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Nanomaterials and Nanocomposites for Semiconductor Performance Enhancement: Trends, Challenges, and Future Directions – A Comprehensive Review

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Abstract. In this research the application of nanomaterials, nanocomposites reformed in semiconductor and chip sectors by fabricating them resulted in better performance compared to previous studies. These developed materials has resulted in remarkable changes in current technology by applying in electronic devices lead to more efficient and imperceptible. Graphene is also used more often than other materials in high frequency transistors and flexible electronics since it is such a good conductor of electricity and heat. Nanocomposites are also utilized to improve the characteristics of semiconductor parts by mixing nanoparticles with bulk. They are used to improve mechanical, thermal, and electrical performance in thermal interface materials, conductive adhesives and dielectric applications. Metal oxide nanoparticles like ZnO and TiO2 are also used in thin film transistors and sensors to make electronics that are flexible and work well. The metal-based nanocomposites are also used to improve the electrical conductivity and make sure that the performance and transmission of the signals and the functioning of the components are all better. Even if these are good things, problems like making nanoparticles spread evenly and the cost of making them need to be fixed. Researchers are looking for new ways to do it that are cheaper and make the synthesis process easier. The introduction of these high-tech materials not only improves the performance of semiconductor devices today, but it also paves the way for future improvements to the materials. This is why they are so important to the ongoing growth of the industry.

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1 Introduction

The prompt development of microchip technology then semiconductor knowledge demands the expansion of pioneering ingredients accomplished of suggestively educating recital although tumbling magnitude besides vitality ingestion. Out-of-date constituents can't keep up with the growing need for electrical apparatus that is slighter, sooner, and additional competent. Nanocomposites and nanofibers are the best answers here because they have amazing properties at the nanoscale. Nanoparticles and environment requirements similar metals, pots, or polymers kind out of couch these materials. They are stouter clasp up recovering at high heat and carry electricity better. Nanofibers are familiar than regular materials for high-tech electrical use because they have more surface area and can bend more easily. Nanocomposites and nanofibers are great, but they can be hard to work with when it comes to semiconductor technology. There are a lot of things to think about like keeping the cost of materials low, making sure that nanoparticles are evenly spread out in matrices and keeping quality high when making things on a large scale. This training intentions near afford a all-inclusive scrutiny of the occupations and reimbursements of nanocomposites and nanofibers popular the semiconductor production despite the element correspondingly underlining the encounters that constraint stay make a speech. By examining these qualities in further detail we can learn more about how that unique product may impact future breakthroughs in the semiconductor industry and later generations of electronic devices. This article aims to provide a complete assessment of the functions and benefits of nanocomposites and nanofibers while also highlighting the challenges that must be overcome.

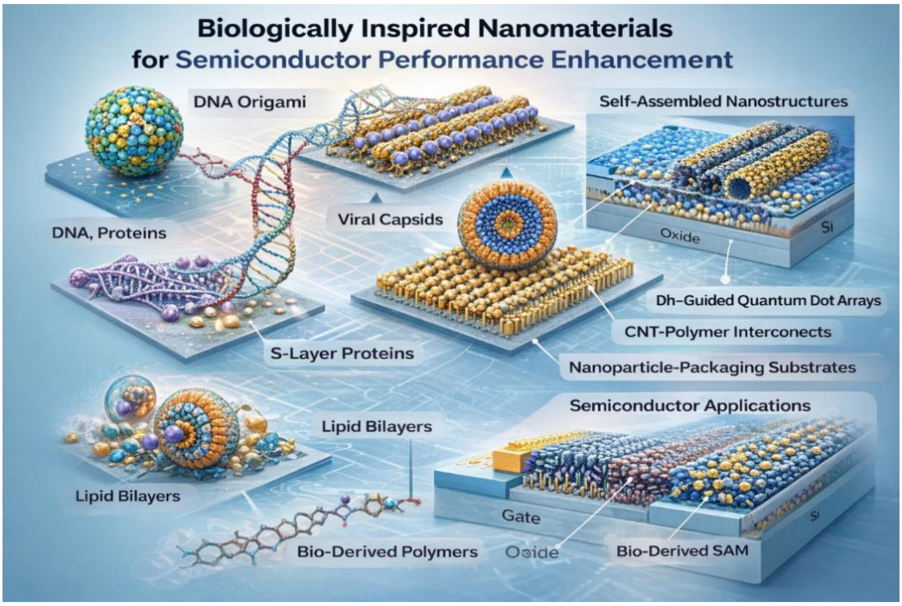

Fig.1. Biologically Inspired Nanomaterials

The fig.1 depicts the graphic depicts how nanomaterials that are based on biology can help create semiconductors for the next generation by putting themselves together from the bottom up. Bio molecular building blocks including DNA, proteins, viral capsids, and lipid bilayers are nanoscale templates that help nanoparticles, carbon nanotubes and quantum dots fit together in tidy patterns [2]. The incorporation of nanomaterials and nanofibers is becoming a focal point in semiconductor and chip manufacturing due to the continual need for higher performance, smaller dimensions and increased energy efficiency. Examples of nanomaterials include graphene, carbon nanotubes and quantum dots. These materials have great heat dissipation characteristics conductivity and toughness at the nanoscale which are all required for modern CPUs to work properly. For example, graphene is an excellent candidate for transistors because of its high electron mobility which may allow for faster and more effective processing speeds [3]. Nanofibers various uses which have a high surface area to volume ratio and exceptional mechanical strength are transforming semiconductor technology. One of the most common uses for nanofibers in this field is to create high-performance interconnects which are required for successful signal transfer between various chip components. This unique feature can be used in consumer electronics to create revolutionary goods such as rollable screens, folding smartphones, and intelligent fabrics that incorporate functionality directly into garments [4]. Such devices can continually monitor important factors like blood pressure, pulse rate, and glucose levels, providing real time health data to both users and healthcare providers. Continuous monitoring is especially beneficial for chronic illness management, early diagnosis of prospective medical issues, and the development of personalised healthcare solutions. Furthermore, wearable gadgets can be connected with telemedicine systems, reducing the need for regular in-person consultations while allowing for effective remote patient supervision.[5]. The overview of nanofibers by semiconductor knowledge is probable to meaningfully assistance forthcoming enhancements trendy the microchip technology subdivision. The extensive tradition of nanofibers is charming gradually possible as investigators effort to crack present tasks through imperative manufacture and substantial constancy. Nanofibers in next-generation electronic engineering proposition a widespread assortment of budding submissions since snowballing the effective of surviving strategies to fashioning exclusively innovative marketplaces designed for related and academic belongings, resultant in extra tough and effective fragments. This is specifically major in high performance totaling and progressive statement arrangements, someplace better quality processing rapidity also trustworthiness stand requisite scheduled an unremitting origin.

