Chapter

Understanding the Need of Raw Materials, and Eco-Friendly and Cost-Effective Methods for Detection and Extraction of Materials to Satisfy Semiconductor Market and Its Applications

Marinela Barci and Wu Hao

Abstract

This chapter describes the need of raw materials, and eco-friendly and cost-effective methods for detection and extraction of materials to satisfy semiconductor market and its applications. Since semiconductor market is increasing progressively mainly driven by automotive, solar cells, smartphone products and IOT, VR applications, the need of raw material also increases. To keep this trend, strategies to increase R&D and expertise in mobility and sustainability, European and intercontinental policies for supplier and material manufacturing are needed. Critical raw materials are explained and since there are few countries who supply them, other countries should invest in finding new ways to recycle and manufacture them in-house. With the scientific progress, more materials, alloys, and smart materials are being used, so we need to consider environmental, moral, and ethical aspects when we choose materials in any product, service, or system. Novel techniques such as LiDAR, robotics, autonomous haulage systems, remote operating, and monitoring centers help to maintain a good equilibrium and enable the increasing semiconductor market trend. Photocatalysis, especially more advanced artificial systems used to directly convert solar energy into storable energy, might be of interest to solve environmental pollution and energy storage issues. The idea is to develop photocatalyst with high efficiency, stability, and low cost using a single-material component.

Keywords: nanotechnology, semiconductors, raw and critical materials, photocatalysis, robotics, LiDAR

1. Introduction

Nanotechnology is a wide discipline, which includes science, engineering, and technology conducted at the nanoscale level of 1 to 100 nanometers according to the

Figure 1.
Estimated materials in one iPhone require 46 different elements reported according to Stanford Advanced Materials (SAM) Corporation [2].

Noble Prize scientist Richard Feynman. At such low scale, even gold has different properties in color, and electrical and chemical compositions, that the ones used to characterize the typical gold in large scale. Nanotechnology includes many sectors such as automotive, medical and healthcare, aerospace, photovoltaics, communication, railways and semiconductors, etc. [1], and each of them uses a wide range of materials and alloys. Our focus on this chapter addresses semiconductor's need for raw materials and how to identify more cost-efficient and environmentally friendly ways of extracting and storing them. The most used semiconductor materials are silicon, germanium, and gallium arsenide, but for each sector the list of more raw materials increases. To better understand the concept, we use as an example a smartphone, a typical electronic device each of us possess. Inside an iPhone are used more than 46 different elements according to Stanford Advanced Materials as reported in **Figure 1** adapted from [2]. The detailed list of materials divided by each electronic component is shown below [3]:

1. The phone's **processor chip** is made of silicon, phosphorus, antimony, arsenic, boron, indium, and gallium

2. **The electrical connections** within iPhone use metals such as **c**opper, gold, silver, and tungsten

3. For **micro-capacitors** component used mainly is tantalum

4. The materials used for **soldering** are tin, copper, and silver

Most of these materials are not abundant in nature and are supplied by few countries. Considering the market of mobile phones, more materials are used daily and to keep up with the demand it is important to recycle. Apple announced that their product iPhone 12 is made of 100% recycled raw materials, and especially, rare earth materials are used for magnetic components [4]. Many other companies follow the same trend as they valorize green energy and carbon-free products.

Industry is collaborating more with research and academia to identify what is the cost of bringing the materials from lab to fab [5] and identifying new fields to help technology facilitate the extraction, storage, and utility of the materials [6].

Many countries are increasing the attention and research in the entire raw material chain from exploration, mining, and mineral processing to substitution, recycling, and circular economy [7, 8]. This opens new possibilities related to R&D and expertise in mobility, sustainability, and European and intercontinental policies for supplier and material manufacturing. The growth is driven by both increasing demand and applications in semiconductor industry and by the investment of big semiconductor companies in the field.

This chapter is divided into the following sections: market study for semiconductor raw materials, suppliers and main semiconductor's companies, geopolitical and social impact, characterization techniques used for the evaluation of material properties, traditional and novel technologies, and semiconductor and new applications for photocatalysis and the last part is dedicated to conclusions.

