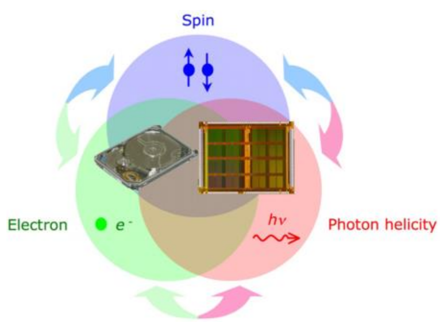
Office of the Assistant Secretary of Defense: Research & Engineering (OASD(R&E))

TECHSIGHT SNAPSHOT REPORT

SEPTEMPBER 2017

Office of Net Technical Assessments (ONTA)

# Spintronics




[1]

## Executive Summary

*Spintronics uses the magnetic nature of an electron's spin for information recording, retrieval and storage. First-generation spintronics (magneto-electronics) has already made a large impact by yielding the high-capacity terabyte hard disk drives that are ubiquitous today. Second-generation spintronics, based on spin dynamics and the integration of new materials such as graphene and dilute magnetic semiconductors, are emerging today. So-called third generation spintronics are geared toward quantum computing architectures, making spintronics a potentially disruptive technology for secure communications, while also increasing storage density three orders of magnitude (i.e. single-spin storage). Spintronics is a large and fast-growing field, producing 2500+ articles per year at an accelerating rate. Meanwhile, patent activity surged after the birth of magneto-electronics in the late 1990's, but has since stabilized to a steady output of 450±50 patents. For decades, the USA has dominated the research and innovation landscape (publications, patents, citations etc…) in spintronics, but in 2013, China has since risen to the top position of most articles generated per year. Future spintronic devices are expected to be more robust than traditional electronics, including tolerance to very high temperatures and potentially offering intrinsic radiation hardening, all with the promise of high-capacity data storage in increasing smaller platforms such as nano-UAVs and swarm-UAVs.*

[1] Graphic element is derived from (Hirohata & Takanashi, 2014)

# I. Introduction to Snapshot Reports

Snapshot reports provide a short overview of recent activity in emerging and potentially disruptive research areas using quantitative metrics generated from the statistical analysis of publication trends in the scientific and patent literature exclusively using ONTA's TechSight System. The aim of these reports is to generate questions for deeper investigations, and they are engineered to be produced monthly in a rapid, timely fashion with figures automatically generated by TechSight. Since these figures are inserted from a dynamic interface, readers are encouraged to access this data on TechSight for further exploration. TechSight is available to all DoD personnel and contractors (*see APPENDIX for access instructions*). Future snapshot reports will analyze top organizations and entities as system improvements to TechSight such as entity disambiguation is implemented.

# II. What is Spintronics?

**"Spintronics is the study of the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices.** It is also called "spin transport electronics, spinelectronics or fluxtronics. (Wikipedia, n.d.)" The basic innovation arises from the observation that "electrons can spin in two directions (clockwise and anti-clockwise), and the spin is detectable as weak magnetic energy. (Spintronics-info, n.d.)" The additional use of the spin state of an electron results in more freedom in information transfer and storage (Wikipedia, n.d.). Another advantage of spintronics over traditional electronics is that "spintronic device do not need an electric current to retain their "spin". Spin is more reliable, and such devices will operate better in high temperature or radiation environments. Theoretically, spintronic devices will be smaller, faster and more powerful than electronic ones (Spintronics-info, n.d.)."

**First-generation spintronic devices based on Giant Magnetoresistance (GMR) and Tunnel Magnetoresistance (TMR) are commercially available today as high-capacity Hard Disk Drives (HDD)**. "Both GMR and TMR are based on the s–d interaction between a local magnetic moment and the conduction electron to be spin-polarized. This is a combination of magnetism and electronics and primarily uses spin-polarized electron transport leading to *magnetoelectronics* (Hirohata & Takanashi, 2014)." In 1997 IBM introduced the "spin-valve" GMR head in a 16.8 GB drive for the Deskstar 16GP personal computer… TMR heads were introduced in 2004 in the Seagate Momentus II, 2.5-inch, 120 GB HDD." Combining this same read-head technology with a perpendicular read/write scheme and new thin film materials produces today's Perpendicular Magnetic Resistance (PMR) hard drives. "All major industry vendors adopted PMR technology and in 2007 HGST introduced a one terabyte (1TB) drive, the Deskstar 7K1000 (The Storage Engine Timelines, n.d.)." Seagate used Shingled Magnetic Recording (SMR), a complicated engineering innovation (rather than a physics-based or material innovation), to extend these technologies into a 5 TB HDD which it started shipping to customers in 2014 (Shimpi, 2013).

