
Technical Expertise & Human Capital	Limited availability of both equipment and technical expertise; insufficient resources to develop in-house thin-film deposition capabilities for certain materials
Process Reproducibility & Quality Control	Achieving high material purity and reproducibility; production of high-quality optical wafers and films; reliable fabrication performance matching design simulations
Logistical & Supply Chain Latency	Limited choice of qualified suppliers; long lead times for new sample fabrication; precursor synthesis and characterization represents a major bottleneck

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Category	Key Bottlenecks Cited by Researchers
Downstream Processing Challenges	Challenges in etching and patterning

Table 5.2 – continued from previous page

5.2 Key Findings

86.4% of the experimentalists in quantum technology research, who participated in the survey, used thin films in their research where about two third of them thin films were absolutely essential.

The research identifies a demand for atomic scale precision in quantum thin films. A critical finding from the survey dataset reveals that nearly 40% of the experimentalists require an atomically smooth surface (roughness less than 1nm) and 70% require a roughness tolerance less than 5nm.

Another key finding is that 40.8% of the experimentalists prefer in house deposition systems for their thin film fabrication while the most cited bottleneck is regarding the maintenance and reliability of equipment. This includes the lead time latency caused by the dependency on overseas manufacturers. A lack of technical expertise, qualified suppliers and financial constraints are also notable in the reported bottlenecks. We also have also listed out more than 50 primary materials used for thin film fabrication, which can be helpful for future thin film industry supporting the quantum ecosystem.

Chapter 6

Conclusion and Future Outlook

The findings of this global survey confirm the heavy reliance second generation quantum technologies have on high-end thin films. By summarizing the inputs from 59 expert groups across 34 countries, this research has mapped a clear technological trajectory and identified the critical dependencies that will define the next decade of quantum industrialization.

Two third of the researchers said that the use of thin films are absolutely essential for their quantum technology research and 20% of the researchers said that they use thin films moderately. That makes about 86% of the researchers depending on thin films for their research in the domain of quantum technology. This means that the growth of the thin film industry, focused on quantum applications, is essential for the future quantum ecosystem.

Thin films with atomically smooth surfaces that have less than 1nm tolerance are required by almost 40% of the experimentalists. This demand highlights a major technical threshold. As quantum devices move toward higher coherence times, surface scattering and interfacial defects, which are often driven by roughness, become the primary source of decoherence. The data also suggests a roughness barrier where 70% of the experimentalists require tolerance under 5nm. This points to the need of high-end thin film deposition which can provide not only thinness, but extreme lateral uniformity also.

While most of the researchers prefer in-house deposition for its flexibility, the top-cited bottleneck, ‘equipment reliability and overseas maintenance’ and ‘limited choice of qualified suppliers’, highlights a fragile global supply chain. For emerging quantum hubs like India, this indicates that localizing the thin film supply chain including precursor synthesis and tool servicing is as critical as the quantum research itself.

Over 50 materials used as thin films have been identified, ranging from superconductors like Niobium to complex dielectrics. And the list is still incomplete and expanding. This diversity suggests that future thin film facilities must be highly versatile and capable of handling multi material stacks.

The need of experts in thin film fabrications and for maintaining the equipment have been addressed more than once by the researchers as a major bottleneck faced by them. This shows a gap in the human capital side and the need of more training programs to enhance the skills in the field of high end thin film fabrication and the maintenance of the related equipment.

The cost for the buying and maintaining the thin film deposition systems are also cited as a major problem. This financial constraint can be tackled by encouraging the collaborations between academia and industry in thin film depositions.

In conclusion, for achieving the goal of quantum sovereignty, the Indian ecosystem needs to build a localized high-end thin film supply chain including precursor synthesis and tool servicing. This will require participation and collaboration between industries and academia on a large scale. We will need to develop indigenous high end thin film fabrication systems which can provide not just thinness, but also atomically smooth surfaces and high purity, reproducible thin films of a very versatile list of materials ranging from superconductors and metals to complex dielectrics. The governments should also introduce more programs and facilities to upskill personnel through hands-on training in high-end thin film fabrication and the maintenance of related equipment to fill the gap in the human capital side. Ultimately by synchronizing all of these above, India can transition from a consumer of quantum components to a global provider of quantum grade components. This approach will not only make India quantum ready, but also a frontier in future quantum technology globally.

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