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Physics of Low-Dimensional Nanomaterials: From Quantum Confinement to Device Applications

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Abstract

Quantum confinement in low-dimensional nanomaterials allows atomic-scale dimensionality engineering to regulate electrical, optical, and topological features. Charge carrier spatial confinement turns continuous bulk bands into discrete quantized states, making the effective band gap size-dependent and reshaping the electronic density of states from square-root in three dimensions to step-like, singular, and discrete spectra in two-, one-, and zero-dimensional systems. Excitonic and many-body effects like greater binding energies and oscillator strengths, result from less dielectric screening and increased Coulomb interactions. Excitons dominate optical response in two-dimensional semiconductors, with dielectric environment and layer thickness regulating their energetics and dynamics. In addition to confinement physics, reduced dimensionality and symmetry breaking stabilize nontrivial topological phases, permitting quantum events. These confinement-driven phenomena affect optoelectronics and energy device performance. Advanced light matter interactions enable ultrathin photodetectors, LEDs, and nanoscale lasers, while mechanically compliant low-dimensional structures enable flexible and wearable photodetection. Through adjustable absorbance and carrier dynamics, quantum confinement increases photovoltaics and photocatalysis. To reach their full potential, these systems need predictive multiscale modeling, precision nanofabrication, and *in situ* characterization to bridge fundamental physics and scalable device integration.

Keywords

Quantum Confinement, Low-Dimensional, Nanomaterials, Excitonic Effects, Topological Phases, Optoelectronic Devices

1. Introduction

Since quantum confinement is a crucial strategy for achieving advanced functionality in the field of low-dimensional nanomaterials, quantum mechanics has had a significant influence on materials research [1]. While quantum confinement was previously demonstrated in semiconductor quantum wells, quantum wires, and quantum dots, the isolation of graphene in 2004 significantly heightened interest in low-dimensional materials by offering a stable two-dimensional platform for investigating confinement-related electronic, optical, and topological phenomena [2]. Beyond the bounds of earlier theoretical promise, the continuous significance stems from the continued development of nanofabrication techniques, which enable better accuracy in the control of material dimensions and form [3].

The paradigm has evolved from size-quantization effects to active confinement as a more sophisticated design consideration for creating certain material properties and functionalities [4]. Materials with properties significantly different from those of their bulk counterparts are made possible by this transition, which allows for the precise modification of electrical, optical, and topological properties at the nanoscopic scale [1] [5]. By reducing dielectric screening and boosting Coulomb interaction, quantum confinement dramatically alters the electronic density of states and amplifies excitonic effects, leading to greater binding energies and larger oscillator strengths [6] [7]. In order to engineer light-matter and charge transport features inside these materials, several modifications are required [8].

It is always difficult to reconcile the results of ideal theoretical physics models with the actual device configuration. While deep elucidation of fundamental optoelectronic properties of nanomaterials is made possible by *ab initio* simulations and sophisticated theoretical approaches, the translation of these observations into stable, efficient, and scalable devices frequently faces challenges in material stability, reproducibility, and integration [9]. For instance, mixed-dimensional van der Waals heterostructures must be used to overcome the difficulty of developing broadband photodetectors with high responsiveness from single, low-dimensional materials [10]. For use in applications like quantum electronic sensing, this class of advanced nanomaterials' stability and dependability are essential [9]. Our goal in this review is to examine the causal relationship between fundamental physics, emergent phenomena, and low-dimensional nanomaterial device applications. We will concentrate on how quantum confinement affects electrical and optical reactions, such as excitonic events and topological phases, and how these characteristics are integrated in contemporary technology. Applications in optoelectronics, such as photodetectors, light-emitting diodes (LEDs), and lasers, energy devices, such as photovoltaics and photocatalysts, and advances in sophisticated light-matter interactions that enable quantum sensing and biological imaging are all included in this domain [3] [11]-[13]. This paper highlights the intricate relationship between engineering and quantum mechanics, highlighting the important role that quantum confinement plays in the creation of novel materials and systems.

This review is founded on an extensive examination of the existing literature

about low-dimensional nanomaterials and quantum confinement. Significant publications were located via prominent scientific databases, including Web of Science, Scopus, Google Scholar, and IEEE Xplore, utilizing combinations of keywords such as quantum confinement, low-dimensional nanomaterials, graphene, transition metal dichalcogenides, quantum dots, nanowires, excitons, topological materials, optoelectronics, and quantum devices. Emphasis was placed on peer-reviewed research articles and authoritative review papers published predominantly in the recent decade, while key prior studies were incorporated when needed to furnish historical context and establish foundational concepts. The chosen literature was categorized based on the fundamental scientific principles of quantum confinement, electrical and optical phenomena, and their application in functional devices, thereby offering a systematic view from basic physics to advanced technologies.

2. Physical Principles of Low-Dimensional Nanomaterials

Quantum mechanical processes can be a potent tool for changing material properties, and low-dimensional nanomaterials have revolutionized materials science. The following section moves away from the straightforward particle-in-a-box comparison and tries to explain the basic material physics that controls these materials' behaviour in order to overcome the problems caused by lower dimensionality. Specifically, we focus on the breakdown of bulk band theory, the revolutionary rearrangement of the electronic density of states, and the enormous change in Coulomb interaction (under confinement), which are essential for comprehending the many device applications.

2.1. Breakdown of Bulk Band Theory

Using ideas like continuous energy bands and the effective mass approximation, the traditional bulk band theory which is essential to solid-state physics is a trustworthy way to explain the electrical characteristics of solid crystalline materials. Conventional bulk approximations eventually lose accuracy as quantum confinement effects become more significant when material dimensions shrink to the nanoscale, especially below the exciton Bohr radius or the de Broglie wavelength of charge carriers. However, effective-mass models and bulk band theory are still useful for characterizing weakly and moderately restricted systems and frequently offer helpful first-order insights. However, in order to effectively represent size-dependent electrical structure, surface effects, and Coulomb interactions for tightly confined nanostructures, many-body techniques and atomistic descriptions are required [1] [2].

2.1.1. Failure of the Effective Mass Approximation

The intricate electron-periodic potential interaction in a crystal lattice can be treated as a quasi-free particle with a modified mass thanks to the effective mass approximation [1]. In extremely quantum-confined systems, like ultra-thin two-dimensional layers or zero-dimensional quantum dots, the electron's wavefunction is limited to nanoscale dimensions instead of spreading across the crystal. The discrete energy levels produced by this localization gradually depart from the

underlying assumptions of the effective-mass approximation. The continuous momentum states in the effective mass model are refuted by this localization, which produces discrete energy levels instead of continuous bands [4]. Therefore, in order to obtain quantitatively accurate predictions for strongly confined nanostructures, atomistic approaches like density functional theory (DFT), tight-binding methods, or many-body techniques (GW and Bethe-Salpeter Equation) are frequently needed, even though the conventional effective-mass approximation is still an effective and commonly used model for many confined semiconductor systems [14]. In order to accurately predict the electronic and optoelectronic properties of nanomaterials, *ab initio* methods such as Density Functional Theory (DFT) and many-body perturbation theories (such as GW and Bethe-Salpeter Equation) are essential. These methods provide parameter-free atomistic comprehension that surpasses empirical approximations [15].