**Second-generation spintronic devices are still being tested in the laboratory or are in development in private sector research**. "While the first generation spintronics, such as GMR heads sharply increased magnetic storage density, it is the **2nd generation spintronics**, integrating magnetic materials with semiconductors, that has the potential to extend the benefits of spin to the wider IT industry. One of the major challenges in developing this second generation of spintronic devices is the synthesis of high quality spintronic materials with Curie temperatures that are above room temperature, large spin polarisation at the Fermi level and matched conductivity between the magnetic material and semiconductor. (Xu, 2010)" A differentiating characteristic between first and second generation spintronics is the focus on spin dynamics. "By further investigating spin precession in the transport process, especially at higher frequencies in the GHz regime, spin dynamics has been studied for **second-generation spintronics**. Spin dynamics is predominantly induced by spin-transfer torque (STT) from a spin-polarized conduction electron onto a local magnetic moment. (Hirohata & Takanashi, 2014)."

**Magnetoresistive random-access memory (MRAM)** is a non-volatile random-access memory that has struggled to compete with today's flash RAM and DRAM technologies, and relies upon first-generation spintronics technology, specifically magnetic tunnel junctions (MTJ). However, where 1st-generation spintronics failed to make a significant impact in nonvolatile memory, 2nd-generation spintronics may be significantly more viable: "A newer technique, STT uses spin-aligned electrons to directly torque the domains. Specifically, if the electrons flowing into a layer have to change their spin, this will develop a torque that will be transferred to the nearby layer. This lowers the amount of current needed to write the cells, making it about the same as the read process. (Wikipedia, n.d.)." In 2016 it was announced that "Samsung Foundry is going to offer both spin torque transfer magnetic RAM (STT-MRAM) and flash as embedded non-volatile memory options on its 28nm FDSOI manufacturing process (Clarke, 2016)."

"**Spintronics also benefits from a large class of emerging materials**, such as ferromagnetic semiconductors, organic semiconductors, organic ferromagnets, high temperature superconductors, and carbon nanotubes, which can bring novel functionalities to the traditional devices. There is a continuing need for fundamental studies before the potential of spintronic applications is fully realized (Žutić, Fabian, & Das Sarma, 2004)."

- **Dilute Magnetic Semiconductors have been studied as candidate materials for a new generation of spintronic devices.** "The field of ferromagnetism in dilute magnetic semiconductors (DMSs) and dilute magnetic oxides (DMOs) has developed into an important branch of materials science. The comprehensive research on these systems has been stimulated by a succession of demonstrations of outstanding low-temperature functionalities such as spin injection , the control of magnetism by means of electric fields and electric currents, tunnelling anisotropic magnetoresistance in planar junctions, and current-induced domain displacement without the assistance of a magnetic field. These findings have brought into focus the interplay of magnetization texture and dynamics with carrier population and currents, which is a broad topic of current research on spintronic materials (Dietl, 2010)."
- **Graphene-based spintronics is a rapidly growing area of research.** "Graphene is a very promising spin channel material owing to the achievement of room-temperature spin transport with long spin diffusion lengths of several micrometres. Moreover, graphene has many interesting physical properties that also make it very attractive for spintronics, including gate-tunable carrier concentration and high electronic mobility. There have been many significant advances in the field of graphene spintronics, including efficient spin injection into graphene, defect-induced magnetism in graphene, theoretical understanding of the intrinsic and extrinsic spin–orbit coupling, and the investigation of the spin relaxation in graphene (Han, Kawakami, Gmitra, & Fabian, 2014)." Earlier this year (July 2017), a graphene-based spin field effect transistor capable of operating at room temperature was demonstrated (Dankert & Dash, 2017).

