

# Magnetic Thin Films used for Memory Devices: A Scientometric Analysis

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## ABSTRACT

Ultra-thin ferromagnetic films coupled with nonmagnetic layers are extensively studied for their potential applications in data storage. The conventional memory industry is currently in the spotlight, with researchers worldwide contributing toward better data storage technologies that can tackle the data storage problems posed by this era of big data. Various technologies such as perpendicular magnetic recording (PMR) and heat-assisted magnetic recording (HAMR) have been introduced since Poulson's idea of storing signals was conceptualized. With the introduction of new technologies, like PMR and HAMR, various materials have to be restudied for potential recording media implementation. It is vital to carry out scientometric/bibliometric studies before extensive research. It gives us an insight into the significance of the topic and the gap in the research work. This paper presents a scientometric study from 2010 to 2022 of all the magnetic thin films used for various applications. It provides an overview of the technologies and literature study of their development in data storage applications. The study discusses the analytic results from different comprehensive high indexed databases such as Scopus, Web of Science (WoS), Google Scholar, and the Institute of Electrical and Electronics Engineers (IEEE). To contribute meaningful insights and the perfect representation of the extracted data, various tools like iMapbuilder, Gephi and RAWgraphs are used in this article.

**Keywords:** Data storage application, Magnetic recording media, Resistive switching memory, Magnetic anisotropy, Ultra-thin ferromagnetic films, Scientometric analysis.

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## INTRODUCTION

Magnetism has overgrown in recent decades, exposing a wide range of magnetic phenomena and enabling the development of several nanodevices. Magnetic advancements have spanned many applications, from compass needles to magnetic storage devices, demonstrating that the human intellect has persisted in developing innovative technologies. Many magnetic phenomena are becoming more well-known because regulating magnetic properties results in significant technological achievements such as nanomechanical devices, spin valves, and quantum computers. Magnetism is explained by quantum physics, namely Pauli's exclusion principle and the presence of electron spin. It is, nevertheless, recognized for a variety of classical phenomena emanating from both short- and long-range forces, and it is intimately connected to microstructure or phase arrangements.<sup>[1]</sup>

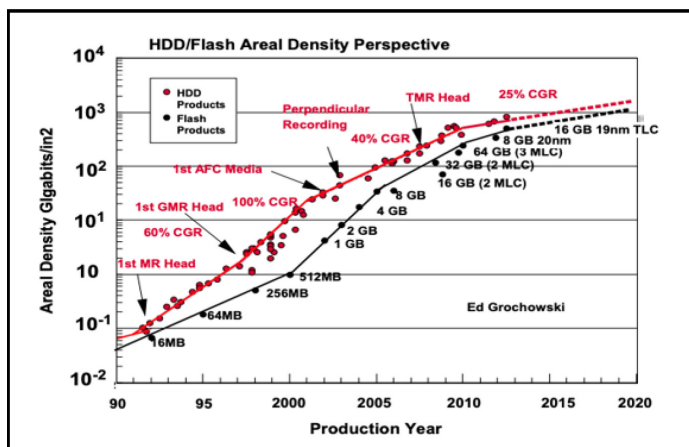
Magnetic thin films and multilayers have attracted much attention in recent years and have emerged as an important area of magnetism research. They have been the subject of extensive research due to their wide range of applications in

sensors, actuators, micromagnetic devices such as inductors, transformers, valves, motors, etc., and in particular magnetic data storage devices such as hard discs, magnetic random access memory, and perpendicular magnetic recording media. Magnetic thin films have unique properties due in part to their overall shape, with the perpendicular coordinate (z-direction) being much smaller than the lateral (x-y directions) coordinates. The main feature of current magnetic thin films is the capacity to deposit material with control over individual atomic layers. This enables the creation of intentionally stacked materials with qualities not present in nature. One of the original structures in this class consisted of two ferromagnetic layers separated by a nonmagnetic spacer, resulting in an antiferromagnetic interaction between the two ferromagnetic layers.<sup>[2-4]</sup>

Since the invention of the hard disk drive, information storage technology has seen significant attention and improvement. Primary research and developments are worldwide to improve these drives' areal storage density. Magnetic recording was invented more than a century ago by Danish scientist Valdemar Poulson.<sup>[5]</sup> Since its discovery, it took 30 years for the magnetic tapes to be successfully commercialized. Because of this mammoth effort, the areal density of recording media has increased exponentially in the last six decades.<sup>[6]</sup> An average annual increase in storage density has consistently been more

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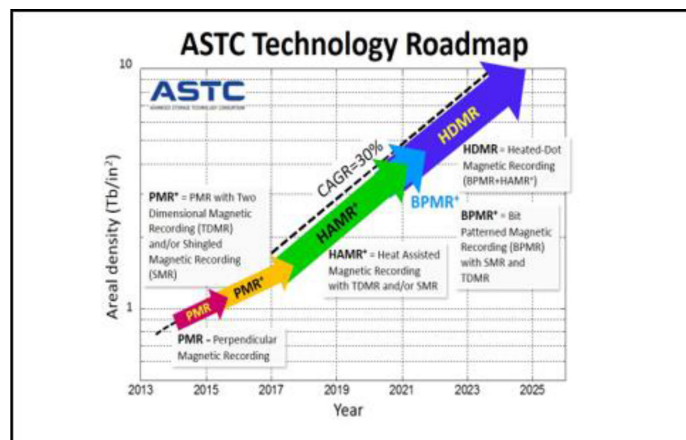