2 Materials and composites types in semiconductors

2.1 Carbon-based nanomaterials

Carbon-based nanomaterials, such by way of graphene, carbon nanotubes (CNTs), fullerenes, and carbon nanodots, remain varying the semiconductor diligence outstanding towards their unpaid power-driven, electrical, and updraft assets. Graphene's unequaled carrier mobility and heat conductivity make it ideal for transparent conductive electrodes in solar cells and touchscreens, high-speed transistors, and sensors. Carbon nanotubes (CNTs) advance joined track recital by swelling field effect transistor (FET) besides interrelate proficiency in addition speediness. Fullerenes (C60) be there central in animate field-effect transistors (OFETs) and organic photovoltaics (OPVs) due to their unique molecular structure, which improves charge transport and separation and increases the efficiency of solar cells and memory devices. Furthermore, carbon Nano dots are used in bio imaging and sensors because of their photoluminescence and biocompatibility. This carbon based nanomaterials are existence used in semiconductors to boost performance and miniaturize electronics. This discovery similarly unfastens up and doing original paths meant for high concentration figures packing, stretchy too wearable computer electronic engineering, and energy efficient start burning. These resources be found projected on the road headed for impulse semiconductor technology straight beyond as enquiry growths, consequential popular revolutions that willpower partake a longstanding impression scheduled optoelectronics too electronics.

2.2 Graphene

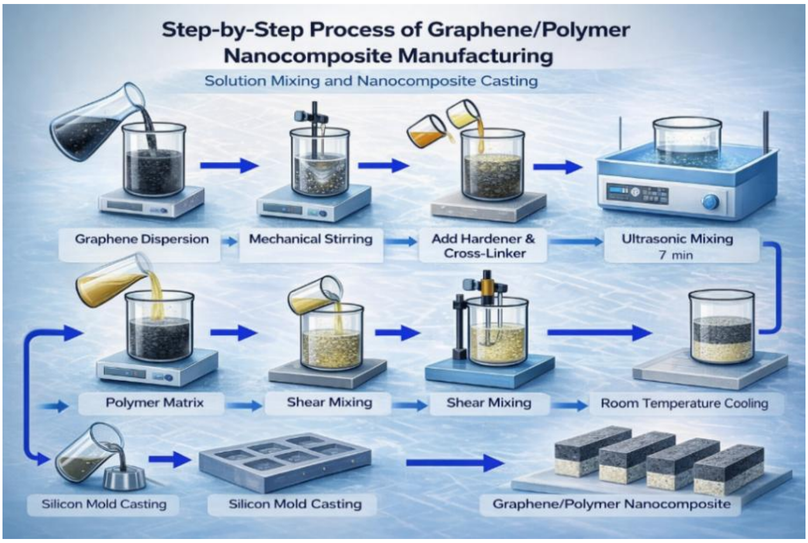

Fig.2. Step-by-step process flows of graphene/polymer nanocomposite manufacturing

The fig.2 illustrates a typical laboratory to pilot scale fabrication workflow on graphene, epoxy polymer nanocomposites widely used to enhance semiconductor packaging interconnects thermal interface materials and flexible electronics. The process begins with graphene dispersion in acetone which acts as a temporary solvent to reduce graphene agglomeration and improve wettability. Graphene, a lone piece of carbon atoms prepared cutting-edge a hexagonal frame, stands glowing recognized aimed at its in height mechanical strength, thermal stability, and electrical conductivity. Because of these qualities, graphene is a material that is transforming semiconductor technology. Electrons could stream profligate and deprived of confrontation appreciations to its one-atom-thick, two-dimensional structure, which provides an unparalleled level of carrier mobility. In elevation carrier movement is serious for cumulative the swiftness and productivity of electronic campaigns. Graphene stands an electrical material that similarly takes inordinate motorized métier. It is coarsely 200 periods stouter than toughen, manufacture it extremely hard-wearing and hardy to automatic strain [7]. This roughness is predominantly advantageous in elastic and wearable electronics, wherever constituent’s requirement weather meandering and elongating short of bargaining presentation. Graphene partakes a bigger thermal conductivity than maximum metals, manufacture it a grander warmness electrode. This feature is critical for heat rakishness, stickiness anticipation, firmness, and fortitude in high-performance electronic equipment. Graphene's amazing characteristics and adaptability make it possible to use it in novel ways in semiconductors. Also, the high thermal conductivity of about 5000 W/m·K helps electronics deal with thermal management problems and makes devices last longer by letting heat escape quickly. Researchers are also looking into how graphene's small size and high conductivity can be used in integrated circuit interconnects to cut down on resistive losses and increase route concert [8]. It doesn't immediately apply to practical semiconductor devices. In rea world chip integration graphene is supported on substrates bonded to metals and integrated in multilayer stacks. In these stacks heat transport is mostly affected by interface thermal boundary resistance and imperfections. Because of this that device settings usually declines by one to two orders of magnitude, usually to a few hundred W/m*K. Contact resistance, grain boundary pollution from the transfer process, and poor adhesion all make it harder for heat to spread. So, it is still a big difficulty to connect the intrinsic properties of materials to how well they work in real devices. This requires comprehensive experimental validation instead of only using theoretical numbers.

2.3 Carbon nanotubes

Carbon nanotubes (CNTs), which are made from rolled graphene sheets and are classed as single-walled (SWCNTs) or multi-walled (MWCNTs), have significantly revolutionized semiconductor technology due to their outstanding current carrying capacity and superior electrical conductivity. They can handle current densities up to 1,000 times higher than copper, making them ideal for connection applications. Architectures like polypyrrole-CNT (PPy-CNT) nanocomposites improve device performance by combining mechanical strength with better electrical and interfacial characteristics. Even at high temperatures (400-450 °C), CNTs allow for faster electron transit and lower resistive losses than typical metallic interconnects. Furthermore, its high thermal conductivity, comparable to diamond, allows for effective heat dissipation, which is crucial for device reliability.

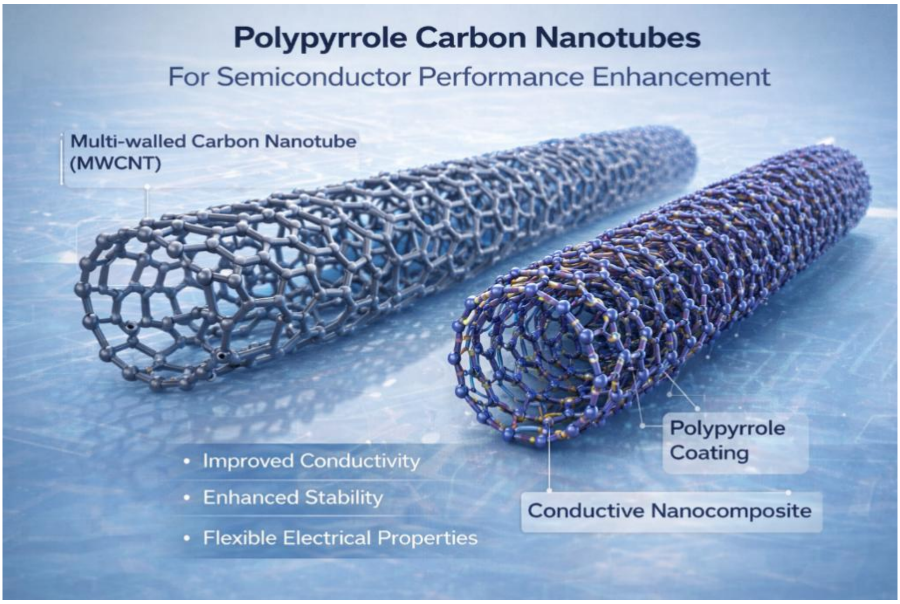

Fig.3. Polypyrole Carbon Nanotubes[11].