2.1.2. Dielectric Mismatch and Surface Polarization

Low-dimensional nanomaterials have a high surface-to-volume ratio, which suggests that a sizable fraction of atoms are at interfaces [1]. This highlights the basic functions of surface polarization and dielectric mismatch, which are crucial at the nanoscale but rarely significant in bulk materials. The sudden change in dielectric constant at the contact with the surrounding media (air, substrate, or solvent) results in dielectric mismatch [4]. Because of this discontinuity, the nanomaterial has less dielectric screening, which increases the Coulomb contact between the charge carriers [6]. Exciton binding energies rise as a result of the enhanced Coulomb interaction, making excitons strong and stable even at room temperature. Additionally, surface polarization brought on by dangling bonds, surface reconstruction, and localized surface states may alter the electronic potential landscape and produce trapping states. The performance and stability of certain optoelectronic devices are directly impacted by these parameters, which also affect carrier dynamics and recombination pathways [3].

2.2. Dimensionality-Driven Density of States Reshaping

By converting the continuous, parabolic distribution of bulk materials into discrete or elaborately structured energy landscapes in restricted dimensions, quantum confinement modifies the electronic density of states [1] [2] [4]. The optical and electrical characteristics of nanomaterials, including as light absorption, emission, carrier transport, and device efficiency, depend on variations in density of states (DOS), which are directly caused by spatial confinement [3].

2.2.1. Van Hove Singularities in 1D Systems

Charge carriers are quantum restricted in two dimensions but free to move along the third in one-dimensional (1D) nanomaterials such as nanowires, nanotubes, or nanoribbons [4]. Van Hove singularities, which manifest as high peaks at specific energies, are prominent in the DOS formed by this anisotropic confinement [2]. These singularities arise from an accumulation of states at specific energies

when the group velocity of electrons approaches zero in reciprocal space. Improved light-matter interactions are made possible by this distinct DOS profile, which also encourages light absorption and emission at specific wavelengths. This increases optical absorption and emission, which can be utilized for more effective lasers, photodetectors, and optical modulators [3].

2.2.2. Step-Like Density of States in 2D Systems

In two-dimensional (2D) nanomaterials, such as graphene and transition metal dichalcogenides (TMDs), charge carriers are restricted in one dimension, while they can move freely in the other two dimensions. This confinement produces a step-like density of states, with each step corresponding to the onset of a new electronic sub-band. Each sub-band contributes a constant density of states over a specific energy range, producing the characteristic step-like DOS of two-dimensional systems. Semiconducting transition metal dichalcogenides (TMDs) and graphene both show a two-dimensional density of states resulting from confinement in a single spatial direction, but their optical and electrical responses are very different. In two-dimensional materials, this unique DOS profile directly affects transport mobility, absorption spectra, and light emission. The performance requirements of two-dimensional material-based field-effect transistors and other optoelectronic devices are governed by this step-like density of states, which is important for light absorption in transition metal dichalcogenides. **Figure 1** illustrates the change from three-dimensional structures to zero-dimensional systems.

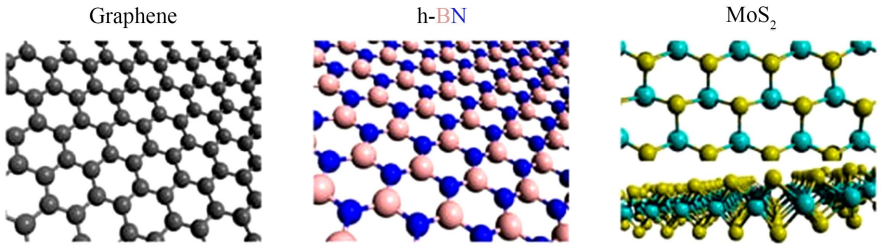

Figure 1. Atomic structures of representative two-dimensional materials graphene, hexagonal boron nitride (h-BN), and molybdenum disulfide (MoS_2) highlighting their distinct lattice configurations [2].

2.2.3. Discrete Manifolds in 0D Systems

Quantum dots (QDs) with no dimensions (0D) are places where charge carriers are physically confined in all three dimensions of space. A discrete, atomic-like energy level spectrum, or discrete manifolds, is produced by such extreme confinement. The size, shape, and composition of quantum dots can be altered to produce adjustable and tailored energy levels for a particular band gap and emission wavelength [4]. Applications needing effective and spectrally pure light emission, like quantum electronic sensors, improved display technologies, and bioimaging, are ideally suited for quantum dots because of their size tunability [9]. Higher quantum efficiency and a very pure spectrum are provided by the absorption and emission peaks that match the discrete density of states in quantum dots. Quantum dots restrict carriers in all

three spatial dimensions, resulting in discrete atomic-like energy levels and extremely size-dependent optical transitions, in contrast to two-dimensional materials whose electronic structure is dictated by confinement in only one direction.

2.3. Coulomb Interactions under Confinement

By quantum confinement in this manner, there is a significant change in the basic Coulomb interactions among charge carriers that produce stronger excitonic effects and exotic many-body states. Such changes are central to the characteristic optical features and functional parameters of low-dimensional nanomaterials [6] [15].

2.3.1. Exciton Binding Energy Scaling and Reduced Screening

A substantial change in exciton binding energy is one of the effects of quantum confinement. Excitons have very high binding energies compared to their bulk counterparts. This is primarily a result of two important factors: the smaller dimensionality reduces the spatial distance between electron and hole, hence enhancing their electrostatic attraction; and the smaller spacing due to less dielectric screening from the surrounding environment which also greatly affects the ionic performance of electron decay [6] [15]. In the case of 2D semiconductors, exciton binding energies can reach hundreds of meV which makes them robust quasiparticles, and control the optical activity at room temperature. Compared to 3D materials, in which Coulomb interactions are screened more, 2D materials' atom-thinness results in higher potential for the electron-hole interaction to be enhanced. The dielectric property and the layers in 2D materials provide more scope to moderate this screening intensity and thus the exciton energetics and dynamics.

2.3.2. Trions, Biexcitons, and Many-Body Renormalization

Beyond the standard neutral excitons, strong Coulomb interactions in a confined environment give rise to non-neutral many-body quasiparticles such as trions and biexcitons. Trions are charged excitons of three carriers (as either one electron and two holes, or two electrons and one hole), and biexcitons are bound states of two excitons, respectively [15]. These complex correlated states are obtained from complex many-body relations of quasiparticles (electrons, excitons and phonons) and are the major focus of condensed matter physics investigation. The occurrence, stability, and optical properties of these particles are direct results of elevated Coulomb interactions by quantum confinement, offering possibilities for new optoelectronic properties and quantum information processing. Additionally, many-body renormalization effects arise as interactions transform the fundamental energy bands and quasiparticle lifetimes. These renormalizations may have the effect on either band gap narrowing or broadening, and may change optical absorption and emission mechanisms, which require extensive theoretical models to fully grasp the effect on material characteristics and device properties. Understanding these complex Coulomb interactions and determining how they can be adequately perturbed is important for obtaining the advanced optoelec-

tronic and quantum properties of low-dimensional nanomaterials [6] [14].

3. Electronic Structure Engineering in Low Dimensions

Electronic structure engineering for low-dimensional nanomaterials involves a transition from more traditional bulk semiconductor design, where band structure behavior is mainly dictated by chemical composition and crystal symmetry. In quantum confinement, electronic bands emerge as characteristic patterns which are intimately linked to size, shape, dielectric environment, and most importantly interface. With decreasing dimensionality, the extrinsic degrees of freedom begin to overshadow the internal lattice effects, and consequently new and relatively limited strategies can now be applied to the control of bandgap and band alignment in these regions. The different degrees of freedom for controlling the electronic structure by way of quantum confinement have been summarized in Table 1. This table makes it clear as to how the electronic states can be altered by varying factors such as geometry, edges, dielectric environment, strain, heterostructure interaction, topology, and quantum dot interactions.