2. Market study for semiconductor raw materials

The semiconductor material market is expected to register a CAGR of 4.17% over the forecast period (2021–2026) stated by Mordor Intelligence Pvt. Ltd. [9].

Market experts project that the semiconductor market (including smartphones, tablet, PC, smartwatch) is about to increase exponentially in the upcoming years, mainly driven by novel applications such as artificial intelligence, internet of things, nano-robotics, high power computing, virtual and augmented reality.

The Semiconductor Industry Association (SIA)-announced global semiconductor industry sales showed an increase of 21.1% over the year 2021 to 2022 with an increase of a total of $42.0 billion [9]. The most growth rate is expected in Asia, while the least impact is predicted for South America and Africa as shown in **Figure 2**.

Other sources such as Techcet [10] divide the global semiconductor market according to process materials, packaging materials, consumable equipment components, and silicon wafers and they project an increase in the market in the upcoming years up to 30% as reported in **Figure 3**.

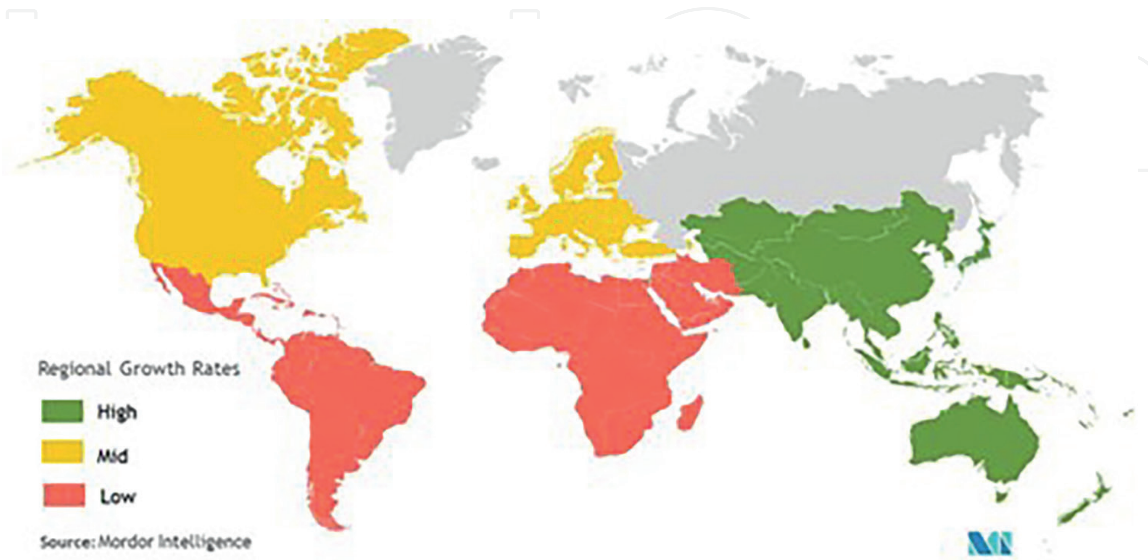

Figure 2.
Global semiconductor material market. Growth rate by region for 2021–2026 according to Mordor Intelligence Pvt. Ltd. market study [9].