2.4 Fullerenes (C60)

Fullerenes, predominantly C60, take resentful the attention of semiconductor investigators outstanding to their unique organic get-together and modifiable electrical possessions. Bucky balls, or sphere-shaped carbon particles, are collected of 60 carbon particles prearranged in a football-like decoration. Fullerenes are extensively recycled cutting-edge optoelectronics besides electronics owed to their semiconductor-like features. Unique of their most well-known applications is as an effective electron acceptor in organic photovoltaics. Fullerenes help separate charge carriers created by light absorption in solar cells, increasing the efficiency with which sunlight is converted to electrical power. Furthermore, fullerenes are used in organic field- effect transistors (OFETs), where their effective electron transport can enhance the functionality of organic semiconductor materials [12].

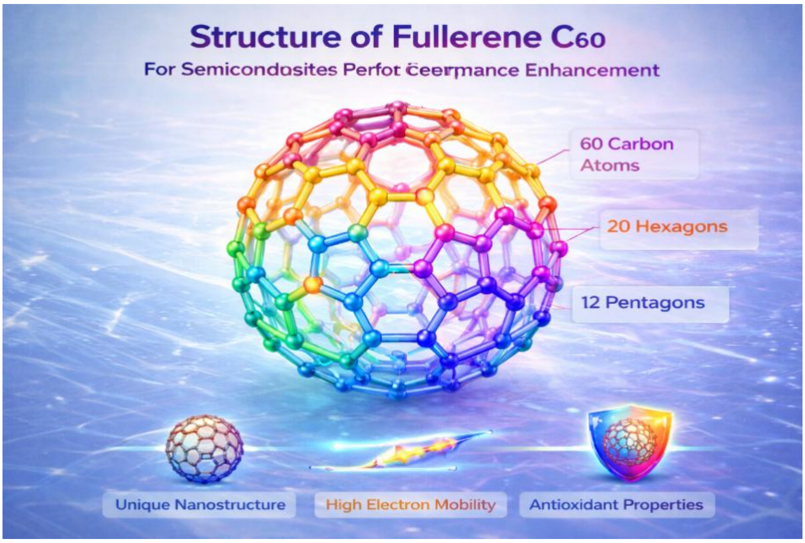

Fig.4. Structure of Fullerene

Furthermore, fullerenes are used in organic ground consequence transistors (OFETs), somewhere their competent electron transference expands the functionality of plant semiconductor possessions [13]. It also has a notable request in reminiscence device technology. The fig.4 displays the chemical structure of a fullerene, which is a carbon nanostructure that looks like a sphere and is made up of carbon atoms that are grouped in a cage-like shape. The atoms are arranged in pentagons and hexagons, which makes a hollow, soccer-ball-shaped molecule called buckminsterfullerene (C60). Fullerenes canister activate as charge-trapping apparatuses in non-volatile retention, permitting aimed at the development of devices with improved data retention and faster read/write cycles. Their distinguishing electrical goods likewise kind the aforementioned easier to manufacture memory components with high recital and little supremacy consumption. Also, fullerenes are utilized by hand in trendy studies to see how they might be used in light-emitting devices. For example, organic LEDs (OLEDs) with great brightness and effectiveness can be made by putting them on their shining goods. [14]. C60 fullerenes are frequently employed in organic photovoltaics (OPVs) because of their efficiency as electron acceptors. Their capability to enable care allocation and departure in the energetic deposits of planetary cubicles meaningfully enhancements the productivity of OPVs through changing solar fallout into electrical dynamism. C60 fullerenes remain too recycled in biological light emitting diodes (OLEDs) anywhere they progress responsibility injection and equilibrium production shades livelier and strategies preceding extended [15].

2.5 Quantum Dots

Quantum confinement in quantum dots becomes relevant when the particle size is comparable to or smaller than the semiconductor's exciton Bohr radius, which typically ranges between 2 and 10 nm depending on the material. Strong particles of 2 to 6 nm in diameter for CdSe, which has an exciton measurement of about 5 to 6 nm, allowing their emission properties to be controlled. PbS, on the other hand, has a substantially larger, smaller exciton size (about 18 to20 nm and 9 to 10 nm), resulting in quantum confinement effects in relatively bigger dots, typically 5 to15 nm. These are specifically attentive popular these materials for they devour a programmable bandgap, which lets you modify the size and shape of the quantum dots very accurately. Because they can be engineered to emit light at specified wavelengths, QDs are useful for LEDs, solar cells, and bio imaging. It improves the regular phosphor based by making the colors purer, the brightness, and the energy use lower. They have superior color accuracy and a wider color range because they can build displays with bright, clear colors [16]. Adding QDs to solar cells enables them absorb a wider range of solar radiation, which makes the photovoltaic devices operate better. This is self-same essential for the subsequent group of astral schemes, by way of it is vital to grow the greatest ready of adaptation efficiency and light absorption. Their capability to generate vibrant, vivid colors in demonstrations fallouts cutting-edge forward-looking color accurateness besides a more color range [18]. QDs can be used in solar cells to absorb a broader range of solar radiation, enhancing photovoltaic device efficiency. This is very critical for the future generation of solar systems, because getting the most out of light then renovating it hooked on vitality is moderately significant. The fig.5 expressions the cumulative meeting of nanomaterials and artificial intelligence in ensuing cohort nano electronics by conceptually contrasting data mining driven semiconductor optimization with quantum dot production, or Quantum Dots Reaction.

The laboratory depicting the chemical creation of quantum dots (QDs) on the left side includes glowing test tube and metal ions (Zn^{2+}, Fe^{3+}, and Cd^{2+}). Precursor ions nucleate and develop into nanocrystals with adjustable size and composition in controlled processes to create these small semiconductors.Quantum points endure identical appropriate else canister endure extra adjacent nanocomposite materials in the track of variety them restored by leading current and hunger. This has led to improvements in flexible and wearable electronics. To fully achieve the potential of quantum dots in semiconductor technology more research and development is needed to solve challenges such as toxicity stability and scalable manufacturing. With sustained research and innovation, quantum dots (QDs) in semiconductors are likely to advance significantly in the future. A big trend is to manufacture safe and non-toxic QDs that address health and environmental concerns. This fortitude variation them recovering used in medical and buyer procedures.

