coatings

Editorial

Special Issue: Recent Advances in Semiconducting Thin Films

Ihor Virt [1,2]

[1] Institute of Physical Sciences, Rzeszow University, Pigonia 1, 35-310 Rzeszów, Poland; ivirt@ur.edu.pl
[2] Institute of Physics, Mathematics, Economy and Innovation Technologies, Drohobych Ivan Franko State Pedagogical University, Stryiska 3, 82100 Drohobych, Ukraine

The application of thin-films as development direction of integrated electronics is based on the sequential build-up of films of various materials on a common base (substrate) with the simultaneous formation of micro-parts (resistors, capacitors, contact pads, etc.) and internal circuit connections from these films.

Relatively recently, semiconductor (solid) and thin-film hybrid ICs were considered as competing research directions in the development of integrated electronics. In recent years, it has become obvious that these two directions are by no means mutually exclusive, but on the contrary, they mutually complement and enrich each other.

A number of modern, highly advanced technologies use a certain form of thin-film coatings. This includes, in particular, superconductivity technology, green energy generation and storage technology, and the new 5G network technology. Thus, there has been a historical evolution, in particular a revolutionary transition from conventional deposition technologies and their fields of application. Along with this progress, there are further problems related to growth modes, specific measurements on micro/nano-level thin-film stress states, the application of models, as well as forecasting prospects for the application of thin-film coatings.

In particular, progress in the thin film field concerns the development and improvement of the primary methods of applying thin film coatings (e.g., chemical vapor deposition and physical vapor deposition methods), uncovering the the evolution of residual stress from valuable modern models to provide a deep understanding of the basic principles of thin film coating methods, and the problems associated with such principles [1–3]. It has been scientifically proven that no technique or model of thin film structures yields ideal results in all scenarios; indeed, the choice of the appropriate coating technique or model depends on the target materials and functions of the thin film system. Public demand and specific challenges in the fabrication and application of thin-film systems indicate that thin-film coatings and problems related to their application will remain bright and active research areas for the foreseeable future. Thus, this practical problem has been a starting point for researchers in these areas for a considerable time.

Single-crystal thin films of metals, semiconductors, and insulators are critical technologies. They are crucial for the production of high-performance electronic and optical devices, but are still challenging to fabricate both scientifically and industrially. Recently, unconventional advanced synthetic approaches have been applied that have made significant progress in diversifying the species of single-crystal thin films [2]. This publication presents new synthetic approaches to the production of large-area, single-crystal thin films from various materials according to the principles of crystallite formation. Mechanisms of grain growth, coincidence site lattice (CSL), and Van der Waals (VdW) epitaxy are presented. Controlled nucleation and growth in solution phases, as recent advances in materials science, are also discussed.

Silicon thin-film technology is the most widely used and widespread application in electronics and photo-electronics. Silicon thin-film photonics [3] is rapidly improving in terms of productivity and capabilities thanks to numerous production facilities and

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process shops. The integration of photonics with electronics has been key to increasing the speed and total bandwidth of silicon-photonics-based assemblies, with several approaches being able to create transceivers with bandwidths of 1.6 Tbps and above. Advances in electronics are also rapid due to the use of thin-film structures with state-of-the-art chips, including switches, that have many tens of billions of transistors. The convergence of the advances in silicon photonics and electronics means that combined silicon photonics and electronics enable continued progress and drive further innovation in both fields. Over the last decade, one of the most intensively researched semiconductor materials with promising applications has been gallium nitride (GaN). It has become an excellent material for the manufacture of power devices. Among the semiconductors for which power devices are already commercially available, GaN has the widest energy gap, the largest critical field, and the highest saturation velocity, making it an excellent material for high-speed/high-voltage components.