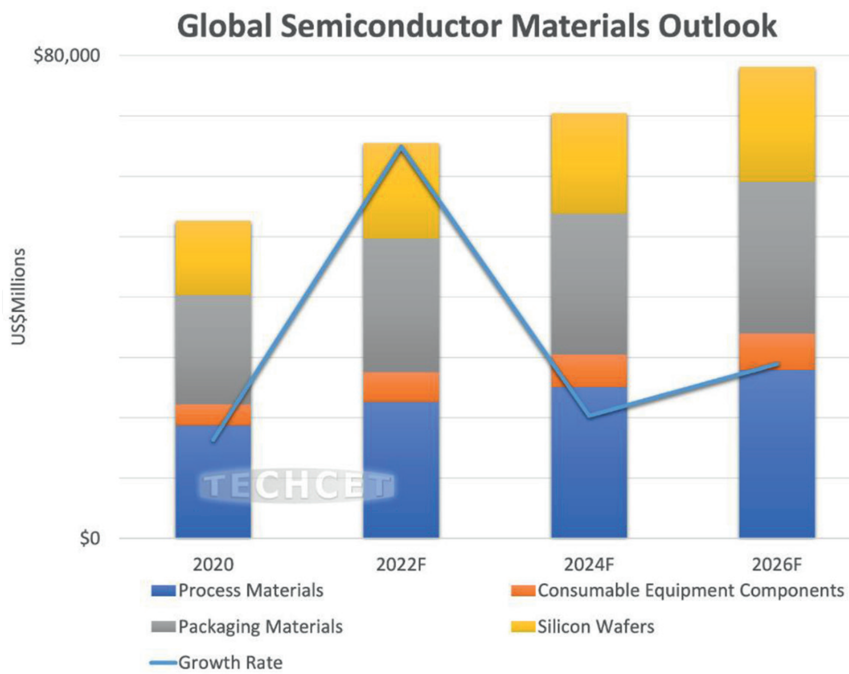

Figure 3.
Global semiconductor material projection by Techcet [10].

Moreover with the new policies for green and carbon-free energy, according to the International Energy Association, the rise of low-carbon power generation is projected to triple mineral demand from this sector by 2040 [11].

3. Suppliers and main semiconductor's companies

Semiconductor devices are made on a single wafer or an epitaxial wafer with a single wafer as the substrate. The Czochralski is a typical melting growth method to create single crystals. The next steps in the semiconductor process are crystal orientation, barrel grinding, reference surface, slicing, grinding, chamfering, polishing, etching, cleaning, inspection, packaging, etc., to produce the final wafer. The growth of a single-crystal thin film into a single-crystal substrate can be made by epitaxy, chemical vapor deposition, magnetron sputtering, and other methods [12, 13].

The modern global semiconductor industry according to [14] is generally divided into two models:

1. Integrated Device Manufacturers that design, produce, and sell their own chips like Intel and Samsung

2. Fabless foundry companies like Nvidia and Arm that design their semiconductors and manufacture them by other foundries like TSMC and SMIC

Semiconductor manufacturing is an integrated, multi-stage process that occupies a big part of the industry chain, such as semiconductor designers and manufacturing suppliers. It includes silicon wafers, photoresists, wet electronic chemicals, electronic gases, reagents, CMP polishing materials, and target materials. Chip packaging materials include package substrates, lead frames, resins, bonding wires, solder balls, and plating solutions [12].

A good explanation of the overall chain is described in **Figure 4**, where it includes as input: manufacturing equipment to chemical and materials, and electronic design automation, while combined with design and manufacture explained before, provides wafers to assemble, test, and package the final product reported to the consumer [14].

Big companies in semiconductors, such as TSMC, Samsung, Broadcom, NXP, Intel, Micron, SK Hynix, Qualcomm [15], announced that they are going to increase their presence worldwide by investing in new plants of production. This news overcomes the issues of chip shortage (definition: sociological or physical change that prevented certain chips from being produced in enough large numbers to satisfy demand) and post-pandemic [16].

Some of the big supplier companies in the materials are Basf SE, Indium Corporation, Kyocera Corporation, Showa Denko Materials Co, Ltd., and Intel Corporation reported in **Figure 5**. More details are given in [9].