**Figure 1:** Improvement in the areal density of hard disk drives since its discovery in 1956. The Figure is taken from Ref.<sup>[8]</sup>

significant than 25% at times, even outpacing Moore's law with areal density increases by 100% per year in the 90s.<sup>[7]</sup> Figure 1 shows the improvement in the areal density of hard disk drives since RAMAC in 1956. Increasing the recording density meant downscaling all the components in a recording system. It is clear from the developments in the past that the design of magnetic media and continuous increase in storage density signifies the reach of saturation towards storage devices.<sup>[6,7]</sup>

The magnetic storage discs are either particle-based or thin-film-based. In the case of particles, an organic binder is used to keep these magnetic particles in place. Most recent magnetic storage technologies are thin-film-based, encompassing complex structures. The medium should be thin and highly coercive for a thin film recording media to have a high areal density.<sup>[9]</sup> Two main concepts are used by thin-film recording media: longitudinal magnetic recording (LMR) and perpendicular magnetic recording (PMR). However, based on the type of recording media discussed, the necessary conditions are different. High magnetic saturation and high coercivity are expected, whereas, in longitudinal recording, media samples with low magnetic saturation and high coercivity are expected.<sup>[10]</sup>

Flexible electronic gadgets have gotten much attention as the Internet of Things (IoT), and wearable goods have grown in popularity. All stiff electronics building blocks, such as active components, optoelectronics, magneto-electronics, and energy storage elements, must be reshaped after production to realize flexible electronics.<sup>[11-13]</sup> Some commercially available shapeable electronics, including electronic displays,<sup>[14-16]</sup> energy storage elements, and integrated circuitry, are currently available. The majority of the research has been focused on manufacturing shapeable high-speed electronics and optoelectronics since the outset. Magnetic capabilities were just recently added to the family of shapeable electronics.



**Figure 2:** Trend observed in data storage technology over the years, also the importance of HAMR in the future of data storage technologies.

As we all know, magnetic materials play a significant role in producing electrical gadgets. Ferromagnetic materials, for example, play a vital role in magnetic sensors and magnetic storage systems.<sup>[17-18]</sup>

The second biggest industrial revolution has presented us with an ever-growing thirst for storage spaces. In the age of cloud computing and smartphones, the need for improved storage spaces to cater to people's needs is never-ending. To address the above issue, researchers from all over the world have developed, and presented different types of magnetic materials. These materials range from bulk ferromagnetic material like Fe (used to store audio signals) to ferromagnetic thin films like Co/Pd,<sup>[19]</sup> Co/Cu,<sup>[20-21]</sup> Co/Au,<sup>[22-23]</sup> and transition metal oxides over time to increase areal density. Figure 2 shows the development in data storage since its inception. The data is taken from (T. International D. D. E. and M. Association, "ASTC-Technology-Roadmap-2014-v8." 2016).

### Related work and bibliometric analysis

As mentioned earlier, Valdemar Poulsen, in 1900, used bulk iron (Fe) films to record audio signals; he created the first-ever magnetic recording device.<sup>[5]</sup> Researchers tried several films and substrate materials to get better recording density, but considerable attention has been given to magnetic multilayers.<sup>[24]</sup> The discovery of perpendicular magnetic anisotropy (PMA), giant magnetoresistance (GMR), tunneling magnetoresistance (TMR), and the oscillatory behavior of interlayer magnetic coupling changed the whole path of recording media. Iwasaki 1980 proposed the concept of perpendicular magnetic recording; till then, longitudinal magnetic technology had been the base for data storage applications. PMR boasted better storage density using thin films than thicker films (10). Following Iwasaki, Carcia *et al.* 1985 reported PMA in Pd/Co coherent structures. They

said that a change in ferromagnetic layer thickness leads to a transition in magnetization.<sup>[19]</sup>

In 1994, Larison *et al.* reported the presence of high demagnetization energy in Pd/Co structures. Their results reveal that the demagnetization factor present in the Co/Pd structures can be controlled upon adding the Cr layer. The article also reported the enhancement of PMA upon adding the buffer layer.<sup>[9]</sup> Lianju Wu *et al.* in 1999 compared the preparation methods of films and noted that the sputtering technique showed better magnetization than physical vapor deposition (PVD). The study also observed the difference in coupling between Co grains. The study showed that air oxidized Co from PVD reported less coupling between Co grains, reducing Co/Pd multilayer magnetization. Holger Stillrich *et al.* 2009, reported that with a change in the thickness of the ferromagnetic layer, the magnetic properties and orientation of the magnetization of the multilayer changed. Their results state in-plane magnetization was observed when the thickness of Co was till 1.3 nm. The result proved that the orientation of the magnetic moments is thickness dependant.<sup>[25]</sup> Amitesh Paul *et al.* 2003 prepared high-quality Co/Cu films. They reported that their Co/Cu films showed GMR, and it largely depended on the thickness of the Co layer. They also said PMA in Co/Cu multilayer.<sup>[26]</sup>