Table 1. Degrees of freedom in electronic structure engineering under quantum confinement.

Engineering Variable	Physical Mechanism	Primary Electronic Effect	Device-Level Consequence	References
Size (Geometric Confinement)	Spatial quantization of carrier wavefunctions	Discrete subbands; bandgap widening; DOS reshaping	Tunable emission wavelength; subband engineering in FETs	[4] [14] [16]
Shape/Edge Morphology	Boundary condition modification; edge states	Mid-gap states; localized transport channels	Variability in nanoribbon transport; leakage pathways	[1] [17]
Dielectric Environment	Reduced screening; image charge effects	Enhanced exciton binding energy; bandgap renormalization	Exciton-dominated photodetectors; altered recombination dynamics	[16] [18]
Strain Engineering	Lattice distortion; band curvature modulation	Bandgap tuning; valley splitting	Strain-tunable LEDs; flexible photodetectors	[3] [7]
van der Waals Heterostructures	Interface band alignment; interlayer coupling	Type-I/II alignment; interlayer excitons	Efficient charge separation in solar cells; long-lived excitons	[10] [11]
Moiré Superlattices	Periodic potential modulation; miniband formation	Flat bands; correlated states	Tunable strongly correlated optoelectronics	[5]
Topological Confinement	Symmetry breaking; spin-orbit coupling	Protected edge states; robust transport channels	Low-dissipation quantum devices	[5]
Quantum Dot Coupling (Ensemble Effects)	Electronic hybridization; miniband formation	Inhomogeneous broadening; minibands	Performance loss at scale (confinement-reality gap)	[19]

3.1. Bandgap Tunability vs. Structural Control

The confinement of the quantum has enabled detailed control of the bandgap by restricting charge carrier motion only to nanometer-scale space. In zero-dimensional quantum dots, for instance, small particle sizes increase kinetic confinement energy, which has been empirically confirmed to have an effect on the size-dependent bandgap shift from different semiconductor nanocrystals [20]. Preliminary theoretical studies suggested that such scaling is consistent with effective-mass expectations only for the largest dimensions but atomistic effects are dominant at strong confinement [21]. The out-of-plane confinement in two-dimensional materials leads to high bandgap renormalization at reduced thickness. A classic example is MoS_2, where a transition from bulk to monolayer thickness leads to an indirect-to-direct bandgap transition caused by confinement-induced change in band extreme [22]. Besides thickness, lateral confinement and edge morphology play important roles in determining the electronic structure. For example, graphene nanoribbons exhibit bandgaps that depend strongly on ribbon width and edge orientation owing to confinement-induced symmetry breaking and edge-state hybridization [23].

The dielectric environment greatly dictates the electronic composition of low-dimensional solutions. Coulomb interactions, which operate outside the physical limits of atomically thin materials, drastically alter quasiparticle bandgaps caused by the substrate screening and encapsulation. Scanning tunneling spectroscopy measurements showed significant dielectric-induced bandgap renormalization in monolayer transition metal dichalcogenides, demonstrating that bandgaps could be adjusted without changing the lattice structure [24]. Except for this nonlocal screening effect which has no similar property in bulk semiconductors and it represents a very low-dimensional tuning mechanism. Despite these advantages, specific geometric manipulation of band structure is inherently limited. In extreme circumstances, electronic activity is affected mainly by surface reconstruction, strain attenuation, and chemical disorder, with quantum scaling rules having very poor fit [25]. Strong excitonic binding energies of 2D semiconductors contribute to the disintegration of optical holes beyond single-particle bandgaps, which further hinders the optimization of the direct bandgap for optoelectronic purposes [26]. These restrictions necessitate design approaches that lie beyond size and form to interface based approaches.

3.2. Interface-Dominated Electronic Structure

With the decrease of dimensionality, surfaces and interfaces shift from being perturbative to the principal contributors to electrical structure. In low-dimensional nanomaterials, a high fraction of atoms is embedded in interfaces, and electronic states connected to surfaces, contacts, and substrates have a significant effect on carrier energetics and transport. Surface states due to dangling bonds, reconstruction, and adsorbates supply localized energy levels within the bandgap that can trap carriers and promote nonradiative recombination. Surface states play a major

role in electrical transport in semiconductor nanowires and lower intrinsic mobility may thereby influence material electronic properties [27].

While surface passivation can reduce trap densities, it often leads to additional dipoles or strain fields, which emphasizes the tenuous balance between chemical stability and electrical integrity [28]. Many interface-induced states lead to high Fermi-level pinning in low-dimensional systems. In metal-semiconductor contacts, interface gap states reduce sensitivity to the metal work function and can stabilize the Schottky barrier height, which results in constraints on contact optimization. Such phenomena are repeatedly studied in bulk and nanoscale interfaces, and extreme in atomically thin materials [29]. The main manifestation of this is Fermi-level pinning at metal-semiconductor junctions. For two-dimensional semiconductor materials, Schottky barrier heights are usually far from the ideal Schottky-Mott limit, driven by gap-induced interface states, rendering band alignment unaffected by metal work function. Recent studies in contact engineering show that the Fermi-level pinning remains a key impediment to low-resistance, reproducible connections in 2D electronics [29]. A reduced level of electrostatic screening in low-dimensional systems exacerbates contact-induced band bending. In ultrathin semiconductors, such depletion zones can extend all through the thickness of a semiconductor material, and the resulting regions of the potential landscape are spatially non-uniform due to the fact that there is a significant impact on carrier transport, exciton dissociation, and device performance. Thus, electrical structure development at scale has a high and very direct relationship to interface and contact, suggesting that it should be recognized that nanoscale electronics are systemic issues.

3.3. Emerging Paradigms in Electronic Structure Engineering

Besides classical confinement and interface effects, new ways of thinking about electronic structure engineering in low-dimensional systems have emerged. One of such approaches is topological confinement, where reduced dimensionality and increase in spin-orbit coupling is conducive to stability of nontrivial band topologies. Theoretically, topological electronic states have been determined by Hasan and Kane [30], and show that confinement can result in robust edge or surface states that govern transport in gapped systems.

A second novel approach is moiré superlattice engineering. At slight twist angles or lattice mismatch with layers in 2D, long-period moiré patterns of the superlattice occur when two-dimensional layers are superimposed, resulting in electronic band-enhancing changes, creating flattening minibands with enhanced correlation effects. The observed linkage between the insulating phases and superconductivity in twisted bilayer graphene has established that moiré confinement constitutes a new band engineering mechanism, one other than just reducing the real-space size [31].

Ultimately, quantum-confined heterostructures embody a cohesive approach that integrates confinement, dielectric screening, and band alignment into a singular framework. Van der Waals heterostructures facilitate the assembly of dis-

parate materials without the limitations of lattice matching, permitting autonomous regulation of electrical and optical characteristics across layers. Geim and Grigorieva outlined the conceptual framework for these systems, establishing heterostructure engineering as a potent approach transcending the limitations of homogeneous materials [34].

Approaches for controlling the electronic structure of low-dimensional materials have been summarized in **Figure 2** as (a) moiré superlattices, (b) van der Waals heterostructures, and (c) quantum confined heterostructures. Bandgap manipulation and alignment are some of the ways that these methods help to control [33] [34].