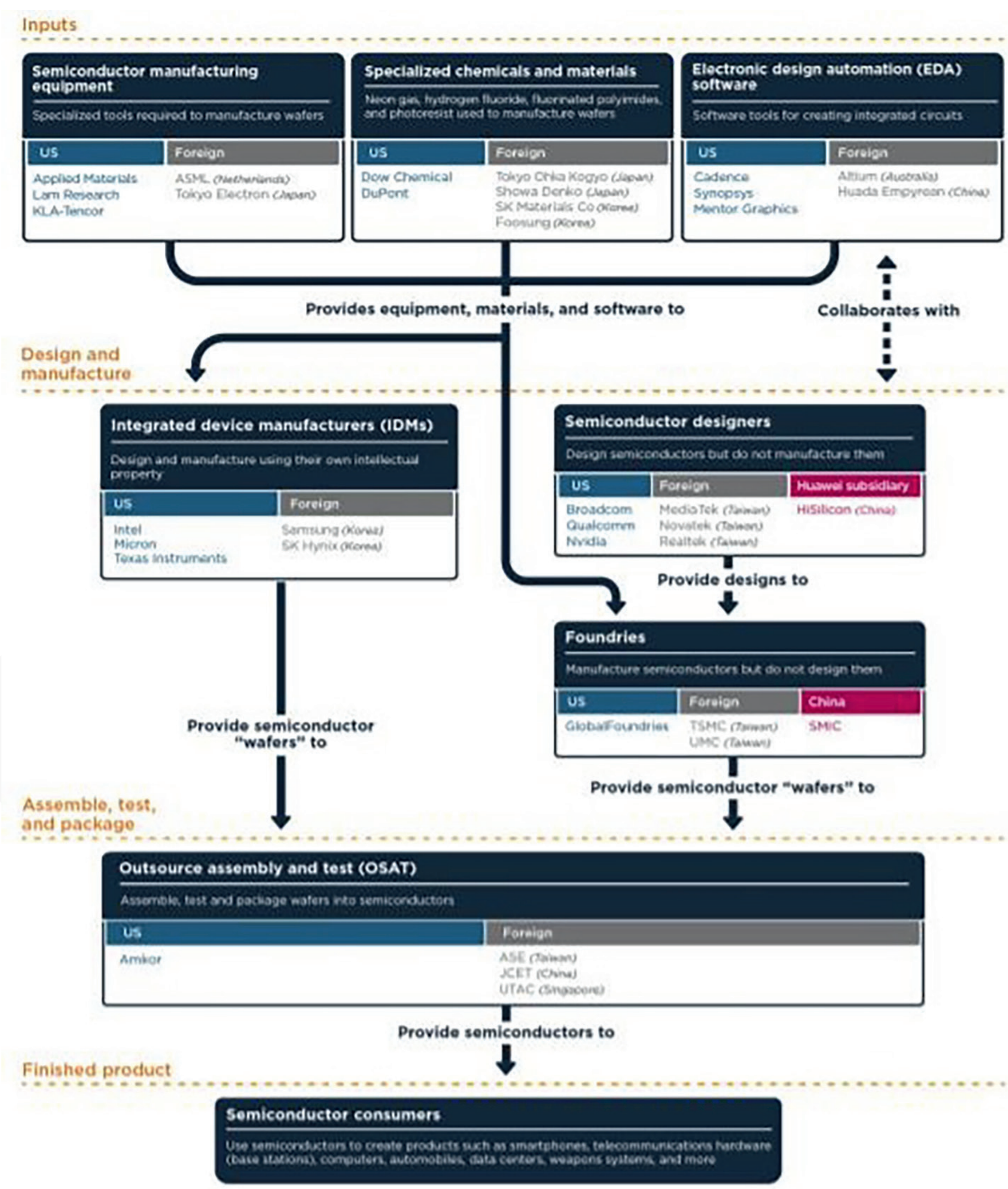

Figure 4.
Semiconductor chain from input to finished product according to source PIIE [14].