Researchers like W. Check-Rouhou *et al.*,<sup>[27]</sup> Donzelli *et al.*, G. Gubbiotti *et al.*,<sup>[28]</sup> and Marcatoma *et al.*<sup>[29]</sup> reported PMA in Co/Au multilayers. Check-Rouhou stated that in Co/Au multilayer system, change in the Co layer leads to variation in magneto-optic response resulting from a change in surface anisotropy. Meanwhile, Donzelli reported that a suitable buffer layer could enhance observed magnetic properties. The buffer layers can also reduce the surface interface roughness of the films. His observations revealed that film preparation condition significantly impacts the film's magnetic properties. Marcato *et al.* reported that with varying film thickness and layer repetitions, we could control the spin reorientation transition taking place in the Co/Au multilayer.<sup>[27-29]</sup>

Various magnetic, nonmagnetic, and magnetic/nonmagnetic films are studied for their potential application in the data storage industry. Different magnetic properties such as magnetic anisotropy, giant magnetoresistance (GMR),<sup>[9,30,31]</sup> exchange bias<sup>[32-33]</sup> and tunnelling magnetoresistance (TMR) are exhibited by these above-discussed films that form the basis for potential data storage applications. Studying and developing knowledge about these properties can help engineer the media that could host better areal density for future data storage applications.

### Need for Bibliometric Analysis

The bibliometric analysis is used to locate the research gaps effectively and provide further insight into the intended field.

The study also contains all the important scientific discoveries, notable works, and other specifics along the timeline related to the field. Alan Pritchard (1969) introduced the term and stated its applications are apropos throughout the streams interested in exploring this field. We performed the quantitative analysis by introducing the potential researcher to emerging materials for data storage applications. As more and more researchers are trained for this research problem of finding better areal density media, the field is getting dense and vast, filled with numerous prospects and concepts to work with. S.N Piramnayagam<sup>[9]</sup> discussed various methods and their forms used for data storage applications. This book had compiled all the recent advances in data storage applications: from a materials perspective until the year 2010. In this article, we provide a detailed quantitative analysis of the topic, which could help the researchers find their respective research problems.<sup>[34-35]</sup>

### Designing Keywords search Strings and Methodology

The predominant thought behind drafting this paper is to pinpoint and accentuate the relevant work in the field of data storage applications. A well-documented review contributes to the well-drafted summary of a specified subject while identifying some research questions. This can be achieved in three systematic steps, as Rowley and Slack.<sup>[36]</sup> The first step is to identify and use accurate and well-defined search keywords, retrieve the literature and analyze the structured literature reviews.

Fahimnia 2015 stated that to improve the efficiency of bibliometric analysis and contribute a reliable historical review, enhancement of the search results has to be done. So, the titles and abstracts of the original articles are screened carefully, and the articles irrelevant to the subject field are discarded. The refined search results comprising all the data, including title, abstracts, keywords, authors, affiliations, and references, were compiled for further analysis. While doing a keyword search, the following observations are considered and met.

1. Initial keyword search resulted in other terms with overlapping meanings.
2. As database key search was standard, acronyms increased the possibility of including non-relevant papers and articles with search results. This anomaly arose due to the existence of common acronyms across different fields.
3. To obtain a complete list of relevant information, non-overlapping keywords are used. This enabled the end-user to fetch data from the data storage applications domain.
4. Keywords are vital components, and precise words can lead to finding related algorithms and similar mathematical models.

### Preliminary Data Analysis

Table 1 shows the proposed keyword search strategy planned and executed for this article. The keywords were kept the same for all the databases to maintain consistency and get precise results.

The extracted data using by above method were analyzed using Microsoft Excel (Microsoft Corporation, USA). In addition, VOSviewer (Leiden University, Netherlands), RAWGraphs (DensityDesign, Italy), IMapbuilder (opensource software, WebUnion Media) Gephi (opensource) were used to construct different types of graphs and Figures which explain the collaborations, geolocations of the publications, etc.

## RESULTS

### Country, Institution, and network analysis

Table 2 shows the paper count per year since 2010 from both Scopus and the web of science database available for researchers. From the above Table, it is clear that publications in the data storage application have seen a sump around 2015 and 2016. However, post-2016, the number of publications

**Table 1: Shows the proposed keyword strategy for Scopus, web of science, and science direct.**

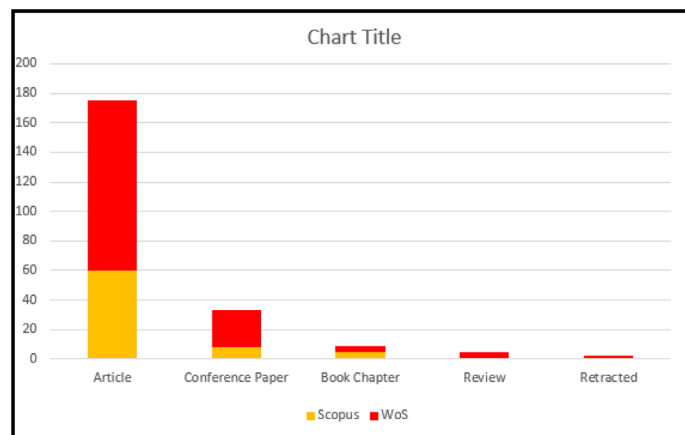
Master Keyword (and)	Magnetic thin films
Primary keywords (and)	“Data storage” or “Magnetic memory devices” or “Magnetic nonmagnetic thin films” or “Magnetic/ Nonmagnetic superlattice”
Secondary Keywords (and)	“Spin reorientation transition” or “magnetic reversal” or “Magnetic switching” or “Magnetic anisotropy” or “exchange bias” or “GMR” or “surface interface roughness”

