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Research paper

Nanophotonic Materials for Next-Generation Optoelectronic Devices

Dr. Shashikant Patil [1] *, Dr. Sidhartha Dash [2], Dr. G. D. Anbarasi Jebaselvi [3], Nagraj Patil [4], Prakriti Kapoor [5], Manish Nagpal [6], Saumya Goyal [7]

[1] *Professor, uGDX, ATLAS SkillTech University, Mumbai, India*
[2] *Associate Professor, Centre for Internet of Things, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India*
[3] *Associate Professor, Department of Electronics and Communication Engineering, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India*
[4] *Associate Professor, Department of Mechanical Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramnagar District, Karnataka, India*
[5] *Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India*
[6] *Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh, India*
[7] *Quantum University Research Center, Quantum University, Roorkee, Uttarakhand, India*
**Corresponding author E-mail: shashikant.patil@atlasuniversity.edu.in*

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Abstract

Nanowires (NW) have attracted significant interest in photonics and Optoelectronics (OE) because of their distinctive properties. Due to their extensive surface area and considerable potential as resonators and waveguides in Photonic Integrated Circuits (PICs), NWs have been utilized in various study domains within Nanophotonics (NP). The hybridization of NWs and two-dimensional (2D) substances has been used in numerous studies to improve the characteristics of light-emitting substances. This study encapsulates recent research on using diverse NW types in NP and OE and integrating NWs with two-dimensional materials. The present study presents NWs functioning as resonators and/or waveguides to boost the efficiency of 2D materials in PICs for light amplification and guidance. The paper delineates the combination of NWs with 2D materials investigated in OE. The article discusses the integration of NWs and 2D materials for NPs and OEs, outlining future research prospects.

Keywords: *Nanophotonic Materials; Optoelectronic Devices; Optical; Nano Technology; Next-Generation; Photonic Integrated Circuits.*

1. Introduction

Nanophotonics (NP) and Optoelectronics (OE) are rapidly emerging domains that combine the manipulation of light at the nanoscale with the development of energy-efficient, compact devices for information processing, sensing, and communication applications [1]. These fields are crucial for enabling next-generation technologies such as Photonic Integrated Circuits (PICs), flexible electronics, and quantum information systems [5]. These fields are crucial for enabling next-generation technologies such as Photonic Integrated Circuits (PICs), flexible electronics, and quantum information systems. The integration of nanostructured materials, including nanowires (NWs) and two-dimensional (2D) materials, has become central to this evolution due to their excellent confinement, tunable bandgaps, and mechanical flexibility [6, 7, 13]. These materials not only enhance optical and electronic properties but also offer compatibility with scalable fabrication platforms, making them suitable for commercial and industrial use.

As miniaturization progresses, the classical Micro-Electro-Mechanical Systems (MEMS) paradigm has transitioned into Nano-Electro-Mechanical Systems (NEMS), and more recently into Nano-Opto-Electro-Mechanical Systems (NOEMS), where optical, electronic, and mechanical functionalities coexist within a single architecture [3, 4]. NOEMS platforms offer novel capabilities such as electrically tunable photonic resonators, strain-sensitive detectors, and quantum-level interaction of photons, electrons, and phonons [12]. These systems serve as a bridge between conventional device architectures and future photonic computing environments. This paper explores the synergy between NWs and 2D materials in NOEMS configurations and analyzes their potential in enhancing nanophotonic and optoelectronic device performance.

Combining Nanowires (NW) with 2D materials enhances NP and OE application performance [14]. NWs consist of metallic substances, semiconductors, or insulation. Metal NWs exhibit versatility, serving dual functions as OE and NP elements. Silver is commonly used as an electrode substance due to its superior transmission, minimal sheet resistance, and exceptional flexibility. Integrating 2D materials like MXene, graphene, or graphene oxide can mitigate some obstacles hindering their practical application. For instance, 2D conducting layers interconnect NWs and create a smoother surface, leading to lower resistance. 2D insulating substances safeguard metal NWs against oxidation. In addition to electrodes, metal NWs function as waveguides, access nanocavities, and regulate light emission characteristics. With advancements in semiconductor technology for production, semiconductor NWs have become prevalent and are a foundation for PICs. A notable benefit of silicon NWs is that they are compatible with Complementary Metal-Oxide-Semiconductor (CMOS) technological advances while offering enhanced OE and NP capabilities [8]. Integrating these NWs with two-dimensional substances in core-shell or NW-on-monolayer configurations will yield a synergistic impact. As a potential quantum light source, 2D materials are being explored in quantum photonics. For instance, 2D semiconductors like monolayers and 2D insulating compounds like Hexagonal Boron Nitride (hBN) possess only one photon transmitter. Integrating NWs enables the control of single photon emission and its routing through the NWs. 2D materials are utilized to investigate Second Harmonic Generation (SHG) , and the mitigation of unwanted emissions has been documented by incorporating semiconductor-like NWs [8].