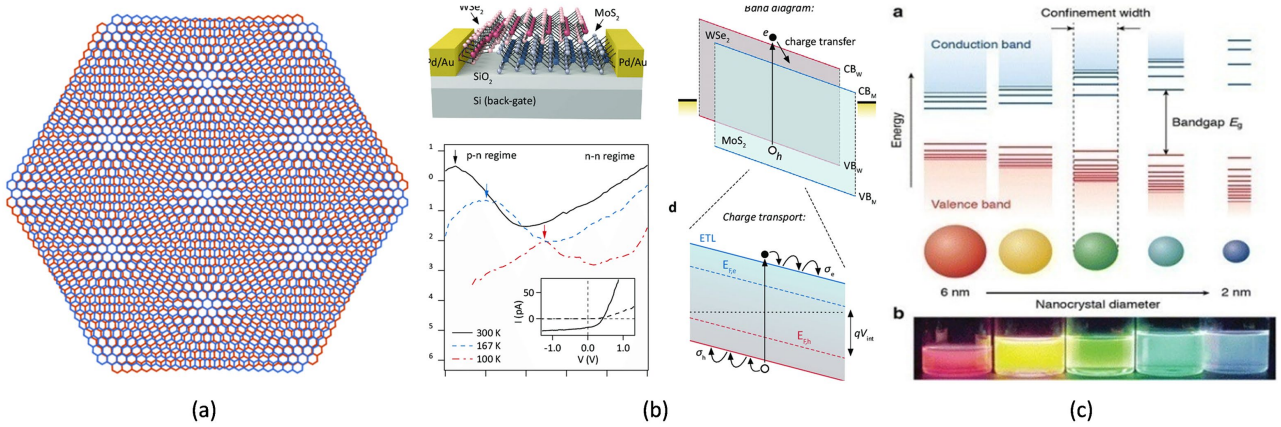

Figure 2. Representative electronic structure engineering strategies in low-dimensional nanomaterials: (a) moiré superlattices, (b) van der Waals heterostructures and (c) quantum-confined heterostructures illustrating size-dependent bandgap tuning [32] [33].

4. Optical and Excitonic Physics at the Device Scale

The development of low-dimensional nanomaterials as devices at the point of origin, from single systems, must also account for the optical versus excitonic systems at the scale of device objects. Unlike bulk semiconductors, where the free carriers only control optoelectronic behavior, reduced dimensions, strong Coulomb interactions and limited dielectric screening lead to the persistence of excitonic quasiparticles at room temperature. Therefore, in low-dimensional devices, a struggle between exciton transport and charge transport is common with the spontaneous emission, the stimulated emission along with nonlinear many-body interactions.

4.1. Exciton Transport versus Charge Transport

Photoexcitation of bulk semiconductors enables fast exciton dissociation into free carriers, allowing for charge transport. In low-dimensional materials, the effect of large exciton binding energies is to stabilize excitons at relevant timescales on the device, thus allowing excitonic transport to prevail over other energies in optical response and energy transfer. This phenomenon is most pronounced in two-dimensional transition metal dichalcogenides, which exhibit exciton binding energies of

hundreds of meV, which exceed thermal energy at normal temperature [16]. Whether exciton- or charge-dominated, the operating regime of a device is essentially driven by how the exciton diffusion length interacts with device dimensions.

From experimental works, it has been determined that in monolayer transition metal dichalcogenides, exciton diffusion lengths are found to range from tens to several hundreds of nanometers, depending on temperature, disorder and dielectric environment [35]. When devices have dimensions similar to or less than these diffusion lengths (such as nanoscale photodetectors, excitonic circuits, or LEDs), excitons may reach interfaces or contacts before dissociation, dramatically changing the functionality of devices. Starting from the discovery of an atomically thin semiconductor and a direct band gap in monolayer MoS_2 to the development of valleytronics, exciton complexes, and van der Waals heterostructures, this timeline summarizes major advance achievements towards the design of 2D semiconductors and their excitonic properties. The rapid development with respect to device-specific implementations like photodetectors, transistors, LEDs, solar cells, interlayer excitons, quantum emitters, high-quantum-yield and dark excitonic states is further shown in **Figure 3**. Collectively, these outcomes demonstrate how essential strong excitonic effects are for low-dimensional materials' optical response and device behavior.

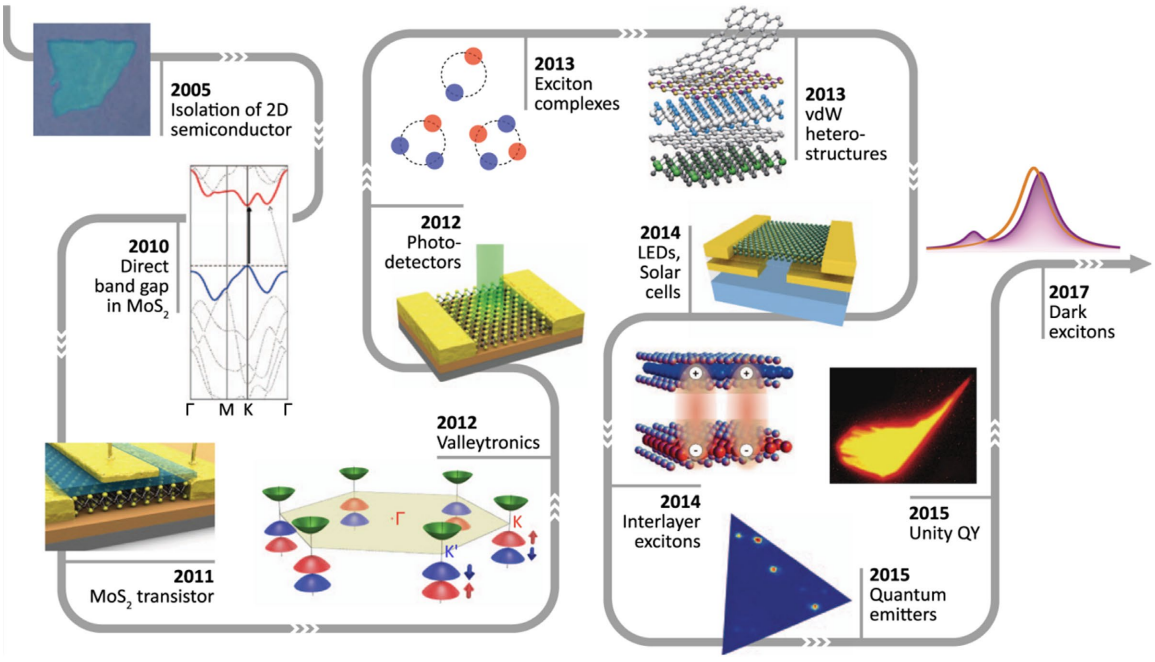

Figure 3. Evolution of excitonic physics and optoelectronic devices in two-dimensional semiconductors [18].

Optimal performance in these devices requires careful fabrication of exciton dissociation at heterojunctions or contacts instead of bulk-like carrier drift and diffusion. This transition underscores the importance of considering excitons not just as short-term intermediate states, but as a dynamic conveyor of information and energy, in low-dimensional optoelectronic systems.