**Table 2: Keyword searches by various databases from 2010 to 2021 (28<sup>th</sup> April 2022).**

Year	Scopus Document count	WoS Document count
2021	06	11
2020	08	10
2019	08	09
2018	07	07
2017	04	08
2016	10	08
2015	05	08
2014	06	18
2013	06	09
2012	05	13
2011	03	12
2010	02	07
Total	76	122

has increased linearly. Most publications are from the web of science (WoS), followed by Scopus. Figure 3 compares several sorts of documents submitted within the time range specified. The data is obtained from Scopus and Web of Science, indicating the nature of the entries registered each year for twelve years. Most entries were in the context of scientific articles, followed by conference pieces and review articles, and book chapters. By comparing the titles and abstracts of the submissions, it is clear that most of the scientific publications submitted are focused on basic research. However, while many studies claim to have specialized or broad applications, most of the study summarised in this article examines the fundamental features of magnetic thin films. Our extensive quantitative analysis shows that knowing the dynamics of the essential characteristics will aid researchers in tuning or modifying thin films for various applications.

Figure 4 depicts the geographical position of the various articles using Imapbuilder (a free open source internet visualization tool). Substantial entries have been filed for



**Figure 3: Data extracted from Scopus and WoS about different types of entries registered in each database from 2010 to 2022.**



**Figure 4: Publications submitted from various parts of the world. The image was developed using Imapbuilder using, Scopus, and WoS databases. The data was searched on 28.04.2022.**

**Table 3: Top 15 countries' publications in the field of magnetic thin films for data storage applications.**

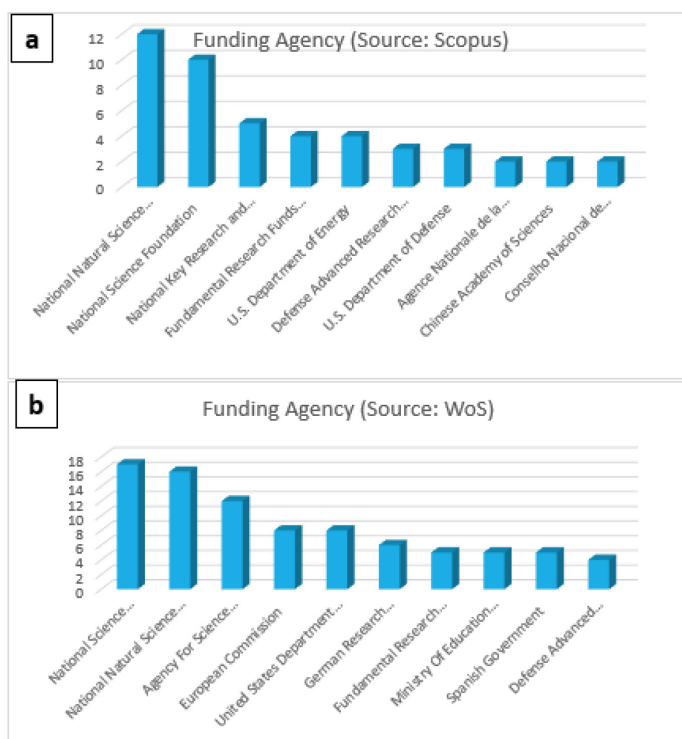
Sl.No	Countries	Scopus database	WoS database
1	Peoples Republic of china	0	50
2.	China	16	45
3.	USA	19	45
4.	Germany	12	31
5.	India	07	19
6.	France	11	17
7.	England	07	13
8.	Switzerland	05	12
9.	Spain	07	10
10.	United kingdom	07	10
11.	Japan	03	07
12.	Poland	01	06
13.	Russia	01	06
14.	Singapore	02	06
15.	Taiwan	02	06

Source: web of science (accessed on 28.04.2022).

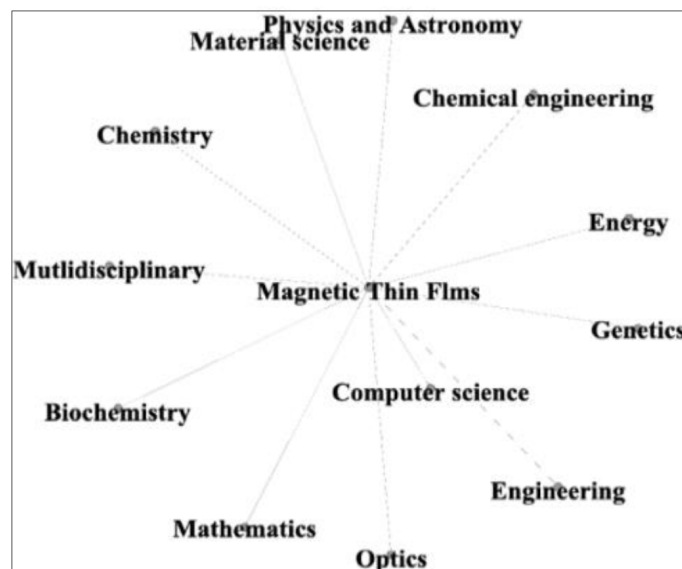
China, the People's Republic of China, and the United States of America using the keywords above. However, nations such as India and European countries like Germany, France, and Switzerland have made significant contributions. Asian countries such as China, India, and Singapore have played an essential role in the area of magnetic thin films. Table 3 shows each publication published in different countries. Figures 5a and 5b depict various financial sponsors from the Scopus and Web of Science databases. The picture clearly shows that the United States and China have supported nearly (85 percent) of the magnetic thin film research. The sponsor's Figure indicates that most of the money is devoted to fundamental research on magnetic thin films. Aside from basic research, the funders include the U.S. Departments of Energy and Defence. This represents the numerous uses of magnetic thin-film technologies. An in-depth quantitative study can give us appropriate nodes and edges that depict transparent networks resembling authors' inter-disciplinary activity in this subject, authors' partnerships, and, eventually, keywords search networks.