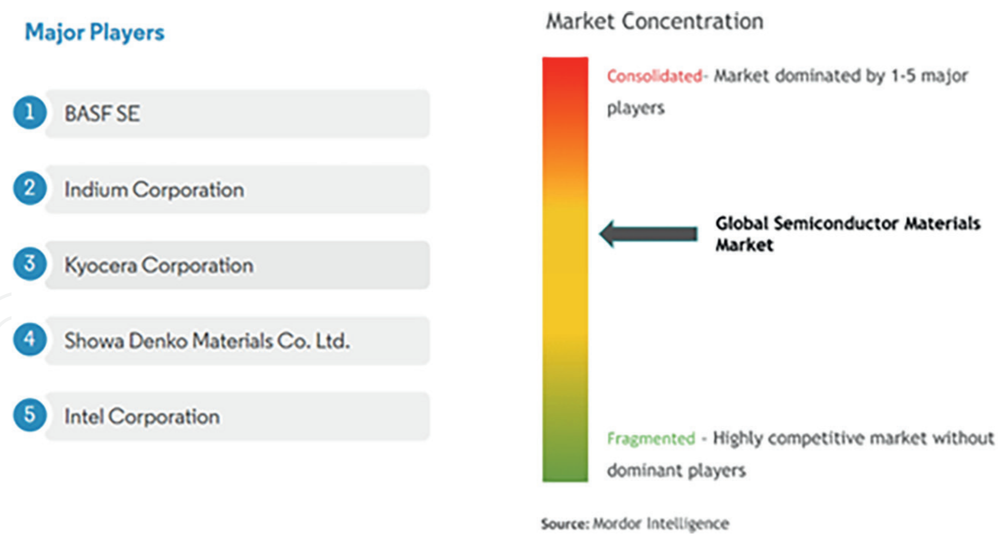

Figure 5.
Global semiconductor material major players—Source Mordor Intelligence Pvt Ltd [9].

4. Geopolitical and social impact

Nowadays, China dominates the manufacturing industry, also due to its abundance in raw materials and low cost-effective ways of producing them [17–21]. China refines nearly 90% of the world's rare earths, which mostly are part of critical raw material list. The raw materials are used in various products such as EVs, advanced ceramics, computers, smartphones, wind turbines, monitors, and fiber optics [21].

Many countries such as Europe, USA, and Canada import most of the critical raw materials from China. A critical material is defined as vital for the world's economy, whose supply may be at risk due to geological scarcity, geopolitical issues, trade policy, or other factors.

In the last years, we have faced coronavirus pandemic and COVID-19 quarantine rules and political tensions [16, 22–24], so it is important that each country develops its internal strategy and has less dependence on other countries. This can be done by increasing the attention in the entire raw material chain from exploration, mining, and mineral processing to substitution, recycling, and circular economy as reported in **Figure 6** [7, 25, 26]. This section will address European Union strategy to overcome the shortage problem. Their experts suggest that the key solution is to boost mineral recycling, identify alternative materials, and promote greater exploration and trade better with World Trade Organization (WTO) to ensure the supply of important raw materials to European industry is not interrupted [26].

Figure 6.
Raw materials of EU project with the purpose of developing new materials into a major strength for Europe [7].

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5. Characterization techniques used for the evaluation of material properties

The increase of scientific discoveries and new technologies has impact in material science widening the choice of materials or smart materials (such as shape memory polymer, shape memory alloy, and hydrogels) to be used in semiconductors. It is important as pointed out by Reference 27 to consider environmental, moral, and ethical aspects when we choose materials in any product, service, or system [27]. The main properties to characterize them are as follows:

- Physical properties such as mass, volume, weight, density
- Electrical resistivity measures the ability of a material to conduct electricity and thermal conductivity how fast the heat is dissipated when there is a gradient of temperature in the material
- Hardness defines the resistance of the material to scratching
- Mechanical properties such as tensile and compressive strength, stiffness, toughness, brittleness, and ductility
- Stress as the ability of a material to withstand pulling force and strain as the ability of a material to withstand being pushed away
- Plasticity is the ability of a material to be changed in shape permanently
- Esthetic characteristics related to taste, texture, smell, and appearance
- Piezoelectricity, shape memory alloys, photochromicity, electro-and magneto-rheostatic
- Thermoelectricity is when electricity is produced directly from heat