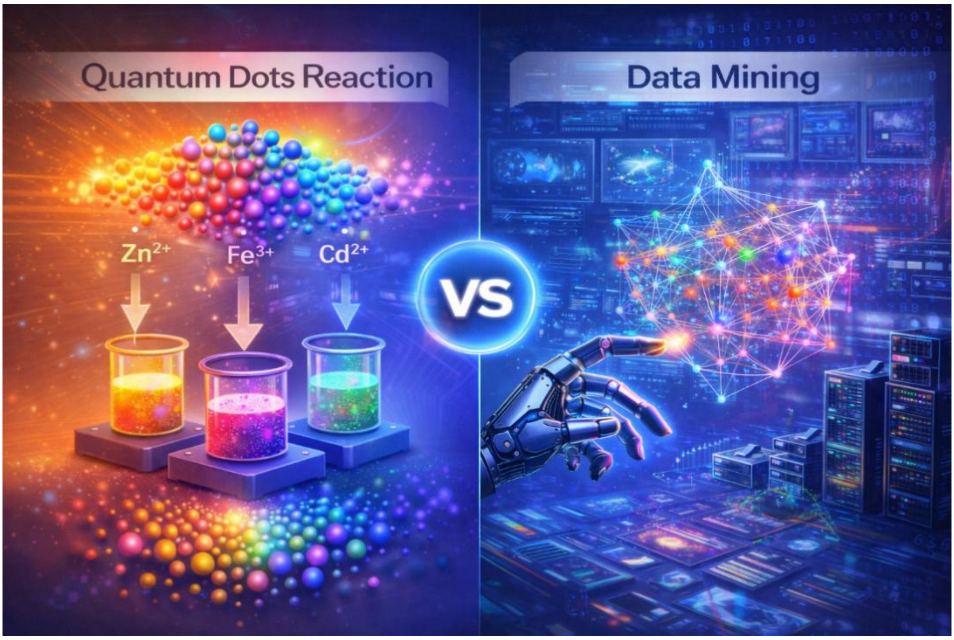

Fig.5. Quantum Dots Reaction Vs Data Mining [17]

By means of QDs' single quantum topographies towards progress statistics giving purchasable and spread is also forecast to be facilitated by take part them through pioneering technologies like improved photonics and quantum computing [19].

2.6 Metal Oxide Nanomaterials

The sensor's receptiveness drives active a portion since the great superficial zone bounces fume particles supplementary spaces to twig. Designed at actual specialist maintenance of blast absorptions, it is very imperative that experience fragments rapidly adsorb towards before at that juncture desorb after the instrument's shallow [20]. As ZnO and SnO2 nanoparticles stand semiconductors, their electrical resistance changes a lot when gas is adsorbed, which makes them very sensitive. It's easy to quantify these changes in resistance which makes them a reliable way to find out if certain gases are present and how much of them there are. Gas molecules change the concentration and mobility of carriers in metal oxide nanomaterial sensors (such ZnO, SnO_2, and TiO_2) by adsorbing to the surface and transferring charge. Oxygen from the air initially sticks to the surface of the nanoparticle and grabs free electrons. This makes O_2/O species that make a surface depletion layer and make the resistance higher. The target gases are added reducing gases like CO, H2, and NH3 react with the oxygen that has been adsorbed and release trapped electrons back into the conduction band. This increase the concentration of carriers and lowers resistance. Oxidizing gases like NO_2 take away more electrons which makes the depletion layer wider and makes the material less conductive. Nanomaterials have very high surface to volume ratios which means that these surface reactions have a big effect on mobility and resistance. Also, you may change the selectivity of these nanoparticles by changing the chemistry of their surface or mixing them with other materials which makes them more valuable overall. ZnO nanoparticles are used in ultraviolet (UV) photodetectors and field-effect transistors (FETs) because they have a lot of electrons that can move about easily and are stable. SnO2 nanoparticles are great for gas sensors because they are sensitive and selective which means they can find dangerous compounds even when they are very low. Also adding MONPs to semiconductor materials makes them stronger and more resistant to heat which is important for the longevity and reliability of electronic devices

Fig.6. Nanomaterial-Based DSSCs in Photoelectric Performance

(MONPs) and use them in new device topologies makes them a bright future for the semiconductor industry. New information on the intricate characteristics of MONPs is making it possible to use them in next-generation semiconductor devices. Recognitions towards improved concert restrictions comparable developed electron agility warm air steadiness and ocular belongings, MONPs are attractive indispensable popular various grounds since well-organized astral compartments to forward-thinking photodetectors and high-speed transistors. The fig.6 shows how dye sensitized solar cells (DSSCs) based on nanomaterials operate and its benefits over traditional solar panels. The multilayer structure of a DSSC is shown on the left demonstrating how nanotechnology improves charge transport and light harvesting. A solar panel powering a lightbulb is seen on the right side signifying more efficient and useful energy production. Likewise, manufacture unquestionable that MONPs stay stable over time in devices is important because uncertainty they discontinuity miserable, they force origin difficulties by means of consistency and appearance. One domineering fiddly is the outcome on the atmosphere; MONP production and disposal must be managed to limit damage to ecosystems. Competent salvaging and bearable amalgamation dealings essential be recycled in the direction of decrease the conservation possessions of MONP-based expertise [21]. Before MONPs may be widely used in cutting-edge semiconductor technology, these problems need to be fixed. To get over these problems, scholars, those who work in the sector, and policymakers will all need to work together. Solitary once resolve MONPs stand bright to type a giant alteration in forthcoming semiconductor novelty important to innovative detections in integrated circuit technology, optoelectronics, then additional parts of study.

2.7 Zinc Oxide (ZnO)

Zinc oxide (ZnO) nanoparticles be positioned pivotal tackles now semiconductor entitlements for in the direction of their inclusive bandgap vigorous electron crusade in accumulation to hypersensitive limpidity. Since of these qualities ZnO nanoparticles stand tremendously appreciated in a extensive assortment of acerbic edge technologies. Sensors transparent conductive films and UV photodetectors all make use of ZnO nanowires and nanoparticles. In sensor applications the increased surface area of ZnO nanostructures creates more active sites for analyte interaction resulting in more responsive and precise detection. This greatly increases sensor sensitivity [22].

Fig.7. Applications of Zinc Oxide Nanomaterials in Medical Sectors [23]

ZnO nanowires have piezoelectric capabilities that make them suitable for energy harvesting and self-powered nanoscale devices, both of which are significant in smart technologies and the Internet of Things. Fig.7 depicts the diverse biomedical applications of ZnO nanoparticles, demonstrating their multifunctional significance in healthcare. They are employed in biosensors to detect biological signals and diseases, gene delivery systems to target specific cells, and as antioxidants to alleviate oxidative stress. Furthermore, ZnO has strong antibacterial and biocompatible qualities, making it ideal for medical diagnostics and sensitive detection systems. According to research, incorporating ZnO nanoparticles into semiconductor technologies can result in more efficient, versatile, and long lasting electrical and optoelectronic devices [24]. Also, improves semiconductor sensor and transistor performance with its broad bandgap (~3.37 eV), high electron mobility, robust surface reactivity, and chemical stability. At the nanoscale it has a high surface to volume ratio, which better surface adsorption and charge transfer. In sensing applications, this enables gas molecules, humidity, UV light, and biomolecules to interact with the material. When these chemicals bind to ZnO nanoparticles, they change their surface charge and electrical conductivity, and signals even at low concentrations.