### Network Analysis

Network analysis can be the best tool to illustrate the relation and the connection between various parameters. Network analysis in the bibliometric reviews plays a crucial role in visually explaining the relationship between the authors from multiple organizations, the use of materials in numerous domains, etc. The cluster analysis in this article has been done using Gephi. Gephi is an open-source program used to perform network and cluster analysis. In Gephi, the data can be altered and displayed



**Figure 5:** Various funding sponsors agencies. The data extracted from (a) scopus database (b) WoS database.



**Figure 6:** Cluster analysis of the use of magnetic materials in various domains.

using nodes and edges. The use of magnetic materials in various domains is illustrated in Figure 6 using the data from Scopus and WoS publications. A significant portion is from Physics and Material Science. These major domains are interlinked with other sectors such as engineering, optics, mechanics, computer science, etc. S.I. Kasatkin *et al.*<sup>[37]</sup> NiFeCo/CoFe/CuAgAu reported their usage in developing state-of-the-art

illness detection systems. The system employs Lab on a chip (LOC) biosensors, with the detecting element consisting of a matrix of thin-film anisotropic magnetoresistive (AMR), giant magnetoresistive (GMR), or spin-tunnel magnetoresistive (STMR), or magnetic field sensors based on multi-chip planar technology. Since the literature has stated that these systems exhibit perpendicular magnetic anisotropy, the same Co/Fe, Co/Au, and Ag/Co/Au systems have been thoroughly explored individually for their recording medium applications (PMA).<sup>[38-40]</sup> Because of the strong coupling between their electrical, mechanical, and optical responses, ferroelectric materials have been extensively studied for a wide range of applications, including sensors, capacitors, nonlinear optical components, piezoelectric actuators, energy harvesting and storage, micro-electromechanical systems, and high-power electronic transducers.<sup>[30,41-46]</sup> Many thin-film systems, including SrMnO<sub>3</sub>, (LaAlO<sub>3</sub>)<sub>0.3</sub>(Sr<sub>2</sub>AlTaO<sub>6</sub>)<sub>0.7</sub>, BiFeO<sub>3</sub>, and BaTiO<sub>3</sub>, are being studied for ferroelectric applications. According to Lee *et al.*,<sup>[47]</sup> electrically induced alignment of these PNRs can produce room-temperature ferroelectricity in strain-free SrTiO<sub>3</sub> films. Damodaran *et al.*<sup>[48]</sup> discovered an increase in ferroelectric Curie temperature in BaTiO<sub>3</sub> films by using defect dipoles to create extra anisotropic lattice deformation.

The initial study demonstrated how ferromagnetic or magnetic thin films are employed in various applications. Thus, we used network cluster analysis to discover the relationship between magnetic light film system applications and how elemental physics analysis assists them to be suitable for various applications. The author's keywords were employed as an input for this cluster analysis, as seen in Figure 7. By these methods, we can comprehend collaborative research done between the researchers and the use of magnetic materials in different domains. Figure 7 clearly shows two significant and many minor clusters. "Fruchterman Reingold" algorithm was used in this analysis.<sup>[49]</sup> The Fruchterman-Reingold layout works well for many major social networks. However, some modifications may be required. It is an example of a force-directed algorithm, which uses the analogy of physical springs as edges that draw linked vertices and a competing repulsive force that pushes all vertices away, whether connected or not. It usually results in edges with comparable lengths, even though the size of edges has no particular value in most network representations. The overall cluster consists of 2361 nodes and 2731 edges, which describe keywords and source titles. In Figure 8, two significant nodes are visible. The two primary nodes result from the keywords "Data storage" and "Magnetic properties." The direct and most well-known application of thin magnetic systems is in data storage. These magnetic thin film systems are widely used in different aspects of a data storage device, eventually becoming a fundamental component.