4.2. Light-Matter Coupling in Confined Systems

Quantum confinement considerably increases the light-matter interaction capacity by increasing the oscillator strength and the spatial overlap of electronic wavefunctions with optical fields. Disparate surface material profiles in low-dimensional semiconductors, with reduced dielectric screening and strong excitonic contributions, result in surprisingly high absorption coefficients and radiative recombination rates of atomic films. Tightly coupled excitons dominate optical absorption and emission in semiconducting transition metal dichalcogenides due to strong Coulomb interactions and decreased dielectric screening. In contrast, pristine graphene's optical response is broadband and appropriate for ultrafast photonic applications due to its gapless electronic bands and very modest excitonic effects. Although smaller than one nanometer in thickness, monolayer transition metal dichalcogenides have shown a large absorption capacity of incident light [36]. To integrate low-dimensional materials in optical cavities or plasmonic nanostructures improves the oscillator strength, allowing entry into the strong coupling domain which has coherent energy exchange between excitons and photons better than dissipative losses. Robust exciton-polariton synthesis can be recorded in monolayer semiconductors at ambient temperature which paves the way for polaritonic devices operating well outside cryogenic settings [37].

In low-dimensional semiconductors, several physical regimes influence the many-body effect and excitonic structure at high light-matter coupling. A schematic example of an optical cavity-based low-dimensional excitonic system, illustrated in **Figure 4(a)**, explains that optical pumping enables relatively controlled photonic modes and excitonic resonances to integrate. The coupling of this type of coupling allows better light and matter interactions in materials with quantum confinement. The valley-resolved band behavior of a two-dimensional semiconductor with spin-valley locking and valley-selective optical transitions that enhance high strength oscillator response and polarization-dependent coupling is illustrated in **Figure 4(b)**. **Figure 4(c)** further illustrates the valley-dependent excitonic configurations and spin-resolved states at the (K) and (-K) valleys, emphasizing the role of valley and spin degrees of freedom in the excitonic response of low-dimensional semiconductors. The observed energy-momentum dispersion reflects the typical anticrossing of exciton and cavity modes, thus producing the upper and lower exciton-polariton branches and indicating the beginning of the intense light-matter coupling regime illustrated in Section 4.2. The further high Coulomb contacts and low dielectric screening in restricted systems are the driving elements for the increased strength of light-matter coupling, and are reflected in optical spectra of a Rydberg series of excitonic states (**Figure 4(d)**). In **Figure 4(e)** generalization of these conceptions to the van der Waals heterostructures providing tunable exciton-photon hybridization and enhanced degrees of freedom to design robust and ultrastrong coupling at the device scale [38]. In these heterostructures, intralayer and interlayer excitons exhibit distinct coupling interfaces.

The ultrastrong-coupling regime, where the light-matter interaction energy

reaches a significant part of the exciton energy, has been extensively investigated in recent studies. In these circumstances, new hybridized quantum states appear and traditional perturbative descriptions fail [39]. These advancements establish low-dimensional materials as a flexible framework for investigating nonperturbative quantum electrodynamics at the device level.

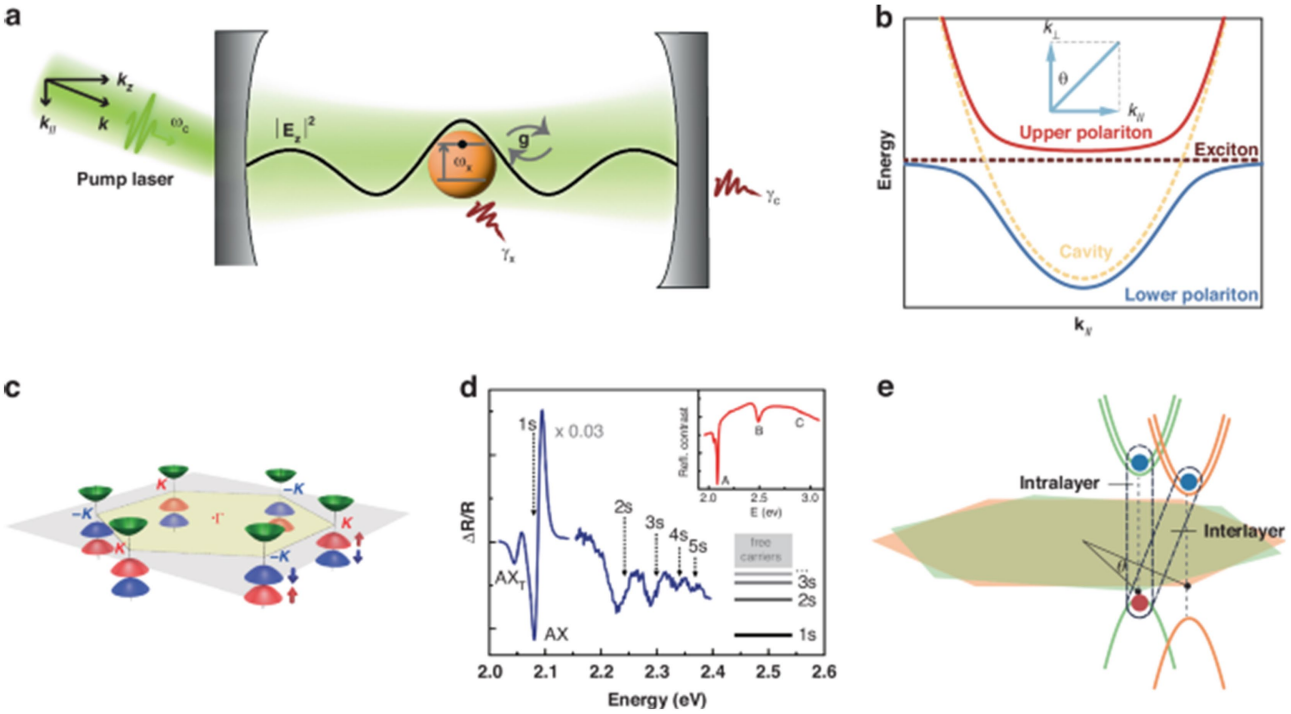

Figure 4. Light-matter coupling, excitonic structure, and many-body states in low-dimensional semiconductors [39].

4.3. Gain, Lasing, and Nonlinearities

Low-dimensional nanomaterials' strong Coulomb interactions result in noticeable optical nonlinearities that radically change gain processes and nanoscale lasing activity. Quantum-confined systems frequently support gain mediated by excitonic and biexcitonic states, in contrast to bulk semiconductors where optical gain usually results from free-carrier population inversion. Biexcitons with binding energies large enough to persist at room temperature are stabilized by reduced dielectric screening and enhanced wavefunction overlap in atomically thin semiconductors, making them effective intermediate states for stimulated emission. Exciton-exciton interactions have been identified as a key component of nonlinear optical response in low-dimensional systems based on experimental observations of tightly bonded biexcitons in monolayer transition metal dichalcogenides [40]. **Figure 5** shows how optical gain and nonlinear response in low-dimensional nanomaterials originate at the microscopic level. Strong exciton-exciton interactions and high biexciton binding energies allow for nonlinear optical processes that are not possible in bulk semiconductors, as shown in Panels (a) and (b), which contrast neutral excitons with biexcitons. Exciton-mediated gain is based on these

many-body states, which offer effective pathways for stimulated emission at lower excitation densities. Panel (c) goes on to show how Fano-type interference is created when excitonic resonances are coupled to plasmonic modes, improving light-matter interaction and altering radiative decay paths. This image is expanded to practical device topologies in panels (d)-(f), where severe optical field confinement is achieved by integrating metallic nanostructures with excitonic nanoplatelets. These hybrid exciton-plasmon systems highlight the crucial role of excitonic many-body physics in controlling gain and lasing behavior in low-dimensional systems by amplifying nonlinearities, lowering gain thresholds, and enabling compact nanolasers and active photonic devices [41].