**Proposed third-generation spintronic devices lead the cutting edge of information science research.** "Future devices (third-generation spintronics) are expected to be three-dimensional (3D), and quantum spintronics will require further miniaturization and precise nano-patterning (Hirohata & Takanashi, 2014)." Quantum spintronics can be thought of as one of the candidate technologies that could contribute to the field of quantum computing: "As qubits, spins in semiconductors have distinct technical advantages. Host-dependent band structure and spin-orbit interactions imprint critical characteristics on spins in different materials, providing widely tunable qubit properties. Particularly in materials where spin-orbit coupling is weak, spins are relatively insensitive to many sources of decoherence in solid-state systems, including electrical noise and thermal vibrations of the semiconductor lattice. Furthermore, experimental methods for coherent control of single spin qubit states are now established, building on decades of research in magnetic resonance. Despite vastly different methods for production and individual advantages and challenges of the different systems, coherent quantum control of individual qubits has been demonstrated in all cases, and in several systems entangled multiqubit devices have been realized in recent years. GaAs/AlGaAs heterostructures provide the means to confine electrons and/or holes into reduced dimensions, to the ultimate limit of a zero-dimensional "box"- a quantum dot (QD) - containing a single spin (Awschalom, Basset, Dzurak, Hu, & Petta, 2013)."

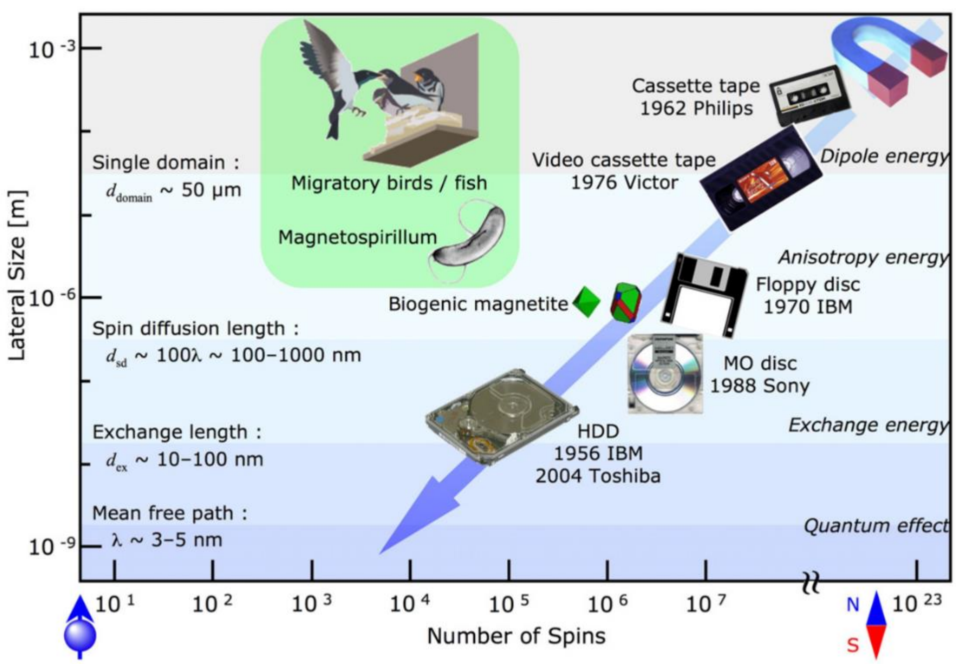



**Figure 1**: Typical magnetic length scales and development of magnetic recording devices. This shows the advancements of magnetic recording and storage technologies over time as a function of the media area and the number of magnetic spins. The examples follow the progression of traditional magnetic recording up to the end of 1st generation spintronics. Future research (2nd & 3rd gen) is expected to drive further into the quantum domain of "single spin" storage and sub-nanometer domain sizes. Figure derived from (Hirohata & Takanashi, 2014).

# III. What is the Research Landscape?

**Top Research Disciplines: Condensed Matter Physics and Materials Science**

- Prevalence of materials-related subject categories suggests (**Condensed Matter Physics, Materials Science, Chemistry, Nanoscience**) that most of the innovations occur at the material level, rather than at the device or system levels. However, device-based research still makes a strong appearance at ~3300 articles (#4) in the **Electrical Engineering** category.
- The appearance of **graphene** in recent years indicates this is an emerging material in spintronics
- Keywords related to 3rd generation spintronics do not make prominent appearances, likely due to the newness of the field, and the sparse research constituting it.