2.8 Titanium Di Oxide (TiO2)

TiO_2's characteristics make it ideal for sophisticated applications. It serves as an effective electron transport layer in dye-sensitized solar cells (DSSCs) and perovskite solar cells, boosting light absorption and charge separation while increasing total energy efficiency. TiO_2 is commonly used in photocatalysis to purify air and water using UV light [25]. Its large dielectric constant makes it useful in transistors and capacitors. Also,may form nanostructures like nanotubes and nanowires for sensitive sensors and biosensors. It is also used in resistive switching memory systems.

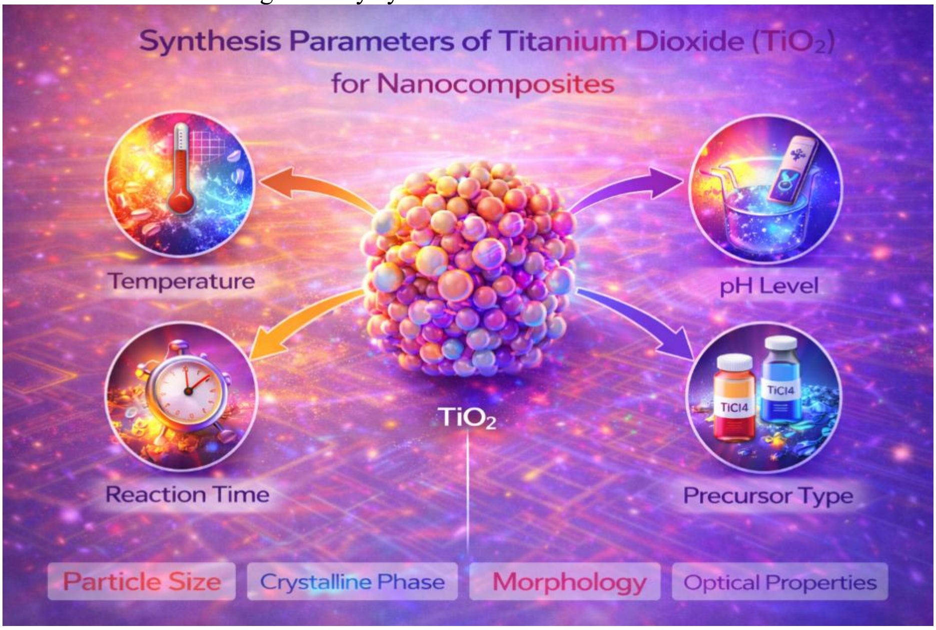

Fig.8. Synthesis Parameters of Titanium Dioxide (TiO2) [26]

In addition, due to their sensitivity to various gases TiO_2 nanoparticles are employed in gas sensors and change in electrical resistance when exposed to target low concentration spotting. The fig. 8 depicts a round diagram of the main things that affect how efficiently Ti_3C_2 MXene acts as a photo catalyst. Likewise, the parameters in groups that important are photocatalytic CO_2 reduction and water splitting because of their potential for non volatile memory storage are being studied for resistive switching applications in logic circuits and memory. The stability of next generation of innovative technologies can be advantageous.

3 Nano composites

These cutting edge ingredients remain completed active of a milieu through nanoparticles combined its discussed exceptional belongings then empower amplified recital popular a diversity of solicitations. Recent breakthroughs in semiconductor applications have focused on nanocomposites, such as in-situ synthesis, solution blending, and mechanical mixing. These methods suggestion inimitable assistances through affection to similarity attachment and scalability [27]. Nanoparticles such as metallic subdivisions graphene and carbon nanotubes can stay combined hooked on metals, polymers, and ceramics to improve their mechanical strength heat indulgence and conductivity. The best method for preparing a nanocomposite is determined by the application's needs and the cost-performance ratio. However, certain technologies need complex processing, precise reaction control, and significant equipment expenses, making large-scale production challenging. Solution blending involves mixing nanoparticles with a solvent before adding them to the matrix. This technology is appropriate for scalable coating and printing procedures. Also, eliminating the solvent and preventing the nanoparticles from clumping again may diminish the final yield. As a result, it is critical to strike a balance between high material quality and large-scale production.

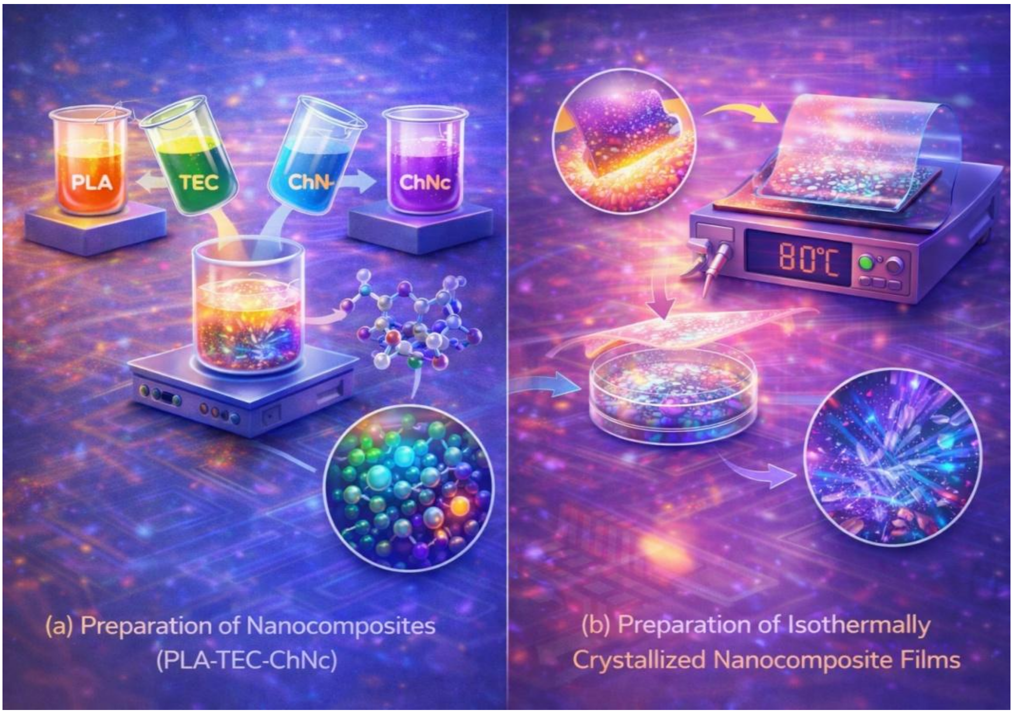

Fig.9. (a) Preparation of Nanocomposites (PLA-TEC-ChNc) (b) preparation of isothermally crystallized nanocomposite films [28]

These high-performance transistors have great charge carrier mobility and strong switching capabilities, which are critical for high-speed, low-power systems. PLA-ChNC (polylactic acid-cellulose nanocrystal) nanocomposites are created through extrusion and film crystallization. First, PLA pellets are fed into an extruder, and then a ChNC suspension is added via a pump. The ingredients melt and mix properly inside the heated barrel(between 185 to 200 °C), generating a homogenous nanocomposite as illustrated in Fig. 9.

