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Recent Developments in Perpendicular Magnetic Anisotropy Thin Films for Data Storage Applications

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The incessant demand for higher density, faster access time and lower power consuming memory devices such as random access memories have driven tremendous research and development of materials with out-of-plane magnetization. Magnetic materials with strong out-of-plane magnetization, i.e. perpendicular magnetic anisotropy (PMA), offer superior qualities compared to the in-plane anisotropy materials for hard disk drive and magnetoresistive random access memory (MRAM) devices and have been successfully commercialized in the last decade. With the recent demonstration of spin-transfer torque (STT) magnetic switching, an urge for new materials has emerged for promising STT-MRAM applications. Here, we present a brief overview of PMA materials for two important data storage applications: perpendicular recording and MRAM. We review the various PMA materials developed in recent years for STT-MRAM applications. We discuss the major requirements, challenges and future prospects of these materials for future STT-MRAM devices.

1. Introduction

The data storage industry has seen tremendous advancements recently because of the development of new materials and fabrication techniques. The never-ending challenge for any data storage technology is to continuously increase the storage density. That is the reason why magnetic recording industry has witnessed a huge transformation from the oldest generation hard disk with a recording density of 2 kbits/in^2 to today's hard disk with recording density of more than 1 Tbits/in^2 [1,2]. 'Smaller, Faster and Efficient', these are the three words which describe the ever-increasing demand for higher density data-storage, faster read-write access times and lower power consuming storage devices. In magnetic storage technology, the binary digital data are stored in the magnetization directions of tiny regions on a magnetic thin film. These regions are then read or re-written by a recording head which is placed a few nanometers above the surface of the disk. In the last five decades, due to the increasing demand for higher storage capacity, the world has witnessed an enormous reduction (by about nine orders of magnitude) of the single magnetic bit storage area. The recording technology has also changed in the meantime. Initially, longitudinal recording was used for magnetic recording. In longitudinal recording, the magnetic bits lie in the plane of the thin film medium. In contrast, in perpendicular recording, the magnetic bits are perpendicular to the plane of the recording media which is made up of material with perpendicular magnetic anisotropy (PMA). The storage density provided by perpendicular magnetic recording (PMR) can be more than an order of magnitude higher than that provided by traditional longitudinal recording and has been first implemented in hard disk drives a few years back in 2005 [3]. Combined with the ultrafast optical magnetization switching, PMA materials are expected to have the potential for ultra-high density data storage media with ultra-high speed (thousands of times faster) read-write access time [4,5]. Initially, research on PMA materials began mainly for the application in PMR [6–10]; however later on, it also attracted huge attention for application in magneto-optic recordings and advanced spintronics devices such as magnetoresistive sensors, high power oscillators and magnetoresistive random access memories (MRAM) which use spin transfer torque (STT) phenomenon [11–14].

We start our discussion with an overview of the current technological applications of PMA materials in PMR and MRAM. Next, we focus on perpendicular spin transfer torque based MRAM and their advantages. We discuss the important parameters which are

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required for the practical implementation of perpendicular STT-MRAM. Next, we present a broad review of the new PMA materials developed in the last six years for its application in STT-MRAM. Finally, we conclude with the summary, challenges and future prospects in this field.

2. Applications of PMA Materials: Recording/Data Storage

PMA materials are one of the best candidates for magnetic storage applications. They can be the building blocks of both the computer storage as well as the random access storage. Based on how the digital information is stored in a computer for user access, it can be distinguished as hard disk drive (HDD) which is actually a permanent storage and random access memory (RAM) which is a temporary storage. In HDD, data is stored for a long time and is accessed only sometimes, however, RAM is necessary for the functioning of the whole computing system. RAM is that storage where information is temporarily stored while it is being accessed or worked on, so these are called volatile memory as the data gets lost if the power cuts off accidently. In contrast, the data which are stored in HDD remains even if the power turns off. The access time or the response time of these two storage types is also different. RAM access time is millions of time faster than that of HDD. In this section, first perpendicular magnetic recording, which is a HDD storage technology, is discussed. Later on, spin transfer torque based magnetic random access memory is discussed.

2.1. Perpendicular magnetic recording (PMR)

Magnetic recording was invented in the year 1900 by the Danish scientist Valdemar Poulsen [15]. This technology is based on the fact that data can be stored in the magnetization direction of magnets, which can be read by sensing the magnetic field existing at the poles. Whereas for writing bits of information, an external field can be used to reverse the polarity of the magnets as per need. So primarily, a magnetic recording device consists of a recording medium which stores the information, a writing element (or a head) to write the bits of information by producing localized magnetic fields, and a reading element (or a sensor) which finally converts the magnetic signals from the media to electrical signals.

