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EDITORIAL

Focus on synthesis, characterization and applications of low dimensional nanomaterials

Arun Kumar[1], **Pramod Kumar**[2] and **Antonio Di Bartolomeo**[1,*]

[1] University of Salerno, Italy
[2] Indian Institute of Information Technology Allahabad, India
[*] Author to whom any correspondence should be addressed.

E-mail: akumar@unisa.it, pkumar@iiita.ac.in and adibartolomeo@unisa.it

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Abstract

This Editorial summarizes the content of a focus collection on the synthesis, characterization and applications of low dimensional materials. The collection groups original research and review articles providing recent results and prospects in the field, with particular attention on optoelectronic applications, dielectric and magnetic properties, and electrochemical and biological performances.

This Focus Issue brings together fourteen articles dedicated to exploring the latest developments, challenges, and future trends in the synthesis, characterization, and applications of nanostructured materials. Research into this interdisciplinary field is rapidly advancing our understanding of the fundamental properties of nanomaterials while highlighting their potential for practical applications.

The papers of the Focus Issue can be grouped into three main areas, namely optoelectronic applications, dielectric and magnetic properties, and electrochemical and biological performances of nanomaterials.

The investigation of optoelectronic properties focuses on the electrical transport and photoresponse of various one-dimensional (nanotube) and two-dimensional (2D) (ultrathin film) nanomaterials in devices with different configurations.

Capista *et al* [1] fabricated a photodetector using a heterojunction of single-wall carbon nanotubes (SWCNTs) and a silicon substrate. The silicon wafer, initially covered by a thick Si_3N_4 layer, was wet-etched to create three zones with varying silicon nitride thickness. The I-V characteristics show diode-like behavior with low rectification due to the large contact area of exposed silicon that yields a high reverse current. The device was modeled as two metal–insulator–semiconductor (MIS) capacitors with different insulator thicknesses and a metal-semiconductor (MS) diode. The photocurrent varied based on the illuminated region, with the MS region generating current without reverse bias, while the MIS capacitors required voltage thresholds to generate photocurrent via Fowler–Nordheim tunneling. By adjusting reverse bias, the device's active surface could be controlled, allowing for 'activated' and 'deactivated' states.

Kumar *et al* [2] investigated the temperature-dependent transport properties and memory behavior of mechanically exfoliated ultrathin black phosphorus (BP) field-effect transistors. The device exhibits a decrease in electrical conductance and field-effect mobility as temperature increases. Field-effect mobility, which is influenced by the gate voltage sweep range, is measured as 283 $cm^2 V^{-1}s^{-1}$ at 150 K and decreases to 33 $cm^2 V^{-1}s^{-1}$ at 340 K. The transfer characteristics display a hysteresis width that broadens with increasing temperature, a feature that can be explored to enable non-volatile memory with a larger programming window at higher temperatures.

Kumar *et al* [3] explored the photodetectors based on large area 2D $MoSe_2$ and $MoSe_2/Bi_2Se_3$ heterojunctions on a sapphire (0001) substrate. The 2D materials deposited via r.f. magnetron sputtering. The $MoSe_2$ photodetectors showed positive photoconductivity (PPC), while the $MoSe_2/Bi_2Se_3$ heterojunction photodetectors showed negative photoconductivity (NPC) under Near Infrared (1064 nm) exposure. The presence of NPC was attributed to the interfacial defects at the $MoSe_2/Bi_2Se_3$ junction or defects induced by selenium vacancies in Bi_2Se_3. The responsivity of the $MoSe_2$ photodetectors was ~1.39 A W^{-1}, while the $MoSe_2/Bi_2Se_3$ heterojunction photodetectors reached ~5.7 A W^{-1}. This nearly four-fold increase in photoresponse highlights the potential of heterojunction structures for advanced optoelectronic applications.

Sumbe *et al* [4] attempted to obtain $Ti_3C_2T_x$ (MXene) phase material via Hydrofluoric Acid (HF) etching of Ti_3AlC_2 (MAX phase), showing that longer etching leads to well-separated 2D nanosheets. X-ray photoelectron spectroscopy (XPS) confirmed Al removal and the incorporation of surface terminations (=O, −OH, −F). The material was tested for field emission. MXene emitters demonstrated enhanced field emission (FE) performance at pre-set values of 10 μA and 100 μA for more than 3 h duration. This was attributed to morphology, metallicity, and low work function that make MXenes a promising alternative to other 2D nanosheet emitters for devices like vacuum field emission transistors.