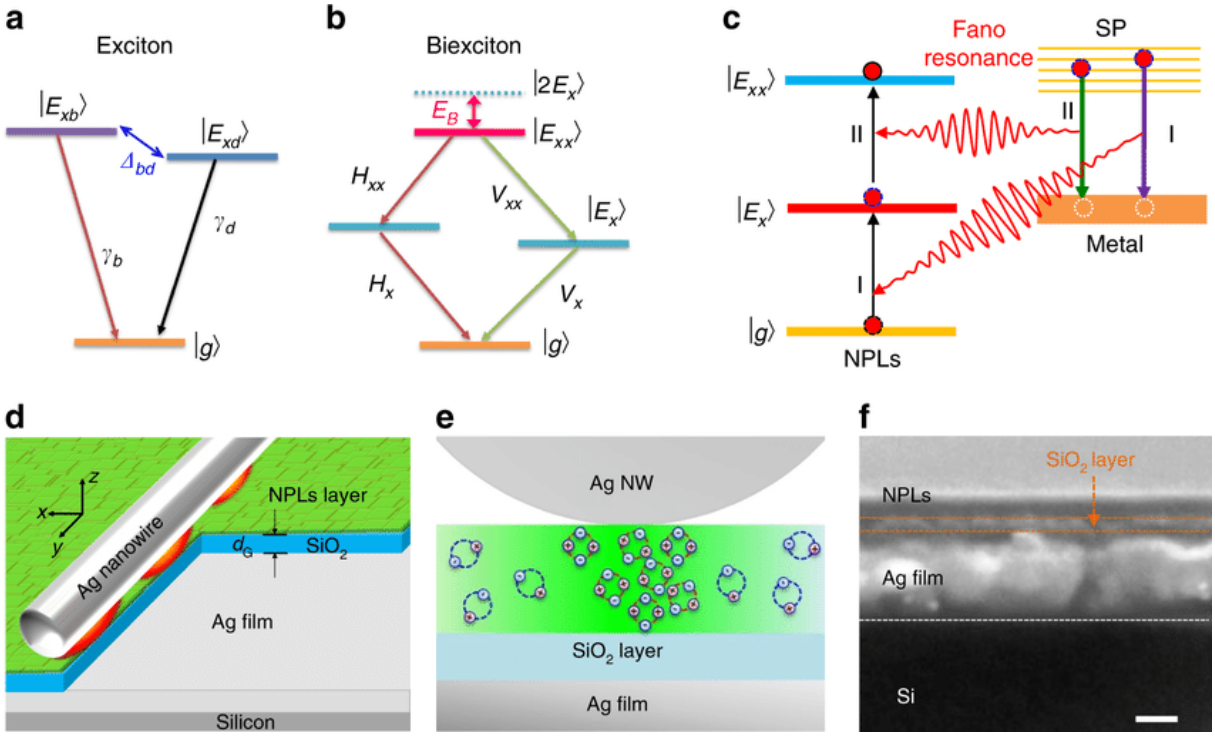

Figure 5. Excitonic nonlinearities and plasmon-enhanced gain mechanisms in low-dimensional systems [41].

The carrier density needed to attain optical gain is reduced by these improved many-body interactions, although nonlinear loss channels like exciton-exciton annihilation are also introduced. The net gain in low-dimensional materials thus represents a fine compromise between density-dependent nonradiative recombination and biexciton-assisted stimulated emission. This equilibrium sets low-dimensional nanolasers apart from their bulk counterparts by placing basic restrictions on possible gain bandwidth, emission linewidth, and operational stability [16].

When it comes to scaling behavior and lasing thresholds, dimensionality is crucial. As system dimensionality lowers, the threshold for stimulated emission is lowered by a combination of reduced density of states, higher oscillator strength, and extreme optical mode confinement. This effect is further enhanced in atomi-

cally thin semiconductors by strong light-matter interaction, which speeds up radiative recombination and makes it easier to switch from spontaneous to stimulated emission at lower excitation densities. Low-threshold lasing in ultrathin active layers can be made possible by confinement-driven enhancements that compensate for the decreased material volume, as demonstrated experimentally by strong coupling and stimulated emission in two-dimensional semiconductors integrated with optical cavities [37]. Generally, excitonic nonlinearities, not conventional free-carrier physics, govern gain and lasing in low-dimensional nanomaterials. Therefore, dimensionality-dependent threshold scaling, exciton-exciton interactions, and biexciton production must be understood and controlled in order to construct stable, room-temperature nanolasers and nonlinear photonic devices based on quantum-confined systems.

5. Quantum Confinement in Functional Devices

The unification of the two: system-level engineering and nanoscale physics is illustrated by the realization of the quantum confinement device. In such low-dimensional materials, there are changes in the energy spectra, the density of states, the Coulomb interactions and the electrostatics due to confinement. Transport and optical processes have to be seen through a quantum mechanical perspective which is more suitable as the device sizes are closer to intrinsic quantum length scales like the exciton Bohr radius or the carrier mean free path. This results in different device function not just assuming bulk materials, but also realizing a feature in sub-band quantization, scattering phase space restriction and interface-controlled electrostatics.

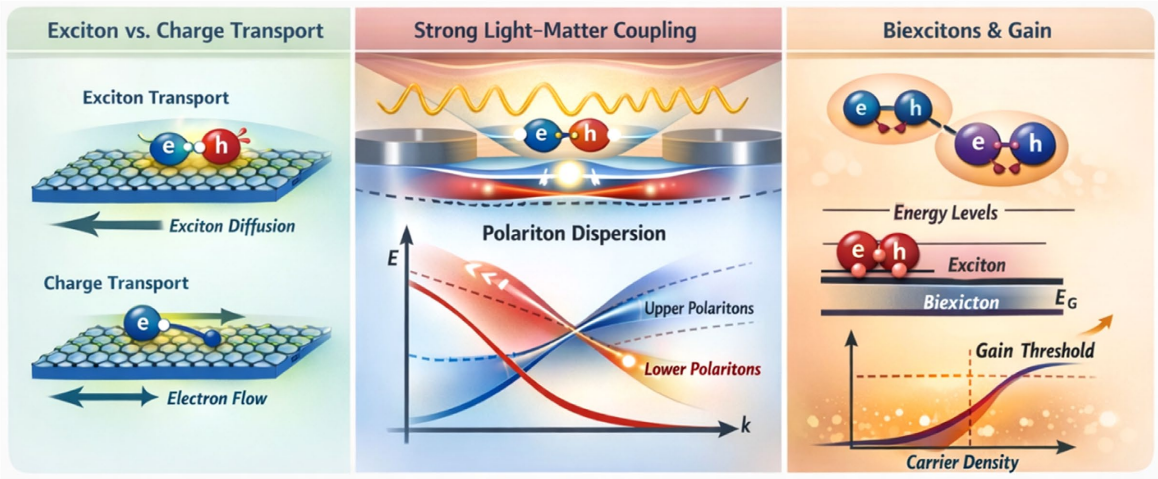

Figure 6. Confinement-driven optical and excitonic physics at the device scale.

