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Ion beam induced crystalline texturing during thin film deposition

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ABSTRACT

Epitaxial films have a variety of important applications including semiconducting and superconducting devices. However, the application of epitaxy is typically limited by the necessity of single-crystal substrates. An alternative substrate technology is to artificially create a biaxially (out-of-plane and in-plane) oriented layer and use that template as the substrate for epitaxy. Here we review ion-beam assisted deposition (IBAD) methods for inducing biaxial crystal alignment during film deposition. In this review we present a historical overview of IBAD texturing and a status of understanding of IBAD texturing. A number of materials have been demonstrated to exhibit IBAD biaxial texturing. IBAD texturing of MgO is the most attractive ion texturing process today because of the high degree of alignment and because of how quickly this alignment develops. MgO texture evolution can be separated into three different regions. During initial IBAD an amorphous layer is formed, followed by onset of biaxial texture that appears in the first 1–2 nm of film deposit. Texture then improves with continued IBAD. Still further texture improvement is seen with growth of epitaxial overlayers without an ion beam, as the grains grow larger. In the best cases reported the mosaic spreads of epitaxial films on IBAD substrates have full width half maxima of less than 1°. The biaxially ordered films produced by IBAD make good templates for subsequent heteroepitaxial growth of functional layers if they are appropriately lattice matched, thus eliminating the need for single crystal substrates. We discuss applications of these artificially crystal-aligned films as substrates for energy applications such as for superconductors and photovoltaics.

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1. Introduction

Epitaxial films are commonly used today in high-performance electronics as well as for other applications such as sensors and actuators. They are also a subject of much research in the scientific community. These films retain atomic registry with the underlying substrate which is usually a highly polished single crystal. As such they are the most perfect thin films that can be grown and, depending on the material, behave almost as a single-crystal layer. Because of this high degree of perfection they typically possess the best electronic properties, such as high electron mobilities. However, epitaxial films require single-crystal substrates that are often not available in large sizes or can be expensive for commercial applications. Furthermore these films are limited by the mechanical, thermal and electronic properties of the substrates. Over the last few decades several alternative approaches have been developed to eliminate the need for single crystal substrates in epitaxy. Ion-beam assisted deposition (IBAD) texturing is one such technology that has gained popularity in the last two decades. This is in large part because it has found fertile ground for application in

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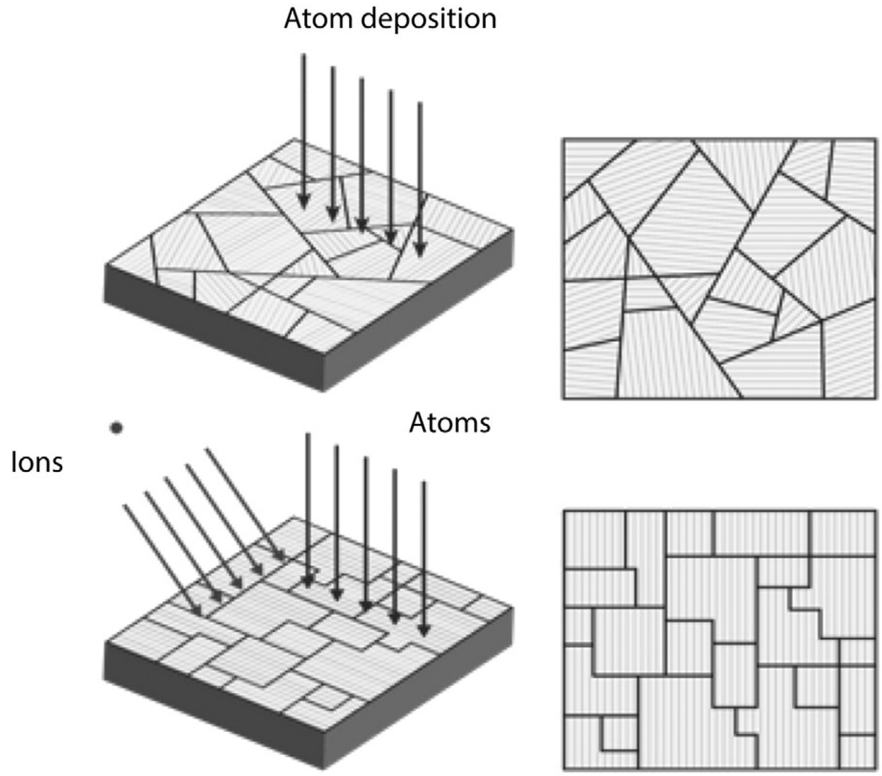