In a review article, Jiménez-Ramírez *et al* [5] provided a comprehensive overview of the synthesis, characterization, and magneto-structural properties of geometrically and compositionally modulated nanowires. They also discussed the emerging challenges and outlined future perspectives and expectations for these new metamaterial-based nanowires.

Further, in another review article, Križan *et al* [6] provided an in-depth analysis of the current research on Cu-based bimetallic nanowires aimed at developing metal nanowire networks with enhanced oxidation resistance. This evaluation identified the most promising bimetallic materials for producing efficient, durable, and cost-effective electrodes.

Magnetic and dielectric properties of nanomaterials are gathering increasing interest and the research in this domain mixes synthesis and characterization efforts.

Swamy *et al* [7] used pulsed laser deposition (PLD) to fabricate CoFeB thin films with thicknesses ranging from 6 to 36 nm, examining their magnetic domain structure, electrical conductivity, and magnetoresistance properties both in the as-deposited state and after annealing. Magnetic force microscopy images revealed large magnetic domains resulting from interactions among nanocrystalline grains in annealed CoFeB thin films. The as-deposited films exhibited non-metallic properties, while the annealed films showed metallic behavior due to increased granularity. The 6 nm annealed CoFeB thin film demonstrated higher magnetoresistance (MR) values compared to thicker films and exhibited nearly temperature-independent MR for both types. Additionally, increasing magnetic fields decreases the resistivity, attributed to the conduction of spin-polarized charge carriers. The study provides valuable results on the magneto-transport properties of crystalline CoFeB thin films, which could be beneficial for the advancement of spintronic devices.

Kumar *et al* [8] reported the enhancement of ZnO dielectric properties obtained by the manipulation of particle size using a surfactant-based approach. These surfactants significantly quench the emission spectra and enhance the blue emissions. The dielectric constant was found to be increased over the decreasing particle size, assessed over a frequency range of 20 Hz to 4000 kHz at room temperature. This could be due to a higher charge density per unit volume. Further, surfactant-assisted nanoparticles exhibited increased AC conductivity and showed a decrease in transit time as particle size was reduced.

Jatiya *et al* [9] utilized the charge compensation method for the synthesis of Sr_2SnO_4, $Sr_2Sn_{0.99}Nb_{0.01}O_4$, and $Sr_{1.995}Sn_{0.99}Nb_{0.01}O_4$. $Sr_2Sn_{0.99}Nb_{0.01}O_4$ exhibited higher conductivity than $Sr_{1.995}Sn_{0.99}Nb_{0.01}O_4$, attributed to excess electrons compensating the overall charge, while in $Sr_{1.995}Sn_{0.99}Nb_{0.01}O_4$, the extra charge is balanced by cationic vacancies. The time-temperature-superposition principle (TTSP) is applied to all compositions, indicating that similar mechanisms drive both conduction and relaxation processes. The dielectric permittivity and dissipation factor ranged from 150 to 175 and 0.2 to 0.5, respectively, suggesting potential applications in millimeter-wave communication with dielectric resonator antennas (DRAs). Furthermore, due to the presence of oxygen ions and the ability to conduct both ions and electrons, materials above 400 °C are suitable for electrode applications in intermediate temperature solid oxide fuel cells (IT-SOFCs). The results point towards investigating defect manipulation via electrical and ionic charge compensation methods that may enhance material properties for future semiconductor technology.

Nanomaterials are widely studied for electrochemical and biological applications, with ongoing research focused on continuously enhancing their electrochemical performance.

Nagpal *et al* [10] report the electrochemical behavior of $BiNi_{0.6}Mn_{0.4}O_3$ composite nanostructures, synthesized using a citric acid and ethylene glycol-assisted hydrothermal process with low-temperature calcination at 400 °C. The specific capacitance of the $BiNi_{0.6}Mn_{0.4}O_3$ electrodes reached approximately 243 F g^{-1} at a current density of 1 A g^{-1} in a 6 M KOH aqueous solution. Further, the nanostructured electrodes exhibited a cyclic stability of about 70% after 4000 charge–discharge cycles at a 6 A g^{-1} current density. The results demonstrate the potential of $BiNi_{0.6}Mn_{0.4}O_3$ composite nanostructures for energy storage devices.