NW monolayers are extensively utilized in Photodetectors (PD) [15]. The combined layer used with ZnO or CdS nanostructures demonstrated enhanced responsiveness and accelerated operation. They increased light absorbance due to the charging carrier transfer produced by band realignment. Perovskite NWs exhibit significant promise for utilization in piezotronic and piezo-phototronic systems. Their optical characteristics are augmented when integrated with Transition-Metal Dichalcogenides (TMDs) substances. This facilitates efficient charge carrier transmission between the waveguide and conducting path while mitigating dark current. The single-layer waveguide is coupled with an optical cable to boost second harmonic generation via evanescent field interaction [10].

2. NW as a multifaceted platform for nanophotonics

NWs provide diverse applications in NP and OE gadgets, functioning as resonators and waveguides. Current reviews outline the mechanisms by which NWs function as cavities and waveguides. NWs are Fabry-Perot (FP) resonances with two reflectors restricting stationary waves. In bulk optical science, optical resonances are generally formed with two mirrors exhibiting near-unity reflectance (R); conversely, NWs composed of semiconductor or dielectric substances utilize reflection resulting from variations in the refraction index (n). The reflectance at the interface of the two substances with refraction indices n_1 and n_2 is governed by Fresnel's formula:

$$R = \left(\frac{n_2 - n_1}{n_1 + n_2}\right)^2 \quad (1)$$

The Q-factor (Q) of the Fabry-Pérot (FP) type cavities is as follows:

$$Q = \frac{2\pi * nL}{\lambda(1-R)} \quad (2)$$

Utilizing an extended wire length (L) and strong refraction indicators at the incident wavelengths is advantageous to optimize light containment. Many studies have used NWs as the FP cavity. Silicon NWs are full nanolasers and comprise optical resonance (OR) and optical gain media. Silicon NWs have garnered considerable interest due to their more straightforward fabrication difficulty compared to other types of nanolasers that necessitate photolithography or electron-beam patterning. Current research encompasses lasing in potassium lead perovskite mite NWs and single-mode ending from NWs. In addition to the FP method, microwires with a micrometer-scale diameter can facilitate Whispered Gallery Mode (WGM). A suitable radius must be determined according to the visual modes intended for usage.

Another commonly utilized geometry for NW electronics is the wire-gap-substrate arrangement, which enables gap modes. The gap layer consists of a thin dielectric substance to attain a gap method, whereas the NW, basis, or both are composed of metal. This vacant mode facilitates precise light focusing, enhancing the Purcell variable, characterized as the Q-factor scaled by the mode size. The NW-gap-substrate configuration is frequently employed in NW lasing investigations. The group successfully created a nanoscale plasmonic light with an optical pattern smaller than diffraction limits, utilizing a silicon NW, which is separated from a silver substrate by an intervening gap.

Recent advances have also explored borophene—an emerging anisotropic 2D material—hybridized with semiconductor nanowires. Borophene–NW heterostructures exhibit ultrafast carrier dynamics and low switching thresholds, making them suitable for high-speed optoelectronic modulators and logic gates. These systems have shown femtosecond-scale response times due to the combination of borophene’s high electronic conductivity and the optical confinement provided by nanowires [6].

In addition to the cavity operation, insulating and metal NWs can function as waveguides. The dielectric waveguides exhibit reduced attenuation compared to metallic waveguides. Metal NWs on dielectric or metal substrates exhibit considerable losses due to transmission via surface plasmon polaritons. This section will address NWs about 2D materials. NWs can enhance the photoluminescence intensity of 2D transition metal dichalcogenides through the cavity effect and direct radiation from 2D materials via a waveguide impact. The study will delineate a hybrid system that uses NWs and 2D materials as a classical light source and photon sensors.