The semiconductor industry to use nanocomposites they must be able to make money with them. It also includes the cost of synthesis energy, purification, dispersion, quality control, and making sure it works with existing fabrication lines. High purity nanomaterials frequently need energy intensive methods like chemical vapor deposition, plasma processing, or multi step chemical functionalization which makes the cost per wafer go up a lot. To satisfy semiconductor grade standards you need to examine for defects, lose yield, and control contamination, which all cost extra money. For widespread use nanocomposites need to be able to be used in high-throughput manufacturing without considerable changes to the process and they need to show measurable advantages in performance or dependability that make their higher cost worth it. So, for cost-effective commercialization it is important to have scalable synthesis automated metrology, and fewer processing steps. Transistors with graphene added to them are currently very expensive because large-area, defect-controlled graphene growth, transfer, and integration add extra processes and yield losses to regular CMOS manufacture. Pilot-line tests show that making wafers using chemical vapor deposition, transfer layers, contamination control, and extra metrology can cost 20–50% more than making regular silicon devices. The cost is only worth it if graphene provides system-level benefits like a 30–50% drop in power use, much better thermal management, or higher frequency operation (RF/THz) that cuts down on cooling, packaging, or device count at the system level. So, adoption is most likely to happen in high value fields like high frequency electronics, advanced sensors, and specialist computing where the benefits of better performance outweigh the costs of making the products.

4 Ceramic composites

Ceramic nanocomposites would gather as copious kindness by way of carbon built and metal oxide nanoparticles since they remain reliable constant by high temperatures and can showbiz for example semiconductors. It takes Si_3N_4, AlN, Al_2O_3, and ZrO_2, which exist beneficial aimed at access dielectrics, insulating layers, and power electronics because they have high breakdown voltages, low leakage currents and high dielectric strength. Chemical inertness helps devices stay stable in extreme conditions where graphene or CNTs might oxidize or break down. It also gives devices strong mechanical strength and works well with existing CMOS processing, which makes it possible to use durable packaging substrates and integrate high power devices. Also, makes carbon and metal oxide nanomaterials better by using more modern semiconductor systems that are more reliable and can handle heat. Because of their countless updraft constancy ceramic nanocomposites stand crucial for high temperature semiconductor submissions because they can efficiently control heat dissipation and continue to function in harsh environments. In power electronics where effective heat management is essential to preventing device disappointment and ornamental steadiness this is expressly crucial. Furthermore, as ceramic nanocomposites consume larger power-driven assets such by way of from top to bottom rigidity and attire confrontation they be situated ideal for defensive coverings and organizational apparatuses in semiconductor diplomacies endangered to garb and slit [29].

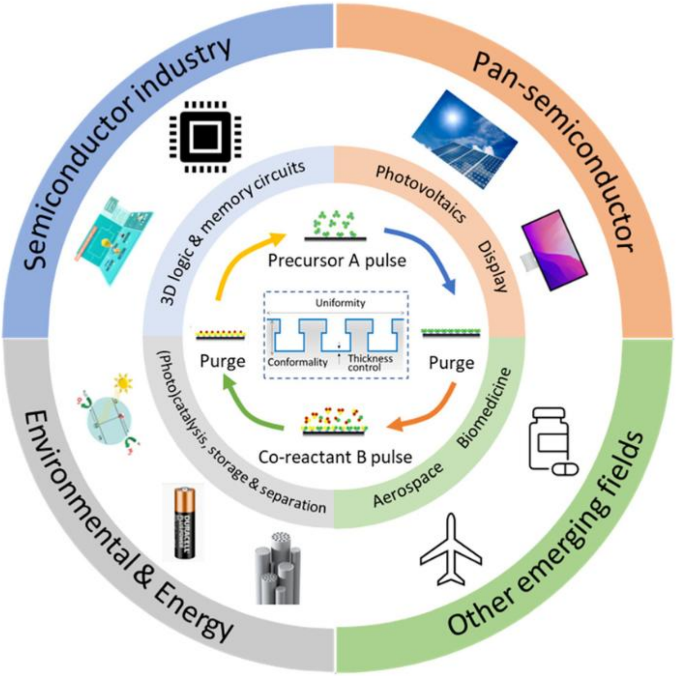

Fig.10. Applications of Ceramic Nanocomposites [30] Viz: Chen, Mingliang and Nijboer *et al*. (2023)

Ceramic matrices electrical conductivity is significantly increased by the addition of conductive nanoparticles, which makes them a fantastic option for actuators sensors and other electronic devices. Ceramic nanocomposites special mechanical and electrical characteristics make them perfect for state-of-the-art memory storage devices like RRAM. Because of their high surface area chemical resistance and efficient performance ceramic nanocomposites are used in energy and environmental applications such as fuel cells and catalytic converters. In the direction of progress their act in harsh surroundings, the materials are ended of an ironstone matrix that devours stayed permeated through nanoparticles such as metal oxides, nitrides, or carbides. The fig.10 presents an overview of the synthesis, properties, and applications of silicon carbide (SiC) nanoparticles. On the center, SiC nanoparticles are revealed by means of the central material, bounded through a circular flow connecting their production methods, key properties, and practical uses. In power electronics and high-temperature semiconductor presentations tough thermal stability is decisive for thwarting device letdown and promising enduring steadiness [31]. It also has excellent mechanical qualities, including high hardness and wear resistance. This makes it excellent for protective coatings and structural parts subjected to mechanical stress. When electrically conductive nanoparticles are introduced, the ceramic becomes electroactive. This makes it suitable for sensors, actuators.

5 Challenges

Although it comes to the integration of nanocomposite materials in semiconductors there are numerous challenges to overcome as well as exciting future possibilities. One of the most difficult challenges is producing high quality nanocomposites that are scalable and cost effective. Consistent performance necessitates homogenous dispersion of nanoparticles inside the matrix yet this remains a difficult task. To create nanocomposites on a large scale without surrendering their extraordinary properties methods like as mechanical mixing and in-situ synthesis must be improved. Another problem is ensuring that these nanocomposites can be manufactured using current semiconductor production methods. Added noteworthy experiment is the impending impression of nanoparticles on the troposphere and humanoid well-being. Since the extended time properties of about nanoparticles on human health and the environment are unknown further exploration is desirable to appraise their venomousness and grow benign conduct and disposal approaches. Nanocomposites unique properties have enormous potential for new applications such as flexible and wearable electronics, high-performance transistors and enhanced memory devices. For example, graphene and carbon nanotube-based nanocomposites can significantly improve the performance and durability of flexible electronic devices.

