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Exploring quantum materials and applications: a review

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Abstract

Researchers in condensed matter physics are currently exploring new materials for specific use in various applications. The peculiar properties of quantum materials (QMs) have garnered significant attention because they have the potential to serve as building blocks for entirely new technologies in modern science and technology. QMs exhibit emerging phenomena governed by quantum confinement, strong electronic correlations, topology, and symmetry, making them exceptional materials. This review paper provides an overview of these unique properties, different types of QMs, and their applications with the latest case studies, presenting a prospective outlook on QMs in multiple domains.

Keywords Quantum materials, Quantum confinement, Strong correlation, Topology, Symmetry

Introduction

The twentieth century witnessed remarkable progress in Physics, significantly enhancing our understanding of sub-atomic and sub-nuclear phenomena. Concurrently, advancements in technology played a pivotal role in driving global development. Most of our quality-of-life improvements over the past half-century can be attributed to semiconductor-based electronics. Many technologies crucial to modern life, including communication, computing, sensing, and measurement, have been redesigned to align with the rules of quantum mechanics. In the last two decades, academia and industry have made substantial investments in researching these technologies, with some already progressing beyond the prototype stage. For instance, photonic, superconducting, and atom-based quantum technologies have demonstrated superiority over their classical counterparts. Recent advances in the quantum physics of materials have led to a profound shift in perspective. While scientists and engineers have long utilized quantum effects in electronic devices, such as optoelectronics and hard-disk drives, the past decade has revealed how subtle quantum phenomena govern the macroscopic behaviour of various materials (Wang et al. 2023; Lee et al. 2018). Quantum materials (QMs) are particularly crucial in the field of quantum computation (Zunger and Malyi 2021). Numerous scientists believe that QMs hold the potential to bring about a revolution in various domains, including highly efficient and low-data communication, data storage (Marković and Grollier 2020; Wendin 2016) energy harvesting, semiconductors, and artificial intelligence (AI) (Schuller et al. 2022; Tokura et al. 2017). In the future, AI will play a vital role in performing and analysing numerous calculations like human brain networks and topology (Head-Marsden et al. 2021; Wang et al. 2021; Shao et al. 2021). To train an artificial brain network, artificial synapses should match the biological data processing characteristics which show dynamic behaviour toward signal response. QMs attracted the research community due to their highly controllable electronic structure and

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non-linear performances. Hence, QMs are a developing area for intelligent society (Dai et al. 2019; Wang et al. 2022).

A material whose properties cannot be fully described by the classical behaviour of materials and whose properties originate from novel quantum effects are described as QMs (Lau et al. 2020; Samarth 2017). In classical materials, the physical performance of the material can be explained by particle interaction. For example, ion motion can be classically explained by electrostatic interactions (Cava et al. 2021). However, a quantum mechanics approach can only provide a complete explanation as classical theory cannot explain many effects that arise in QMs, such as quantum fluctuation and spin entanglements (Fürst et al. 2014). Complicated electronic states in QMs originate from the interactions of the degree of freedom (lattice, charge, orbital, and spin (Basov et al. 2017). The discovery of high-temperature superconductivity in copper oxides (1986) initiated a significant expansion in QMs research, revealing that macroscopic quantum phenomena could exist beyond extreme conditions (Bednorz and Müller 1986). This breakthrough prompted extensive exploration into the influence of Coulomb interactions on conduction electrons, leading to the investigation of diverse materials. QMs contain novel entanglement or topological properties, i.e. materials with entanglement beyond the requirement of Fermi statistics and with topological responses (Keimer and Moore 2017). Phenomena like quantized vortices in superconductors provide evidence the topological nature of quantum wavefunctions is described by quantized vortices in superconductors (Thouless et al. 2012). These vortices arise due to the necessity of a well-defined phase in the superconducting condensate, with the phase's coupling to magnetic flux governed by gauge invariance (Thouless et al. 2012). Topological invariants, such as the integer winding number dictating the phase's winding around vortices, remain fixed under smooth system changes, impacting various materials beyond superconductors and facilitating phenomena like dissipation less transport (Benyamini et al. 2019) and unique quasiparticle excitations (Saeed et al. 2023). Secondly, the non-local entanglement inherent in specific quantum states has been emphasized, notably in experiments displaying teleportation with widely separated photons (Kusne et al. 2021). Non-local entanglement, which highlights the inter-connectedness of quantum states, even within large systems of electrons, offers us a new frontier for technological advancements and fundamental physics (Horodecki et al. 2009; Zyczkowski et al. 2001). Entanglement happens in even simple materials, like metals, where the wave functions of many electrons become very closely linked because electrons are fermionic. Understanding these quantum phenomena is a scientific pursuit and a pathway to practical applications and innovation. Examples of QMs include hydrogen sulfide, transitioning from a foul-smelling gas to a superconductor with record-setting transition temperatures exceeding 200 K under high pressure (Drozdov et al. 2015), and diamonds, where the entanglement of electronic and nuclear spins at defect centres enables long-lasting quantum coherence even at room temperature, offering promising prospects for quantum technologies (Balasubramanian, et al. 2009; Maurer, et al. 1979).

The Nobel Prize in Chemistry for 2023 recognizes the innovative discovery and advancement of quantum dots (QDs) ("Nobel Prize - Chemistry, Discoveries, Innovations | Britannica". 2024). Usually, an element's properties are dictated by its number of electrons. Still, when the matter is reduced to nanoscale dimensions, quantum phenomena come into play, governed by size rather than electron count. Ekimov discovered the semiconductor nanocrystals known as QDs in 1981 and explored size-dependent quantum effects in nanoparticles using copper chloride nanoparticles (Ekimov et al. 1985). Louis Brus further advanced the field by proving size-dependent quantum effects in freely suspended particles a few years later. In 1993, Moungi Bawendi's contributions produced almost perfect QDs, a crucial step for their practical applications (Murray et al. 1993). Today, QDs illuminate screens in QLED technology, enhance the lighting of LED lamps, and aid biochemists and doctors in tissue mapping. These tiny particles hold immense promise, potentially impacting flexible electronics, miniature sensors, thinner solar cells, medical surgery, biological mapping, and encrypted quantum communication, signifying just the beginning of their transformative potential.

Over the past years, the Nobel Prize has been awarded in the field of the quantum domain, signing a rapid and transformative evolution in this domain. QMs play a crucial role in driving advancements in quantum technology, highlighting their significance in shaping the future of this field. Figure 1 express the past, current, and future trends of research in very brief. QMs have gained substantial attention in materials science, yet the literature lacks comprehensive reviews due to their recent emergence in various applications. Our paper focuses on introducing QMs, unique properties (quantum confinement, strong electronic correlations, topology, and symmetry), and different applications. This paper is a valuable resource for researchers, scientists, and engineers looking to better understand QMs and their applications.

Unique properties of QMs

The term "Quantum Materials" is relatively new in the scientific community, leading to some confusion despite these materials being studied for a while. Research in this

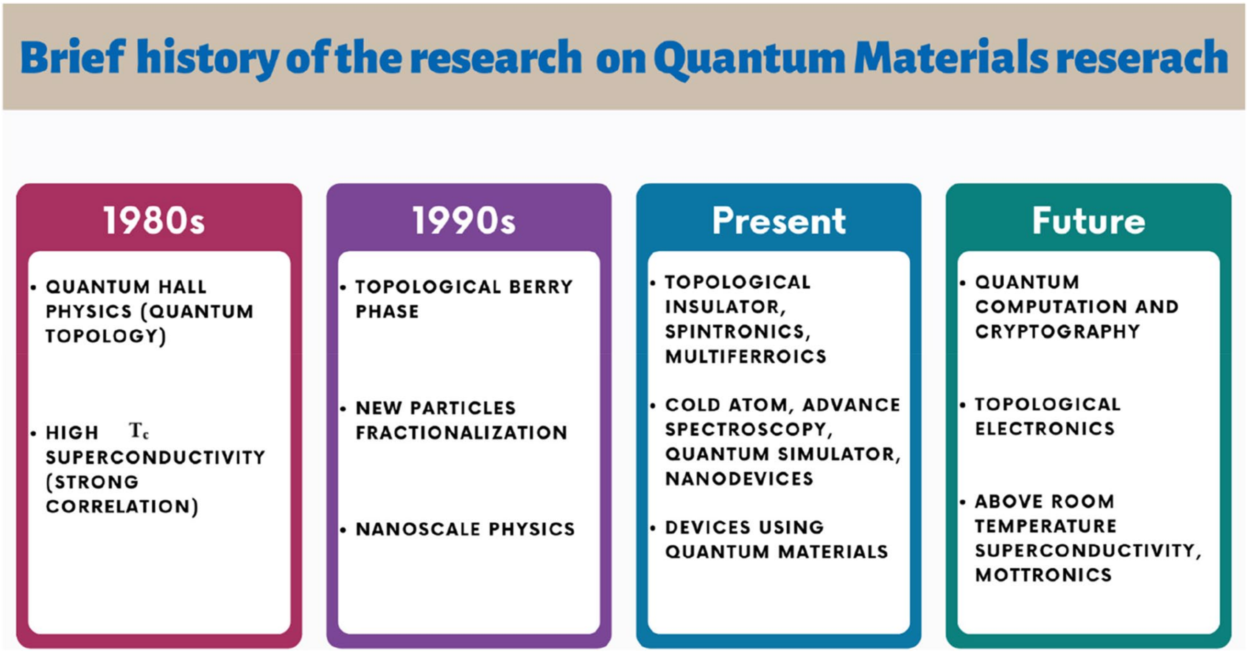

Fig. 1 Brief historical research breakthrough in QMs research

area is rapidly expanding, driven by the need for detailed consideration of electron wave functions and their surroundings. By Robert Cava, "I will not endeavour to provide a precise definition of what a quantum material is, but I know one when I see it." (Cava et al. 2021). Examples of QMs that you may generally be familiar with are those that display the quantum hall effect or superconductivity, TIs, spin liquids, qubits, quantum sensors, or QDs. Interactions of fundamental degrees of freedom—lattice, charge, orbital, and spin—result in complex electronic states on the atomic scale. In this section, we will briefly discuss the fundamental properties of QMs—quantum confinement, strong electronic correlations, topology, and symmetry.

Quantum confinement

It is a fundamental phenomenon in nanoscale materials, particularly semiconductors and other confined systems. It refers to the effect of restricting the motion of electrons and other quantum particles within a region smaller than their characteristic wavelength. We use quantum mechanics to describe particles like electrons as discrete particles and waves with associated wavelengths. A particle's de Broglie wavelength (λ) is inversely proportional to its momentum (p). As the size of a confined region becomes comparable to or smaller than the de Broglie wavelength of particles, their wave-like behaviour becomes significant. In bulk materials, electrons have continuous energy bands due to the large number of atoms. However, in nanoscale materials, the confined dimensions impose boundary conditions that limit electrons' possible standing wave patterns (orbitals). This leads to the quantization of energy levels, where only specific energy values are allowed. The energy levels become discrete, resembling the rungs of a ladder rather than a continuous slope. The bandgap of a material is the energy difference between the highest energy electron in the valence band and the lowest energy electron in the conduction band. In bulk materials, the bandgap remains relatively constant. In nanostructures, especially semiconductor nanoparticles or QDs, the bandgap increases with decreasing particle size due to quantum confinement. (Ramalingam et al. 2020; Ramalingam et al. n.d.). This is shown pictorially in Fig. 2. This means the electronic transitions responsible for optical properties occur at higher energies (shorter wavelengths) than in bulk materials.

To learn more about quantum confinement, we need to know about QDs. It is now possible to see quantum confinement effects in a new type of material called QDs. QDs are nanometer-sized semiconductor crystals, and molecules comprise tightly packed electrons or pairs of electrons and holes called 'excitons' (Mueller and Malic 2018). When an electron is excited into a higher energy state, either through absorption of a photon or by another excitation method such as electroluminescence, this creates a positively charged space at the lower energy level, known as a hole. This results in the formation of the

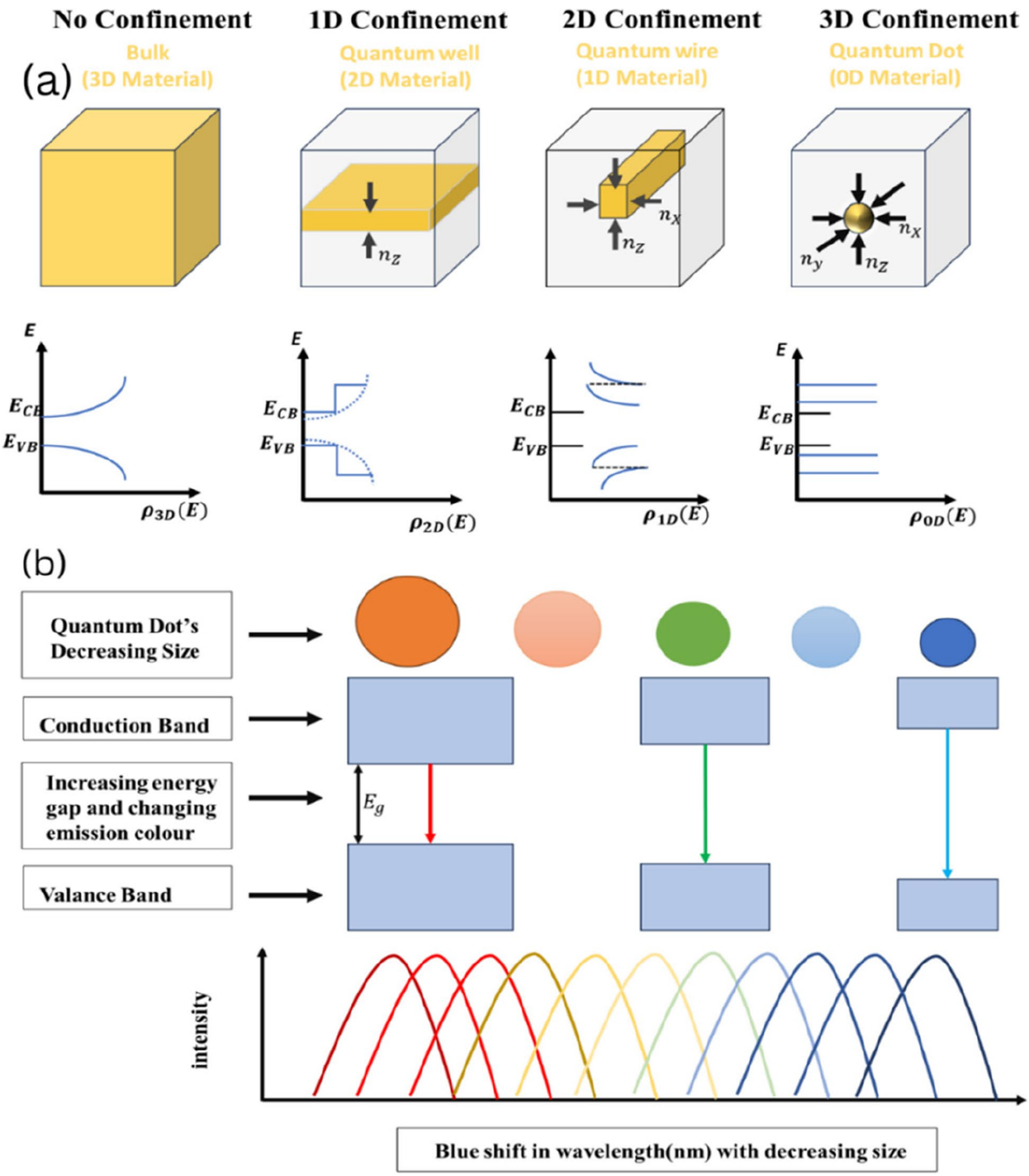

Fig. 2 **a** Representation of confinement with corresponding energy levels and density of states of the QMs. **b** Bandgap energy variation with size of the QMs

electron–hole pair. These two particles sometimes exist in a bound state, forming a single quasi-particle known as an "exciton" (Mueller and Malic 2018). Within an exciton, the electron and the hole pair are bound together by coulombic interaction, and this strength of the bond is quantified by its exciton binding energy.

Excitons have an average physical separation between the electron and the hole pair, referred to as the exciton Bohr radius. Every semiconductor material has a characteristic exciton Bohr radius; depending on this, we classify them into Frenkel and Wannier excitons (Shiau and Combescot 2023). Frenkel: has a tightly bound radius of a similar magnitude as the unit cell, and Wannier: has a large radius exceeding the size of the unit cell. While the de Broglie wavelength is very small compared to the size of the limiting structure, the particle acts like it is free. The energy states stay the same at this stage, and the bandgap returns to its original place. Another energy spectrum does not stay continuous; it breaks up into discrete waves as the size of the confining object shrinks to the nanoscale, as represented in Fig. 2. So, the bandgap has properties that rely on particle size, which eventually leads to a blue shift in the light emitted as the particle size decreases. However, this result shows what happens when you keep the electrons and electron–hole pair (also called excitons) in a space close to the critical quantum limit, known as the Bohr exciton radius (Zhang et al. 2022). We can classify it into three regimes based on the exciton Bohr radius. Weak confinement regime: the radius of the crystallite is greater than the exciton Bohr radius. Moderate confinement regime: the radius of the crystallite is comparable to the exciton radius. Strong confinement regime: the radius of the crystallite is smaller than the Bohr exciton radius (Ramalingam et al. 2020). The band gap (E_g) increases in magnitude (increase in energy of the band-to-band excitation peaks (blue shift)) as the semiconductor particle radius decreases in size to the point when it becomes comparable or smaller than that of the exciton radius as shown in Fig. 2. This property has led to various fields: semiconducting quantum wells and superlattice devices, non-linear optical materials, photocatalysis, and imaging systems (Brus 1984).