3. Optoelectronics

From the viewpoint of microscopic fragments, the physical process of NOEMS fundamentally involves the relationship of electrons and phonons. The interaction among electrons and photons in the OE action is augmented through the manipulation of phonons. The refraction index of a NOEMS gadget can be altered by an external electric field owing to the photoelastic impact resulting from the reverse piezoelectric impact of atomic structures, enhancing the OE effect. Figure 1 illustrates the underlying physical mechanisms within a typical Nano-Opto-Electro-Mechanical System (NOEMS). The diagram includes core components such as a metallic nanowire acting as a resonator, a 2D material layer facilitating photon absorption and carrier modulation, and an electrode interfaced with an external bias source. The structure is designed to demonstrate the dynamic interaction between photons (input light), electrons (excited carriers), and phonons (generated by mechanical vibrations). These interactions influence the refractive index, enabling signal modulation, energy conversion, and photodetection within the device. The coupling between mechanical strain and the optical/electrical field is achieved via piezoelectric or photoelastic effects, which are tunable through voltage bias or substrate deformation.

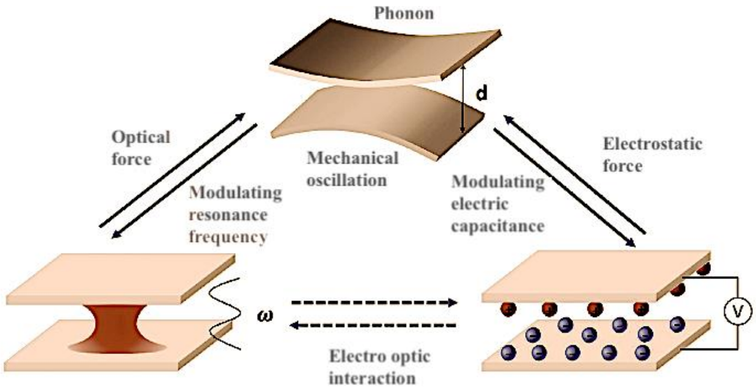

Fig. 1: Figure 1: Schematic Representation of a Nano-Opto-Electro-Mechanical System (NOEMS) Illustrating the Interaction Between Photons, Electrons, and Phonons in a Hybrid Nanowire–2D Material Platform..

Numerous 1D/2D hybrid substances applications have been implemented in OE, including PD, Light-Emitting Diodes (LEDs), and phototransistors. Using 1D/2D hybrid substances is a compelling aspect of such uses. PDs have garnered significant attention in recent years owing to their attractive applications across numerous fields. A prevalent strategy involves utilizing materials modified with nanoparticles or altering their chemistry or morphological features to improve application performance. Utilizing heterojunctions in bulk or nanomaterials is a predominant technique for high-performance PDs. These hybrid materials showed significant enhancement in responsivity relative to their equivalents. The responsiveness (R) is calculated as $I_{ph}/(P \times A)$, wherein I_{ph} is the net photocurrent, P is the incoming light strength, and A is the actual lit area of the sensors. The primary tactics employed in these investigations aim to improve PD efficiency through efficient charge carrier transport and light entrapment.

NWs are extensively utilized in PDs due to their versatility, including using flaws to enhance electrical and optical characteristics. 1D/2D hybrid substances represent a strategy employed to increase the optical properties of PDs. The research looked at engineered Ga-As NWs and GaAs atomic stacked sheets as materials for PDs to improve responsiveness and detectivity. These hybrid substances established a beneficial interface condition, resulting in enhanced efficiency. ZnO NW possesses multiple uses in NPs and OE due to its fundamental, piezoelectric, and OE characteristics.

Comparative Analysis of 1D/2D Hybrid Photodetector Configurations

While both ZnO/WS and CdS-based hybrid photodetectors have demonstrated enhanced performance due to band alignment and charge transfer properties, their operational efficiencies vary across metrics such as responsivity, recovery time, and stability under varying environmental conditions. The ZnO/WS core–shell architecture exhibits superior responsivity due to the high optical absorption of WS_2 and its favorable carrier mobility, which facilitates faster charge separation. In contrast, CdS-based hybrids offer broader spectral response due to their tunable bandgap and improved crystallinity from van der Waals epitaxial growth techniques. However, CdS is relatively more sensitive to environmental degradation, especially in humid conditions, compared to the more robust ZnO-based heterostructures.

These trade-offs are summarized in Table 1.