The whole field of the device-scale excitonic and optical processes affected by quantum confinement is illustrated in **Figure 6**. The comparison of exciton-mediated and free-carrier transport in low-dimensional systems is illustrated in the left panel and the important role of dissociation pathways and diffusion length in

determining whether energy or charge controls behavior of the device. The central panel focuses specifically on the improved light-matter interaction in confined semiconductors, enabled by greater oscillator strength and decreased dielectric screening, and thus, a modified dispersion under cavity coupling, while also enabling exciton-polariton production. A visual illustration of many-body nonlinearities, such as biexciton generation and gain processes that reduce lasing thresholds in quantum-confined emitters, can be observed on the right panel. Collectively, these approaches indicate that reduced dimensionality unites transport physics, coherent coupling, and nonlinear emission within a single confinement-controlled framework, remaking not just electronic structure but also the collective optical response.

5.1. Transistors and Quantum Transport

Transport behavior is radically changed by quantum confinement, which discretizes the electronic spectrum into subbands when transistor channels are shrunk to one- or two-dimensional geometries. Quantized subbands are created via transverse confinement in one-dimensional nanowires and nanotubes, and these subbands are progressively filled under gate bias. The quantized transport characteristics that result from each subband contributing a finite conductance channel differ from the bulk drift-diffusion assumptions. Atomic-scale thickness in two-dimensional semiconductors eliminates short-channel effects and offers remarkable electrostatic gate control, allowing aggressive scaling beyond the constraints of bulk silicon [42].

The equilibrium between ballistic and scattering-dominated regimes is altered by confinement. Phase space for phonon scattering is constrained by reduced dimensionality, enabling quasi-ballistic transport over brief channel lengths [43]. But confinement also increases sensitivity to contact resistance, remote phonons, and interface disturbance. Therefore, the conflict between confinement-enhanced scattering and sub-band engineering determines device performance. Nanoscale transistors must be viewed as quantum transport systems rather than conventional mobility-limited devices because switching behavior in ultrathin channels is increasingly defined by quantum capacitance and injection barriers. In summary, quantum confinement leads to improved electrostatic gate control via subband engineering and reduced channel thickness, enabling better device metrics, e.g., higher carrier mobility for quasi-ballistic transport, steeper subthreshold characteristics, reduced short-channel effects, and lower power consumption in nanoscale transistors.

5.2. Optoelectronic Devices

The dynamics of optical absorption, emission, and carriers are significantly altered by quantum confinement, which causes optoelectronic devices to enter exciton-dominated regimes. Different material classes have different dominant optical mechanisms: semiconducting TMDs rely on strong excitonic transitions con-

nected to their direct bandgaps, graphene mainly uses broadband absorption and ultrafast carrier dynamics, and quantum dots use discrete, size-tunable electronic states for spectrally selective absorption and emission. Even at ambient temperature, bound electron-hole pairs are stabilized by high exciton binding energies in atomically thin semiconductors [16] [18]. **Figure 6** schematically illustrates how the rivalry between confinement-enhanced absorption and exciton dissociation efficiency is crucial to photodetector performance. Interface design and built-in electric fields are crucial to responsivity optimization because, whereas strong oscillator strength and discrete density of states improve absorption, strong Coulomb binding can hinder charge extraction [18] [44].

Because quantum confinement increases oscillator strength and decreases density of states, it lowers population inversion thresholds in LEDs and lasers. At low carrier densities, radiative recombination frequently occurs through excitonic channels, whereas at higher densities, nonlinear many-body processes such exciton-exciton annihilation are introduced [45]. Therefore, confinement causes density-dependent losses while also improving emission efficiency.

Bandgap tunability by confinement allows for better absorption close to band edges and spectral matching in solar cells. Furthermore, tailored van der Waals heterostructures overcome the inherent thickness absorption trade-off in ultrathin photovoltaic systems by using confinement to enable exciton separation and directional carrier extraction [18] [46]. As a result, the confinement-induced modifications of electronic structure and excitonic dynamics directly translate into experimentally observable improvements of device performance, such as higher photodetector responsivity, higher external quantum efficiency of light-emitting devices, lower lasing thresholds, and higher power conversion efficiency of ultrathin photovoltaic devices.

5.3. Quantum and Neuromorphic Devices

New device paradigms that take advantage of many-body coherence and discrete quantum states are made possible by quantum confinement. Electronic states are isolated into distinct energy levels appropriate for qubit application through confinement in quantum dots or defect centers. While allowing for coherent electrical or optical manipulation of quantum states, spatial localization inhibits ambient coupling [47]. Coherence periods, transition frequencies, and coupling strengths in solid-state qubits are defined by the quantized energy spectrum produced by confinement.

An alternative method that uses neutral quasiparticles as information bearers is exciton-based logic. Nonlinear switching, interference phenomena, and collective many-body dynamics at lower power densities are made possible by strong exciton-exciton interactions in restricted systems [16] [48]. Excitonic circuits depend on Coulomb-mediated quasiparticle interactions, which arise immediately from confinement-enhanced screening reduction, in contrast to traditional charge-based logic.

According to Awschalom *et al.*, hybrid classical quantum designs combine scalability and quantum functionality by integrating constrained quantum elements with traditional electronic circuitry [49]. Similar to this, neuromorphic devices made of low-dimensional materials mimic synaptic activity by utilizing memristive switching, adaptive carrier dynamics, and confinement-enhanced nonlinear conductance [20]. The basic operational degrees of freedom in each scenario whether they be discrete qubit states, excitonic nonlinearities, or adaptive conductance states are determined by confinement. By tuning confinement-induced quantum states and many-body interactions, these systems achieve better device metrics such as longer qubit coherence times, lower switching energy, higher operational fidelity and enhanced synaptic plasticity, all of which are critical for scalable quantum and neuromorphic computing architectures.

6. Scalability, Disorder, and the Confinement-Reality Gap

Although quantum confinement offers extraordinary control over electrical structure, optical response, and quantum functionality at the nanoscale, it is still difficult to translate these benefits into technologies that can be manufactured on a large scale. When devices are scaled to wafer-level integration or built into dense arrays, the remarkable performance that is typically seen in isolated nanowires, single quantum dots, or mechanically exfoliated monolayers usually decreases. This disparity, which we call the confinement-reality gap, results from environmental perturbations, fabrication variability, ensemble averaging effects, and structural variation, all of which fundamentally alter confinement physics outside of idealized laboratory settings [18].

Quantum confinement is inherently sensitive to geometric precision at the nanoscale. Small changes in thickness, diameter, edge form, strain distribution, or dielectric environment have instantaneous effects on subband spacing, bandgap energy, exciton binding strength, and local density of states [16]. In solitary nanostructures, these characteristics can be carefully regulated or separately characterized. However, in large-area films, patterned arrays, or integrated circuits, structural heterogeneity inevitably introduces spatial oscillations in confinement strength. In atomically thin semiconductors, electrical and optical transitions can be drastically changed by even a single layer thickness shift. In one-dimensional systems, diameter dispersion can change subband energy and lead to carrier localization. Edge disorder in nanoribbons can result in mid-gap states that dominate transport, suppressing the same bandgap engineering that confinement was intended to achieve [18]. In a similar vein, variations in substrate dielectric screening lead to nonuniform Coulomb interactions, which provide spatially varied excitonic characteristics and widened optical features [19].

These nanoscale variances are crucial for the shift from single-object measurements to ensemble-based device implementations. Many famous confinement effects, such conductance quantization in nanowires or discrete emission lines in quantum dots, are first observed in carefully separated structures [44]. However,

real devices typically employ ensembles such polycrystalline monolayer sheets, quantum dot films, or nanowire networks. The inherent size and structural dispersion in these ensembles are responsible for the inhomogeneous broadening of energy levels and transport characteristics. The discrete quantization signals observed in individual structures are smeared into a larger continuum when averaged over thousands or millions of elements. Because of this, ensemble devices may exhibit relatively bulk-like behaviour even while each component is still quantum limited at the microscopic level. Consequently, the ensemble effect obscures the intrinsic advantages of confinement and complicates the interpretation of device-scale observations [20].