Depending on the confinement dimension, we can classify confinement as shown in Fig. 2. Electrons confined in one direction, i.e., quantum wires: electrons can quickly move in one dimension (1D), quantum wells (thin films): electrons can promptly move in two dimensions (2D), so two dimensions are quantized. Figure 2a is a representation of the confinement of QMs, their corresponding energy levels, and a schematic example of broken symmetry and the functional form of the density of states in one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) confined QMs. Where E_{CB} energy of the conduction band, EVB is the energy of the valence band, ρ density of states, and n is the number of state per unit space. Figure 2b demonstrates that when particle size decreases and reaches the nanoscale, it decreases in confining dimension and makes energy levels discrete, and this increases the band gap and also increases in band gap energy (Edvinsson 2018).

Quantum confinement significantly affects the absorption and emission of light in nanoscale materials. As the energy levels are quantized, the energy difference between electronic transitions becomes more significant, resulting in more energetic absorption and emission peaks. This can lead to enhanced fluorescence, luminescence, and colour tunability of nanomaterials, which have applications in displays, lasers, and biological imaging.

In bulk materials, the conductivity is mainly determined by the concentration of free charge carriers (electrons or holes). In quantum-confined systems, the discrete energy levels create an energy gap between the highest occupied and lowest unoccupied states. This can hinder the movement of charge carriers and reduce the conductivity. However, quantum tunnelling becomes more prominent at specific energy levels, allowing carriers to pass through energy barriers and leading to exciting conductivity behaviours. Quantum tunnelling is a phenomenon in which particles can penetrate a potential energy barrier that is higher than the particle's total energy. This occurs due to the wave-like nature of particles described by quantum mechanics, where the particle's wave function can extend into the barrier region and allow a finite probability of the particle appearing on the other side. The probability of tunnelling depends exponentially on the barrier width and height, as well as the particle's energy. This type of motion is not allowed by the laws of classical dynamics (Mohsen Razavy et al. n.d). Quantum tunnelling is important in many physical operation of semiconductor devices like tunnel diodes ("Tunnel Diode - GeeksforGeeks". 2024) and scanning tunnelling microscopes (Anirban 2022).

Quantum confinement is crucial in the development of nanoscale electronic devices. QDs can be used as single-electron transistors (Kiyama, et al. 2018), quantum bits (qubits) (Zhang et al. 2018) in quantum computing due to their discrete energy levels and controllable charging behaviour, in bioimaging (Abdellatif et al. 1951) due to higher brightness, photostability, and ability to made water-dispersible, in photovoltaic devices (Cotta 2020) due to tuneable absorption and high excitation coefficient and in other applications like quantum dot light-emitting diode (QLEDs), sensing application, laser, and beyond due to their characteristics properties (Bera et al. 2010).

Strong electronic correlation

QMs exhibit unique electronic, magnetic, and optical properties from quantum mechanical effects at the atomic and subatomic levels. Strong correlation effects in QMs are a fascinating and intricate aspect that plays a crucial role in determining their behaviour. These correlation effects emerge due to the strong interactions between electrons within the material, leading to non-trivial behaviours that cannot be understood using classical physics alone. Electrons in classical materials frequently function as self-sufficient individuals, but in quantum QMs, significant interactions predominate due to factors such as Coulomb repulsion. This complex interaction results in emergent behaviours that deviate significantly from traditional classical expectations. High-temperature superconductivity, seen in certain QMs, is one notable example in which electron pairs termed Cooper pairs travel coherently along the lattice, resulting in zero electrical resistance (Holten et al. 2022). This phenomenon defies conventional wisdom and can transform power transmission and energy storage technology (Bednorz et al. 1986). To understand strong correlation better, we will delve into the strong correlation properties of QMs and their significance in various physical phenomena.

In metals like copper and aluminium, mobile electrons interact slightly due to Coulomb forces but are largely unaffected by them due to their high kinetic energy. This allows for a perturbative approach based on single-electron theories. However, traditional theories struggle when Coulomb interactions become comparable to or exceed the kinetic energy, as in strongly correlated systems (Si et al. 2001). These materials offer fertile ground for discovering new physics, especially near zero-temperature phase transitions, where quantum critical fluctuations can lead to exotic excitations and novel quantum phases. Strongly correlated electron systems have driven significant theoretical advancements, including highly entangled phases of matter and quantum critical points that extend beyond conventional frameworks like Landau's theory (Wen 2017).

In QMs, electrons are the charge carriers, and the principles of quantum mechanics govern their behaviour (Morosan et al. 2012). When electrons interact strongly with each other, their collective behaviour can deviate significantly from that predicted by simple models. This interaction gives rise to various quantum phases, such as Mott insulators (Mila 2024), correlated metals (Zhang et al. 2016), and high-temperature superconductors (Zhou et al. 2021). Many materials' electrical, magnetic, optical, and mechanical properties depend on electron–electron interactions. Hund's rules in transition metals illustrate that Coulomb energy savings make d electron spin alignment and spatial orbital living profitable. Based on electron–electron repulsion and quantum physics, these and related exchange interactions underpin magnetic order, which is essential in industry and physics. The complicated interaction between electron–electron interactions, lattice structure, kinetic energy (via electron quantum–mechanical tunnelling in crystals), and magnetic degrees of freedom is noteworthy. Ground states with differing symmetries and low energy excitations compete, as do 'local' quantum degrees of freedom associated with lattice sites and longer-scale fluctuations and excitations. When an electronic population or magnetic field tilts the energy scale balance, new phases often develop at quantum phase transitions. These phases can have surprising and useful properties like high-temperature superconductivity. Technologically relevant features include orders-of-magnitude electrical conductivity shifts (metal–insulator transitions), perhaps modified by a magnetic field ('colossal magnetoresistance'). Strong correlations can function as a lever arm at certain behaviour cusps, making modest controllable factor changes affect material attributes. Strong electron correlations enable complicated electrical material properties but make examination difficult. Well-developed perturbative approaches like expansion, local density Hartree–Fock approximations, Thomas–Fermi screening in metals, and others allow us to understand the electronic behaviour of relatively modest electron–electron repulsion compared to kinetic energy. Controlled theoretical techniques are limited when interactions are high, as in d and f electron systems. The problem is open except for 1D systems with analytical and computational methods. The 'renormalization group' paradigm and Landau's adiabaticity principle save the day.

Figure 3 illustrates various materials housing strongly correlated electrons, including cuprate high-temperature superconductors (Keimer et al. 2015), ruthenates, transition metal oxides (Tokura and Nagaosa 1979), heavy fermion systems (Si and Steglich 1979), iron-based superconductors (Si et al. 2016), organics (Oike et al. 2015), and low-dimensional materials (Cao et al. 2018). These systems primarily involve d or f orbitals, which maintain some localization within the solid, resulting in heightened Coulomb interaction and narrower bandwidths compared to s or p orbitals. Furthermore, these orbitals generate localized moments within the materials under specific filling conditions. Figure 3 describes the functionality of strongly correlated materials by illustrating selected classes of such materials and how interactions between their low-energy degrees of freedom, often referred to as 'building blocks' and symmetry, can give rise to various functionalities like superconductivity, etc.

The Mott transition is a classic example of a strong correlation in materials. It is characterized by a phase transition from a metal to an insulator due to strong electron correlations. This transition is often associated with a marked change in the electronic structure, such as the transition from long to short c-axis layered perovskite structures. Factors like changes in orbital order drive the Mott transition and can occur together with structural transformations (Wang et al. 2019). This phenomenon

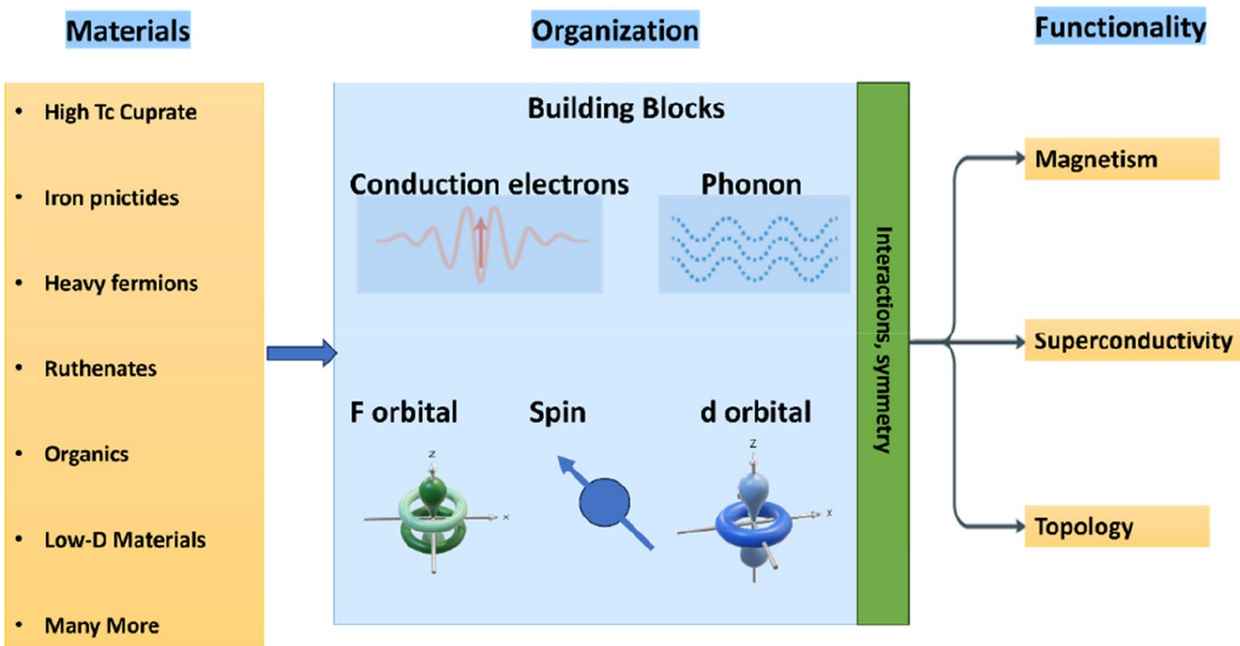

Fig. 3 The operational characteristics of strongly correlated materials and their functionality with their organization (Paschen and Si 2020)

is a collective manifestation of the imbalance in the particle-wave duality of electrons. It is considered a quantum critical transition in many materials, showcasing the intricate interplay between electron interactions and material properties (Furukawa et al. 2014).

Another remarkable manifestation of a strong correlation is high-temperature superconductivity. These materials can conduct electricity without resistance at temperatures significantly higher than traditional superconductors ("Superconductivity - High Temp, Magnetic Fields, Condensed Matter | Britannica". 2024). In conventional superconductors, electron–phonon interactions pair electrons and allow them to flow without resistance. However, electron–electron solid interactions in high-temperature superconductors are thought to play a crucial role in enabling superconductivity at temperatures much higher than conventional theories predict (Sun et al. 2021). Understanding and controlling these correlations are critical challenges in condensed matter physics. The discovery of high-temperature superconductors, such as copper oxide materials, has revolutionized the field of superconductivity, offering the potential for practical applications in various industries. High-temperature superconductivity challenges conventional theories of superconductivity and highlights the complex interplay of electron interactions in these materials, showcasing a strong correlation between electronic properties and superconducting behaviour (Orenstein and Millis 1979).

Quantum phase transitions occur at absolute zero temperature, representing a unique phenomenon in quantum systems ("Quantum Phase Transitions - Rosenbaum Lab". 2024). These transitions are characterized by changes in the ground state of a system as specific parameters in its Hamiltonian are varied, leading to distinct phases at absolute zero temperature. Strong correlations can drive quantum phase transitions between ordered or disordered states. Unlike classical phase transitions driven by thermal fluctuations, quantum phase transitions at absolute zero are governed by quantum fluctuations and the interplay of quantum correlations. These transitions are exciting due to the novel and deep properties in the quantum critical region, offering insights into various behaviours in condensed-matter systems. The study of quantum phase transitions provides valuable information about the fundamental nature of quantum systems and their behaviour at the quantum critical point.

The lattice structure of a material indeed plays a crucial role in the emergence of strong correlation effects in quantum mechanical systems. The arrangement of atoms in a lattice influences the effective interactions between electrons, affecting their movement and interactions within the material. This connection between the electronic and lattice degrees of freedom is fundamental in understanding the behaviour of quantum mechanical systems, especially in strongly correlated electron systems where the interplay between electron–electron interactions and lattice dynamics is intricate. The lattice structure can modify the electronic properties of a material, leading to phenomena like high-temperature superconductivity or Mott transitions, highlighting the significance of considering both electronic and lattice aspects when studying strongly correlated quantum systems (Izsák et al. 2023; Tokura et al. 2017).

Describing and predicting the behaviour of strongly correlated quantum mechanical systems pose a significant theoretical challenge due to the intricate interplay between different degrees of freedom. Traditional mean-field approximations often need to catch up in capturing the complexities of these systems. Advanced techniques such as dynamical mean-field theory (DMFT) (Qu et al. 2022), density matrix renormalization group (DMRG) (Verstraete et al. 2023), and tensor network methods (Orús 2019) are employed to address these challenges. These methods offer more sophisticated approaches to model and understanding the behaviour of strongly correlated quantum systems by considering the dynamic nature of electron correlations and interactions. Techniques like DMFT focus on the local behaviour of electrons, providing insights into the effects of strong correlations on electronic properties. DMRG, on the other hand, is particularly useful for 1D systems, offering a powerful numerical method to study quantum many-body systems. Tensor network methods provide a framework to represent quantum states efficiently, enabling the study of entanglement and correlations in strongly correlated systems. By utilizing these advanced techniques, researchers can delve deeper into the complexities of strongly correlated quantum systems and gain a more comprehensive understanding of their behaviour and properties (Vollhardt 2019; Tsuchimochi and Scuseria 2009).

Topology and symmetry in QMs

Figure 4 shows the topology and band inversion in insulators. Atomic limit energy levels determine the natural order of occupied (blue line) and unoccupied (yellow line) orbitals (Fig. 4a). As the lattice parameter (a) lowers, the gap between the occupied and unoccupied Bloch states closes at a critical point and reopens inverted concerning the atomic order, achieving a topological state. Semimetal topological state classification (Fig. 4b). Materials can be bulk band inverted to create topological semimetals. Crystalline rotational or mirror symmetry protects the inverted valence and conduction band crossings (left). Dirac semimetals have fourfold degenerate crossing points shielded by rotational symmetry in the presence of inversion (P) and time-reversal (Θ) symmetries. Weyl semimetals have twofold degenerate band crossings that form chiral Weyl fermions separated in momentum space. The distance between oppositely charged Weyl nodes protects the phase. Kramers–Weyl fermions and non-symmorphic semimetals generate topological semimetals without bulk band inversion. Non-symmorphic crystal symmetries protect spin–orbit coupling band crossings. Degeneracies and energy–momentum relationships near band touching points classify topological semimetals (Singh et al. 2023).

Condensed matter physics, focusing on particle systems' motion patterns and laws, has emerged as a vital subdiscipline. The discovery of the integer quantum Hall effect (IQHE) in 1980 (Lv et al. 2021), alongside subsequent findings of various topological quantum states, has unlocked a realm for global scientists. Topology and symmetry play crucial roles in QMs by influencing their properties and behaviour. In the realm of QMs, topology refers to the study of properties that remain unchanged under continuous deformations,

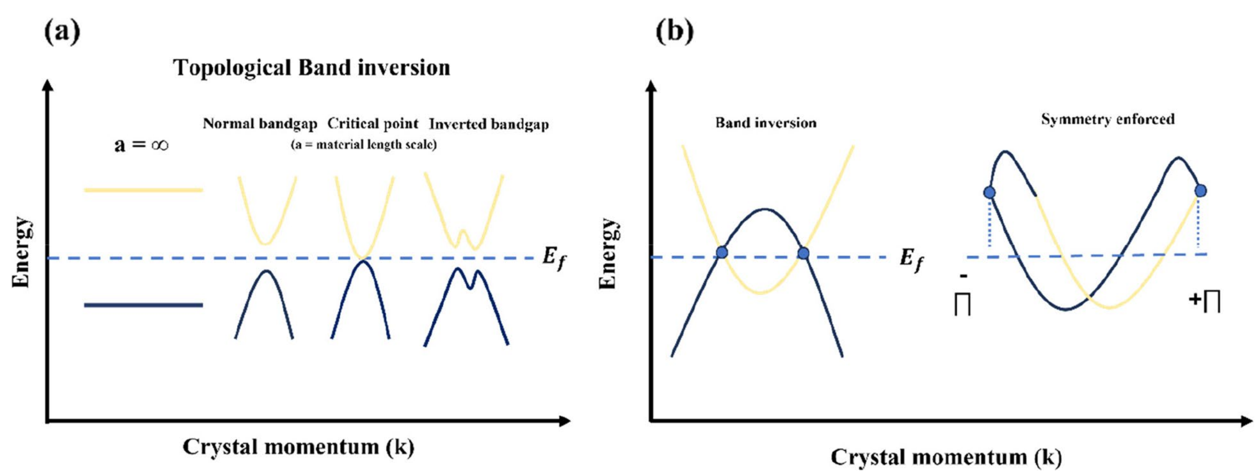

Fig. 4 **a** Topology and band inversion in insulators. **b** Semimetal topological state classification

like stretching or bending, without tearing or gluing. On the other hand, symmetry involves operations that leave a system invariant, such as spatial isotropy, translations, time reversal, and various internal quantum numbers. Topology and symmetry are fundamental concepts in QMs, influencing their phases, properties, and behaviour by defining symmetries, order parameters, and the structural characteristics that underpin their unique quantum phenomena. It is challenging to summarize everything here, but we will briefly discuss the main things here.