Fig. 1. Typical film deposition on a polycrystalline substrate is shown schematically on top and ion induced grain alignment is shown at the bottom.

fabrication of 2nd generation high temperature superconductor (HTS) wire known as "coated conductor." This application will be discussed further at the end of our article, but for now we note that it has been an impetus for much of the research and development in IBAD texturing. We first review texturing in films.

When a thin film is deposited on a planar unoriented substrate, the crystallites usually comprise a random configuration. Under some conditions, such as high surface mobility during deposition, grains can have a particular lattice vector oriented normal to the substrate surface corresponding to a low energy surface. Such a "fiber-textured" film possesses only uniaxial ordering: there is no preferred direction for the in-plane crystal axes.

In the early 1980s, in a research effort at IBM Research Labs led by Harper, it was discovered that biaxial ordering could be induced in a growing polycrystalline film by bombarding it with an oblique-incidence (off-normal) ion beam during deposition [1]. The irradiation favors the growth of grains on the surface that have a crystallographic axis aligned with the direction of the incident ions. In the absence of the ion beam there would be no biaxial ordering of the grains; see Fig. 1.

The next big step in this field was done at Fujikura Ltd. Labs in Japan in the early 1990s in the research group led by Iijima. The researchers at Fujikura showed that they could biaxially texture (100)-oriented yttria-stabilized zirconia (YSZ) [2]. The texture was sufficiently good to be used as a template for epitaxial growth of high temperature superconductors with much higher critical currents than one could achieve on a polycrystalline substrate.

Following that, the third major development in biaxial texturing, with even better texture attained, came from a team at Stanford University in the mid-1990s led by Dr. Robert Hammond (also one of the co-workers from the earlier IBM effort). This process is now known as "IBAD-MgO." What Hammond and coworkers discovered is that during the very early stages of IBAD of MgO, grains of crystalline MgO can immediately nucleate with biaxial alignment [3]. These grains are typically only a few nm in size and the film is less than 5 nm thick at this stage. Unlike the other IBAD processes for crystalline alignment known before, IBAD-MgO occurs right at grain nucleation and selection. For this reason, we call this process ion-beam texturing at nucleation (ITaN). Although a macroscopic theoretical model exists to explain how biaxial order slowly evolves in IBAD for materials such as Nb or YSZ [4], a complete understanding of the fundamental mechanisms of IBAD is lacking, esp. for ITaN. ITaN is clearly more complicated and several physical processes are at play during IBAD, as we will describe later in our article.

We start our review article by first giving a historical perspective on the IBAD texturing research. We then follow with a review of some key understandings of the processes. Finally we discuss some of the applications of IBAD-textured substrates. Table 1 shows a quick overview of the key initial research on the various materials.

2. Historical overview of IBAD textured material systems

2.1. Early work on metal systems

Historically the first systems to be studied for ion beam induced texturing were metals. There was early work going back to the 1950s at the CNRS-Bellevue in France [5] on ion bombardment on gold films and subsequently in the 1970s, among others most notably at the Institute of Physical Chemistry in Sofia, Bulgaria [6]. This process involved change of crystalline orientation, i.e. recrystallization of films upon normal incidence of energetic ion beams, ≥10 keV, in a variety of metals.

Simultaneous deposition and ion bombardment, i.e., IBAD was technologically enabled by the development of suitable ion sources in the 1980s and studied for crystalline orientation by several groups. The first report was by Dobrev in Sofia [7] who found the change of fiber texture in silver films from <111> (without ion bombardment) to <110> with 10 keV Ar ions. The texturing model proposed that the grains with their crystallographic planes most open to channeling, i.e. (110) planes, remained the coolest and then served as recrystallization