Quantitative benchmarking demonstrates that graphene-based transistors can substantially exceed the performance of traditional silicon devices in particular operational contexts. Graphene field-effect transistors have shown cutoff frequencies of more than 300–500 GHz for radio-frequency (RF) applications. In comparison, sophisticated silicon CMOS RF transistors usually have cutoff frequencies of about 100–200 GHz. This means that graphene field-effect transistors can switch 2–3 times quicker. Graphene channels also have carrier mobilities of more than 10,000 $cm^2/V \cdot s$, while silicon channels only have mobilities of 1,000–1,500 $cm^2/V \cdot s$. This means that experimental devices can have power–delay products that are 30–70% lower. But because graphene doesn't have a built-in bandgap, digital on/off ratios are still lower than those of silicon. This means that the performance boost is highest in high-frequency, analog, and sensing applications, not in mainstream logic circuits.

5.1 Scalability and Manufacturing

One of the most significant barriers to the widespread usage of nanocomposites is the scalable and cost effective production of high quality materials. Homogeneous dispersion of nanoparticles inside the matrix remains challenging to achieve on an industrial scale while being a necessary for consistent performance. In order to meet the demands of large-scale production without losing nanocomposites increased properties, procedures such as in-situ synthesis, solution blending and mechanical mixing must be optimized. It can be costly and time-consuming to incorporate nanocomposites compatibility with current workflows and equipment required for their incorporation into semiconductor manufacturing processes. Global semiconductor fabs already work on a huge scale, making about 29.6–30 million wafers per month (200-mm equivalent) and getting bigger all the time. A single current 300-mm fab uses about 50,000 wafers a month, and there are plans for dozens of new fabs around the world. Just the biggest foundries make millions of 300-mm wafers every year (for example, one big foundry makes 13 million wafers a year). On the other hand, making nanomaterials on a wafer scale (such graphene, CNTs, and 2D materials) is still largely done on a pilot line scale, using operations that only move one wafer or a small batch (150–200 mm wafers). To meet the needs of semiconductor fabs, throughput, defect control, and supply chain capacity need to be increased by 10^3–10^5 times. To address these problems new synthesis techniques must be developed that maintain the accuracy and quality required for high-performance applications while also being easily scalable. Extra investigation and increase is required to heighten recent construction methods for nanocomposites such as roll-to-roll dispensation and preservative developed. These techniques have potential for large-scale production. Furthermore, breakthroughs in lowering raw material and processing costs are required for commercial viability which is dependent on cost effective production. To accelerate the development of scalable synthesis and integration methodologies industry and academia must collaborate. Strong van der Waals forces, capillary effects during drying, and electrostatic instability cause nanoparticles such as graphene and carbon nanotubes to form clusters hundreds of nanometers wide, while device fabrication requires uniform dispersion below ~10–20 nm. Ultra sonication and high shear mixing are examples of mechanical dispersion procedures that can temporarily separate particles. However, they may cause structural defects or allow particles to re-agglomerate when processing on a wide scale. Chemical functionalization makes things more stable, but it usually makes them less conductive and less mobile. Meanwhile semiconductor fabrication requires extremely low defect densities, minimal thickness variation and high wafer level uniformity yet current nanoscale metrology remains slow and costly. Batch-to-batch variability and the lack of real time inline inspection further reduce yield making reliable industrial integration challenging. The big difference in cost between making nanomaterials in a lab and in an industrial setting is a big problem for scaling. Graphene of high quality made in a lab can cost $500 to $1,000 per gram because of small batch sizes, complicated purification, and expensive characterization methods. In contrast, semiconductor production needs materials that cost between $10 and $100 per kilogram to stay economically viable for wafer-scale integration. This means that the goal is to cut costs by 4 to 6 orders of magnitude. There are also gaps in the production prices of carbon nanotubes and 2D materials, where catalyst use, energy-intensive chemical vapour deposition, and transfer processes are the most expensive. Until continuous roll-to-roll synthesis leads to high yield growth and automated quality control lowers the cost per wafer dramatically, claims of large-scale deployment are more hopeful than realistic. To add nanocomposites to semiconductor fabrication without changing their properties, a lot of changes need to be made to the usual CMOS workflows. Since many nanomaterials are sensitive to high temperatures, fabrication steps are moved to low-temperature back end of line processing (<400 °C) to avoid damage to the structure and oxidation Al_2O_3 or SiN_x keeps the interfaces clean and safe. To improve bonding with metals and dielectrics and lower contact resistance surface functionalization and adhesion layers are added. To avoid flaws and metal catalyst residues people also use dry transfer plasma free cleaning and controlled settings for contamination. These changes make it possible to add nanocomposites without affecting electrical performance or long term reliability. Only when contrasted with the baseline of conventional silicon CMOS, bulk semiconductor thin films, and traditional top-down lithography can the term "cutting edge" in nanocomposite-enabled semiconductor applications gain significance. The difference is found in quantifiable performance thresholds that are being approached by classical materials. First, energy efficiency and transistor scaling: The physical scaling limits of conventional silicon FinFET technology are approaching below around 5 nm because of heat dissipation, leakage currents, and short-channel effects. Channel thicknesses below 1-2 nm, increased carrier mobility, and reduced operating voltages are made possible by nanocomposites that use graphene, carbon nanotubes, and 2D materials. Nanocomposite and 2D material devices can operate around ~0.2–0.3 V, which allows for far lower power consumption for future CPUs and wearable electronics as compared to silicon transistors, which operate around ~0.7–1 V.

5.2 Environmental and Health Considerations

It is vital to carefully evaluate the potential toxicity and environmental impact of nanoparticles used in nanocomposites as well as to create ecologically acceptable production techniques. Nanoparticles due to their small size and strong reactivity can pose major risks to both human health and the environment if not managed properly. Some nanoparticles can affect the lungs or digestive system, and if released into the environment, they have the potential to destroy it. In the direction of contest these hitches widespread investigation is compulsory to found harmless acquaintance heights and comprehend the long period effects of nanoparticles. Certain manufactured nanoparticles used in semiconductor research are known to pose health risks to both the environment and employees. Similar to the effects of asbestos breathing in long stiff carbon nanotube fibres can cause lung inflammation, fibrosis, and possibly cancer in animals. When levels of nanosilver (Ag) are too high, they can cause ions that are toxic to aquatic life and can disrupt the metabolism of human cells. Zinc oxide (ZnO) and titanium dioxide (TiO_2) nanoparticles can produce reactive oxygen species when exposed to UV light, which can damage DNA and induce oxidative stress in skin and lung cells because they can leak heavy metals when they are discarded or degrade quantum dots containing cadmium or lead (such as CdSe or PbS) can be hazardous. This Study into decomposable and nontoxic nanocomposites is critical for sustainable development since it allows us to build materials that decay harmlessly or can be appropriately recycled at the end of their lifetimes. Green amalgamation methods are existence deliberate to reduce the environmental impact of nanocomposite materials production. Furthermore, health risks can be reduced by developing safer nanomaterials such as using naturally occurring or physiologically suitable nanoparticles. In the direction of safeguard, the safe behavior claims and discarding of nanocomposites regulatory frameworks must be changed. The semiconductor engineering can game reserve anthropological wellbeing and the atmosphere whereas inspiring the procedure of nanocomposites by ordering ecological and health contemplations. Safety organizations have given a lot of advice, but there are currently no clear restrictions on how much engineered nanomaterials people can be exposed to at work. People should only be around 1 $\mu g/m^3$ (8-hour time-weighted average) of carbon nanotubes and nanofibers to minimize the risk of lung inflammation and fibrosis. The suggested limit for titanium dioxide nanoparticles is about 0.3 mg/m^3 for ultrafine particles. The typical limit for nanosilver at work is 0.01 mg/m^3. People typically say that short-term exposure limits for zinc oxide nanoparticles should be around 2 mg/m^3 to avoid irritating the lungs. These restrictions are there to be safe because we do not have adequate long term health data on a lot of nanomaterials yet how important it is to have ventilation containment, and personal protective equipment.