**Top Research Topics: Magnetoelectronics & DMS**

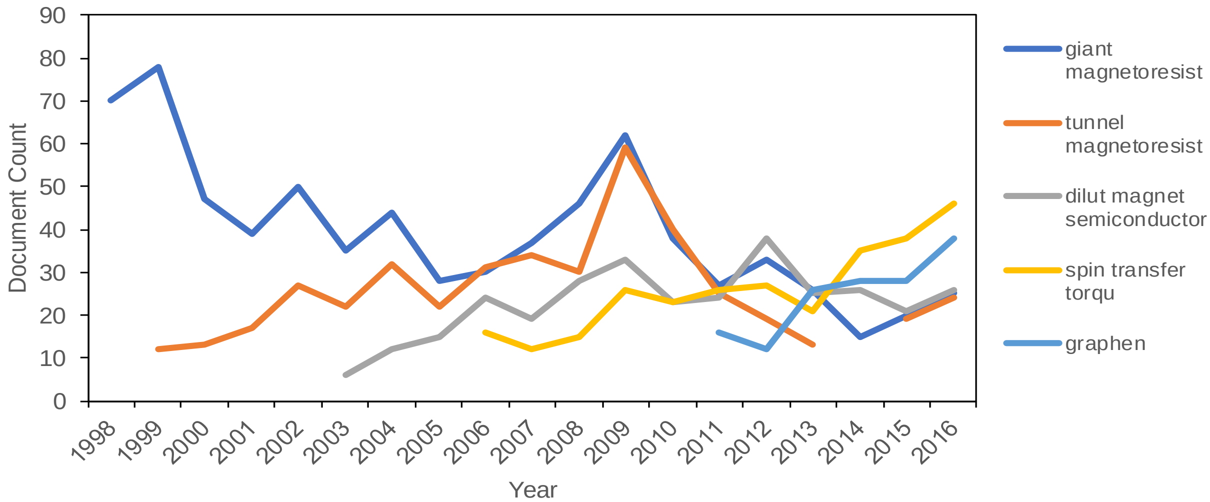
- **Giant Magnetoresistance, Tunnel Magnetoresistance, Magnetic Tunnel Junctions** are all 1st-generation spintronic devices which have reached commercial maturity and since they were seeded in the query, it is not surprising to see them appear as a high-frequency keyword. Although **Spin Valves** are associated with GMR, we note that they were not seeded like the other terms, but likely still appear at high frequency due to weighting at the query level.
- The time-dependent keyword trends show the progressive nature of multi-generation technologies:
  - First generation:
    - Twenty years ago, GMR was the predominant technology discussed in the literature, but over time it has slowly decreased.
    - TMR, the next step after GMR, starts increasing around twenty years ago, slowly increases as it matures, then decreases to the same rate as GMR.
    - This drastic reduction in research suggests that these technologies (GMR and TMR) have reached full maturity and researchers have moved on to other areas
  - Second generation:
    - STT begins slowly increasing about ten years ago, and is currently one of the most popularly found terms
    - Graphene has only recently emerged in the last five years and continues its upward trend.
- When combined with what we know of the press releases of new hard drives, it's also fair to conclude that spintronics has a strong infrastructure and demonstrated market demand in the digital hard disk drive sector. This implies 2nd generation spintronics will have an established and mature infrastructure and sophisticated customer base from which to launch from.
- While 1st-generation spintronic devices are well represented in the patent literature, some areas of 2nd-generation devices (i.e. STT-RAM) are recently receiving their patent protections while other areas (graphene spintronics) have only recently made their debut in the patent literature. In both cases, while 1st generation Spintronics is eclipsing, 2nd generation spintronics is now underway, (3rd generation spintronics still remains largely notional).
- **Dilute Magnetic Semiconductors (DMS)** are a new class of materials that have both ferromagnetic and semiconductor properties and have a wide variety of applications, only one of which are spintronics-related. The high frequency of occurrence indicates this may be an important material in 2nd generation spintronics.

### Top Application Areas: Digital Memory & Information Storage

- **“Memory Film and Hybrid Circuits”** is the top-ranked patent classification. The patent classification **“Data Recording”** appears as a supporting function to this digital storage application.
- **“Memory”** is #4 ranked patent term is, with the top three terms not being application-specific.
- The appearance of terms “magnetic,” “tunnel,” and “junction,” separately in the patent terms can be interpreted as pointing to “magnetic tunnel junction” as an important component, which is associated with GMR. This is not surprising given the late maturity of this technology and the large footprint of today’s hard disk drive industry.