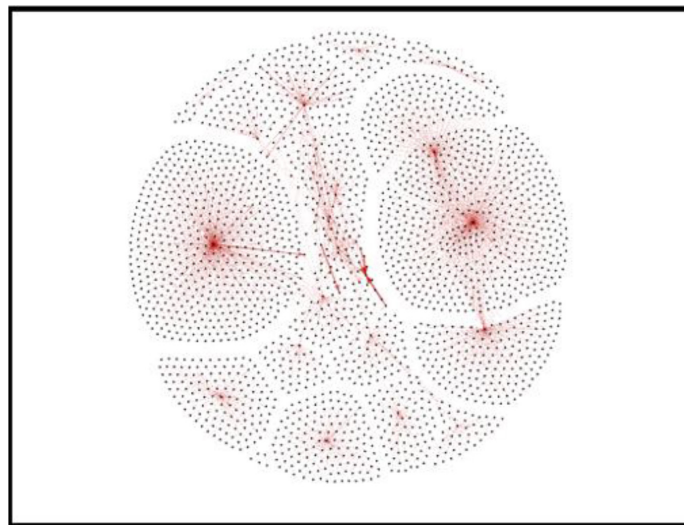
Furthermore, this was highly evident from our earlier remarks and the authors' funding agency. As a result, this node has more nodal connections than the others in the analysis. The second node is "Magnetic Properties," It is abundantly evident that each magnetic thin film exhibits unique magnetic properties. The presence of one or more magnetic properties qualifies the thin-film system for the application. As a result, this node has more nodal connections than the others in the analysis. The second node is "Magnetic Properties," It is abundantly evident that each magnetic thin film exhibits unique magnetic properties. The presence of one or more magnetic properties qualifies the thin-film system for the application. As a result, in addition to the major node, this node has two minor spheres along its perimeter that are linked to the major node. These small sphere nodes are analogous to the key term magnetic property in their respective applications. The above-stated observation is well reflected in Figure 8. The cluster analysis in Figure 8 shows a major node in the center, followed by very few nodes on the outer ring. Figure 8 consists of 915 nodes and 1639 edges in total. However, Yifan Hu's algorithm was used for this analysis. This analysis is excellent in analyzing the cluster network related to the author's publication and citation. Numerous branches follow the bright central nodes.

### Author Statistical Analysis

The top ten contributing authors in data storage applications are considered and mentioned in Table 4 for in-depth analysis to understand the influence of a specific author in the field.

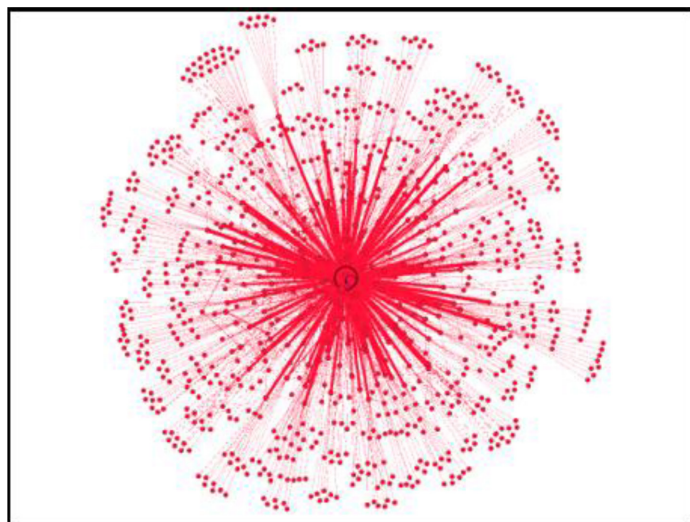
### Author Affiliation Analysis

The majority of the authors are associated with reputed colleges or institutes worldwide. Notable examples include



**Figure 7:** Cluster analysis of keywords used by the author and source title (journals).

Data source: WoS



**Figure 8:** Cluster analysis of the Authors' citations and the networks. Data source WoS.

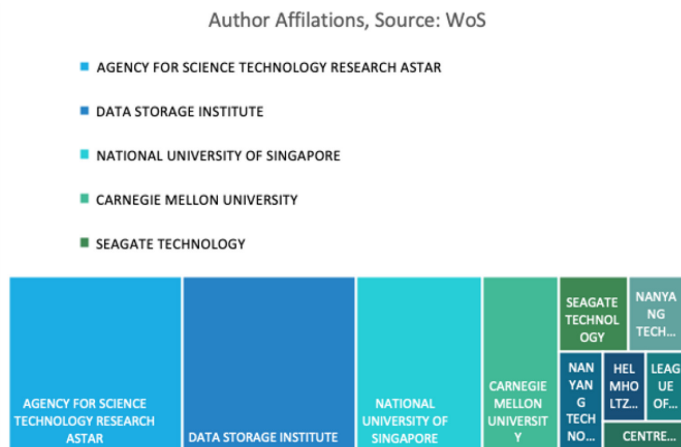
**Table 4: Authors contributing in "Magnetic thin films for data storage applications".**

Top ten Author rank	Author name (Scopus)	Author name (WoS)	Author count	
			Scopus	WoS
1	S. Valencia	S.N. Piramanayagam	03	10
2	M. Albrecht	J.S. Chen	02	08
3	L.Balcells	T.C Chong	02	06
4	C. Feng	R. Sbiaa	02	06
5	Y. Han	G.M. Chow	02	05
6	F. Kronast	G.C. Han	02	05
7	D. Makarov	H.K. Tan	02	05
8	G. Markandeyulu	M.H. Kryder	02	04
9	F. Radu	J.R. Chen	02	03
10	P. Rajasekhar	S.C. Chen	02	03

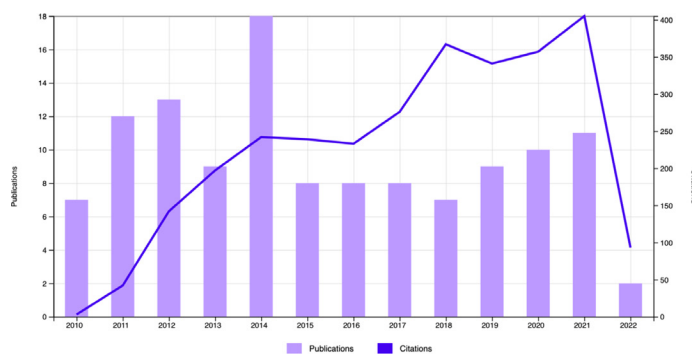
source: Web of Science database (Accessed on 28.04.2022)

the agency for science, technology, and research in Singapore, the data storage Institute (affiliated with A\*Star), the National University of Singapore, and others.