To evaluate which element gives the best properties or the desired properties mentioned above for a given product, there are several characterization techniques. The main parameters that differ one method from the other are resolution or detection limit (of the order of nm), physical basis (scattering, emission of electrons…), material sensitivity (linked to refractive index or atomic number), environment of testing (vacuum, air, liquid), and measured parameters (size, shape, morphology, composition…) that we want to extract and analyze. Some good reference to each method is given in [27, 28]. In this short chapter, we will limit to mention some of the most used characterization techniques and basic utility and working mechanism:

1. Scanning electron microscopy (SEM) produces images using electrons instead of visible light
2. Transmission electron microscopy (TEM) uses electrons instead of light and is used for the evaluation of nanostructures such as particles, fibers, thin films, and imaging of atoms

3. Atomic force microscopy (AFM) is used to study the samples at a nanoscale. It takes an image in a three-dimensional topography and provides surface measurements

4. Energy-dispersive X-ray spectroscopy (EDS) is a non-destructive analytical technique. It analyzes near-surface elements and estimates the elemental proportion at different positions

5. Ultraviolet-visible spectrometry (UV-vis) consists of tungsten lamp for the ultraviolet and visible region wavelengths, respectively, a monochromator and sample—reference beams and a detector

6. Fourier transform infrared spectroscopy (FTIR) uses infrared light for scanning the organic, inorganic, and polymeric materials

7. X-ray diffraction (XRD) mainly used to detect the crystallinity of the sample

6. Traditional and novel technologies

In the previous sections, we described the semiconductor material market, main players, applications, challenges, and prospective and we understood that the raw material for semiconductor applications is a booming market. The mining sector that provides the raw materials will need to grow tremendously to enable the required technological demands. Technological innovation should satisfy the growth market need, but need to be also eco-friendly and at low cost. Some people refer to sustainable technology as the society economic equilibrium between raw materials, land, industries, sites, and industrial resources like workers, technology, equipment, machinery, fuels. This model comes more into focus as we are threatened by climate change and environmental degradation [29].

The most innovative technologies predicted to transform mining industry include robotics, autonomous haulage systems, remote operating, and monitoring centers as described in [30]. We will focus in particular in light detection and ranging (LiDAR) technology. LiDAR blocking diagram is composed of laser, light detector, signal and data processor, CPU, and display.

LiDAR is a remote sensing technology based on time-of-flight principle: A target is illuminated with a laser, the laser pulses travel at the speed of light to the object, and

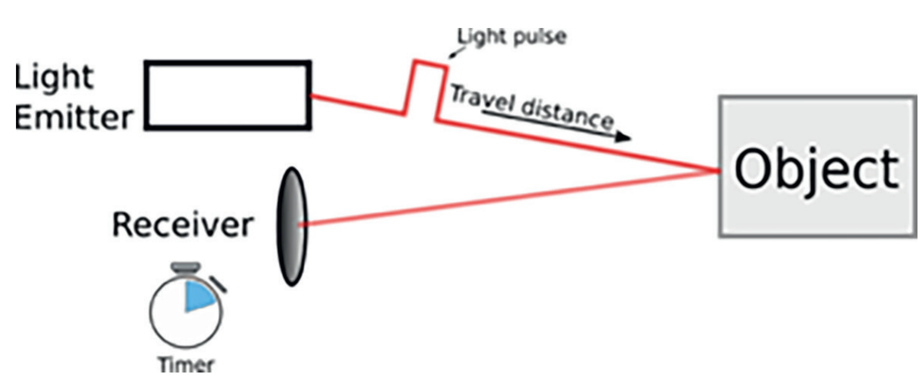

Figure 7.
LiDAR working principle adapted from Reference [31].

the laser is then reflected back to the sensors as illustrated in **Figure 7**. The time taken for the pulses to hit the object and be reflected back to the sensor is calculated and then used to calculate the distance to the object [31].