Raj *et al* [11] presented an environmentally friendly method to produce $BSA/Zn_3(PO_4)_2/Cr_2O_3$ nanocomposites for electrochemical catalysis through the chemical reduction of Cr_2O_3 nanoparticles, which are supported by $BSA/Zn_3(PO_4)_2$. The resulting nanocomposite exhibits excellent electrocatalytic activity for the oxygen evolution reaction (OER), with a high electrochemical active surface area (ECSA) and a small overpotential of 216 mV to achieve a current density of 10 mA/cm^2 in 1 M KOH solution. The incorporation of Cr_2O_3 and BSA enhances the active areas, electron conductivity, and electronic structure, improving catalytic kinetics for OER. The BSA/$Zn_3(PO_4)_2$/Cr_2O_3 nanoflowers display small Tafel slopes, making them a promising material for OER catalysis.

Kumar *et al* [12] synthesized $MnO_2/Mn_3(PO_4)_2$ composites with MnO_2-decorated $Mn_3(PO_4)_2$ nanowires, exhibiting excellent and durable electrocatalytic performance in water electrolysis. The electrocatalyst shows enhanced performance in the oxygen evolution reaction (OER), with a low overpotential of just 244 mV and a current density of 10 mA cm^{-2} in an alkaline medium, demonstrating remarkable durability. This exceptional performance is attributed to the synergistic effects of the $MnO_2/Mn_3(PO_4)_2$ nanowires, which offer accessible active sites, enhanced charge transport, and structural stability. The findings highlight the potential of precious metal-free mixed metal phosphate-based composites as efficient electrocatalysts for water splitting, marking a significant advancement toward sustainable and environmentally friendly energy production.

In a technical note, Rustembekkyzy *et al* [13] proposed a facile spin-coating method for depositing TiO_2 nanoparticle-based inverse opal-like films. It was demonstrated that a subsequent dip-coating treatment significantly enhances the photoelectrochemical (PEC) activity of the films by forming a thin TiO_2 connecting layer. Specifically, the photocurrent density of dip-coated films increased by approximately 38.5% compared to untreated films. Comprehensive analysis indicated that the enhanced PEC activity resulted from improved film crystallinity, reduced reflectivity, decreased charge carrier recombination rates, and better connections between the TiO_2 nanoparticles and the FTO substrate. This methodology can be easily adapted for fabricating both undoped and doped inverse opal-like metal oxide films, making it a valuable approach for producing low-cost porous films for various applications such as next-generation photovoltaics, electrochromic devices, photocatalytic systems, and gas sensors.

Chavez-Esquivel *et al* [14] explored silver-doped graphite oxide (GrO) composites as antimicrobial agents against *Staphylococcus aureus*, *Escherichia coli*, and Tatumella terrea, evaluated using direct TLC bioautography. It was found that silver acetate doping within the GrO matrix can modulate silver particle dispersion, promote crystalline phases, affect particle size distribution, and enhance the release capacity and antimicrobial activity of silver particles. High-silver-doped GrO composites improve electrostatic interactions with bacterial cell surfaces. At the interface, these composites disrupt cellular functions, break cell membranes, and compromise cellular integrity. Consequently, the GrO-1.5Ag composite (1.5 wt% silver acetate) emerges as a promising alternative for inhibiting the growth of both Gram-positive and Gram-negative bacteria.

In summary, this Focus Issue collects a series of original research articles, two review papers, and one technical note providing new insights into the fundamental understanding and potential applications of nanostructured materials. We are confident that the Focus Issue will provide the scientific community with the latest prospects in the fields of nanomaterials synthesis, characterizations, and applications.

Data availability statement

No new data were created or analysed in this study.

Conflicts of interest

The authors declare no conflict of interest.

ORCID iDs

Arun Kumar https://orcid.org/0000-0002-6333-2198
Pramod Kumar https://orcid.org/0000-0003-1617-3232
Antonio Di Bartolomeo https://orcid.org/0000-0002-3629-726X

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