Singapore has three of the top three spots. Singapore has been particularly active in data storage technology innovation through its numerous institutions and organizations. S. N. piramanayagam, for example, is a member of the same university. In the past and present, agencies for science, technology, and research have been actively involved in creating some high-quality research through their fundamental approach to the world's pressing problems. The data storage institute's more focused division has contributed significantly to data storage applications. Other institutions include Carnegie Melon University in the United States, Seagate Technologies in the United States, Nanyang



**Figure 9:** Top ten institutional or organizational affiliations in the field. Data source: WoS Accessed on 28.04.2022.



**Figure 10:** The number of publications recorded each year along with their citation. Source WoS accessed on 28.04.2022

Technical University in Singapore, Nanyang technological university National institute of education (NIE) (Singapore), and Helmholtz Association (Germany). Seagate Technologies is a well-known and prominent data storage corporation. The company has been working on novel data storage technologies collaborating with various universities and research institutions worldwide. This article indicates that collaborative work happens between tech companies and universities worldwide.

### Citation Analysis

Figure 9 and 10, show the trend in citations from 2012 to the latest. The trend shows increasing citations with the year.

### Summary of Magnetic Thin-films for Data Storage Applications

The numerous advantages of magnetic thin films are discussed in this article. The definition of thin films has evolved as deposition processes, and precise thickness control has developed. This section focuses on films smaller than 50 nm thick since they encompass practically all of the technologically

significant situations, both in terms of research and electrical devices that are now in production. This paper employs a careful and thorough scientometric analysis to provide an academic overview of the use of magnetic thin films in several industrial applications today and in the future. Various graphical and statistical methods emphasize data obtained from two independent databases, Scopus and Web of Science (WoS).

The concept of magnetic recording was invented almost a century ago by Valdemar Poulsen<sup>[51]</sup> and was commercialized successfully 30 years after.

Various concepts of magnetic recording and recording media are developed and introduced to future researchers working in this field. Data storage technologies are more prominent in south Asian countries like Taiwan and South Korea than in the rest. Major production facilities for global flash drives and some complex disk components exist in this region. This results in international countries working with South Asian countries to develop state-of-the-art data storage technologies.

Katine *et al.*<sup>[50]</sup> created 100 nm-diameter thin-film pillars out of two Co films of varying thicknesses separated by a Cu spacer in 2000. The scientists investigated the effect of spin-polarized currents flowing perpendicular to the layers on controlled reversal of moment direction in the thinner Co layer. The spin-transfer torque (STT) phenomenon provided the first experimental proof of switching and spin-wave excitation. Hard, permanent magnet thin films are often thought of in the context of recording media, where coercivity has progressively grown from a few hundred Oe in the mid-1980s to around 5 kOe at present. Our investigation revealed that CoCrPt alloys were widely used for recording media until the early 2000s, with current research and development activities focusing on FePt alloys with L10 ordering, RE-FeB systems, where RE is a rare-earth element (typically Nd or Nd/Pr), and SmCo<sub>5</sub> are the two forms of thin-film permanent magnets that have attracted the most attention in recent years. Because they offer the most significant energy product (B. H.) max of any commercially available material, Nd<sub>x</sub>FeB-based magnets are the materials of choice for many applications. Kruusing, Serrona, and Chen *et al.* improved base coercivity and magnetic saturation by using different alloying systems such as NdFeB, FeB. The analysis also emphasizes a recent work that focuses on the influence of seed layers of Cu<sup>[51-52]</sup> and Ru<sup>[53-54]</sup> in improving the microstructure and magnetic characteristics of SmCo<sub>5</sub> for data storage applications.

The analysis also praises the usage of CoCrPt-based alloys, which demonstrated considerable areal recording densities ranging from 10 Mbit/in<sup>2</sup> to 600 Gbit/in<sup>2</sup>. It should be mentioned that ordered alloys of FePt, FePd, and CoPt are now being investigated to understand their fundamental

characteristics better and assess their feasibility for future data storage applications. The preliminary research and findings summarised by multiple research groups on CoCrPt-based alloys, most notably Yung *et al.*,<sup>[55]</sup> Toney *et al.*,<sup>[56]</sup> and Barmak *et al.*,<sup>[57]</sup> sparked a special interest in CoCrPt-based alloys as a viable medium in a heat aided magnetic recording system.