Topology is a mathematical idea that ignores small details and gradual changes. Think of a doughnut with a hole—the number of holes is a topological feature that tells us about its shape in space. This applies to materials, too, like how atoms are arranged in crystals or how electrons behave (Po et al. 2017). These special materials, called topological QMs, have unique qualities because of their topological structure. The discovery of the integer and fractional quantum Hall effects (IQHE and FQHE) has unveiled a unique form of matter known as the topological quantum state. Investigating the topological characteristics of these materials involves identifying similar properties in electronic band structures and physical quantities, leading to physical states less affected by material defects. (Hasan and Kane 2010; Nayak et al. 2008).

The 'topology of states' refers to how electron states are organized in a material, understood through unique numbers called 'topological invariants.' These numbers describe the shape of electron wavefunctions in momentum space (Song et al. 2018). A material with a 'non-trivial topological number' has unique electron wavefunction shapes, guaranteeing special surface or edge states that are resilient to small changes in the material. An analogy is the unchanging basic shape of an object under gentle deformations. The appearance of these particular states in a material indicates a unique shape in its electron wavefunctions, as seen in the quantum Hall state (QHS), where the bulk becomes electrically insulating under a strong magnetic field in a 2D material. In contrast, chiral conducting states form along its edges. These edge states persist despite attempts to eliminate them, making QHS a precise standard for resistance and determining fundamental constants like the fine structure constant.

The band theory paradigm, a framework used in physics, has been used in predicting new topological materials and confirming their unique properties through experiments involving spectroscopy and transport. This analyses band structures and topological invariants derived from topology and crystalline symmetry considerations. Recent advancements in band theory, which integrate topology and crystalline symmetries, have enabled a comprehensive classification of topological states. For instance, insulating non-magnetic materials encompassing 230 space groups have been identified to support around 3000 different options (Po et al. 2017).

Topology serves as a keyway to organize and understand quantum states. It is all about the shape of the electronic wave function and how it behaves in k space, which is a mathematical representation of momentum space. The specific shape depends on the symmetry group of the crystal lattice. These topological characteristics control how materials respond to environmental changes and stay consistent even when the material's properties change smoothly. Imagine a scenario where the order of electron energy levels switches at specific points near the Fermi level. This change in order is like a band inversion, leading to a topologically nontrivial state.

Three main methods are commonly used to determine the unique properties of materials: (1) directly calculating specific characteristics that indicate their topological nature and symmetry indicators (Soluyanov and Vanderbilt 2011; Bradlyn, et al. 2017), (2) employing a gradual transition to link the topological state of an unfamiliar material with that of a known one (Lin, et al. 2013), and (3) utilizing the relationship between bulk and surface states to identify the nontrivial properties of materials (Essin and Gurarie 2011). The first two methods involve analysing the symmetry properties of bulk states, often represented in their irreducible forms at specific points in the Brillouin zone. Initially conceived as a parity criterion for materials with inversion symmetry, this method was expanded to cover all types of space groups. The third method reveals the unique states of materials by examining their connections with bulk bands, offering experimental clues to confirm their distinctive properties.

Insulators are materials that do not conduct electricity, and they have a primary state where they are electrically inactive due to an energy gap between their filled and empty states. TIs are a newer insulator type with a gap in their bulk but can still conduct electricity along their surface because of unique metallic states caused by the arrangement of their bulk states. We can understand this by examining the material's structure with and without specific effects. If we remove a particular effect called spin–orbit coupling (SOC) (Fu et al. 2007; Bernevig and Zhang 2006), the material behaves like a regular insulator or a metal. But if we gradually introduce SOC, we observe a change from a regular state to a particular state where the gap in energy closes at a critical point, marking a transition. The nature of the material remains the same as long as its bulk properties stay intact. The surfaces of these materials act like a boundary between the unique interior and the regular outside, and this boundary results in unique surface states that connect the filled and empty states within the material. TIs are characterized by a property called Z_2, which can be either 0 or 1, indicating whether they are ordinary or extraordinary. This property can be calculated by analysing the behaviour of electronic states within the material. These unique properties also affect the behaviour of surface states, which have interesting features like linear energy patterns and a specific spin alignment that make them resistant to certain disruptions.

Topological states in semimetals are special because of their unique band structures close to the Fermi energy, which have distinct topological properties. These states are grouped based on their nodal band structures and surface states, with types such as Dirac, Weyl, or line–node semimetals identified by their node dispersion and the symmetries that protect these characteristics (Velury and Hughes 2022; Schoop et al. 2018). In semimetals, these topological band crossings can either happen accidentally, like Dirac points and lines, which are preserved by specific crystal symmetries and remain stable under small changes, or they can be enforced by symmetry, arising from non-symmorphic symmetries and remaining stable even with significant deformations of the system. These topological states are crucial for various material properties and applications, showcasing unusual transport behaviours, durable surface states, and distinctive responses to electromagnetic fields. These topological semimetals, like Dirac and Weyl semimetals, have been supported by theoretical predictions from first-principles calculations (Lv et al. 2021), emphasizing the importance of understanding and exploring these materials for future technological progress.

One of the defining features of topological states is their remarkable robustness against local perturbations and disorder (Zhang et al. 2021). This robustness arises from the nontrivial topology of the electronic wavefunctions. The disorder can scatter electrons and degrade their behaviour in conventional materials, leading to effects like resistivity in electronic systems. As highlighted in the provided sources, this property is a pivotal advantage of topological systems, showcasing the absence of electronic backscattering in phenomena like the quantum Hall effect and spin-Hall effect. Topological states exhibit unidirectional waveguiding and edge states that persist despite imperfections or impurities, making them highly resilient to small perturbations and fabrication flaws. This robustness against disorder and defects allows for efficient energy and information routing in various 2D platforms, ranging from quantum electronics to classical photonic and phononic devices, offering significant application potential across different fields of research and technology.

In the study of TIs, specific key terms are vital to understand. TIs often have an 'energy gap,' a range of energy levels where electrons cannot exist. This gap is crucial for stability, preventing unwanted energy fluctuations that could cause data loss (Wang et al. 2023). Another important aspect is the emergence of 'edge states' along boundaries like edges or surfaces. These states are localized and conduct electricity without scattering. This protection allows for robust information transfer and transport, even in impurities or defects (Yurkevich and Kagalovsky 2021).

The quantum Hall effect (QHE) is a remarkable discovery in physics where, in 2D electronic systems, the Hall resistance is quantized in integer multiples of a fundamental constant (Klitzing et al. 1980). This phenomenon arises from the unique topological characteristics of the system, resulting in the precise quantization of the Hall conductivity despite any disorder. Interestingly, this effect does not rely on electron interactions, as even a single particle in a magnetic field exhibits behaviour similar to that of multiple particles. The quantization of the Hall resistance occurs in distinct plateaus, each corresponding to a specific number of filled Landau levels. Crucially, edge states along the boundaries of the system, known as chiral modes, play a pivotal role in maintaining the quantization of the Hall conductivity. These edge states, a consequence of the system's topological properties, remain robust against external perturbations. The QHE has revolutionized our understanding of condensed matter physics, inspiring new theories and driving experimental advancements, emphasizing the significance of topological properties in electronic systems under strong magnetic fields ("Fractional quantum Hall effect at zero magnetic field observed in an unexpected material" 2024; Klitzing, et al. 2020).

Time-reversal symmetry plays a significant role in classifying topological states. Sometimes, TIs exhibit a Z_2 invariant, indicating whether the material is a trivial insulator or a nontrivial topological insulator (Lan et al. 2022). This Z_2 invariant is protected by time-reversal symmetry and determines the presence of protected edge states. TIs are materials with a bulk excitation gap generated by the spin–orbit interaction that differs from conventional insulators. This distinction is characterized by Z_2 topological invariants representing the ground state. A single Z_2 invariant distinguishes the ordinary insulator from the quantum spin-Hall phase in two dimensions (2017). Four Z_2 invariants distinguish the ordinary insulator from 'weak' and 'strong' TIs in three dimensions. These phases are characterized by gapless surface (or edge) states (Lan et al. 2022).

The anti-de Sitter/conformal field theory (AdS/CFT) (Ramallo 2016) correspondence is a theoretical framework that relates specific strongly interacting quantum field theories to higher-dimensional gravitational theories. Certain topological states, like TIs, can be connected to gravitational theories in a higher-dimensional space, suggesting a deep connection between topology and gravity.

In this section, we delve into the unique properties of QMs, particularly focusing on quantum confinement, strong electronic correlation, topology, and symmetry. Reviewing all these properties in one go is challenging, but we aim to provide a concise overview. To facilitate a better understanding of these properties in a single location, we include Fig. 5, which depicts all these properties simultaneously.

Applications of QMs

QMs, at the forefront of materials science, have ignited a revolution in technology and applications. These remarkable materials, with their unique electronic and optical properties arising from quantum mechanical effects, hold immense promise for a wide range of exceptional applications. From ultra-efficient photodetectors to quantum computing, QMs drive innovation and redefine the boundaries of what is possible in electronics, energy storage, and beyond. As we delve deeper into their properties and harness their potential, we are poised to unlock a new era of technological advancement that will shape the future in ways we are only beginning to imagine. In the following subsections, we will provide significant experimental studies reported in the last 5 years of QMs from the perspective of potential applications of QMs. In Table 1, we include different types of QMs and corresponding fundamental key properties and application with a suitable reference.

Advanced electronics

QMs-based electronic devices are revolutionizing technology and materials science, offering remarkable properties and diverse applications. QDs leverage quantum confinement effects for precise control over electronic and optical properties. Nanowires provide a platform for ultra-compact, high-performance devices with exceptional electronic transport properties and versatile integration possibilities. 2D materials, like graphene and transition metal dichalcogenides (TMDs), enable the development of ultra-thin and flexible devices with outstanding electrical, thermal, and mechanical characteristics. These quantum material-based electronic devices hold promise across various fields, including electronics, photonics, energy harvesting, and quantum computing, fuelling innovation and pushing technology boundaries. They represent the next generation of transistors, sensors, and high-performance computing, harnessing quantum mechanics for superior performance compared to traditional silicon-based electronics (Fig. 6).

In 2017, Takeda Hirotaka introduced an innovative approach to fabricating nanowires to create a remarkably transparent and electrically conductive nanowire film ("Nanowire, process for producing nanowires, nanowire dispersion, and transparent electroconductive film - n.d.). The proposed method involves the synthesis of nanowires

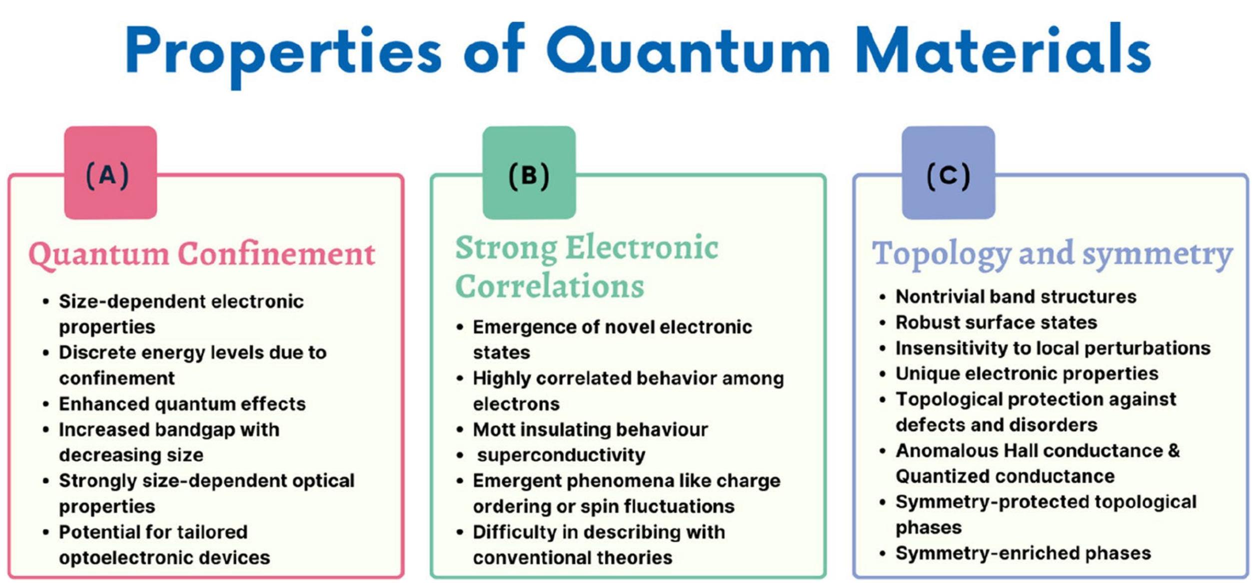

Fig. 5 A pictorial representation of properties of QMs (**A**–**C**)

Table 1 Representation of various type of QMs and corresponding key properties and their multidisciplinary applications

S.No	Quantum materials	Fundamental physics and key properties	Applications	Ref
1.	Superconductors	Zero electric resistance, perfect diamagnetism, Meissner effect	Quantum computing, energy transmission, medical imaging	(Delft and Kes 2010) (Hirsch 2011)
2.	Topological insulators	Topology, conducting surface states, insulating bulk, time-reversal symmetry, spin–orbit coupling, bad structure, topological invariants, quantized conductance, edge states	Spintronics, quantum computing, low-power advanced electronics	(Anirban 2023)
3.	Topological superconductors	Superconductivity, topological order, Majorana fermions, topological invariants, quantum spin hall effect, phase transition	Quantum computing and sensing, skyrmion crystal for computing	(Balaguera and Bisquert 2024) (Mandal et al. 2023) (Sato and Ando n.d.) (Rohr 2023)
4.	Quantum magnets	Spin exchange interactions, quantum fluctuation, quantum phase transition	Data storage in computers and generating electricity in generators	("Oersted, electric current and magnetism | IOPSpark". 2024)
5.	Frustrated quantum magnets	Geometric frustration, degeneracy, order by disorder, topological states	Advanced electronics, high temperature superconductivity	(Odoh et al. 2015)
6.	Quantum wells, wires, dots	Quantum confinement effects	Advanced electronics, optoelectronic devices, i.e. lasers, photodetectors, solar cells	(Scappucci, et al. 2020; Maximov, et al. 2020)
7.	Superfluid helium	Zero viscosity, quantum vortices, Bose–Einstein condensate, fountain effect	Cryogenic applications, fundamental physics studies	(Halperin 2021; Schmitt 2015)
8.	Majorana fermions	Non-Abelian anions, robustness against decoherence, zero energy modes	Topological quantum computing fault-tolerant qubits	(Franz 2010; Sau et al. 2020)
9.	Nitrogen-vacancy centres	Spin dependent dynamics, long coherence times	Quantum sensing, magnetic resonance imaging, quantum information processing	(Zhang et al. 2023; Bürgler et al. 2023)
10.	Quantum Hall effect	Discrete quantization of Hall conductance Chiral edge states	Metrology, fundamental constant determination	Weis 2005) (Girvin 2007; Solomon 2010)
11.	2D materials	Quantum confinement effects, high carrier mobilities, superconductivity, good thermal conductivity, layering, and stacking	Electronics, Photonics, Sensing devices, energy storage, biomedical devices	(Basu and Bhattacharyya 2012) (Mas-Ballesté et al. 2011)
12.	Quantum Dots	Quantum confinement, bandgap tunability, high quantum yield, size-dependent properties	Optoelectronics, quantum cryptography, drug delivery	(Dabbousi et al. 1997) (Kim et al. 2022) (Fröbel, et al. 2018) (Bae, et al. 2013) (Bang et al. 2021) (Chen et al. 2014)
13.	Quantum spin liquids	Frustrated spin ½ systems, quantum fluctuations, gauge theories, anyon excitations, topological order	Quantum computing, high temperature superconductors, topological qubits	(Zhou et al. 2017; Norman 2016) (Shimizu et al. 2003) (Banerjee et al. 2017)
14.	Metamaterials/metasurfaces	Negative refractive index, artificial electromagnetic properties, sub-wavelength control, anisotropy	Superlensing, cloaking, advanced imaging, optical devices, wireless communication, energy harvesting	(Solntsev et al. 2021) (Kuznetsov et al. 2024)
15.	Weyl semimetals	Weyl fermions, topologically protected surface states, chiral anomaly, high carrier mobility, Fermi arc surface states, broken inversion or time-reversal symmetry, Berry curvature effects	Quantum computing, spintronics, ultrafast electronics, high-sensitivity sensors, energy-efficient devices	(Chiu et al. 2020)