Perpendicular magnetic recording was first proposed in 1978 by Professor S. Iwasaki [16]. However, it took quite a long time before its actual practical implementation in commercial HDD devices. This was due to the high risks and investments needed for the manufacturing of proper PMR media and PMR read/write system as compared to the conventional longitudinal recording technology. Longitudinal recording was quite successful but faced the scalability restriction which limits its storage density at about 100 Gbit/inch^2 [3]. This limitation is due to the superparamagnetic effect, a thermal effect where magnetization can spontaneously reverse when the particle size is below a certain limit [17]. PMR was first realized in the year 2005 in the HDD of a music player manufactured by Toshiba, Japan [3,18]. After its successful implementation, research on PMR media became intense receiving huge attention from researchers worldwide [9,19–21]. Fig. 1 shows the usage trend of both recording types indicating the takeover by perpendicular recording [18].

In longitudinal recording, as the bits lie laterally in the recording media, it takes more space almost three to five times than if those are placed vertically. The fields between two adjacent bits with opposite magnetizations are separated by a transition region. To increase the storage density, the individual bits can be made smaller by placing them closer, but this increases the demagnetizing field which can erase the bit information. Thus, for a meaningful increase of the storage density in longitudinal media, the

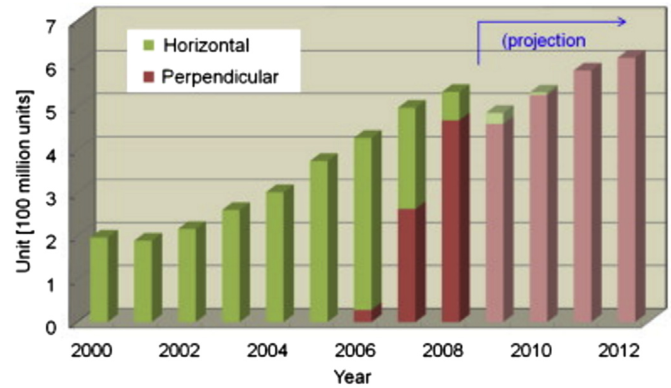

Fig. 1. An illustration of the shift from Longitudinal or Horizontal magnetic recording to Perpendicular magnetic recording hard disk drives in the world. Reprinted from reference [18]., page no. 2, Copyright (2012), with permission from Elsevier.

coercivity needs to be higher so that it counteracts the demagnetizing field to keep the bits stable under thermal fluctuations. In PMR, the bits are more stable as the magnetic field they experience is attractive in nature. The greatest advantage of PMR is that with the increase of linear storage density, the comparatively weaker in-plane demagnetizing field permits stable and low noise data storage [16]. It also reduces the interference between adjacent bits. Fig. 2 shows the schematic diagrams illustrating the working principle of longitudinal and perpendicular recording technologies. In longitudinal recording, information is written with the help of the fringing field emanating from the gap of the recording head. If the strength of the fringing field is higher than the coercivity of the medium, writing is achieved. In perpendicular recording, the vertical field is created with the help of a main pole, which then propagates through the recording medium completing a closed flux at the return pole with the help of the underlying soft under layer (SUL) which has in-plane magnetization. The SUL acts as a magnetic mirror and helps in improving the read signal [22].

The first material used for the perpendicular recording was a Co-Cr alloy film grown by RF magnetron sputtering by Iwasaki et al., in 1978 [23]. They found that the magnetocrystalline anisotropy gives rise to the perpendicular anisotropy of the films. Later in 1979, they developed another composite material consisting of the Fe-Ni soft film and Co-Cr PMA film, which showed enhanced sensitivity compared to the previous films [24]. Soon, lots of work started for finding new materials for enhanced perpendicular anisotropy and different materials were proposed such as CoCrNb, CoCrPt, CoCrTa and some ferrites [6,7,25]. Carcia et al. [26] first proposed a good PMA in Co based multilayers and after that lots of work started in different ferromagnetic multilayers [8,9,27,28]. In the last decade, quite satisfactory development has been made in PMR technology due to the successful fabrication of new and improved magnetic materials and use of giant magnetoresistance (GMR) based magnetic read heads. The detailed description of the development of recording heads and challenges to PMR technology are out of the scope of this review and can be found elsewhere [1,10,29,30]. In the following, we discuss about MRAM and PMA materials for MRAM applications.

2.2. Perpendicular STT-MRAM

2.2.1. MRAM basics

Magnetoresistive random-access memory or MRAM is the type of RAM where unlike other RAMs, information is not stored as the charge or current but as the magnetization of the reading/writing