Research fields comprise different thrusts and self-organization of articles often occurs around key questions and drivers in the field. The semantic content of the technical language, namely the technical terms, is typically a good indicator for tracking this activity. Similarly, how this research populates curated hierarchical subject categories can indicate what disciplines influence and dominate the field as well as other fields where this research has been influential. To extract the research field of interest, the following Boolean query was used:

> *spintronics OR spinelectronics OR fluxtronics OR "spin transfer torque" OR "tunnel magnetoresistance" OR "giant magnetoresistance" OR "spin-wave logic" OR "magnetic tunnel junction"*




**Top Publication Keywords**

| Rank | Keywords | Counts | Citations |
|---|---|---|---|
| 1 | spintron | 1,810 | 17,405 |
| 2 | magnetoresist | 858 | 10,678 |
| 3 | giant magnetoresist | 771 | 7,459 |
| 4 | magnet tunnel junction | 660 | 7,052 |
| 5 | magnet properti | 546 | 5,756 |
| 6 | tunnel magnetoresist | 474 | 4,923 |
| 7 | magnet | 375 | 4,180 |
| 8 | ferromagnet | 368 | 6,728 |
| 9 | dilut magnet semiconductor | 334 | 2,854 |
| 10 | spin valv | 330 | 4,409 |

**Top Patent Terms**

| Rank | Term | Counts | Citations |
|---|---|---|---|
| 1 | magnetic | 5,097 | 61,765 |
| 2 | layer | 3,629 | 46,798 |
| 3 | device | 2,925 | 31,096 |
| 4 | memory | 2,850 | 40,471 |
| 5 | magnetoresistive | 1,988 | 23,237 |
| 6 | tunnel | 1,959 | 20,423 |
| 7 | junction | 1,894 | 21,590 |
| 8 | element | 1,789 | 23,483 |
| 9 | sense | 1,509 | 18,361 |
| 10 | forming | 1,460 | 15,104 |

**Top Publication Subjects**

| Rank | Subject | Counts | Citations |
|---|---|---|---|
| 1 | physics, applied | 10,876 | 179,742 |
| 2 | physics, condensed matter | 9,539 | 184,792 |
| 3 | materials science, multidisciplinary | 6,760 | 121,664 |
| 4 | engineering, electrical & electronic | 3,299 | 25,190 |
| 5 | physics, multidisciplinary | 2,529 | 78,861 |
| 6 | nanoscience & nanotechnology | 2,467 | 44,019 |
| 7 | chemistry, physical | 2,177 | 70,152 |
| 8 | chemistry, multidisciplinary | 1,279 | 32,950 |
| 9 | multidisciplinary sciences | 824 | 63,083 |
| 10 | metallurgy & metallurgical engineering | 720 | 5,564 |

**Top Patent Classifications**

| Rank | Classification | Counts | Citations |
|---|---|---|---|
| 1 | (u) memories,film and hybrid circuits | 4,025 | 52,682 |
| 2 | (l) electro-(in)organic | 3,072 | 41,587 |
| 3 | (u) semiconductor materials and processes | 1,951 | 25,631 |
| 4 | (u) discrete devices | 1,665 | 29,054 |
| 5 | (t) data recording | 1,554 | 23,442 |
| 6 | (t) digital computers | 1,207 | 12,252 |
| 7 | (s) electrical instruments | 806 | 7,675 |
| 8 | (v) inductors and transformers | 786 | 12,230 |
| 9 | (s) engineering instrumentation | 321 | 3,437 |
| 10 | (w) telephone and data transmission systems | 280 | 2,162 |

**Figure 2:** These figures are derived from a search query performed to define the spintronics field. **Top Graphic:** a heatmap showing micro-trends of term popularity (darker colors indicates more documents appearing with that term) in the Web of Science **(Top, Left Table)** Shows the popular keywords used in Web of Science. **(Top, Right Table)** Shows the popular terms used in the title section of patents in the Derwent Patent Index. **(Bottom, Left Table)** Shows the subject categories used in Web of Science. **(Bottom, Right Table)** Shows the patent classification keywords used in the Derwent Patent Index.

# IV. How Mature is the Field?

ONTA estimates that Spintronics are rapidly maturing with a large footprint in both research and innovation. It bases this judgment on the factors below.

**Size: Large**

- The field is relatively large with ~27,000 publications and ~7,500 patents.

**Growth: Rapid**

- Though research extends long before the 1990s (with hundreds of articles being published at the start of our scanning range), the entire field has been experiencing super-linear growth.
- There are ~1000 articles more per year published than 10 years ago (~2500 vs ~1500)
- On the other hand, patent activity in recent years has remained stable, showing little growth since the year 2000. Thie surge in growth shortly after this coincides with the growth of GMR and TMR hard drives being commercially available around this time.

**Influence: High**

- Publications in this field average about 20 citations per paper
- Patents average about 12 citations per filing.