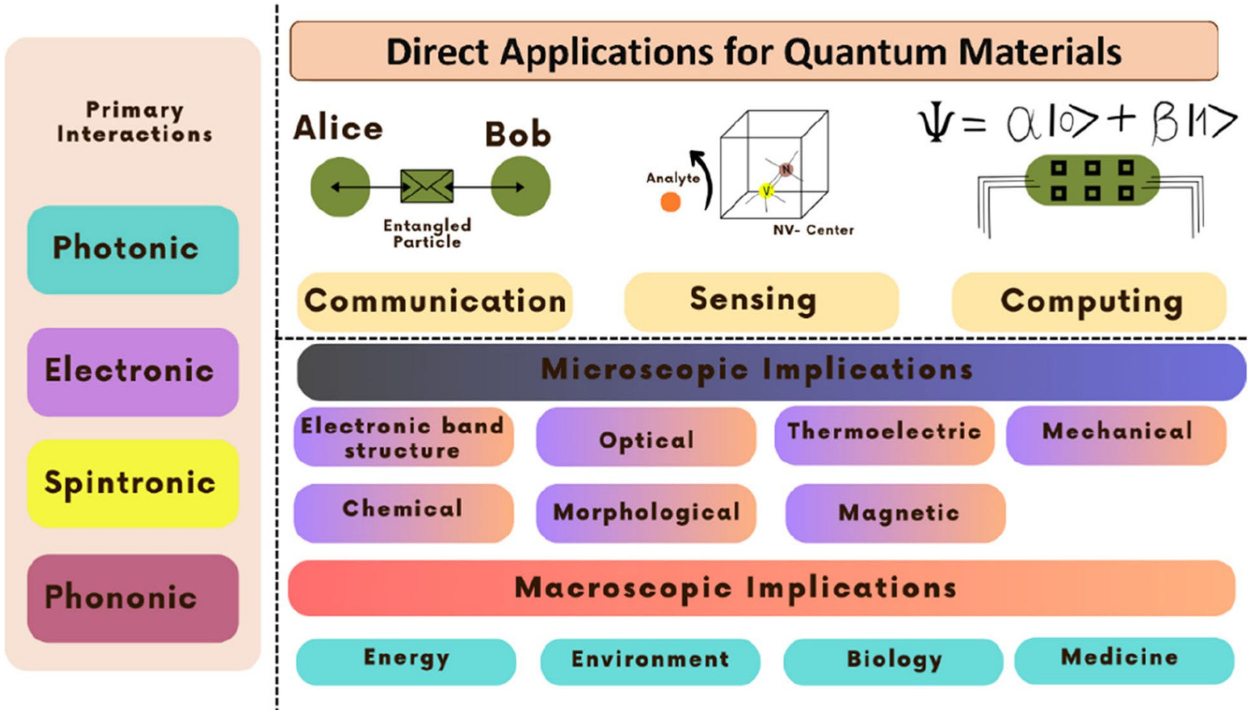

Fig. 6 A wide range of QMs applications, promising innovative solutions, and advancements across various fields

featuring a linearly interconnected structure formed by multiple particles. Notably, the nanowires are engineered with a carefully controlled diameter ratio falling within the range of 15 to 25 (A/B), ensuring that the resulting nanowire film exhibits outstanding transparency and excellent electrical conductivity. This breakthrough holds significant promise for applications requiring materials with dual transparency and electrical conduction characteristics, opening new avenues for advanced technologies in fields such as electronics, optoelectronics, and beyond.

In 2020, Zhong successfully synthesized silver nanowires (AgNWs) through a polyol reduction process, employing $FeCl_3$ and NaBr as reaction inhibitors (Zhong and Wang 2020). Notably, they found that varying the molar ratio of $FeCl_3$ to NaBr influenced the yield of AgNWs but had minimal impact on their morphology. These AgNWs were then utilized to fabricate transparent conductive films on glass slides, exhibiting commendable electrical conductivity, high transmittance, and a smooth surface texture. The AgNWs film heaters displayed rapid heat response characteristics and efficient electrothermal conversion, achieved with low input voltages. Furthermore, they observed that these AgNWs films remained structurally intact up to 170 °C, beyond which they fused into discontinuous segments at 200 °C. Overall, his findings mark the promising potential of AgNWs for transparent and efficient heating applications, while shedding light on the nuanced relationship between reactant ratios and nanowire yield.

In 2022, Xu et al. developed a novel gas sensor that uses black phosphorus QDs (BP QDs) modified $Ti_3C_2T_x$ nanosheets ($BQ/Ti_3C_2T_x$) as its sensing channel. This sensor shows remarkable performance in NO_2 detection at room temperature (Xu et al. 2022). This sensor boasts a wide linear detection range, rapid response time, and exceptional specificity. Furthermore, the study delves into the influence of humidity and temperature on gas detection and introduces a practical calibration approach to mitigate humidity's impact, thereby ensuring the precision of NO_2 detection. The sensor's heightened sensitivity and selectivity can be attributed to the augmented adsorption energy of $BQ/Ti_3C_2T_x$ towards target gas molecules and the formation of P-O-Ti bonds. This research provides valuable insights into developing sensitive and selective gas sensors, highlighting the promise of functionalized MXene materials in this field.

A recent study by Li et al. in 2023 showcases the promising application of transfer printing QDs as an effective colour-converting layer for advancing full-colour micro-LED displays (Li et al. 2022). Through the strategic design and creation of a distributed Bragg reflector (DBR), the study successfully enhances the colour purity of red and green light emitted by QDs while optimizing the utilization of blue light from micro-LEDs. This technology's implementation involves transferring red QDs onto the DBR as a colour-converting layer, subsequently integrated with blue micro-LEDs. This innovative approach facilitates the down-conversion of blue emission from the micro-LEDs into vibrant red emission, thereby realizing a full-colour display. This research presents a significant step towards enhancing the quality and versatility of micro-LED displays, with potential applications ranging from consumer electronics to advanced visualization systems.

Chaudhary et al., in 2023, explored the utilization of nitrogen-doped carbon QDs (CQDs) on graphene to develop field-effect transistor (FET) based optoelectronic memories that are programmable via UV illumination (Chaudhary et al. 2023). The study showcases the successful creation of such memories, emphasizing the pivotal role played by the charge-trapping properties of nitrogen-doped CQDs in ensuring long-lasting memory retention. Additionally, the interaction between the CQDs and graphene FET enables a photo-gating effect, enhancing the versatility of these memories. Notably, the research reveals that memory erasure can be achieved by applying a positive gate bias, facilitating the removal of trapped charges through recombination. This work marks the immense potential for engineering high-performance all-carbon, non-volatile FET-based optoelectronic memories by manipulating and coupling charge-trapping properties between colloidal CQDs and graphene.

In 2023, Zhou et al. researched metal halide perovskite QDs, which possess remarkable optical properties that make them promising candidates for LED devices (Zhou et al. 2023). However, the conventional ligands used in these QDs have limited their practical application due to their instability. In an exciting breakthrough, incorporating the dual-function ligand DDA-MeS has proven to be a game changer. This innovative approach has significantly enhanced the electrical performance of green QDs-LED devices and yielded impressive results. With DDA-MeS, the external quantum efficiency soared to 10.18%, the maximum brightness reached an impressive 8025 cd/m^2, and the turn-on voltage was reduced to just 2.5 V. This success highlights the tremendous potential of dual-function ligands in advancing the performance of perovskite quantum dot LED devices, paving the way for brighter and more energy-efficient lighting solutions.

Cao et al. in 2023 achieved a significant breakthrough in lighting technology (Cao et al. 2023). They successfully synthesized multicolour nitrogen-doped graphene QDs (NGQDs) through a one-pot method and refined the process further with column chromatography purification. These NGQDs exhibited three distinct emission colours: vivid blue, captivating cyan, and radiant yellow. Leveraging this innovation, the team integrated these NGQDs with InGaN chips to engineer LEDs capable of emitting these specific colours. Most notably, by strategically reducing the number of yellow NGQDs used in the blend, they created a white LED with precise colour coordinates of (0.324 and 0.334). This achievement paves the way for developing highly customizable and energy-efficient lighting solutions with broad applications in various fields.

Ali et al. in 2022 found an intriguing phenomenon of the metal–insulator transition (MIT) within WSe_2 devices, focusing on the pivotal role played by the thickness of the WSe_2 channel and the associated unscreened charge impurity and trap density near the interface (Ali et al. 2022). Our investigation revealed a compelling relationship between the thickness of the WSe_2 channel and the behaviour of the MIT. Specifically, as the WSe_2 channel thickness decreases, they observed a pronounced increase in critical carrier and trap densities. This effect engendered significant potential fluctuations and charge density heterogeneity within the system. Notably, this tuneable MIT behaviour is predominantly attributed to the substantial rise in trap density as WSe_2 thickness diminishes. Remarkably, our findings highlight a remarkable congruence between thinner WSe_2 devices and percolation theory, starkly contrasting the behaviour exhibited by multilayer WSe_2 devices, which defy percolation theory. This study marks the critical importance of thickness control in manipulating the metal–insulator transition dynamics in WSe_2 devices and paves the way for novel applications in the field of nanoelectronics.

In 2022, Oh et al. showcased 2D transition–metal dichalcogenide (TMD) semiconductors, namely MoS_2, $MoTe_2$, and WSe_2, which were skilfully employed to construct van der Waals vertical heterostructures for tunnelling field-effect transistor (TFET) applications (Oh et al. 2022). The fabricated TFETs featuring $MoS_2/MoTe_2$ or MoS_2/WSe_2 heterostructures exhibited remarkably low subthreshold swings of 9.1 mV/dec and 7.5 mV/dec, respectively. This remarkable achievement signifies the efficient band-to-band tunnelling processes harnessed in these devices. The electrical characteristics of these heterostructures were thoroughly investigated, revealing negative differential transconductance, negative differential resistance, and temperature-dependent I–V characteristics, all of which solidified the band-to-band tunnelling mechanism. Incorporating atomically thin 2D materials and van der Waals vertical heterostructures in TFETs showcases substantial potential for advancing the development of next-generation wearable, stretchable, and flexible low-power electronic devices.

An impactful study in the domain of biosensing by Silvia Rizzato emerged FETs as indispensable tools, boasting an array of advantages including exceptional sensitivity, rapid response times, the potential for miniaturization, and the convenience of portable read-out systems (Rizzato et al. 2022). The integration of 2D nanomaterials into FETs has yielded auspicious outcomes, showcasing superior performance characteristics such as an impressive surface-to-volume ratio, enhanced carrier mobility, localized gating capabilities, heightened transconductance, and the ability to operate efficiently at low voltages. This paper delves into a comprehensive review of the progress and prospects of 2D materials in FET biosensors, shedding light on the myriad opportunities, recent applications, associated challenges, and forthcoming possibilities. Indeed, integrating 2D nanomaterials into biosensors is key to unlocking heightened sensing capabilities and optimizing device performance. With their compact size and remarkable sensitivity, FETs are poised to revolutionize real-time monitoring across a broad spectrum of biomedical diagnostic applications.

A recent study in electronics materials by Zou and Noh (Zou and Noh 2023) introduced a solution-processed 2D transition metal dichalcogenides (TMDs) which hold significant promise for the future of complementary metal–oxide–semiconductor (CMOS) technology, thanks to their atomic thinness and impressive electrical and mechanical properties. Nonetheless, the journey towards their practical application presents hurdles. Achieving scalable, high-purity 2D semiconductor mono- and few layers with sizable lateral dimensions and a narrow thickness distribution remains a formidable challenge. Furthermore, the field-effect mobility of solution-processed 2D TMD transistors lags behind counterparts produced through alternative methods, with the underexplored realm of solution-processed p-type 2D TMD transistors adding to the complexity. Despite these obstacles, there have been notable strides in developing solution-processed CMOS devices utilizing both n-type and p-type 2D TMD transistors bolstered by advancements in deposition techniques, device fabrication, and CMOS applications. As this field progresses, ongoing research endeavours will be essential to surmount current limitations and steer this technology toward its full potential.

Peng et al. show the presence of Weyl nodes in TaAs Weyl semimetals by angle-resolved photoemission spectroscopy, which suggests promising applications in thermoelectric devices due to their unique transport properties (Peng et al. 2016). Using first-principles calculations and semiclassical Boltzmann transport theory, they examined the electrical transport behaviour of TaAs and found high anisotropy. The calculated Seebeck coefficients align well with experimental data. Additionally, they analyse the lattice dynamics of TaAs, with phonon frequencies matching well with experimental observations and calculate the lattice thermal conductivity using a self-consistent iterative method. Anisotropy is also observed in the lattice thermal conductivity. For n-doped TaAs along the Z direction, they find a peak thermoelectric figure of merit ZT of 0.63 at 900 K. Lastly, they also investigate the size-dependent behaviour of lattice thermal conductivity and thermoelectric properties, which provides insights for the design of thermoelectric nanostructures.

Quantum sensing and imaging

QMs are revolutionizing sensor technology and imaging. They offer unique properties like superconductivity and magnetism, enabling ultra-precise sensors for medical imaging and environmental monitoring. Integrating QMs into techniques like magnetic resonance imaging (MRI) and microscopy enhances our ability to study atomic and molecular structures. Applications include highly sensitive magnetometers for medical diagnostics and QDs sensors for biomolecular sensing. Interferometry involving QMs, such as Bose–Einstein condensates and atom interferometers, offers unparalleled precision in measuring gravity and inertial forces. These sensors can detect minute changes in acceleration and rotation and find applications in navigation, geodesy, and tests of fundamental physics. In this section, QMs drive a new sensor development and imaging era, propelling scientific discovery to new heights.

A study by Milekhin et al. in 2016 on surface-enhanced Raman scattering (SERS) within semiconductor nanostructures (Milekhin et al. 2016). It investigates the manifestation of SERS through confined optical and surface optical phonons in a diverse range of materials, including CdS, CuS, GaN, and ZnO nanocrystals, along with GaN and ZnO nanorods and AlN nanowires. The findings reveal that SERS by phonons exhibits a resonant nature, with the most substantial enhancement observed in CdS nanocrystals and surface optical modes within ZnO nanocrystals. Moreover, this study unveils the augmentation of Raman scattering due to confined optical phonons and the emergence of novel Raman modes with distinct frequencies distinct from those found in ZnO bulk. These phenomena are attributed to surface optical modes within the nanostructures and are validated through calculations employing the dielectric continuum model. Furthermore, SERS by phonons is harnessed as a powerful tool for exploring the phonon spectrum in nanocrystal ensembles characterized by an exceptionally low areal density when coupled with metal plasmonic nanostructures. This research significantly advances our understanding of the intricate interplay between phonons and nanostructures. It offers valuable insights into their resonant behaviour and the possibilities for phonon spectroscopy in the nanoscale regime.

Corgier et al. in 2020 introduced a novel source engineering concept aimed at enhancing precision atom interferometry for binary quantum mixtures with extended drift times (Corgier et al. 2020). The authors created a multi-stage, non-linear atomic lens sequence to generate dual ensembles characterized by ultra-slow kinetic expansion energies, specifically below 15 pK. This innovation serves the crucial purpose of mitigating wavefront aberrations, a prominent source of systematic errors in precision atom interferometry. Furthermore, the authors developed a scaling approach to address the non-linear dynamics of binary quantum mixtures, thus expanding the potential applications of this technique in scenarios involving various intra- and inter-species interaction regimes. This research opens exciting possibilities for achieving more precise and stable atom interferometry measurements over extended timeframes.

Nitrogen-vacancy (NV) centres in diamonds are quantum defects with unique spin properties that allow them to sense magnetic and electric fields with high sensitivity. NV centres can detect small magnetic signals, such as in biomagnetism imaging and MRI, and measure electric field gradients in neuronal activity. In 2022, Bätge et al. delved into the domain of electric-field noise detection on the surface of the diamond, employing shallow NV centres as their investigative tools (Bätge et al. 2022). Their exploration reveals a fascinating phenomenon: the electric-field noise exhibits a power-law frequency dependence, its behaviour intricately intertwined with temperature and the activation energies of two-level systems. As temperature ascends from 295 to 420 K, the noise experiences a gradual increase, but it diminishes swiftly at even higher temperatures. The origin of this noise lies in ensembles of two-level systems characterized by activation energies spanning from 0.3 eV to 0.6 eV, a behaviour elucidated by the Dutta–Horn model. Notably, the study indicates the superiority of solid covering material, specifically PMMA, over its liquid counterpart, glycerol, in mitigating electric-field noise on the diamond surface. This superiority is attributed to the presence of surface-modified photonic coupling noise. Overall, this research enhances our comprehension of the underlying factors contributing to surface 1/f electric-field noise and sheds light on the choice of optimal covering materials for augmenting the coherence time of near-surface NV centres.

In a very recent study in 2023 by Jeffrey Neethi Neethirajan, this paper delves into the formidable challenges confronting near-surface negatively charged NV centres, encompassing issues such as charge-state instabilities, diminished fluorescence, and NV coherence time (Neethirajan et al. 2023). These impediments significantly hinder the sensitivity of magnetic imaging, a concern that becomes particularly pronounced at the demanding conditions of 4 K and ultrahigh vacuum (UHV). However, the authors present a promising solution by demonstrating the efficacy of in situ adsorption of H_2O on the diamond surface, which offers a pathway toward the partial restoration of shallow NV sensors. They highlight the pivotal role of controlled surface treatments as an indispensable element in implementing NV-based quantum sensing protocols under cryogenic UHV conditions. This research paves the way for improved performance and applications of NV-based quantum sensors in challenging environments.