LiDAR can be used in many fields such as oil and gas exploration, geology, mining, and robotic mining. The information gathered by LiDAR can identify the areas with oil or gas deposits to help geologists know exactly where they need to mine. It can also help to determine the soil structure where the crops or species of plans can grow in a particular region.

Advanced LiDAR technology can detect what minerals exist in a given area and can analyze the mine's structure to prevent them from collapsing after mines have been drilled for minerals.

In robotic mining, LiDAR sensors are used in obstacle detection during mining by the robotic mining vehicles, to prevent the human risk [32].

7. Semiconductor and new applications for photocatalysis

The term photocatalyst is a combination of two words such as **Photo,** which is related to photon, and **Catalyst**, which are substances that alter the reaction rate of materials, mainly semiconductors in the presence of light [33]. This is done through chemical reactions known as photocatalythic reaction or photocatalysis that generate an electron-hole pair, when a semiconducting material is exposed to light. The photocatalysis can be categorized into two types depending on the physical state of reactant and semiconductor.

If both (the semiconductor and reactant) are in the same phase such as gas, solid, or liquid, we refer to homogeneous photocatalysis. Otherwise, if semiconductor and reactant are in different phases, they are called heterogeneous photocatalysis [33, 34].

Photocatalysis is a branch of chemistry and it is referred to as a green chemical pathway, as the main applications studied are environmental applications, biotechnology, and health care such as solar cells, water splitting, and purification, wastewater treatment, pollutant degradation, cancer treatment, antibacterial, air purifying, antifogging, self-cleaning, batteries and conservation and storage of energy, etc. [35].

When considering the main materials compatible for photocatalysis, some parameters need to be taken into account such as photocatalyst loading, pH, surface area and morphology, reaction temperatures, contaminant concentration, and calcination temperature of photocatalysts [36]. Many materials are used for these applications, and among them TiO_2, TiN, Pt, Si, MoS_2, MoS_2/TiO_2 are the most basic materials used as photocatalyst and they are at low-cost, abundance in nature, chemically stable, and transparent to visible light [33, 36–39].

TiO_2 seems to be an excellent photocatalyst and the most used one. The concept to use TiO_2 as photocatalytic for water purification was introduced in 1977 by Frank and Bard. They notice that if you put catalytically active TiO_2 powder into a pool filled with polluted water and then illuminate it with sunlight, the water will gradually become purified. This concept is very interesting and still used by researchers nowadays for purifying water and then extended to purifying air, cancer treatment, etc. [40].

As reported in many scientific works and in the previous paragraphs, environmental pollution and energy shortage are becoming the big challenge for the developed and in developing countries. Photocatalysis, especially more advanced artificial systems used to directly convert solar energy into storable energy, might be of interest to solve these issues. The idea is to develop photocatalyst with high efficiency, stability, and low cost using a single-material component.

8. Conclusion

This chapter clearly describes the need for materials in nanotechnology and its sectors, especially semiconductors, and also brings the attention of experts and researchers in the field. Industry is collaborating more with research and academia to identify what is the cost of bringing the materials from lab to fab and identifying new fields to help technology facilitate the extraction, storage, and utility of the materials.

In the last years, we have faced coronavirus pandemic and COVID-19 quarantine rules and political tensions, so it is important that each country develops its internal strategy and has less dependence on other countries. This can be done by increasing the attention in the entire raw material chain from exploration, mining and mineral processing to substitution, recycling, and circular economy. Novel technologies such as LiDAR, robotics, autonomous haulage systems, remote operating, and monitoring centers can help the raw material industry to enable semiconductor market which is projected to increase mainly by increasing smartphone, tablets, VR, IOT, robotics, photovoltaic, and automotive industry.

Photocatalysis, especially more advanced artificial systems used to directly convert solar energy into storable energy, might be of interest to solve environmental pollution and energy shortage, which remains of particular interest for developed and developing countries.

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Author details

Marinela Barci* and Wu Hao
HUAWEI Technologies R&D, Leuven, Belgium

*Address all correspondence to: marinela.barci@huawei.com

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