**Maturity: Developed (1st generation), Emerging (2nd-generation), Pre-emerging (3rd-generation)**

- The high ratio of patents to publications indicates a high level of transition from basic research to real-world applications.
- Additionally, the large number of patents in this area indicate that that areas of this field (i.e. GMR and TMR) have reached a stable level of maturity. In fact, in the last 15 years, patent output has been stable at ~450 (+/-50) patents filed per year.

| | Publications | Patents |
|---|---|---|
| Document Counts | 27,319 | 7,548 |
| Citations | 522,037 | 90,996 |
| Authors/Inventors | 40,029 | |

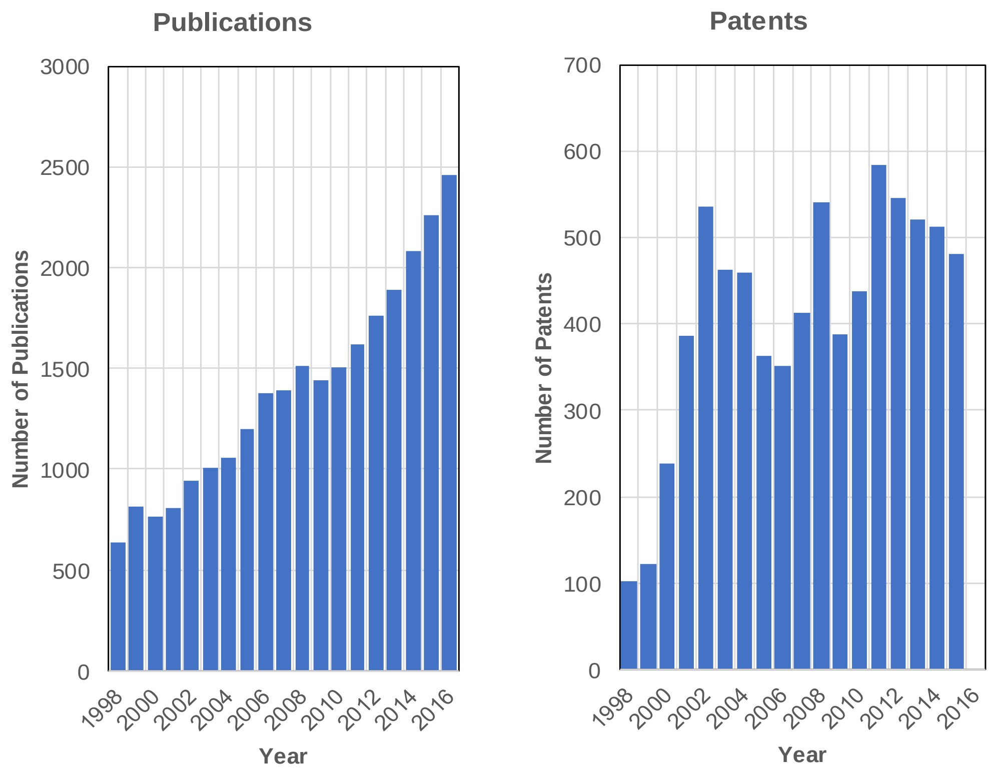



**Figure 3 (Top, Left)** Shows the *document counts, author counts and citation counts* for Spintronics in the Web of Science. These fields correlate to *accumulated knowledge, workforce size and influence/quality*, respectively. **(Top Right)** Shows the *patent counts and citation counts* for the field of Spintronics in the Derwent Patent Index. **(Bottom Left)** Shows the number of articles and conference proceedings mentioning Spintronics in the title or abstract per year of publication. **(Bottom Right)** Shows the number of patents mentioning Spintronics in the title or abstract per year of publication. The current year has been omitted since not all the publications for this year have been indexed.

# V. What are the Leading Countries?

**Top Research Producer: USA**

- USA is the top producer of academic research, and exceeds its nearest competitor, China by about 1000 articles (or 15%).
- USA has the most research citations by nearly 4 times its closest competitor, China.
- Starting in 2013, China started producing more publications in Spintronics than the USA and is currently the world leader. While the USA shows a similar, increasing trend, China has so far maintained a steady lead in growth.

**Top Innovator: USA**

- USA-based companies produced the most patents of any country, nearly 70% more than its closest competitor, Japan.