Quantum cascade lasers (QCLs) exploit quantum mechanical principles, providing coherent and tuneable mid-infrared and terahertz radiation. QCLs are used in spectroscopy to identify specific molecular vibrations, enabling the detection of trace gases, pollutants, and chemicals in diverse environments. Impactful research in 2020 by Yohei Matsuoka was carried out on QCL (Kim et al. 2018). It is a remarkable semiconductor device that emits light through electronic transitions between subbands within a heterostructure conduction band, granting it the unique capability to emit light at multiple photon energies. This paper offers a comprehensive insight into the fundamental physics underpinning QCLs, shedding light on their intricate fabrication process and introducing a novel approach to achieving enhanced power and brightness through broad-area QCLs. The paper also delves into the intriguing physics and optics associated with external cavity tuneable QCLs, which present the fascinating ability to finely tune the laser's emission wavelength. In contrast to conventional diode lasers, which emit light at a fixed energy level, QCLs exhibit the flexibility to emit light at various photon energies, making them a promising candidate for different applications in photonics and spectroscopy.

Yang et al. in 2020 researched MRI and introduced an efficient and swift approach to fabricate Gd-doped $ZnCuFeS_3$ QDs adorned with surface ligands such as oleyl amine, oleic acid, and mercaptan (Yang et al. 2023). Due to their remarkable features, these QDs hold great promise as contrast agents in nuclear magnetic resonance imaging. Notably, they exhibit an adjustable fluorescence spectrum, allowing for versatile imaging applications while maintaining stable chemical properties. This innovative method opens new possibilities for enhancing the precision and versatility of imaging techniques, making it a valuable contribution to medical diagnostics and research.

In a study by Zhenjie Wang, 'Single Photon Avalanche Diode (SPAD) Circuits For Ultra-Violet Imaging' (Zhenjie Wang, Ivor Fleck, Bhaskar Choubey), the development of a compact CMOS—SPAD pixel tailored for ultra-violet imaging is described. Achieved through a standard high-voltage CMOS process with a dedicated passivation opening for the diode, the pixel boasts dimensions of 35×40 μm and an 8% fill factor. An active quenching circuit is introduced to optimize avalanche quenching and recharge, significantly enhancing speed and reliability. Additionally, incorporating a 9-bit digital counter within each pixel facilitates precise photo-counting operations. This innovative SPAD pixel holds promising potential for various applications in ultra-violet imaging, particularly in scenarios requiring single-photon detection capabilities.

An impactful research by He et al. in 2022 developed a remarkable device featuring a substantial InGaAs absorption region complemented by an anti-reflection layer. This combination has yielded an impressive quantum efficiency of 83.2% (He et al. 2022). The device's single-photon performance was meticulously assessed by implementing a quenching circuit, resulting in a remarkable maximum detection efficiency of 55.4%. Even more impressively, this achievement was accompanied by a dark count rate of just 43.8 kHz and an incredibly low noise equivalent power of 6.96×10^{-17} W/Hz$^{1/2}$ at a temperature of 247 K. What sets this device apart from previously reported detectors is its ability to maintain a higher single-photon detection efficiency while operating at a more elevated cooling temperature, underlining its promising potential for various applications in the field.

In a study (2022) by Liu Chen, 'Avalanche-photodiode-based near-infrared single-photon detectors', notably the InGaAs/InP variant, have become increasingly popular owing to their exceptional sensitivity, rapid response times, and seamless integration capabilities (Liu et al. 2022). This paper delves into the latest advancements and diverse applications of InGaAs/InP photodiodes, showcasing their continuous performance enhancements achieved through structural optimization and external quenching circuits. These detectors boast remarkable attributes, including substantial internal gain, heightened sensitivity, swift response, compact form factors, and ease of integration. Furthermore, the study provides a brief overview of alternative near-infrared single-photon detection technologies founded on novel materials and mechanisms, hinting at the promising potential for further breakthroughs in this dynamic field.

Quantum communication and information processing

QMs play several key roles in quantum communication and information processing. They are crucial for developing efficient quantum memory systems that store and retrieve light-generated quantum information. Ytterbium-based materials, for instance, show promise in this regard, as they can store and protect quantum information at high frequencies. QMs are essential for realizing quantum interconnects, including components like quantum switches, repeaters, and frequency converters. These interconnects facilitate the transfer of quantum states between different devices while preserving coherence and entanglement. Certain QMs serve as platforms for implementing qubits, such as semiconductor QDs, colour centres in wide-bandgap materials, and superconducting materials, enabling diverse qubit types for quantum computing. Additionally, QMs with unique properties, like diamonds with colour centres, are used for quantum sensing, providing highly sensitive sensors for various applications. Lastly, QMs are pivotal for quantum communication security, enabling protocols like quantum cryptography and quantum key distribution, which utilize superposition and entanglement to ensure unbreakable data encryption.

An impressive paper by Scappucci et al. in 2021 (Scappucci et al. 2021) shows the significance of high-purity crystalline solid-state materials in advancing quantum information processing, particularly in qubit technologies reliant on spins and topological states. It highlights the potential and challenges associated with semiconductor heterostructures for spin qubits, with GaAs, Si, and Ge as established platforms demonstrating two-qubit logic. Additionally, the abstract emphasizes the promise of topologically non-trivial materials like topological insulator thin films and materials such as PbSnTe for creating topological qubits. It calls attention to the need for advancements in fabrication and characterization techniques to enable integration with Josephson junctions and the development of high-quality QMs. In conclusion, the paper identifies the most promising avenues for advancing qubit technology through enhancements in these material systems, with a strong emphasis on improving material quality and heterostructures to mitigate decoherence and enhance solid-state qubit performance.

In 2022, a study was carried out by Pelet et al., introducing an achievement in quantum communication, a metropolitan quantum network utilizing energy-time entanglement-based QKD (Pelet et al. 2022). This pioneering system spans 50 km, connecting three nodes within Nice via optical fibres. It achieves a notable raw key rate of 40 Kbps per pair of channels and adheres to the ITU 100 GHz standard for telecom-grid compatibility. To bring this innovative network to life, the researchers harnessed a high-quality source of energy-time entangled photon pairs and implemented robust clock synchronization techniques, eliminating the need for dedicated communication channels. The post-treatment software facilitated real-time key generation, culminating in successfully establishing secret keys. This research marks a historic milestone by presenting the world's first fully operational entanglement-based metropolitan quantum network, demonstrating its feasibility and remarkable performance in a real-world setting.

In 2024, Scheie and Tennant closely examined $KYbSe_2$ by simulations, entanglement analysis, and neutron spectroscopy, which approximates a 2D quantum spin liquid ("A proximate model material for triangular lattice quantum spin liquids" 2023). It shows magnetic ordering at low temperatures. Its magnetic behaviour is driven by fractionalized excitations with unusually high quantum entanglement, suggesting that $KYbSe_2$ displays quantum spin liquid characteristics over finite timescales. Applying entanglement witnesses from quantum information theory offers valuable insights into the physics of newly synthesized materials in condensed matter research.

Quantum spin liquids (QSLs) represent a quantum-disordered state characterized by significant entanglement and fractionalized excitations. As a highly pursued state of matter, QSLs are anticipated to host spinon excitations and emerge in systems with frustrated spins and substantial quantum fluctuations. A study by and Tennant (2024) presents experimental evidence and theoretical modelling of QSL characteristics in monolayer 1 T-$NbSe_2$ ("A proximate model material for triangular lattice quantum spin liquids" 2023). It shows a new two-dimensional material with charge density wave and correlated insulating properties. Scanning tunnelling microscopy and spectroscopy confirm spin fluctuations in monolayer 1 T-$NbSe_2$ by observing the Kondo resonance as it interacts with metallic monolayer 1H-$NbSe_2$. Further STM/STS imaging at the Hubbard band energy reveals a long-wavelength charge modulation consistent with the spinon modulation expected in QSLs. These observations highlight monolayer 1 T-$NbSe_2$ as a promising QSL candidate.

Resonant excitation of electronic transitions using coherent laser sources enables the formation of quantum coherent superpositions among electronic states. While most time-resolved studies have concentrated on gases or isolated subsystems within insulating solids for quantum information applications, Mankowsky et al. focus on controlling orbital wavefunctions in the correlated quantum spin liquid $Tb_2Ti_2O_7$ (Mankowsky et al. 2024). Results demonstrate that resonant excitation with an intense THz pulse generates a coherent superposition of the lowest energy Tb 4f states, manifesting as a macroscopic oscillating magnetic dipole detectable through ultrafast resonant X-ray diffraction. This approach to coherent control of orbital wavefunctions offers a promising technique for rapidly manipulating and exploring QMs.

QSLs have emerged as a central topic in magnetism research due to their distinctive characteristics, which include long-range entanglement, fractionalized excitations, and topologically protected behaviours. The exploration of QSL candidates has recently expanded to include three-dimensional materials despite the challenge posed by reduced quantum fluctuations in higher dimensions. Gonzalez et al. explored the $K_2Ni_2(SO_4)_3$ 3D spin liquid model, which belongs to the langbeinite family and comprises two interconnected trillium lattices (Gonzalez et al. 2024). Although this material displays magnetic ordering, it maintains a highly dynamic and correlated state. In this study, they investigate the magnetic properties of $K_2Ni_2(SO_4)_3$ through a combination of inelastic neutron scattering experiments, density functional theory (DFT), pseudo-fermion functional renormalization group (PFFRG), and classical Monte Carlo simulations, achieving a strong correlation between theoretical and experimental findings. The analysis attributes the dynamic state in $K_2Ni_2(SO_4)_3$ to a magnetic network of tetrahedra arranged on a trillium lattice.

Weyl semimetals have attracted significant interest due to their unique topological properties, with notable implications across various research domains. When integrated with s-wave superconductors, these materials can support supercurrents along their topological surface states, creating junctions that mimic Majorana-bound states. Chiu presented a transmon-like superconducting quantum interference device (SQUID) utilizing lateral junctions made from the Weyl semimetal Td-$MoTe_2$ and superconducting niobium nitride (NbN) leads (Chiu et al. 2020). The SQUID is coupled to a readout cavity made of molybdenum rhenium (MoRe), whose high-power response confirms the presence of the Josephson junctions (JJs). The circuit's loop geometry allows tuning of the readout cavity's resonant frequency by applying magnetic flux. They demonstrate a Josephson junction based on $MoTe_2$ and a flux-tunable, transmon-like circuit incorporating Weyl semimetals. This study establishes a platform for using topological materials in SQUID-based quantum circuits, with potential applications in quantum information processing.

Energy conversion and storage

QMs have emerged as revolutionary components in energy conversion and storage devices, transcending the limitations of classical materials. Their exceptional properties, often harnessed at the nanoscale, enable leaps in efficiency and performance. In energy conversion, QMs like perovskite solar cells exhibit unprecedented light-harvesting capabilities, efficiently converting sunlight into electricity. Similarly, QDs offer tuneable electronic and optical properties, enhancing the efficiency of LEDs and photodetectors. QMs such as graphene and TIs in energy storage contribute to supercapacitors and batteries with enhanced charge storage and faster energy release. Quantum phenomena like entanglement can be leveraged to develop quantum-enhanced devices for even more efficient energy conversion and storage, paving the way for a sustainable energy future. In this section, we will describe the utilization of QMs in energy conversion and storage devices and discuss advancements in quantum dot solar cells, thermoelectric materials, and quantum-enhanced energy storage.

Due to their unique properties, tin oxide QDs (SnO_2 QDs) are gaining attention for energy storage. Tin oxide is an eco-friendly semiconductor with stability, and it is found in solar cells, capacitors, batteries, and gas sensors (Xiao et al. 2018). SnO_2 QDs have advantages like high surface area for better reactions, cost-effectiveness, high capacity, fast charging, stability, and compatibility with other materials. In a study, a hybrid of SnO_2 QDs and activated carbon showed a capacitance of 222 Fg^{-1} and high energy/power densities (Zarshad et al. 2021). These composite holds promise for portable electronics and energy storage systems.

Cadmium sulfide (CdS) QDs possess a large surface area and low band gap (2.42 eV), making them vital II–IV semiconductors (Kyobe et al. 2016). Their exceptional electrochemical, optical, and fluorescence properties are ideal for pharmaceutical analysis and element detection. CdS QDs' effectiveness is influenced by their size and structure, prompting research into proper forms and dimensions. Various methods, like sol–gel, hydrothermal, organic solvent, and microwave processes, produce CdS QDs with different properties. Smaller CdS QDs exhibit improved capacitance and cyclic stability. Recent studies highlight CdS QDs' potential as electrode materials in supercapacitors (SCs) due to their high capacitance, cycling stability, and rapid charge–discharge rates. Organometallic perovskites and CdS QDs were used in layers for thin-film electrochemical capacitors, enhancing cycling properties and energy densities. Challenges include CdS QDs' low conductivity and toxicity, prompting strategies like carbon-based hybridization and non-toxic alternatives. While CdS QDs hold promise for SC electrodes, further research is needed to address challenges and fully unlock their potential, potentially through innovative synthesis methods, hybridization, and exploring non-toxic alternatives (Li et al. 2020; Wang et al. 2018).

QDs of MoS_2 have caught the attention of researchers due to their unique properties, like light interactions and electrical behaviour (Arul and Nithya 2016). These dots have various potential applications in sensors, energy, and healthcare. They are small and emit controllable light, making them useful for biosensors and imaging (Fan et al. 2015). Scientists have found different ways to make MoS_2. They used techniques like UV–vis's absorbance, luminescence, and microscopy to study the dots' size and appearance. Compared to other MoS_2 structures, these dots showed better performance in terms of their electrical behaviour. They had a more significant potential range and higher capacity. A device using these dots also showed impressive stability and retained its capabilities even after many use cycles.

Recent advancements in 2D layered inorganic materials, like monolayer and few-layer sheets of tungsten disulfide (WS_2) and other dichalcogenides, are currently under close investigation (Štengl et al. 2015). WS_2, with its unique trigonal prismatic structure, falls under transition metal dichalcogenides (TMDs) and shares a layered arrangement like graphite (Xia et al. 2019). Due to its potential applications in solid lubricants, lithium batteries, bioimaging, hydrogen evolution reaction (HER), and more, researchers are actively exploring the controlled production of innovative and superior WS_2 micro-nanomaterials, sparking widespread interest.

The porous graphene sheet combined with attached GQDs forms a GQDs/Gr hetero junction, enhancing ionic diffusion and active sites for ion storage. At the same time, AL contributes to activated carbon with a dense pore structure. The hybrid supercapacitor works up to a 1.4 V voltage (as shown in the charts) and exhibits specific capacitances of 9.8, 8.5, 7.28, 6.45, and 5.85 F cm^{-3}. The CV curves and GCD profiles reveal pseudocapacitive charge storage alongside EDLC. S, N-$GQDP_2$ nanocomposite excels with an estimated 645 Fg^{-1} Csp, outperforming pure PANI, S, N-$GQDP_1$, and S, N-$GQDP_3$ samples at 177, 224, and 134 Fg^{-1}, respectively (Ramkumar and Minakshi 2015). Heteroatom-doped S, N-GQDs exhibit enhanced capacitance due to sulphur and nitrogen trapping electrolyte ions. The incorporation of heteroatoms boosts conductivity. Similar enhancements are seen with $CoMoO_4$ nanosheets modified with chitosan. Combining pseudo-capacitor and quasi-zero-dimensional carbon materials enhances energy storage through their high surface area, conductivity, and stability. Further research is necessary for optimization. Solution- and solid-type electrolytes employ GQDs with acid oxygen groups for improved supercapacitor performance (Sun et al. 2006; Chen et al. 2011; Bhojane 2022). Neutralizing acidic GQD groups enhances capacitance efficiency and rate capability. The storage capacity of nanocrystals and SP-derived CDs in an H_2SO_4 electrolyte increases with electrolyte amount, yielding 643 $mFcm^{-2}$ due to reduced resistance and better wettability.

Various characterization techniques were employed to study synthesized graphene QDs (GQDs). Electrochemical experiments were used to explore GQDs' supercapacitive properties (Rabeya et al. 2022). An electrode made from GQDs demonstrated a specific capacitance (SC) of 257 F g^{-1} at 3 Ag^{-1} current density, retaining 96% capacitance after 3000 cycles. GQDs were also used as active material in a flexible symmetric supercapacitor (SSC) with promising outcomes even after 1000 cycles. The SSC exhibited a rectangular cyclic voltammogram (CV) shape, indicative of reversible ion adsorption–desorption and a dual-layer capacitive nature. Galvanostatic charge–discharge (GCD) tests displayed symmetrical triangular curves with minimal internal resistance drops, confirming high-rate capabilities. The SC values at varying current densities were calculated, highlighting the devices' resilience to high current densities. Stability tests further validated the long-term performance (Yoon et al. 2014). Additionally, GQDs were employed as solid-state electrolytes, offering stability and compatibility with various electrode materials. The work extended to transparent and flexible micro-supercapacitors using GQDs, exhibiting remarkable transparency, energy storage, quick relaxation time, cycle retention, and stability (Song et al. 2018; Lu et al. 2018). The synergy between MoS_2 QDs and PANI in a hybrid conductive xerogel enhanced capacitance and stability (Zhao et al. 2015). The study demonstrated the potential for novel energy storage devices with wide-ranging applications.