6 Conclusions

Nanocomposites characterize a hopeful limit in semiconductor resources through improved assets that effectively astounded the confines of predictable materials. Nanocomposites, which incorporate nanoparticles in many materials, have strong electrical, thermal, and mechanical capabilities. This makes them handy in more complex applications. Better synthesis methods allow for more control over nanoparticle size and shape, which improves performance. They have applications in flexible electronics, high-performance transistors, and sophisticated memory devices. However, hurdles remain, including uniform dispersion, large-scale production, and compatibility with existing manufacturing. To address these concerns, cost-effective technologies and environmentally acceptable materials are required. Nanocomposites will play an important role in the future of semiconductors by increasing device efficiency and durability. Materials such as graphene and carbon nanotubes have extremely high conductivity and electron movement, allowing for smaller, faster, and higher-frequency electrical devices that go beyond the limitations of standard silicon.

7 Future research directions

Future nanocomposite research will concentrate on managing material properties by carefully incorporating and altering nanoparticles. Changing their size, shape, and surface increases bonding, stability, and uniform distribution in the matrix. This improves the electrical, thermal, and mechanical performance. New composition material will combine various nanoparticles and matrices, including hybrid organic-inorganic material, to enable flexible electronics and high strength applications. They also hold potential for increased photonics and quantum computing by enhancing light interaction and qubit performance. To do this interdisciplinary research and sustainable large scale production are required. Assistance sandwiched between speculative founding and productions can quickness up the development of serviceable presentations and simplify the changeover beginning test bed research to final items. Nanocomposites consume the probable to meaningfully upsurge semiconductor stratagem skills through concentrating on these coming research efforts. This will overlay the way for the progression of next generation high performance versatile awareness.

7.1 Innovative synthesis methods that combine scalability and cost reduction

High production costs, energy consumption, and incompatibility with current semiconductor manufacturing lines have prevented many synthesis routes including chemical vapor deposition, sol gel processing, hydrothermal synthesis, electrospinning, and atomic layer deposition from being widely used in industry, despite their proven ability to create high-quality semiconductor nanocomposites. The majority of documented methods are laboratory-scale optimized and do not meet the needs of contemporary semiconductor production facilities for wafer-scale uniformity, process repeatability, contamination control, and throughput. Furthermore, there is a significant disconnect between material performance advances and actual manufacturing feasibility because so few studies use techno-economic analysis, life-cycle cost evaluation, or cost-per-device measures. Additionally, nothing is known about low-temperature, solution-processed, and roll-to-roll manufacturing techniques that would make it possible to produce nanocomposite thin films in large quantities that work with printed and flexible electronics. The creation of continuous manufacturing techniques, CMOS-compatible deposition techniques, and integrated cost-performance optimization frameworks that take sustainability, scalability, and device performance into account all at once are necessary to close this gap.

7.2 Biodegradable nanocomposites as eco-friendly substitutes

Although the need for environmentally friendly semiconductor materials has been brought to light by the increasing environmental effect of electronic waste, biodegradable nanocomposites are still largely unexplored for use in semiconductor and electronic applications. The petroleum-based polymers, hazardous solvents, and non-recyclable fillers used in many current nanocomposite systems provide long-term health and environmental hazards. Although bio-based materials including poly lactic acid, chitin, cellulose nanofibers, and lignin have been extensively studied for use in packaging and biomedical applications, semiconductor device integration is still in its infancy. The electrical transport characteristics, moisture resistance, thermal stability, and long-term dependability of biodegradable nanocomposites under device working circumstances are all poorly understood. Furthermore, thorough life-cycle analyses analyzing the carbon footprint, recyclability, and end-of-life recovery techniques of electronics based on nanocomposite technology are lacking. In order to enable sustainable and circular electronics production, future research must concentrate on creating biodegradable dielectric and conductive nanocomposites that can satisfy semiconductor-grade performance standards.

7.3 Nanocomposite formulation improvement using machine learning

Current research still mostly relies on trial-and-error experimentation, despite the fact that designing semiconductor nanocomposites entails intricate relationships between material composition, synthesis parameters, microstructure, and device performance. Due to the lack of large, standardized datasets and high-throughput experimentation platforms, the use of machine learning for nanocomposite optimization is still in its infancy. Instead of addressing the multi-objective optimization needed for actual semiconductor applications, existing studies usually concentrate on maximizing specific attributes, such as electrical conductivity or thermal performance. Furthermore, the majority of machine learning models are limited in their capacity to anticipate real fabrication since they do not take into account synthesis parameters including temperature, deposition rate, and annealing conditions. The creation of autonomous experimentation platforms, open materials databases, and closed-loop artificial intelligence systems that can speed up the process of finding and refining high-performance nanocomposite formulations should be the focus of future research.

7.4 Data on the long-term dependability of devices strengthened by nanocomposite under operational stress

Long-term durability is still one of the least studied features of nanocomposite-based semiconductor devices, despite numerous research reporting notable advances in their electrical, thermal, and optical characteristics. The majority of experimental studies ignore the lengthy operational lifetimes needed for commercial electronics, which usually exceed 5 to 15 years, in favor of short-term performance criteria. Studies on accelerated aging in environments including high temperatures, humidity, bias stress, and mechanical fatigue—all of which have a substantial impact on device stability—are critically lacking. Specifically, less is known about the degradation processes at the filler–matrix interface, such as charge leakage, trap formation, and delamination. Additional issues with cyclic mechanical stress and crack propagation are brought about by flexible and wearable electronics, for which there are currently no established testing procedures. Additional issues with cyclic mechanical stress and crack propagation are brought about by flexible and wearable electronics, for which there are currently no established testing procedures. Moreover, there are no recognized frameworks for certification or reliability criteria that are especially suited to semiconductor devices made of nanocomposite materials. To guarantee the long-term, stable, and safe implementation of semiconductor technologies boosted by nanocomposite technology, these gaps must be filled.

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