The presence of spontaneous and piezoelectric polarization allows the creation of a two-dimensional electron gas with high mobility and high channel density in the absence of any doping due to the use of AlGaN/GaN heterostructures [4]. This contributes to the minimization of resistive losses. At the same time, for GaN transistors, switching losses are very low due to small parasitic capacitances and switching charges. Device scalability and monolithic integration enable high-frequency operation with corresponding advantages in terms of miniaturization. For high-power/high-voltage operation, vertical device architectures are proposed and explored, and 3D structures—rib-shaped, trench-structured, or nanowire-based—show great potential. Prospects for the use of oxides of transition metals are demonstrated in [5]. Extremely diverse quantum functional properties such as high-temperature electrical conductivity, colossal magnetoresistance, multiferroicity, two-dimensional electron gas, and topological insulators are indicated. In this regard, the growth of atomically controlled epitaxial thin films and heterostructures will allow for control over the corresponding energy scales. This is achieved, for example, by adjusting various factors, such as dimensionality reduction, the introduction of interfaces, the modification of interfacial octahedral inclinations, and symmetry breaking. Also of great importance is the fact that atomically controlled epitaxial thin films and heterostructures of multifunctional oxides offer promising potential for next-generation oxide electronics. Quantum-correlated phenomena are present in low-dimensional oxide materials, and there has been progress in the application of functional oxides over the past couple of decades. Among others, zinc oxide (ZnO) is a promising candidate due to its unique physical properties, including a direct band gap in the ultraviolet (UV) spectrum. ZnO has good ferroelectric characteristics and is thus piezoelectric, has a moderate Debye length in its nanostructures (quantum dots, nanowires, nanoparticles), etc. [6]. ZnO is a very versatile material. Researchers in this area are focused on many devices based on epitaxial structures, namely thin films, thick films, and nanostructures, but also with a significant number of unsolved problems, such as the problem of efficient p-type doping [7]. A number of publications are devoted to the development of technological processes of growing thin films [8–12]. Multidimensional ZnO nanostructures and superlattices also have extremely different morphological features [13]. The development of various growing methods allows control over the morphologies of interfaces, which is useful in the field of nanoelectronics, gas and chemical sensors, conductive electrodes, and various biological applications. Quite interesting prospects have been presented for the oxide compound titanium dioxide [14]. TiO_2, in its rich phase diagram, is a truly multifunctional material with diverse properties that have been shown to span dielectric to conductor characteristics, in addition to its well-known catalytic properties. At the same time, the down-scaling of microelectronic devices has led to an explosive growth in research on atomic layer deposition (ALD) on a wide range of thin-film boundary materials, among which TiO_2 is one of the most popular.

Another promising thin film material is gallium beta oxide (b-Ga_2O_3). It is a novel ultra-wide bandgap (4.8 eV) semiconductor with attractive properties for future power and radio frequency (RF) electronics, optoelectronics, and sensors for detecting solar quenching gases and UV radiation. In addition to these promises, b-Ga_2O_3 films have excellent mechanical properties, making them suitable materials for micro/nanoelectromechanical systems (M/NEMS). An overview is presented in [15] on new b-Ga_2O_3 M/NEMS and their role in complementing Ga_2O_3 power and radio frequency electronics. Two aspects of b-Ga_2O_3 M/NEMS are analyzed: β-Ga_2O_3 vibrational channel transistors for potential integration with β-Ga_2O_3 power and radio electronics with operating frequencies above 1 GHz and b-Ga_2O_3 resonant transducers for photon emission detection.

Regarding oxide films, interesting ferroelectric properties in oxides with a fluorite structure, such as hafnium and zirconium, are attracting increasing interest [16]. They have various advantages, such as compatibility with additional silicon-based metal oxide semiconductors, improved deposition methods, low dielectric constants, and, as a result, a reduced depolarization field and stronger resistance to hydrogen annealing. Thus, this paper addresses the main advantages of fluorite-structured ferroelectrics for memory devices in terms of their material applications.

The molecular beam epitaxy (MBE) method has found the greatest application for the production of new promising thin film structures with unique physical properties, for example, in applications for the formation of low-dimensional objects with topological characteristics [17]. Linking the fundamental science of topological materials with applications in electronics requires the production of high-quality thin films. One of the long-standing problems in this field remains the understanding and control of the basic material properties of epitaxial thin films. Understanding the fundamental properties of topological materials grown by molecular beam epitaxy (MBE) is key to advancing knowledge of the underlying physics while developing a new generation of topological devices.

The most efficient non-toxic, thin-film, multi-element photovoltaic devices containing many chemical elements are made of Cu, Zn, Sn, S, and Se. These materials have received a relatively rapid increase in efficiency from the moment of their creation, reaching a current electricity conversion efficiency of 12.6%. A review article [18] discusses pathways for increasing the efficiency of these materials, including film growth methods, post-growth processing, and device fabrication. It is indicated that the main limitation of increasing the V_{oc} is the fundamental volume point defects. Improvement in device performance occurs due to the additional processing of films, in particular grain boundary passivation and interface modification. It is clear that there are problems concerning the degradation and stability of the characteristics of thin-film photovoltaic systems (PV), which are directly related to the technological processes of production [19].

