Solar Energy Materials & Solar Cells 99 (2012) 166–175

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Review

Preparation of thin films and nanostructured coatings for clean tech applications: A primer

Claes G. Granqvist*

Department of Engineering Sciences, The Ångström Laboratory, Uppsala University, P.O. Box 534, SE-75121 Uppsala, Sweden

ARTICLE INFO

Article history:
Received 29 September 2011
Accepted 28 November 2011
Available online 26 December 2011

Keywords:
Thin film deposition
Coating
Clean tech
Nanostructure
Tutorial review

ABSTRACT

Thin films and nanostructured coatings are of great and increasing importance for clean tech, including applications to solar energy and energy efficiency. This tutorial review discusses why this is so and surveys the major preparation technologies and their characteristics. Particular attention is given to techniques requiring vacuum or plasmas—with foci on evaporation and sputtering—but a wide range of other techniques is surveyed as well. Large-scale deposition is discussed in some detail, and perspectives are given on possible future developments.

Contents

1. Introduction: the importance of thin films and nanostructured coatings

Thin films and nanostructured coatings are essential for many—perhaps most—clean tech technologies. These technologies are of intense interest today and include solar energy utilization, energy savings and methods for assuring clean air and water.

We first contemplate the importance of clean tech and begin by looking at the world's population, which was around one billion in the year 1800, grew to about 2.5 billion in 1950, and is now (2012) around seven billion. The population growth is not expected to stabilize until around the year 2100, at what time it has reached a stunning ten billion or even more [1]. This population explosion has been accompanied by a growth in the overall standard of living, and people in the Third World expect—as they rightly should—to possess the same amenities and qualities of life that we are accustomed to in the more affluent countries. The unavoidable implication is that the demands on the world's natural resources are increasing very steeply so that we, already at present, make an unsustainable use of riches of all kinds, including fuel, minerals, water, etc. The dangers to humanity are both direct, and connected with exhaustion of essential resources, and indirect and for example associated with the burning of fossil fuels and firewood, which produces carbon dioxide emission and hence global warming, rising sea levels, harsher weather, enlarged dangers for the spreading of diseases, mass migrations, etc [2,3]. Furthermore the geographically uneven distribution of many natural resources, as well as the global climate in itself [4], can lead to civil conflicts and human disasters.

The only sustainable way forward goes via increased adoption of clean tech—also referred to as "green" or "eco-friendly"

* Tel.: +46 18 4713067; fax: +46 18 4713270.
E-mail address: claes-goran.granqvist@angstrom.uu.se

0927-0248/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.solmat.2011.11.048

technology—which is affordable and operating in harmony with nature's own energy flows [5]. Furthermore, these uses of new technology must be accompanied by changes in life style.

Thin films and nanostructured coatings are essential to clean tech because they allow one to do a lot with a little. This is illustrated next by two examples: consider *first* a block of aluminum, which is small enough that it easily can be carried by hand. By an appropriate thin film technology one can deposit this material so that it yields a reflecting surface over a square kilometer; under full solar irradiation the surface reflects roughly a Gigawatt that otherwise might have been absorbed in the material behind the reflector. In a *second* example we imagine that this aluminum surface is overcoated with an equally thin nanostructured layer comprising metallic nanoparticles included in an oxide matrix. This surface is now no longer reflecting visible light but appears dark and can serve as an efficient "spectrally selective" absorber that gathers solar energy and retains it so that it can be used for heating purposes. These were two examples only, and there are many analogous ones related to thin films and nanostructured coatings that can be employed to achieve not only energy efficiency—as in the examples above—but also human comfort and security [5].

The films of concern for clean tech applications have thicknesses typically lying between 10 nm and 10 μm. They can be metallic, semiconducting or dielectric and backed by rigid substrates of metal, plastic or glass or by flexible foils of metal or plastic. There is a multitude of ways to make such thin films, and thin film science and technology are huge fields of very large importance not only for clean tech but for virtually every contemporary technology. There are numerous books and tutorial texts on the subject [6–16].

This tutorial paper presents a brief overview of the most important technologies for preparing thin films and nanostructured coatings and also includes a number of illustrative examples. The exposition—which to some extent reflects the author's own experience and perhaps prejudices—considers films produced by vacuum-based and non-vacuum-based techniques as well as coatings prepared from nanoparticles. For the vacuum-based techniques, emphasis is put on the possibilities to construct nanostructures by carefully selected deposition conditions. Large-scale preparation of thin films and nanostructured coatings is discussed, and the presentation ends with some remarks. Nanofeatures—and they are legion [17,18]—are emphasized throughout the paper. This tutorial is an adaptation and extension of one small part of an earlier treatise [5].

2. The major thin film technologies, and some examples

Table 1 presents the most important thin film technologies, which are organized according to the depositing species being atomistic (or molecular), particulate or in bulk form, or whether the surface of a material is modified so that it produces a layer with properties that are significantly different from those of the underlying material. Atomistic deposition is most common for clean tech applications.

2.1. Vacuum-based and plasma-based techniques: basics of evaporation and sputtering

Evaporation is a widely known technique for making thin films and is in daily use in research laboratories all over the world since sixty years or more. It is also used industrially, mainly for metalizing. The raw material of the film is heated in vacuum so that a vapor, consisting of atoms or molecules, transports material to the substrate at a high enough rate [19,20]. The energy of the vapor species is typically a fraction of an electron volt. The necessary heating can be obtained by an electrical current going through a resistive coil or boat—usually of tungsten—in contact with the material to be evaporated or by thermionic emission from a wire and focusing of the electron beam onto the material to be evaporated from a water-cooled "electron gun". This latter technique is called electron-beam (e-beam) evaporation.

Sputter deposition is used on a very large scale to produce uniform coatings on glass, polymers, metals, etc. Essentially, a plasma is established in a low pressure of inert or reactive gases, and energetic ions in the plasma knock out atoms or molecules from a solid plate or cylinder of the raw material of the film (the target) and deposit these atoms or molecules as a uniform thin film on a nearby surface (the substrate) [21–25]. The sputter plasma can be inert, typically consisting of argon ions, and then the target and the thin film consist of the same material; alternatively the sputter plasma can be reactive and contain for example oxygen so that an oxide film can be produced by sputtering from a metallic target.

Table 1
Survey of thin film deposition technologies.

Atomistic deposition	**Particulate deposition**	**Bulk coating**	**Surface modification**
Vacuum environment • Evaporation • Molecular beam epitaxy • Ion beam deposition	**Thermal spraying** • Plasma spraying • Flame spraying • Detonation gun	**Wetting processes** • Printing • Dip coating • Spin coating	**Chemical conversion** • Anodic oxidation • Nitridation
Plasma environment • Sputter deposition • Ion plating • Plasma polymerization • Glow discharge deposition	**Fusion coating** • Enameling • Electrophoresis	**Printing**	**Leaching**
		Cladding • Explosive • Roll-binding	**Thermal surface treatment** **Ion implantation**
Electrolytic environment • Electroplating • Electroless deposition		**Weld coating**	**Laser glazing**
Chemical vapor environment • Chemical vapor deposition • Spray pyrolysis			
Liquid phase epitaxy			