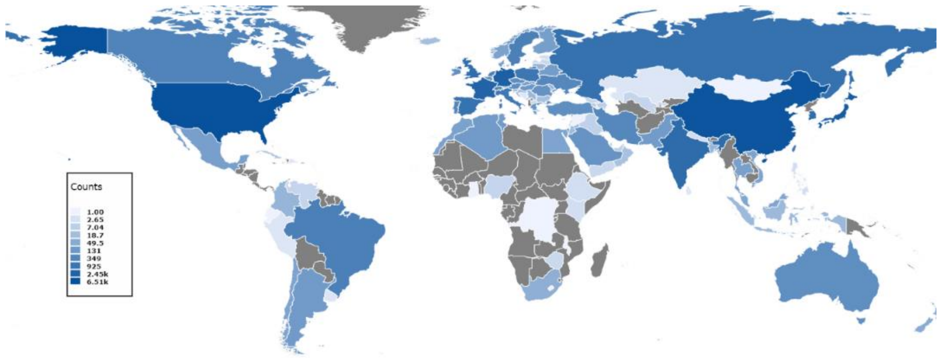
- The USA has the most patent citations, nearly doubling its closest competitor, Japan.
- South Korea ranks third, but also makes strong showings at lower ranks in the other two categories (publications and patent-offices).

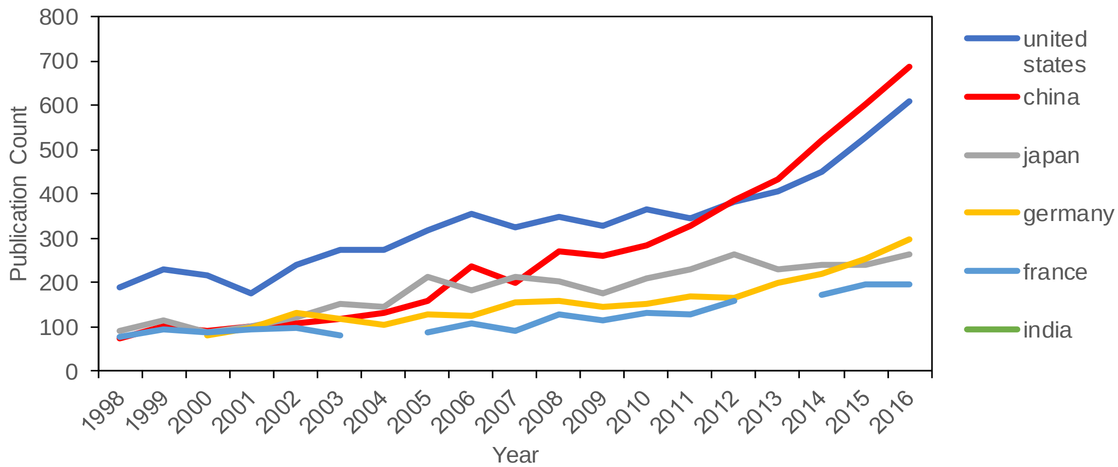
**Top Market for Innovation: USA**

- U.S. Patent Office has granted the most patents in spintronics, followed by a wide margin by Japan

Additionally, we also see South Korea having a large footprint in all of these innovation spaces: (#7) in publications (#4) in patents and (#5) in markets.

The country affiliation of articles and patents are inferred through the mailing address. These broadly indicate a country's contribution and expertise. Additionally, we can also analyze the patent-granting authority, which is often associated with a country and indicates where an innovation area has the most protection and coverage.




**Top Countries by Publication**

| Rank | Country | Articles | Citations |
|---|---|---|---|
| 1 | united states | 6,512 | 226,812 |
| 2 | china | 5,312 | 60,744 |
| 3 | japan | 3,571 | 78,366 |
| 4 | germany | 2,872 | 62,173 |
| 5 | france | 2,337 | 54,144 |
| 6 | india | 1,545 | 16,619 |
| 7 | south korea | 1,383 | 14,556 |
| 8 | united kingdom | 1,375 | 33,600 |
| 9 | russia | 1,098 | 12,459 |
| 10 | spain | 1,042 | 28,326 |

**Top Countries by Patents**

| Country | Patents | Citations |
|---|---|---|
| united states | 3,527 | 58,607 |
| japan | 2,161 | 33,991 |
| south korea | 857 | 4,654 |
| china | 577 | 3,508 |
| netherlands | 373 | 4,321 |
| germany | 298 | 3,715 |
| france | 228 | 2,287 |
| taiwan | 217 | 2,360 |
| united kingdom | 79 | 2,031 |
| singapore | 78 | 320 |