Demand for energy storage devices has spurred the need for cost-effective QDs production, focusing on their potential applications in batteries and supercapacitors (Arul and Nithya 2016). These applications heavily rely on the nature of electrode materials, where carbonaceous materials, particularly graphene and its nanometer-sized derivatives known as GQDs, have exhibited excellent electrochemical properties due to their structure (Liu et al. 2021). GQDs offer unique attributes such as electron–hole pairs for conductivity, functionalization potential, and wettability for improved electrochemical properties. QDs also act as templates for distinct structures and can be incorporated through various methods. Recent studies highlight the impact of quantum dot morphology on the electrochemical performance of composite materials (Zhao et al. 2020). For instance, CdS QDs with rod-like morphologies displayed enhanced charge storage capacity and cycling stability, a crucial consideration in organic polymer composites for supercapacitor applications. Additionally, the synthesis of quantum dot composites as anode materials for energy storage devices has shown promising results, such as TiO_2 QDs anchored on graphene for rapid and stable lithium/sodium storage (Zhu et al. 2017). These innovative advances, along with ongoing research, hold the potential to shape the future of sustainable and renewable energy sources, addressing pressing environmental challenges and transforming the energy landscape.

A very recent and very effective study by Wang et al. in 2023 (Wang et al. 2018) on the potential of GQDs as interfacial engineering materials for perovskite solar cells (PSC) underlining their appeal due to their low toxicity and superior charge mobility when compared to other metallic-based QDs within semiconductor applications. However, it also raises a crucial concern about the emergence of structural defects attributed to the use of GQDs, leading to the formation of shallow trap states that contribute to decreased PSC performance. To shed light on this issue, the paper employs thermally stimulated current (TSC) and density–voltage (J–V) plots as analytical tools, offering valuable insights into the influence of structural defects and trap states on PSC efficiency. To mitigate these challenges, the paper proposes implementing a carefully controlled fabrication process, thus offering a path forward to harnessing the potential of GQDs while minimizing their associated trade-offs in PSC technology.

Another recent study of 2023 by Li et al. on indium oxide QDs (In_2O_3) was successfully incorporated into a $MAPbI_3$ film, effectively addressing the issue of low film quality caused by inherent defects (Li et al. 2020). Introducing In_2O_3 QDs led to a remarkable improvement in film quality by suppressing these defects. The resulting $MAPbI_3$:In_2O_3 film exhibited optimized time-resolved photoluminescence component ratios, which indicated enhanced carrier dissociation and improved transport efficiency. When this advanced film was employed in the fabrication of solar cells, it yielded significant improvements in performance metrics. Specifically, the solar cells using the $MAPbI_3$:In_2O_3 film demonstrated higher fill factor, short circuit current density, and power conversion efficiency than those using the $MAPbI_3$ film alone. These findings pave the way for developing more efficient and reliable solar cell technologies, with the potential for significant advancements in renewable energy generation.

In a study in 2023 by Wang et al. about the domain of advanced photodiodes and solar cells (Wang et al. 2023) explores the design and performance of a 2D ReS_2/MoS_2 semi-vertical heterojunction photodiode with a unilateral depletion region, showcasing remarkable attributes such as self-powered capability, a broad photovoltaic response, high responsivity, power conversion efficiency, and excellent detectivity. Moreover, this photodiode exhibits an impressively rapid response time and a detectable signal cut-off frequency, rendering it highly suitable for demanding photodiode applications. The outstanding performance of the 2D ReS_2/MoS_2 semi-vertical heterojunction photodiode makes it a promising candidate for various high-performance photodiode applications. Furthermore, incorporating photosensitive PbS QDs into the heterojunction further amplifies its sensitivity, resulting in a significant 21% enhancement in device responsivity under 532 nm illumination. This underlines the immense potential of ReS_2/MoS_2 heterostructures for utilization in advanced photodiodes and solar cells.

Another very recent study in 2023 by Nanxin Fu introduces a novel photodetector device that capitalizes on a hybrid dimensional heterostructure incorporating multiwall carbon nanotubes (MWCNTs) and multi-layered MoS_2 (Fu et al. 2023). This innovative approach enables the photodetector to achieve broadband detection capabilities from visible to near-infrared light. The results are auspicious, with the device demonstrating exceptional responsivity, detectivity, and external quantum efficiency. Specifically, the photodetector exhibited a remarkable responsivity of 3.67×10^3 A/W at a wavelength of 520 nm and an impressive 718 A/W at 1060 nm. These values were accompanied by detectivity (D*) figures of 1.2×10^{10} Jones at 520 nm and 1.5×10^9 Jones at 1060 nm. Moreover, the external quantum efficiency (EQE) values were strikingly high, measuring approximately 8.77×10^5% at 520 nm and 8.41×10^4% at 1060 nm. In summary, this research showcases the potential of mixed-dimensional heterostructures in photodetector technology, enabling proficient detection across visible and infrared spectra. This development paves the way for innovative optoelectronic devices built upon the foundation of low-dimensional materials, marking a notable advancement in the field.

Advancements in energy conversion and storage technologies have greatly influenced the development of next-gen tech. Batteries and supercapacitors (SCs) play a crucial role in cutting-edge electronics. SCs are reliable for real-time applications due to their benefits, such as high-power density and long lifespan at lower costs. They are ideal for future energy-focused tech like solar systems, electric vehicles, and wind power (Prasath et al. 2018). Scientists are working to enhance SCs, and this review highlights QDs and nanocomposites' role in improving SC performance. Effective QD use boosts SC efficiency, and QDs have broad applications in battery materials, medical tech, sensors, and more. The review zeroes in on QD-based electrode materials and flexible devices, showcasing their potential impact.

Spintronics applications and topological superconductors

TIs are intriguing materials with insulating bulk, but conductive surface states protected from scattering by symmetrical constraints and non-trivial band topology. These properties, arising from the interplay of quantum mechanics and topology, hold immense potential for quantum computing and spintronics. TIs offer stable qubits less prone to decoherence, crucial for scalable quantum computers, while in spintronics, they combine electron spin with motion to create efficient spin currents for novel device functionalities, promising energy-efficient computing and data storage solutions. Topological superconductors, with surface metal and interior superconducting states, Majorana fermions for faultless quantum computing, while topological magnets exhibit chiral edge states, merging magnetism and topology for low-energy loss electronic devices. These materials facilitate robust electronic states critical for reliable and fault-tolerant devices, and various growth methods exist for their fabrication.

Angle-resolved photoemission spectroscopy (ARPES) plays a crucial role in uncovering and understanding topological phases by revealing non-trivial electronic structures (Sobota et al. 2021). Additionally, ARPES helps measure topological invariants that classify different phases and study the impact of external forces. A notable example is the topological magnet $CoSn_2S_2$ (Kanagaraj et al. 2022), which displays fascinating magnetic properties and potential applications in storage. The quantum anomalous Hall effect (QAHE) is significant for low-energy electronics and topological superconducting quantum computing, and efforts to enhance QAHE continue with high-throughput calculations predicting potential materials. These advances open doors for high-temperature QAHE materials and innovative spintronics devices, harnessing properties for diverse applications like information storage and charge transport. Topological states have been studied before, especially in topological superconducting materials.

A physical property measurement system (PPMS) is a helpful tool to identify superconductivity in these materials (Sharma et al. 2017). This transition is typically seen in temperature-dependent resistance, magnetization, and heat capacity. Heat capacity measurement at varying temperatures is a reliable way to analyse superconductor properties. There are additional methods to characterize topological superconducting materials, but they need to be more detailed here due to space limitations. Taking $PbTaSe_2$ as an example, it has topological surface states (Chang et al. 2016). These surface states possess a distinct isolated band with helical spin texture due to their hybridization with bulk states and spin-momentum locking. This gives rise to helical topological superconductivity. The combination of topology and superconductivity results in a new quantum state, a topological superconductor, which is crucial for quantum computing. Overcoming errors caused by decoherence is a significant challenge in quantum computing, and topological quantum computing can solve this.

Majorana zero-energy modes on the surface of topological superconductors offer high fault tolerance for topological quantum computation. Anisotropic Majorana-bound states have been observed, opening avenues for novel heterostructures (Fang et al. 2019). Topological superconductivity has been detected in various systems, with nanowires showing promise. Majorana fermions might emerge from coupling superconductors with spin–orbit-coupled semiconductor nanowires (Frolov et al. 2020). These advancements hold potential for stable qubit modules in quantum computing and necessitate further research and understanding of the physics involved.

In 2023, Yoon et al. conducted a study (Yoon et al. 2014). In this study, the researchers delved into the intriguing question of the origin of the planar thermal Hall effect within the Kitaev magnet α-$RuCl_3$, a material thought to potentially host Majorana fermions and non-Abelian anyons, vital components of Kitaev spin liquids. Previous observations of an unusual planar thermal Hall effect in α-$RuCl_3$ had stirred controversy over whether it stemmed from Majorana fermions or bosonic magnons. To resolve this ambiguity, the authors conducted meticulous low-temperature measurements of specific heat and thermal Hall conductivity, employing in-plane field rotations as a discriminating factor. Their findings showcased a closure of the low-energy bulk gap and a sign reversal of the Hall effect along the honeycomb bond direction. They offered conclusive evidence favouring the Majorana-fermion origin of the thermal Hall effect in α-$RuCl_3$. These results bolster the notion that α-$RuCl_3$'s field-induced quantum-disordered state harbours Majorana fermions and non-Abelian anyons, solidifying its status as a promising candidate for Kitaev spin liquids. This research successfully settles the long-standing debate surrounding the thermal Hall effect's origin, definitively supporting the Majorana-fermion hypothesis based on compelling experimental observations.

Han et al. report on a quantum criticality crossover in the Kitaev quantum magnet α-$RuCl_3$, which reveals two distinct universal scaling regimes (Han et al. 2023). α-$RuCl_3$ exhibits symmetry-breaking antiferromagnetic ordering and long-range entangled topological order characteristics of a quantum spin liquid. Theoretical analyses of inelastic neutron scattering, ac-magnetic susceptibility, and specific heat measurements reveal a transition from Wilson–Fisher–Yukawa-type 'conventional' weak-coupling quantum criticality at high-energy scales to a heavy-fermion-type 'local' strong-coupling criticality at low energies. These results provide significant insights into the evolution of quantum criticality in topological systems where fermions and bosons interact, which leads to diverse types of deconfined fermions.

Beenakker et al. 2023) underlined the significance of the method of tangent fermions in discretizing the Hamiltonian of TIs and superconductors. This method stands out for its exceptional ability to safeguard the topological protection of massless excitations, whether Dirac or Majorana fermions. Tangent fermions operate within a 2 + 1-dimensional lattice framework with a tangent dispersion, sidestepping the problematic fermion doubling lattice artifact that could otherwise jeopardize the system's topological integrity. Although the resulting discretized Hamiltonian exhibits non-local characteristics, it can be transformed into a localized generalized eigenproblem, ensuring its practicality in both spatial and temporal domains. Moreover, the paper delves into various applications of tangent fermions, encompassing phenomena such as Klein tunnelling, resistance to localization by disorder, the anomalous quantum Hall effect, and the intriguing concept of the thermal metal involving Majorana fermions. Altogether, the method of tangent fermions emerges as an auspicious approach for discretizing the Hamiltonian of TIs and superconductors while upholding their topological protection and preserving the fundamental symmetries inherent in the Dirac Hamiltonian.

In 2022, Martin did an impressive review on the interface of organic and inorganic for spin injection using carbon nanotubes and graphene for spintronics applications (Martin et al. 2022). Another domain of quantum technology called spintronics adds spin quantum degrees of freedom to CMOS devices. Since the discovery of giant magnetoresistance in 1988 by Fert (Baibich et al. 1988) and Grunberg (Binasch et al. 1989), spintronics has transformed everyday gadgets like hard drives and magnetic memories. This review focused on Carbon-based nanomaterials like nanotubes, graphene, and molecules, which are physically and chemically compatible. Their high electrical mobilities, weak spin dispersion, and hybridization lead to strong spin polarizations that meet the critical requirements of spintronic devices. In this regard, the first technological endeavour to integrate nanomaterials for spintronics shows superior spin diffusion lengths. They focus on material, physical, and chemical compatibility to achieve remarkable performance in the next generation of spintronics devices. This novel approach needs advances in surface chemistry, spin transport physics, and device theory, as detailed in this article. Ongoing research is breaking new ground, with advancements like all-spin-logic circuits and neuromorphic chips nearing fruition. Carbon nanostructures like molecules, graphene, and nanotubes play a vital role. Recent experiments emphasize the significance of calibrated tunnel barriers in graphene-based spin valves, boosting spin signals and diffusion length in non-magnetic materials. These developments highlight spintronics' dynamic nature and potential to revolutionize modern electronics.

Another study in 2021 on spintronics by Xu et al. introduced a radio-frequency signal that produces spin dynamics in a spintronic resonator, which the spin-diode effect detects (Xu et al. 2021). Ferromagnetic metals and spin torque are used in such resonators. QMs can enable new technologies, such as transition metal oxides with phase transitions that give spintronic resonators hysteresis and memory. It highlights the impact of Ni, permalloy ($Ni_{80}Fe_{20}$), and Pt layers over V_2O_3; the first-order phase transition causes systematic resonance response alterations and hysteretic current control of the ferromagnetic resonance frequency. A DC current can locally change the state of the output signal to vary systematically. These findings show neuromorphic computing-relevant spintronic resonator functions. The study reveals systematic alterations in resonance response and hysteretic current control of ferromagnetic resonance frequency. Moreover, it demonstrates the manipulation of output signal via state changes in V_2O_3 induced by a DC current. Temperature significantly influences resonance amplitude, while structural phase transitions in V_2O_3 reshape ferromagnetic resonance conditions. Emphasizing the quantum material spintronic resonator's memory retention, this research underscores its remarkable and distinctive attributes.

A study by Swapnali Makdey in 2020 shows a novel and efficient approach for designing magnetic tunnel junctions (MTJs) structures utilizing molybdenum disulfide (MoS_2)/GQDs/MoS_2 (Makdey et al. 2020). They create a device that exhibits superior efficiency coupled with low power consumption. With 2D MoS_2 as ferromagnetic electrodes and GQDs acting as barriers, the MTJ tunnel magnetoresistance reached 1450% at zero bias voltage. Investigating spin relaxation and magnetization relaxation further extended the spin's lifetime. The proposed MTJ structure for spintronics demonstrated notable effectiveness, underscored by comparative analysis with existing MTJ designs.

A recent study on MTJs in 2022 by Zhan was carried out to explore the potential of 2D $MnBi_2Te_4$ by investigating their spin-dependent electronic and transport properties (Zhan et al. 2022). In this study, they used the first principles of quantum transport simulations. They designed the MTJs based on 2D van der Walls layered $MnBi_2Te_4$ and observed that by increasing the thickness of the $MnBi_2Te_4$ layers within the MTJs, the research found significant enhancements in spin polarization and TMR ratios at the Fermi level. TMR ratios of up to 100% and 500% were observed for varying thicknesses of $MnBi_2Te_4$ layers, with a remarkable increase to 500% and 4000% when accounting for the spin–orbit coupling (SOC) effect. These findings represent the potential of $MnBi_2Te_4$ -based MTJs for advancing spintronic device performance, suggesting promising avenues for further investigation and development in this field.

Weyl semimetals (WSMs) have garnered significant attention as they provide unique platforms for investigating fundamental physical phenomena and for applications in topotronics. Although numerous WSMs have been discovered. Finding WSMs with widely spaced Weyl points (WPs) in candidate materials has been challenging. Sun et al. theoretically demonstrate the presence of intrinsic ferromagnetic WSMs in $BaCrSe_2$, with their non-trivial properties confirmed through Chern number calculations and analysis of Fermi arc surface states (Sun et al. 2023). Unlike previously known WSMs where WPs of opposite chirality are in close proximity, the WPs in $BaCrSe_2$ exhibit a large spatial separation—extending to half of the reciprocal lattice vector—indicating high robustness against perturbations. These findings not only deepen the understanding of magnetic WSMs but also highlight $BaCrSe_2$'s potential for applications in topotronics.

QMs for quantum computing

The exploration of QMs is pivotal for advancing quantum computing platforms, leveraging principles like quantum coherence, superconductivity, and topological properties. These specialized materials provide physical platforms for quantum bits (qubits), the fundamental units of quantum information, allowing researchers to manipulate and control quantum states. QMs enable the development of stable and reliable qubits, which are essential for complex calculations currently intractable for classical computers. By focusing on the synthesis, characterization, and utilization of QMs, scientists aim to unlock the full potential of quantum computing, revolutionizing computation with profound implications across diverse fields of science and technology. QMs facilitate the creation of multi-qubit systems interconnected for complex calculations, leveraging quantum behaviours like superposition and entanglement. Superconducting materials, for example, enable the creation of superconducting qubits, which are crucial for operations surpassing classical computing capabilities. Quantum error correction, utilizing QMs, creates fault-tolerant qubits that are less sensitive to environmental disturbances, which is essential for reliable quantum computing. Specific QMs, such as those in superconducting qubits, play critical roles in specialized quantum computing approaches like quantum annealing, which exploits quantum tunnelling effects for optimization problems. Researchers explore how quantum properties of materials inspire novel algorithms for more efficient problem-solving, leveraging quantum parallelism and interference.