Table 1. Comparative Performance of ZnO/WS and CdS-Based Hybrid Photodetectors

Parameter	ZnO/WS Core-Shell Hybrid	CdS-Based vdW Hybrid
Responsivity (A/W)	3.2 A/W	58.3 A/W
Response Time	56 ms	~80 ms
Detectivity (Jones)	$\sim 1.2 \times 10^{10}$	1.42×10^{10}
Environmental Stability	High	Moderate
Spectral Range	UV-visible	Visible-NIR
Fabrication Scalability	Moderate	High (vdW assembly)

This comparative analysis highlights the importance of material pairing and interface engineering in tailoring photodetector performance. Further research should explore heterostructures that combine the fast response and stability of ZnO/WS with the high detectivity and spectral range of CdS-based hybrids.

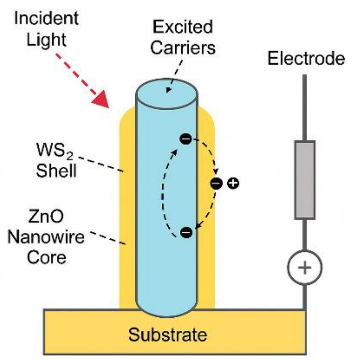

Fig 2: Schematic of a Hybrid Photodetector Based on ZnO Nanowire Core and WS_2 2D Shell Structure.

Figure 2 shows a representative NW–2D hybrid architecture used in high-performance photodetectors. The core–shell configuration enables strong light-matter interaction at the interface, efficient charge separation, and reduced recombination losses. ZnO serves as a high-mobility core, while the WS_2 shell enhances visible-range absorption and acts as an electron blocking layer. This spatial separation supports fast response times and high responsivity.

In addition to conventional 2D materials like graphene and TMDs, emerging materials such as phosphorene have demonstrated excellent performance in broad-spectrum photodetection. Owing to its tunable direct bandgap and high carrier mobility, phosphorene-based hybrids show extended spectral sensitivity into the near-infrared region while maintaining a high responsivity-to-dark current ratio. These characteristics position phosphorene as a strong candidate for integration into 1D/2D hybrid photodetectors, especially for applications requiring broadband light capture and low-noise operation [2].Enhanced the separation accuracy of electron-hole pairs generated by photosynthesis, leading to more excellent responsiveness and detectivity.

It have drawbacks such as long response and recovery times. The study presented a ZnO/WS core-shell hybrid to enhance the reaction time of PDs. The research improved photodetection by applying a monolayer on the NW. monolayers exhibit a direct bandgap of 1.82–1.94 eV and demonstrate significant optical absorption capabilities. The hybrid compound was synthesized by depositing WO_2 on ZnO NWs using magnetic sputtering of metallic carbide in an Ar/O environment, followed by annealing in a sulfur atmosphere. The substance was conveyed to a gold electrode utilizing a nanomanipulator probe. The reactivity of the core-shell NW at 415 nm was measured at 56 ms, whereas the original ZnO NW had a response period of 6.0 s. The WS_2 shell shields the ZnO surface, reducing oxygen absorption and surface-related photoconductivity. Density Functional Theory (DFT) simulations indicated that the WS shell has functioned as a charge carrier route in the ZnO/WS heterostructures.

The research team generated NWs with a WS nanosheet to augment light sensitivity. The hybrid substance was created using the technique. The responsiveness was measured at 3.2 A/W with a bias voltage of 5 V and a source power of 12 mW/cm², whereas the pure model exhibited a 28 mA/W responsiveness. The heterojunction exhibits enhanced photoreceptive capabilities at a negative bias power due to spontaneously charged carrier transfer driven by band alignments. Owing to van der Waals epitaxial development, CdS was readily synthesized without the limitations of the lattice. Photogenerated carriers can move efficiently across these surfaces by circumventing lattice deformation, enhancing photodetection sensitivity.

A substantial on/off detection ratio can be attained by integrating an NW hybrid. The study employed nanoflakes and crystallized NWs to construct van der Waals heterostructures (vdWH) light detectors. The engineered PD demonstrated an improved on/off proportion, responsiveness, and detectivity of up to 112.24, 58.3 A/W, and 1.42×10^{10} Jones. Compared to a pure channel, van der Waals heterostructures generate a depletion level. This results in a reduction of black current, hence enhancing the on/off ratio. A hybrid substance was fabricated on a film to investigate the strain-induced properties. The research demonstrated that the photocurrent was augmented with tensile strain and diminished with compressive stress due to the piezo-phototronic action produced by NWs. The elevated on/off ratio and strain-induced light current facilitate the advancement of highly efficient and versatile PDs.

Hybrid substances are frequently examined in the domain of LEDs. The research studied flexible perovskite LEDs (PeLEDs) to improve light outcoupling. The study established a framework for a silver NW-based electrode that included crystalline and defect-passivated perovskite emission. The configuration resulted in lower nonradiative recombination rates.