### Summary of Magnetic Thin-films for other Applications

In recent years, thin films prepared from Heusler alloys have received much interest. An interest that is strongly tied to the evolution of spintronics research. Cu<sub>2</sub>MnAl was the first compound discovered in this class of materials in 1903 by Friedrich Heusler,<sup>[18,58]</sup> after whom the system is called the Heusler alloy. Summarized studies from Johnson *et al.*,<sup>[59]</sup> in 1996, Inomata *et al.* in 2003, Wang *et al.*<sup>[60]</sup> in 2009, and H. Sukegawa *et al.*<sup>[60]</sup> in 2010 together provided a more profound knowledge of the ideas of Heusler alloys for future generations, as well as a road map of its numerous practical applications. Heusler alloys have applications in various domains, including spintronics, the spin Seebeck effect, semiconductors, thermoelectric, superconductors, and spin calories.

Biosensors are made from materials with high magnetoimpedance, such as FeCoCrSiB, FeCoSiB, and Co<sub>64.5</sub>Fe<sub>2.5</sub>Cr<sub>3</sub>Si<sub>15</sub>B<sub>15</sub>. These sensors are used to determine the amount of saline and urea in the body. For spin-Seebeck effect (SSE) applications, several magnetic thin-film systems such as Y<sub>3</sub>Fe<sub>5</sub>O<sub>12</sub> (YIG) and zigzag graphene nanoribbon (GNR) are employed. The spin-Seebeck effect SSE is a phenomenon that allows heat currents to be converted into a spin voltage, a potential for generating non-equilibrium spin currents, in a ferromagnet, and it was recently identified utilizing the inverse spin-Hall effect. Depending on the phenomena being studied, several types of magnetic thin films are utilized, such as permalloy for AMR, Co/Cu multilayers for GMR, and Fe, Co, CoFe, CoFeB, NiFe, or Heusler alloys for TMR. Finally, it is worth mentioning that different writers are studying the subject of nonmagnetic thin films, which has a wide range of possible uses. Thin films such as GaMnAs, Tl<sub>x</sub>D<sub>x</sub>MnO<sub>3</sub>, La<sub>1-x</sub>Sr<sub>x</sub>MnO<sub>3</sub>, CoFe<sub>2</sub>O<sub>4</sub>, MnFe<sub>2</sub>O<sub>4</sub>, and NiFe<sub>2</sub>O<sub>4</sub> are used in contemporary spintronics, biomedical and other sensors, and so on.

Our analysis shows similar results. Major research articles in the field of data storage technologies are since the last decade is from the USA, China, and India a minor percentage of reports coming from France and the united kingdom. Tech giants like Seagate, western digital are found to be the chief funding sponsors in these articles. The analysis also shows increased publications with increased citations from 2014. These observations could reveal the active work in data storage applications to cater to the needs for increased data storage.



With increased technological advancements, the demand for increased storage space in smartphones and in computers is evident.

Another major finding is that the magnetic materials used in the data storage industry are also used in various other fields for different applications. Our study suggests that Co/Au and Co/Cu magnetic thin films exhibiting giant magnetoresistance (GMR) are chiefly used for neuroimaging applications and MRI scans.<sup>[9,61]</sup> The medical industry heavily uses magnetic materials in the form of nanoparticles for targeted drug delivery, cancer treatments etc.<sup>[62-63]</sup> Likewise, our analysis shows a further implementation of discussed magnetic materials in other fields such as material science for developing GMR sensors and other biosensors,<sup>[64]</sup> genetics for gene mapping,<sup>[65-66]</sup> and drug delivery, space applications.<sup>[67-68]</sup>

Furthermore, we identified various approaches related to data storage applications. Recent reliable methods like heat-assisted magnetic recording (HAMR) can be used to fabricate devices that could possess increased data storage density. HAMR methods show significantly less demagnetization factor associated with the magnetic thin films. Essential elements needed for better storage density, such as high coercivity and high magnetic saturation, were also observed with heat-assisted magnetic materials. Finally, these materials are stable at high temperatures, which shows their stability and longevity.

### Future Scope

The research on “magnetic thin films for data storage applications” is continuously getting explored worldwide. The industrial sector perhaps demands a desirable and promising solution in data storage applications. The industrial revolution increased smartphones, and computer sales may fuel the research during the big data storage companies like Seagate and IBM fund the study. Upon introducing new technologies like HAMR, there is more scope in material optimization for further development. Many new magnetic materials are researched and tested for their stability and the ease of fabrication for having economic but stable heat-assisted magnetic recording devices.

### CONCLUSION

Metallic magnetic thin films are a bright and busy field of scientific study that serves as the foundation for numerous technological developments. Much of this attention is centered on films thinner than 50 nm, influencing the work discussed above. However, it is acknowledged that this is an arbitrary Figure 10, and work on thicker films is noted if needed. The rising capacity of lithographic methods to build nanoscale structures in all three dimensions. This enables several thin-film phenomena to be utilized through the ability to concentrate spin current to create spin-transfer

torque devices or fabricate structures suitable with magnetic length scales, i.e. the exchange length 10 nm. The worldwide research in “Magnetic thin films for commercial applications” is witnessing steady growth. The huge demand for better recording media, flexible sensors, renewable energy, and the availability of better technology to support and help optimize the materials needed for forming a better media can always bring new researchers to the field. Various magnetic thin films are potential candidates for better recording media. Apart from magnetic thin films, recent literature suggests that some transition metal oxides can also be used. With better sputtering technologies and better lithography technologies, better ultra-thin films can be formed and studied. By understanding the fundamental properties of the materials, they can be further engineered and enhanced for memory applications.

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### CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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