Another limitation that is frequently disregarded is reproducibility. Tiny fabrication flaws can cause significant device-to-device mismatch because confinement magnifies the nanoscale geometric and electrostatic differences. Transistors' subthreshold characteristics and threshold voltage can be altered by slight changes in the dielectric interface morphology, channel thickness, or edge roughness [18]. The reaction time, quantum efficiency, and emission wavelength can all affect the exciton binding energy and defect density of optoelectronic devices. The deterministic characteristics of quantum information systems are impacted by differences in confinement potential, which directly impact coherence times and energy level spacing [19]. These quantum-confined systems transform atomic-scale flaws into observable and potentially dominant device fluctuations, in contrast to bulk materials whose small structural variation eventually causes incremental performance changes [49]. Large-scale production hinders industrial scalability by sometimes producing stochastic performance distributions instead of homogeneous features [20].

Therefore, rather than a quantum mechanical failure, the apparent loss of confinement gains at scale is caused by conflicting disorder-driven processes. Discrete energy levels are blurred by inhomogeneous broadening caused by structural dispersion. Ballistic transport is inhibited and mobility is decreased when dispersed by a motion disorder. Coulomb links are weakened and excitonic enhancements are reduced by environmental filtering by substrates or encapsulation layers [16]. At operating temperatures, quantization fingerprints are obscured by thermal phonons. In order to restore bulk-like behaviour, adjacent restricted parts of the nanostructures can be electrically connected to emplace minibands in dense assemblies. An increase in each of these events gradually reduces the gap between a well-designed confinement physics and device functionality, undermining the advantages anticipated of fully controlled nanoscale systems. Two strategies are needed to close the confinement reality gap: reducing structural disorder and creating gadget designs that can withstand inevitable variability. To maintain confinement-induced features for broad coverage, developments in atomic-layer fabrication, strain engineering, dielectric encapsulation, and deterministic synthesis are crucial. It is similarly important to develop methods for multiscale modelling and *in situ* characterization that may link atomic structure to macroscopic device

performance [18]. Designing materials and interfaces that maintain confinement-enhanced functionality will be just as important to the scalability of low-dimensional technologies in a practical operating environment as having strong confinement. In this instance, the limited reality split may be a helpful tool rather than a barrier. It identifies the exact locations where nanoscale physics and fabrication difficulty collide and, consequently, how much may be improved. Whether the remarkable capabilities made possible by quantum confinement continue beyond laboratory demonstrations into scalable technologies that are the hallmark of electronic, photonic, and quantum systems which will be our next generation of devices, depend on how this intersection is understood.

7. Future Outlook: From Quantum Control to Quantum-Informed Device Design

Over the past 20 years, the development of low-dimensional nanomaterials has been initially driven by quantum confinement processes such as bandgap renormalization, discrete subbands, enhanced excitonic effects, and topologically protected states. Early research focused on demonstrating and characterizing these processes in carefully controlled solitary nanostructures. A major change is currently occurring in the science: the goal is to predictably create and integrate confinement into functional systems rather than merely observe it. If low-dimensional technologies are to progress, quantum confinement must be transformed from a passive physical effect of reduced dimensionality to an actively changeable design element integrated into device architecture [16] [31].

A new quantum-informed design framework is required as a result of this modification. Instead of being regarded as an intrinsic material property, confinement needs to be co-optimized with electrostatics, the dielectric environment, strain distribution, optical cavity design, and contact engineering [19]. For example, gate geometry, contact resistance, subband structure, and quantum capacitance must all be considered simultaneously in nanoscale transistors. In optoelectronic systems, exciton binding energy, radiative lifetime, and dielectric screening cannot be separated from heterostructure alignment and optical mode confinement. In quantum and neuromorphic architectures, discrete energy spacing, coherence periods, and coupling strengths must be designed alongside classical control circuitry [20] [49]. The most significant insight is that confinement does not operate in a vacuum but rather dynamically interacts with architecture, interfaces, and external fields.

Before quantum confinement can be fully utilized in practical devices, a number of basic physics issues need to be resolved. First, there is still a lack of a predictive understanding of disorder in constrained systems. Real materials have spatial heterogeneity, interface traps, strain gradients, and dielectric fluctuations that alter quantum states in intricate ways, whereas idealized models accurately depict subband creation and excitonic spectra. Multiscale modeling frameworks that can connect mesoscopic transport simulations with *ab initio* electronic structure com-

putations are necessary to bridge the gap between atomic-scale disorder and device-scale variability.

Second, little is known about many-body interactions in practical operational environments. Screening effects, plasmon-exciton hybridization, carrier-phonon coupling, and exciton-exciton annihilation all change dynamically with temperature and carrier density. Nonequilibrium quantum kinetics, rather than equilibrium characteristics, frequently determines device performance. Predictive device engineering thus requires the development of precise time-resolved and nonlinear models of restricted systems.

Third, phonon engineering and heat control are uncharted areas. Reduced dimensionality modifies heat dissipation and phonon dispersion pathways in severely restricted systems, which affect optical gain, coherence time, and carrier mobility. Maintaining performance at technologically relevant temperatures requires an understanding of how confinement concurrently alters electronic and phononic spectra.

Going ahead, confinement should be seen as a continually adjustable characteristic rather than a binary attribute that may be classified as either bulk or confined. Parameters for adjusting confinement strength include strain, electrostatic gating, dielectric encapsulation, thickness, lateral dimension, and twist angle in moiré systems. Quantum-informed architecture emerges when these characteristics are combined into a single design space. Under this approach, rather than relying on post-hoc optimization, device shape and material dimensionality are co-designed from the beginning, guided by quantitative predictions. A route to this objective is provided by the combination of machine learning-assisted modeling, enhanced *in situ* characterization, and deterministic nanofabrication. Local band bending and direct mapping of excitonic landscapes are now possible thanks to high-resolution spectroscopies. Sub-nanometer thickness control over wafer-scale regions is made possible by atomic-layer synthesis. The investigation of confinement-property interactions is accelerated by data-driven materials discovery. All of these developments point to the possibility that, as design gets more predictive, the confinement-reality gap mentioned in the previous section may progressively close.

In the end, quantum confinement may have a more revolutionary effect on enabling radically new device paradigms than on enabling small performance gains. Enclosure-controlled energy landscapes are essential to architectures that take advantage of topologically protected channels, strong light-matter interaction, excitonic transport, or hybrid classical-quantum functionality. In this way, the ability to precisely manipulate quantum states across scales will define the future of nanoelectronics and nanophotonics, rather than the smallest possible dimension. As a result, the field is maturing from seeing quantum confinement to regulating it and using it in design. It will be necessary to embrace confinement as a co-design variable integrated into architecture, interfaces, and operating environments in order to create low-dimensional technologies that are scalable, reproducible, and

versatile. Confinement will stop being a lab trick and start to form the basis of next-generation functional materials systems when quantum control is commonplace in device design.

Author Contributions

Tvishaa Prabhu: Conceptualization, literature review, methodology, analysis, and manuscript preparation. Sananjay Biswas: Supervision, conceptual guidance, critical review, and manuscript editing. Both authors reviewed and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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