The research demonstrated an external quantum efficiency of 25.6%, facilitated by outcoupling improvement through quasi-random nanopatterns on an adaptable substrate. The vdWH, including 1D and 2D materials, has been extensively investigated in the context of phototransistors. The study demonstrated an epitaxial structure suitable for a high-responsivity device, including Au-CN NWs atop graphite. When photogenerated electrons and hole particles in Au-CN migrate across graphene, excess charges will build in Au-CN due to the potential at the Au-CN NW and graphene contact. This resulted in a tunable photo-response contingent upon the supplied gate voltage. This straightforward synthesis process offers a means to enhance the yield of hybrid materials by examining various circumstances for growth. The study employed a dual-channel phototransistor utilizing trigonal selenium nano belts and films. The connection between nano belts and films enhanced the separation accuracy of electron-hole pairs generated by photosynthesis, leading to more excellent responsiveness and detectivity.

4. Conclusion

NWs are demonstrated to be a viable choice for utilization in NP and OE components by integrating 2D materials. This review presents noble metal NWs, silicon NWs, and perovskite NWs, highlighting their new applications in traditional settings, integrating photonic circuits, light improvement, route control, and OE. The paper presents significant enhancements by integrating 2D materials, including MD layers, graphene, and graphene oxide. The investigations indicated that optimizing the structural properties of these 2D materials, including their dimensions and the spacing between NWs, is essential. A comprehensive examination of maximizing these attributes is expected.

The study examined NWs for NP and OE devices using 2D materials. NWs can be applied as resonators and waveguides in PICs. The features of NWs and their hybridization with 2D materials have been explained. The properties and applications of various NWs and 2D materials are anticipated to provide novel insights for developing new hybrid substances, ultimately transforming existing devices with enhanced efficiency.

Despite promising laboratory-scale results, a key bottleneck remains the scalable synthesis of 1D–2D hybrid structures. Ahmed et al. (2024) demonstrated a low-temperature, transfer-free process to grow vertically aligned nanowires onto pre-patterned 2D substrates using plasma-assisted vapor deposition. This advancement could lead to scalable fabrication techniques for flexible, conformal photonic circuits integrated into next-generation wearable or edge devices [9].

Several disadvantages of these hybridizations remain to be addressed. For instance, the easy synthesis process should be investigated in the context of nanomaterial mixing. An intricate synthesis procedure results in low production, is time-intensive, and incurs comparatively high costs. Their long-term durability requires further investigation. Harsh conditions like elevated humidity and harsh temperatures result in suboptimal performance.

Additionally, the environmental impact of commonly used nanowire materials—particularly lead-based piezoelectric compounds like PZT—poses a significant challenge for sustainable integration. As a response, recent efforts have focused on developing lead-free piezoelectric materials such as barium titanate ($BaTiO_3$) and potassium sodium niobate (KNN). Zhang et al. (2023) demonstrated that these alternatives offer sufficient piezoelectric performance while being environmentally friendly and suitable for integration with flexible substrates. These developments represent a critical step toward sustainable nanophotonic device manufacturing and long-term deployment in consumer and biomedical electronics [11].

Enhancing their reliability, consistency, and efficacy in adverse conditions is essential for future advancements. Initiatives to improve the effectiveness of these materials are presently underway. The study devised a fabrication technique that enhances the crystallization of zirconia NWs for ultrasensitive PDs. Despite notable advancements in NW–2D hybrid device performance, several challenges remain that require focused investigation. One key limitation is the scalability of synthesis methods. Techniques like van der Waals epitaxy and atomic layer deposition offer precision but are often limited by cost and throughput. Future research should explore low-temperature, roll-to-roll, or transfer-free deposition methods to enable industrial-scale fabrication of NW–2D heterostructures. Additionally, long-term durability under ambient or harsh conditions must be addressed through encapsulation strategies and defect-tolerant material design. From a systems perspective, integrating these hybrid platforms into real-world optoelectronic infrastructures, such as quantum photonic processors or 6G wireless communication backbones, opens new application frontiers. Research questions such as "How can NW–2D junctions be stabilized for room-temperature single-photon emission?" or "What device architectures support high-speed optoelectronic switching at THz frequencies?" can guide future directions. Forthcoming applications are expected to optimize outcomes by improving material crystallization and examining appropriate device configurations to achieve scaled and integrated solutions.

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