An awe-inspiring study in 2021 by Oreg Yuval explored a quantum computing device comprising a carbon nanotube, superconducting substrate, and magnet, with a particular emphasis on the spin-triplet aspect and the longitudinal magnetic field. Furthermore, the study delves into an alternative quantum computing setup involving multiple superconducting substrates and a non-superconducting structure exhibiting robust spin–orbit coupling interactions, highlighting the significance of phase variations among substrate order parameters. The paper's conclusion affirms the feasibility of constructing a quantum computing device using a carbon nanotube, superconducting substrate, and longitudinal magnetic field, with a keen focus on the spin-triplet element. Additionally, it posits that an alternative quantum computing apparatus can be realized by utilizing multiple superconducting substrates and a non-superconducting structure with potent spin–orbit coupling interactions, stressing the importance of phase distinctions within substrate order parameters.

A review by Lordi and Nichol in 2021 (Lordi and Nichol 2021) discussed the immense potential of quantum computers over classical counterparts; the presence of noise and material imperfections has emerged as a formidable obstacle. The ongoing progress in materials synthesis, characterization, and modelling is a pivotal cornerstone in surmounting these challenges, thereby unlocking the full capabilities of quantum computing. In recent years, these advancements have catalysed exciting breakthroughs in the noisy intermediate-scale quantum (NISQ) realm, where the delicate balance between preserving the excellence of single qubits and facilitating high-fidelity qubit interactions is paramount. As we look ahead, it becomes evident that the continued advancement in the synthesis, characterization, and modelling of materials for quantum computing will remain integral to shaping the future landscape of quantum technology.

An impactful review was carried out in 2022 by Hoffmann (Hoffmann et al. 2022). In this review, he focused on neuromorphic computing, which relies on QMs to efficiently process extensive data volumes, as these materials possess distinctive properties that facilitate energy-efficient hardware implementations of neuromorphic concepts. These materials display robust correlations, leading to profoundly non-linear responses that can be effectively utilized for both short- and long-term plasticity and data classification. In conclusion, the utilization of QMs holds significant promise for enabling energy-efficient neuromorphic computing at the hardware level, thanks to their inherent characteristics, which empower them to offer valuable solutions in data processing and artificial intelligence.

In a most recent study in 2023 by Jackson et al., he introduced diamond-like structures where Li^+ ions and diamines replace carbon atoms and C–C bonds, respectively, creating novel materials capable of hosting diffuse electrons around each lithium tetra-amine centre (Jackson et al. 2023). These materials display either metallic or semiconductor properties, contingent upon the length of the diamine chain. Our gas-phase calculations accurately predict the properties of proposed crystalline Li-diamine materials, offering the potential for further development and insights. Through spin-polarized and unpolarized calculations across various hydrocarbon sizes, we reveal valuable information about their geometrical and electronic band structures, spin density contours, and density of states. These materials hold promise for applications such as redox reactions and quantum computing, where diffuse electrons can be harnessed as qubits. Our future endeavours will tailor the hydrocarbon backbone to control electron association for precise quantum computing and propose materials suitable for selective redox catalysis.

Metamaterials or metasurfaces, optics and photonics applications

In recent years, metamaterials and metaphotonics have seen rapid advancements, which have significantly transformed the landscape of optics. Traditional, bulky optical systems, which consist of large lenses, mirrors, and prisms, are now replaced with thin, nanostructured films known as metasurfaces. These are designed with microscopic patterns at the scale of light's wavelength, and they can manipulate light in highly precise ways and offer new capabilities in optical systems that were once unimaginable with conventional optical elements. Metasurfaces operate by controlling light's phase, amplitude, and polarization to allow extraordinary functionality. This ability to manipulate light at a fundamental level has led to innovative developments in classical optics, including beam shaping, lensing, and imaging. Metasurfaces have been used to replace bulky optical devices with flat, compact alternatives, enabling a wide range of applications in areas like telecommunications, imaging systems, and display technologies. Their ability to perform complex optical functions with a much smaller footprint transforms industries and enables miniaturized, high-performance optical devices. Recently, these innovations in metamaterials and metasurfaces have begun to influence quantum photonics (a field dealing with light's quantum properties). Quantum photonics seeks to harness the peculiar properties of light at the quantum level, such as quantum state superposition, quantum entanglement, and non-classical photon statistics. These phenomena are central to emerging technologies like quantum communication, quantum computing, and cryptography. In the quantum realm, light behaves in ways that are fundamentally different from its classical counterpart. For instance, quantum light sources, such as single-photon sources, emit individual photons that can exist in superposition, meaning they can be in multiple states simultaneously. Additionally, quantum entanglement allows for two particles (or photons) to become correlated so that the state of one instantaneously affects the state of the other, even if they are far apart. These phenomena are essential for the development of quantum technologies.

Applying metasurfaces to quantum photonics is an exciting frontier beginning to unfold. By integrating metasurfaces with quantum light source and detectors, researchers are exploring novel ways to generate, manipulate, and detect non-classical light. For example, metasurfaces can be engineered to selectively control the quantum properties of photons, such as their polarization or momentum, allowing for the creation of advanced quantum optical devices like entangled photon sources or quantum gates for quantum computing. In addition to manipulating light, metasurfaces can improve single-photon detection, an essential task for many quantum communication and sensing applications. Traditional single-photon detectors have limitations in terms of efficiency and speed. Still, by coupling these detectors with metasurfaces, it is possible to enhance their performance, making them more sensitive and capable of detecting single photons at higher rates. In this perspective, Solnstev wrote an impressive and in-depth review of the recent progress in the emerging field of quantum-photonics applications of metasurfaces (Solntsev et al. 2021). They focused on the innovative and promising approaches researchers are exploring to use metasurfaces to control and manipulate non-classical light. This includes advancements in quantum light generation, manipulation of photon entanglement, and the development of highly efficient quantum light detectors. The unique properties of metasurfaces are opening new possibilities in the realm of quantum photonics, providing tools to realize applications that were once thought to be beyond reach. This exciting new field holds immense potential for advancing quantum technologies and could lead to transformative breakthroughs in quantum communication, quantum computation, and beyond.

Metasurfaces have emerged as a key area in optical research, offering exceptional functionalities for applications such as imaging, beam shaping, holography, and polarimetry, while maintaining compact device sizes. Although a wide array of fundamental metasurface designs has been extensively explored, research in this field is expanding rapidly. Metasurfaces are now influencing lots of areas like computational imaging, augmented and virtual reality, automotive technologies, displays, biosensing, non-linear and quantum optics, optical computing, and more. The capability of metasurfaces to deliver optical functions within compact systems has spurred significant interest across various industries that benefit from miniaturized, efficient, and cost-effective optical components suitable for integration into optoelectronic systems. This expanding interest presents a unique opportunity for metasurfaces to make substantial scientific and industrial contributions. Very recently, in 2024, Kuznetsov et al. have written a review article 'a roadmap for optical metasurfaces' (Kuznetsov et al. 2024). The purpose of this roadmap is to highlight the current 'golden age' of metasurface research and outline future directions to inspire ongoing advancements toward scientific achievement and widespread industrial application. It is a good resource for readers to explore in depth about metasurfaces.

Two-dimensional arrays of engineered nanostructures have been a key driver in miniaturizing various optical functions and devices. The range of materials for metasurfaces has broadened significantly, with recent years seeing a rise in meta-optical elements made from high-index, transparent materials exhibiting strong non-linear and electro-optic properties. Crystalline lithium niobate ($LiNbO_3$), a leading material in integrated photonics, has demonstrated substantial potential for new meta-optical applications due to its high electro-optic coefficient, second-order non-linear response, and wide transparency range from visible to mid-infrared wavelengths. Advances in nanofabrication have now enabled the development of $LiNbO_3$-based metasurfaces, marking a significant step toward ultrathin, monolithic non-linear light sources, efficient quantum photon-pair sources, and electro-optic modulators. Fedotova's review highlights these recent developments, explores their prospective applications, and discusses potential challenges and limitations of these emerging $LiNbO_3$ metasurface technologies (Fedotova et al. 2022).

Weyl semimetals offer significant potential to transform non-reciprocal optical components due to their distinct topological features. These materials can exhibit non-reciprocal magneto-optical effects without needing an external magnetic field, which makes them ideal for miniaturized, energy-efficient designs. Their intrinsic topological stability limits tunability, which is essential for some applications. Chistyakov presents a novel method to increase their tunability by employing multilayered, twisted configurations of anisotropic Weyl semimetals (Chistyakov et al. 2023). Their design enables controlled and reversible isolation by varying the twist angle between anisotropic layers. In the mid-IR frequency range, this setup achieves notable isolation above 50 dB with an insertion loss of only 0.33 dB in the Faraday geometry. Additionally, the in-plane anisotropy in Weyl semimetals can eliminate one or both polarizers in typical isolator setups, significantly reducing device size. This advancement paves the way for versatile, ultra-compact optical isolators, promising to advance integrated photonics and quantum technologies.

Also, Weyl semimetals have unique optical properties, particularly in the mid-infrared region. However, the potential for developing optical polarizers based on Weyl semimetals remains largely unexplored. Hong et al. recently presented numerical simulations under the Voigt geometry, demonstrating that an ultra-thin Weyl semimetal film (thickness L = 100 nm) can achieve a remarkable polarization extinction ratio exceeding 40 dB, with a broad acceptance angle (Hong et al. 2024). The proposed sandwich structure also allows fine-tuning of the TE mode transmission peak, resulting in reduced insertion loss (from 0.06 dB to 0.03 dB) and a wider-angle acceptance range (from 49.5° to 71°). By incorporating a gradient Fermi level structure, the design effectively eliminates Fabry–Perot cavity resonance and significantly increases bandwidth (around 60% improvement). This ultra-thin, wide-angle polarizer holds great promise for applications in optical communications and omnidirectional polarization detection.

Novel topological semimetal materials and their exotic non-equilibrium properties spark significant fundamental interest. It opens exciting possibilities for new applications, particularly in light-induced phenomena such as non-linear optics and optoelectronics. These are especially promising for terahertz (THz) technology, which benefits from the gapless nature of their electronic structures. He et al. explored type-II Weyl semimetals, which exhibit strong non-linear interactions with THz waves due to their complex quantum wavefunctions and distinctive band structures (He et al. 2024). They report the selective growth of the type-II Weyl semimetal $NbIrTe_4$ using a self-flux method, a material known for its strongly tilted Weyl cones and unique Fermi arcs. The engineered oscillating THz field, generated by an antenna, is structured in a planar metal-topological semimetal-metal design with van der Waals stacking, facilitating self-powered photodetection at room temperature. Their findings highlight the exceptional performance of $NbIrTe_4$-graphene heterostructure photodetectors, with a responsivity of up to 264.6 V/W at 0.30 THz, a fast response time of 1 μs, and a low noise equivalent power of 0.28 nW $Hz^{-0.5}$ which demonstrates high-quality imaging at THz frequencies. These results promise significant advances in using topological Weyl semimetals for efficient low-energy photon harvesting.

Summarizing all applications of QMs in a review paper is a challenging task. We add some of the latest and

Table 2 A compilation of review papers highlighting recent advancements in QMs applications

S.No	Title of paper	Ref
1.	Gate-controlled Quantum Dots Based on 2D Materials	(Jing et al. 2022)
2.	The Promise of Soft-Matter-Enabled Quantum Materials	(". n.d.(Thedford, R. Paxton, et al.2023)
3.	Organic quantum materials: A review	(Wang and Zhang 2023)
4.	Quantum Spin Liquids from a Materials Perspective	(Clark and Abdeldaim 2021)
5.	Benchmarking Noise and Dephasing in Emerging Electrical Materials for Quantum Technologies	(Islam et al. 2023)
6.	Quantum-Engineered Devices Based on 2D Materials for Next-Generation Information Processing and Storage	(Pal, et al. 2023)
7.	Graphene/Quantum Dot Heterostructure Photodetectors: From Material to Performance	(Zhang et al. 2022)
8.	Recent advances in topological quantum anode materials for metal-ion batteries	(Obeid and Sun 2022)
9.	Materials for Silicon Quantum Dots and their Impact on Electron Spin Qubits	(Saraiva et al. 2022)
10.	Quantum Sensing for Energy Applications: Review and Perspective	(Crawford, et al. 2021)
11.	Layered materials as a platform for quantum technologies	(Montblanch et al. 2023)
12.	Heterostructures of 2D materials-quantum dots (QDs) for optoelectronic devices: challenges and opportunities	(Yadav et al. 2021)
13.	Hexagonal Perovskites as Quantum Materials	(Yadav et al. 2021)
14.	Micro-Light-Emitting Diodes Based on InGaN Materials with Quantum Dots	(Liu, et al. 2022)
15.	Topological quantum materials for energy conversion and storage	(Luo et al. 2022)
16.	A Review on Quantum Dot Light-Emitting Diodes: From Materials to Applications	(Tian, et al. 2023)

Table 3 Various common synthesis methods for QMs with their advantages and challenge

S.No	Synthesis method	Description	Applications	Advantages	Challenges
1.	Solid-state reaction	Mixing and heating powdered reactants at high temperatures to form solid products, commonly used for ceramics and oxides	Ceramic materials, oxides, superconductors	Simple and cost-effective; scalable; can produce stable, high-temperature materials	Requires high temperatures and long reaction times; limited control over morphology and particle size; often requires grinding and multiple heating cycles
2.	Sol–gel process	Conversion of metal alkoxides or metal salts into a gel, followed by drying and calcination to form oxides and ceramics	Catalysts, coatings, thin films, aerogels	Precise control over stoichiometry and composition; low processing temperatures; excellent homogeneity; can produce porous structures	Sensitive to processing conditions; complex precursor handling; risk of cracking during drying; requires specialized equipment for large-scale applications
3.	Hydrothermal synthesis	Reaction in a high-pressure, high-temperature aqueous solution, typically in an autoclave, allowing crystallization of materials	Nanomaterials, zeolites, ceramics, biomaterials	Enables control over crystal size, phase, and morphology; eco-friendly with minimal toxic by-products; good for large single crystals	Requires specialized equipment; limited to certain temperature and pressure ranges; reaction times can be long
4.	Chemical vapor deposition (CVD)	Deposition of thin films from gaseous reactants at elevated temperatures, widely used in semiconductor and coating industries	Semiconductors, solar cells, coatings, thin films	Produces high-quality thin films with excellent uniformity; can be used on complex geometries; versatile for a range of materials	High equipment and operational costs; often requires high temperatures and toxic/hazardous precursors
5.	Physical vapor deposition (PVD)	Deposition through physical processes like sputtering or evaporation; used for coating surfaces with thin films	Electronics, optical coatings, hard coatings	Produces pure, dense films; adaptable to various substrates; commonly used in microelectronics and optical devices	Requires vacuum conditions and specialized equipment; typically, slower process; may require high temperatures or energy for evaporation
6.	Electrochemical deposition	Use of an electrochemical reaction to deposit material on a substrate from a solution, primarily for conductive surfaces	Battery electrodes, metal coatings, nanomaterials	Low-cost; scalable; simple setup; can produce highly conformal coatings on complex shapes; good control over thickness	Limited to conductive substrates; requires careful control of solution pH, current density, and other parameters
7.	Laser ablation	A laser vaporizes a target material, and the resulting vapour deposits as a thin film on a substrate	Thin films, nanomaterials, complex oxides	High precision and control over material composition; suitable for complex materials; minimal chemical by-products	High cost of laser equipment; limited scalability; can lead to non-uniform film thickness due to high localized heating
8.	Self-assembly	Spontaneous organization of molecules into structured arrangements driven by non-covalent interactions, often in solution	Nanomaterials, drug delivery, biomaterials	Low energy requirement; ideal for creating nanoscale structures and patterns; versatile for functional nanomaterials	Limited control over final structure; reproducibility issues; slow formation process; structures can be sensitive to environmental changes
9.	Microwave-assisted synthesis	Rapid heating of reactants using microwaves, reducing synthesis time and enhancing reaction rates	Nanoparticles, polymers, catalysts	Fast heating, energy-efficient; allows for rapid and uniform temperature distribution; suitable for nanomaterials and polymers	Limited scalability; requires microwave-transparent vessels; high microwave power can cause non-uniform heating and material degradation
10.	Melt quenching	Rapid cooling of molten material to create amorphous or glassy structures, preventing crystal formation	Glasses, amorphous metals, high-strength materials	Simple; low-cost; can produce glassy or amorphous materials with unique properties such as high strength or corrosion resistance	Limited to glass-forming compositions; requires extremely high temperatures; thermal gradients can induce stress and cracking

Table 3 (continued)