Some quite interesting fundamental problems are related to the scaling of optoelectronic devices to the nanoscale and, in recent decades, the development of composite films which, for example, use the plasmon response of metal structures. At longer wavelengths associated with the mid-infrared, a host of deleterious and/or parasitic effects make nanoscale optoelectronics at microscale wavelengths particularly challenging. Using a class of infrared plasmonic materials, heavily doped semiconductors can be integrated into a number of optoelectronic device architectures [20]. A class of highly doped semiconductor materials offers the opportunity to produce monolithic, fully epitaxial device architectures that outperform current state-of-the-art commercial devices. Moreover, there are prospects for such materials for infrared nanophotonic optoelectronics.

One of the possible development directions related to nanoelectronics is the work being carried out on the creation of materials and elements of IR technology [21–23]. The increased interest in $A_{IV}B_{VI}$ compounds is due to their excellent ability to detect infrared radiation (IR) in a wide range of wavelengths. This explains the practical application of these compounds in various optoelectronic devices. Lead chalcogenides (PbS, PbSe, and PbTe) are excellent materials for mid-IR detection. Lead chalcogenides may exhibit higher sensitivity compared to their single-crystal counterparts [21]. Increased interest in $A_{IV}B_{VI}$ compounds is due to their use in thermoelectric devices [24]. This unique feature allows for the preparation of chalcogenide detector systems (mid-infrared region) integrated with silicon technology, in particular, on compound epitaxial films HgCdTe [20].

Prospects for the development of ferromagnetic and spintronic devices are in the application of hybrid materials of graphene and metals. Graphene is an attractive candidate for spintronics for a number of reasons, including its electric-field-controlled conductivity and its two-dimensional nature. The application of graphene requires the development of high-quality ferromagnetic thin films in contact with graphene. In [25], the growth of planar epitaxial ultrathin films of Co metal on graphene by pulsed laser deposition is reported. The existence of perpendicular magnetic anisotropy, epitaxy, and ultra-thinness open new prospects for graphene-based spintronic devices with the potential to control the electric field of magnetism.

The application of structures on the nanocarbon axis is undergoing rapid development. The discovery of graphene prompted intensive study and research into nanohybrid heterostructures. These structures combine the functionality of semiconductor nanostructures with the high mobility of graphene charge carriers, as well as extraordinary mechanical strength and flexibility for a variety of applications. For nanohybrids of ZnO/graphene heterostructures, the low thermal budget for the growth of crystalline ZnO makes the direct deposition of ZnO onto graphene with a controlled morphology and surface possible. This enables the development of a wide range of devices, including photodetectors, gas sensors, strain sensors, and self-powered devices. Recent progress made in ZnO/graphene heterostructure nanohybrids has been made due to the development of the ZnO/graphene interface [26]. There are recent achievements in the field of using hybrid nanostructured composites consisting of semiconducting metal oxides and graphene and its derivatives. These are graphene oxide, reduced graphene oxide, graphene quantum dots and carbon nanotubes in certain applications [27], namely, photovoltaics, water splitting, photocatalysis, and supercapacitors.

These hybrid materials have attracted considerable attention during the last decade in their thin films versions. The application of thin films in the field of flexible electronics is quite interesting [28]. In particular, thin-film transistors (TFTs) are important building blocks for flexible platforms. These are the most common thin film devices. Oxide-based flexible TFTs are highly compatible with flexible electronic systems due to their low process temperature, high carrier mobility, and good uniformity. There is also a positive forecast of possible development trends. A growing interest in organic–inorganic systems (films, nanostructures, composites, etc.) stems from the possibility of achieving combined properties that are unique for each of the constituting phases [29–31]. Electrical stability of an inorganic material can be combined with the mechanical flexibility of the organic one. The production of transparent and flexible electronics involve large-area and low-temperature material processing during device fabrication. This imposes several limitations for materials that can be used either as active parts or as passive ones, including transparent contacts [32].

The production of thin films is widely used in metrology to measure various physical quantities. Thin-film sensors are used to monitor environmental conditions. Using thin-film technology, the sensors are able to make accurate measurements [33]. In addition, the measurements are stable and reliable, and the sensor devices are relatively inexpensive. There are potential applications of thin film sensors in biomedical, optical, and corrosion detection devices.

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