S.No	Synthesis method	Description	Applications	Advantages	Challenges
11.	Biomimetic synthesis	Mimicking natural biological processes to produce materials with complex, hierarchical structures	Bone-like materials, composites, biomaterials	Environmentally friendly; often low-energy; produces materials with unique structural properties, beneficial for biomedical applications	Limited to specific applications; slow synthesis rate; requires complex biochemical handling; may have limitations on mechanical properties
12.	Mechanical Milling	High-energy milling of powders in a ball mill to reduce particle size or induce reactions, often used for nanopowders	Nanomaterials, alloys, composites	Simple and cost-effective; versatile; effective for creating nanostructured and amorphous materials; scalable for large quantities	Requires extensive post-processing; potential contamination from milling media; can introduce unwanted defects due to high mechanical stress
13.	Spray pyrolysis	Solution droplets containing precursor salts are sprayed into a hot zone, decomposing into particles	Metal oxides, catalysts, ceramics	Scalable and continuous process; can produce nanoparticles and thin films with controlled composition and size	Control over droplet size and drying conditions is challenging; non-uniform particle size; high energy consumption for large-scale applications
14.	Template-assisted synthesis	Material growth occurs within the confines of a template, creating structures with shapes determined by the template	Nanotubes, nanowires, porous materials	Allows precise control over material geometry; suitable for creating complex structures like nanowires or tubes	Template removal may involve harsh chemicals; limited template reusability; costly for large-scale production
15.	Precipitation and coprecipitation	Formation of fine particles by precipitation from a solution, used to create homogeneous composites or doped materials	Ceramics, pigments, catalysts	Simple process; precise composition control; can produce fine, homogeneous particles	Limited control over particle size and morphology; requires controlled pH, temperature, and concentration; post-synthesis washing needed to remove impurities
16.	Electrospinning	Fabrication of nanofibers by applying a high voltage to a polymer solution, resulting in fibre formation	Nanofibers, tissue engineering, filtration	Produces high surface-area nanofibers; versatile for polymers and composites; scalable for nanofiber production	Requires high voltage and precise environmental control; limited to polymers that can be dissolved in appropriate solvents; may require post-processing
17.	Pyrolysis	Decomposition of organic or inorganic materials at high temperatures in the absence of oxygen, often forming carbon materials	Carbon materials, nanoparticles, catalysts	Produces carbon-rich, high-temperature-resistant materials; scalable; can use biomass as a precursor	High energy consumption; limited control over purity and structure; by-products can be hazardous
18.	Atomic layer deposition (ALD)	Deposition of thin films one atomic layer at a time, used to create ultra-thin films with atomic precision	Semiconductors, microelectronics, protective coatings	Excellent thickness control; uniform deposition on complex shapes; used for high-precision thin films in electronics	Slow deposition rate; requires high-cost equipment and precursors; challenging for large-scale production
19.	Microemulsion technique	Uses nanoscale droplets in emulsions as reaction vessels to form nanostructures with controlled size and shape	Nanoparticles, drug delivery systems, catalysts	High control over particle size and distribution; adaptable for various nanoparticles and quantum dots	Sensitive to surfactant concentration; complex preparation process; difficult to scale

Table 3 (continued)

S.No	Synthesis method	Description	Applications	Advantages	Challenges
20.	Flame spray pyrolysis	Combines spray pyrolysis with high-temperature flame, producing metal oxide nanoparticles from precursor solutions	Catalysts, ceramics, nanocomposites	Continuous, scalable process; high purity; good control over particle size	Requires high energy; limited particle shape control; challenging to avoid aggregation
21.	Sonochemical synthesis	Use of ultrasonic waves to induce chemical reactions, often forming nanoparticles through rapid cavitation	Nanoparticles, catalysts, polymers	Environmentally friendly; simple and rapid; good for nanoscale materials with high surface area	Limited scalability; possible contamination; not suitable for all materials
22.	Molten salt synthesis	Uses molten salts as a reaction medium to facilitate the growth of crystals or nanoparticles at relatively lower temperatures	Ceramics, oxides, battery materials	Enables high diffusion rates; allows growth of specific morphologies; cost-effective for certain compounds	Handling of molten salts can be challenging; waste disposal of salts required; limited to high-temperature processes
23.	Freeze-drying method	Freezing of a solution or suspension, followed by sublimation to create porous structures or nanomaterials	Biomaterials, porous structures, catalyst supports	Produces highly porous structures; preserves material composition; good for biomaterials and tissue engineering applications	Time-intensive; requires specific freeze-drying equipment; low scalability
24.	Top-down lithography	Physical or chemical patterning (e.g., photolithography, e-beam lithography) used for micro/nanoscale structure formation	Microelectronics, MEMS, photonic devices	Extremely high precision; enables creation of complex structures; suitable for microfabrication	High cost; requires cleanroom facilities; limited to specific substrates; challenging for large-area synthesis
25.	Exfoliation techniques	Peeling off thin layers from bulk crystals (e.g. for graphene or 2D materials) through chemical or mechanical methods	2D materials, electronics, sensors, energy storage	Produces highly pure 2D materials with unique properties; simple and cost-effective for small-scale production	Limited scalability; difficulty controlling thickness and uniformity; often requires post-processing
26.	Atomic layer epitaxy (ALE)	Controlled layer-by-layer growth, often for compound semiconductors, with precision similar to ALD but specialized for epitaxy	Semiconductors, photovoltaics, optoelectronics	Atomic precision; excellent control over composition and layer thickness; ideal for heterostructures	High cost; requires strict process control and ultra-clean conditions; limited to compatible substrate materials
27.	Plasma-enhanced chemical vapor deposition (PECVD)	CVD process enhanced with plasma to lower reaction temperatures, improving film adhesion and quality	Semiconductor, coatings, photovoltaics	Lower temperature deposition; allows high-quality films with improved adhesion; suitable for temperature-sensitive substrates	Complex equipment; requires vacuum and plasma generation; potential for contamination from plasma by-products
28.	Electrospinning with coaxial nozzles	Variation of electrospinning that produces core–shell fibres by using coaxial needles to load multiple materials	Drug delivery, tissue engineering, filtration	Allows incorporation of different materials in core and shell; enhances functionality for biomedical and filtration applications	Requires specialized equipment; high voltage needed; sensitive to environmental factors (humidity, temperature)
29.	Spark plasma sintering (SPS)	Uses electrical discharge and pressure to consolidate powder materials at lower temperatures	Ceramics, composites, hard metals	Shorter processing times; fine microstructure control; lower energy consumption compared to conventional sintering	Requires specialized equipment; limited to conductive materials or additives

Table 3 (continued)

S.No	Synthesis method	Description	Applications	Advantages	Challenges
30.	High-pressure synthesis	Synthesis under extreme pressures (often in diamond anvil cells) to produce phases or materials not accessible at ambient pressure	Superhard materials, superconductors, planetary science	Enables synthesis of unique high-pressure phases; can achieve novel crystal structures	High cost and specialized equipment; scalability issues
31.	Chemical bath deposition (CBD)	Thin-film deposition by controlled precipitation from a chemical bath; often used for oxide, chalcogenide, and metal films	Solar cells, sensors, antireflective coatings	Low cost; simple equipment; good for large-area films; often suitable for low-temperature substrates	Limited control over film thickness and uniformity; potential for contamination and secondary phases
32.	Metal–organic framework (MOF) synthesis	Assembly of metal ions and organic linkers into porous, crystalline structures with large surface area	Gas storage, catalysis, drug delivery, sensing	High porosity; tunable chemical properties; highly specific functionalization possibilities	Complex synthesis and purification steps; limited stability under certain conditions (e.g. high humidity, heat)
33.	Supercritical fluid synthesis	Uses supercritical fluids as solvents, enhancing solubility and diffusion to produce nanoparticles or unique morphologies	Pharmaceuticals, catalysis, porous materials	Low viscosity and high diffusivity; good for creating small, uniform particles; solvent-free recovery	Requires high-pressure equipment; costly setup and operation; limited precursor solubility
34.	Molecular beam epitaxy (MBE)	A highly controlled vacuum deposition process where materials are evaporated in the form of molecular beams and then condensed on a substrate to form thin films or heterostructures	Semiconductors, quantum dots, superconductors, photonic devices	Atomic-level precision; excellent control over thickness and composition of thin films; ideal for creating heterostructures and quantum wells	High cost and complexity of equipment; requires ultra-high vacuum; slow deposition rate; challenging for large-scale production
35.	Solvothermal synthesis	Similar to hydrothermal synthesis but uses organic solvents instead of water to create materials at high pressure and temperature	Nanomaterials, ceramics, catalysts, superconductors	High-purity products; flexible in terms of precursor choice; can produce materials with high crystallinity	Potential for environmental toxicity; requires careful solvent handling; high pressure complicates scale-up
36.	Cryogenic synthesis	Involves the synthesis of materials at extremely low temperatures (below 0 °C) to preserve the delicate structures or phases	High-performance superconductors, materials with fragile structures	Preservation of metastable phases; helps prevent unwanted phase transitions and defects during material growth	Equipment cost: handling and synthesis at such low temperatures can be difficult and expensive
37.	Atomic diffusion synthesis	Uses high temperatures to induce atomic migration and self-assembly to form nanostructures or ordered phases	Nanostructured alloys, quantum dots, thin films	Simple and low-cost; allows for the creation of high-purity materials; can create novel phases	Control over diffusion rate and uniformity is difficult; not suited for large-scale production
38.	Laser chemical vapor deposition (LCVD)	Combines laser ablation and CVD to deposit materials from a gaseous precursor in a laser-heated zone	Thin films, sensors, electronic components	Highly localized deposition; allows precise patterning; useful for creating microstructures and coatings	Expensive equipment: scaling up for larger surfaces is challenging; laser focus may cause local heating issues

various types of studies from past years. With this, for a deep understanding of applications, we have included a helpful reference in Table 2, where we cite recent review papers that delve into the diverse applications of QMs. This table is a valuable resource for readers seeking a more comprehensive insight into the subject. This section explores numerous applications and critical research prospects related to QMs. Various synthesis methods are available to prepare the QMs. Advantages and challenges of some of the common methods are given in below Table 3.

Conclusion and outlook

QMs, with their unique properties arising from quantum mechanical effects, hold great promise for many applications, including quantum computing, electronics, energy storage, etc., which is discussed in detail in Sect. 3. However, after reviewing the literature, they also come with several challenges that researchers are actively addressing in synthesizing and scaling high-quality quantum materials presents challenges in achieving consistency and large-scale production and compatibility issues with devices and sensors applications. Many QMs are sensitive to environmental factors during synthesis, necessitating the development of reliable methods for mass production to make them practical for real-world applications. So, characterization and imaging techniques are crucial to understanding the complex behaviours of QMs. This includes studying the emergence of new electronic phases and investigating the impact of defects in these materials. Quantum machines can be highly sensitive to external conditions such as temperature, pressure, and humidity, affecting their stability and performance. Ensuring the stability of these systems under various conditions is essential for practical use, driving researchers to develop encapsulation and protection strategies against environmental impacts. Integrating QMs into functional devices, like transistors or sensors, poses significant challenges due to interface issues and compatibility with existing technology. Achieving successful integration is vital to leverage the unique properties of quantum mechanics effectively. Quantum control and manipulation are essential for applications in quantum information processing and computing. However, precise control of quantum states within these materials is hindered by challenges such as coherence time, noise, and error correction. Moreover, scaling up quantum systems to a practical level with many qubits remains a substantial hurdle in quantum computing. Addressing issues related to quantum decoherence and error correction is crucial for unlocking the potential of quantum computers. Ethical and safety concerns must also be addressed as quantum materials and technologies advance, including encryption vulnerabilities and societal impacts, necessitating regulatory considerations. Bridging the gap between fundamental research and commercialization is crucial, requiring collaboration between academia and industry. Standardization of synthesis, characterization, and evaluation processes is essential for consistency and reproducibility in research and development, ensuring the advancement of quantum materials for practical applications.

QMs offer vast potential across various applications, particularly in revolutionizing computing, communication, energy generation, and materials science. In computing, QMs serve as qubits in quantum computers, capable of exponentially faster calculations than classical computers, and their inherent quantum properties make them ideal for quantum information processing. Additionally, QMs contribute to ultra-sensitive sensors and imaging devices, finding applications in medical diagnostics, mineral exploration, and national security. Moreover, QMs' unique electronic and thermal properties offer avenues for more efficient energy generation and storage systems, including advanced photovoltaics, thermoelectric generators, and supercapacitors. They are crucial for developing secure quantum communication systems, such as quantum cryptography and key distribution protocols, and offer revolutionary potential in electronics, enabling ultra-fast, low-energy-consumption devices and superconductors with high transition temperatures, promising to transform power grids and transportation systems. Advancements in QMs will continue to drive progress in quantum computing, with a focus on stable and scalable qubits and integrating quantum error correction protocols to counter decoherence effects. Machine learning offers promising prospects in predicting and understanding the behaviour of QMs, enhancing the discovery of novel materials with exceptional properties. Collaborations within the scientific community are essential for advancing knowledge and applications of QMs. Additionally, exploring exotic phenomena in van der Waals QMs holds promise for fundamental science and technological advancements, with potential applications in electronic devices, quantum computing, and optoelectronics. Similarly, exploring new physics in interacting quantum many-body systems can lead to breakthroughs in quantum computing, simulations, and understanding exotic states of matter like topological insulators and quantum Hall systems. Developing hybrid systems combining QMs with established technologies and specialized measurement techniques can further enhance QM applications while deepening our understanding of quantum physics. In Fig. 7, we demonstrated a pictorial representation of challenges in QMs research and possible solutions in long- and short-terms.

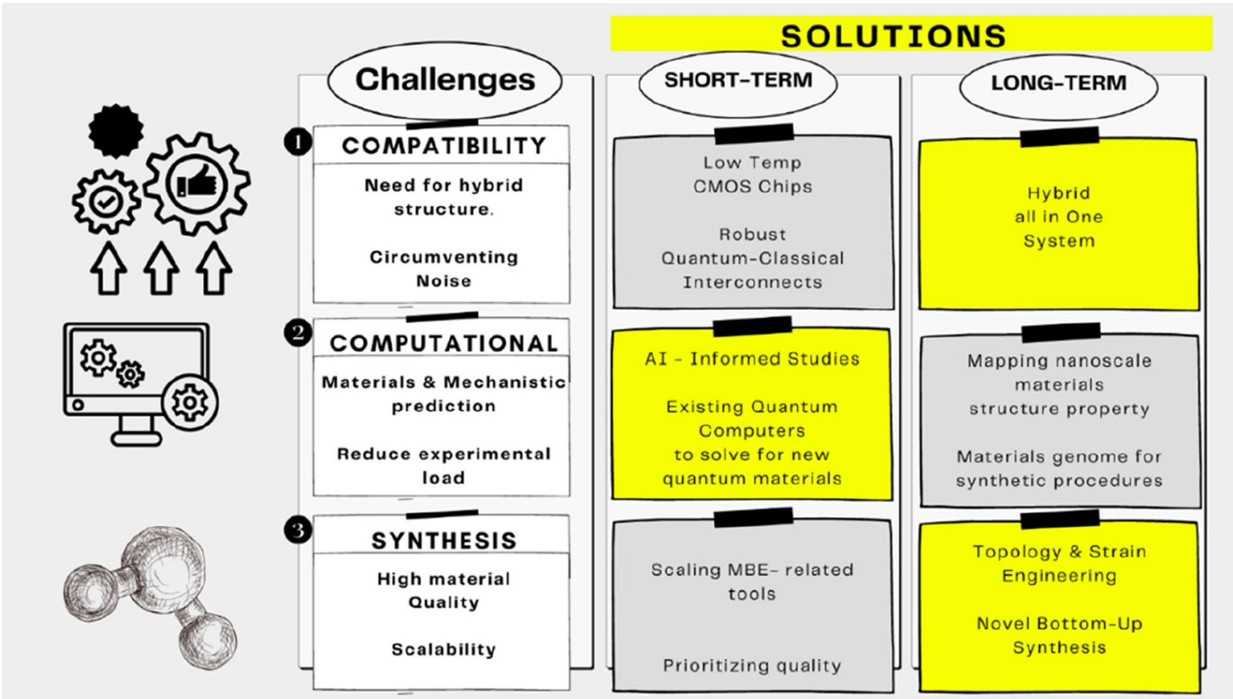

Fig. 7 Representation of challenges and solution in quantum materials progress

Addressing the multifaceted challenges QMs pose demands a concerted effort from various disciplines, including physicists, chemists, materials scientists, and engineers. These materials often exhibit intricate quantum phenomena and unique properties, necessitating a deep understanding of their underlying physics, precise chemical synthesis techniques, comprehensive characterization methodologies, and the engineering skills to integrate them into practical devices. QMs hold immense promise in revolutionizing electronics, energy storage, and quantum computing. Thus, overcoming the obstacles associated with their synthesis, manipulation, and integration into devices is not merely a scientific endeavour; it is essential for harnessing their full potential and realizing their transformative impact on various technological domains. Successful interdisciplinary collaboration is the key to surmounting these challenges and ushering in a new era of innovation and discovery.

In conclusion, this comprehensive review paper has shed light on the intricate world of QMs, unveiling their pivotal role in reshaping the technological landscape. Throughout this journey, we have delved deep into these materials' unique properties, including quantum confinement, strong electronic correlations, and topology and symmetry, and explored their wide-ranging applications across diverse fields. This review highlights the profound and transformative influence of QMs in the ongoing revolution of technology. As we stand on the cusp of unprecedented advancements, it is increasingly clear that the potential of these materials is nothing short of extraordinary, promising ground-breaking innovations in electronics, energy generation, and numerous other domains. The future of QMs research is paramount, as it is critical to unlocking new horizons of innovation and discovery. These materials, with their profound implications and limitless possibilities, are a testament to the remarkable journey that science and technology are poised to embark upon. Our collective responsibility is to continue pushing the boundaries of knowledge and technology, guided by the wondrous possibilities that QMs offer. Through collaboration, dedication, and curiosity, we can harness the full transformative power of these materials and usher in a new era of scientific and technological achievement.

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Authors' contributions
All the authors contributed a review paper. Rajat Kumar Goyal designed it. Shivam Maharaj, Pawan Kumar, and M. Chandrasekhar have given valuable comments to rectify problems. Rajat Kumar Goyal wrote the first and final draft of the manuscript. Pawan Kumar and M. Chandrasekhar have made the corrections. All the authors commented on the previous version and read and approved the final manuscript.

Declarations

Competing interests
The authors declare that they have no conflict of interest.

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