**Top Patent-Granting Offices**

| Office | Patents | Citations |
|---|---|---|
| united states | 6,074 | 88,362 |
| japan | 2,519 | 43,140 |
| world intellectual property organization | 1,626 | 26,652 |
| china | 1,518 | 24,235 |
| south korea | 1,463 | 24,407 |
| european patent office | 1,093 | 23,465 |
| taiwan | 705 | 16,017 |
| germany | 513 | 11,801 |
| india | 169 | 2,953 |
| australia | 167 | 6,120 |

**Figure 4** Shows the top countries in Spintronics based on: **(Left)** the country affiliation of the authors in the Web of Science, **(Middle)** the country affiliation of the assignee from the Derwent Patent Index, **(Right)** the patent granting authority (typically a country) from the Derwent Patent Index. **(Top)** A heatmap showing higher publication count as more darkly colored areas. **(Middle)** A trend chart for the top 5 publication-producing countries.

# VI. Questions for Further Study

Snapshot reports are meant to be quick scans of S&T and to ultimately stimulate interesting questions using only statistical data from the S&T literature. Answering these questions requires other methods, including interviewing stakeholders and experts.

### International Competition

- The USA has long dominated the area of spintronics across all our measurable metrics, but can we count on the same trend holding for the future? (Currently, China produces more publications on spintronics than the USA, a trend that started in 2012).
- What are the differences between the investments of different countries in spintronics? How is this distributed among 1$^{st}$, 2$^{nd}$, 3$^{rd}$ generation spintronics? Will this investment in next generation (i.e. 2$^{nd}$ generation) spintronics translate into an industry lead in disk storage or computation?

### Technology Advancements

- Literature in the last 20 years is strongly dominated by first-generation spintronics advancements. Scoping such a large area was necessary in gauging the size of the entire field for this report. However, this may obscure recent and projected developments. Separating out second-generation and third-generation technologies would be a valuable exercise (perhaps in future reports) to answer questions like:
  - What are the most promising materials in 2$^{nd}$-generation spintronics?
  - What are the key challenges in 3$^{rd}$ generation spintronics, such as quantum spintronics?
  - What countries are leading in patenting specific 2$^{nd}$ and 3$^{rd}$ generation spintronic technologies like STT-RAM?
  - What is the current outlook for graphene spintronics?
- The discovery of spintronics has been the key innovation that has led to the terabyte hard drives we enjoy today, but recent advancements such as SMR are not physics or materials-based innovations.

### Impacts

- Can spintronics-based nonvolatile memory be useful in radiation hardening applications?
- Can spintronics-based devices be useful for
  - Personal electronic devices or flexible electronics?
  - Very small platforms such as nano-UAVs?
  - Or even smaller, swarm-based systems?

# VII. Further Reading (Most Cited Work)

| Rank | Citations | Article Title | Source | Year |
|---|---|---|---|---|
| 1 | 6,970 | Spintronics: A spin-based electronics vision for the future | SCIENCE | 2001 |
| 2 | 5,639 | Spintronics: Fundamentals and applications | REVIEWS OF MODERN PHYSICS | 2004 |
| 3 | 5,630 | A comprehensive review of ZnO materials and devices | JOURNAL OF APPLIED PHYSICS | 2005 |
| 4 | 3,038 | Exchange bias | JOURNAL OF MAGNETISM AND MAGNETIC MATERIALS | 1999 |
| 5 | 2,435 | Colossal magnetoresistant materials: The key role of phase separation | PHYSICS REPORTS-REVIEW SECTION OF PHYSICS LETTERS | 2001 |
| 6 | 2,415 | Half-metallic graphene nanoribbons | NATURE | 2006 |
| 7 | 1,991 | Electrical spin injection in a ferromagnetic semiconductor heterostructure | NATURE | 1999 |
| 8 | 1,809 | Mixed-valence manganites | ADVANCES IN PHYSICS | 1999 |
| 9 | 1,754 | Magnetic domain-wall racetrack memory | SCIENCE | 2008 |
| 10 | 1,707 | Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions | NATURE MATERIALS | 2004 |

| Rank | Citations | Patent Title | Assignee | Year |
|---|---|---|---|---|
| 1 | 369 | Non-volatile memory element resistance computation method e.g. for ROM, involves applying read electric pulse to electrodes to determine resistive state of element corresponding to desired base k number | UNIV HOUSTON SYSTEM | 2001 |
| 2 | 306 | Nano-whisker for use in semiconductor applications comprises column having different crystalline material along its length | QUNANO AB, BRITISH TECHNOLOGY GROUP LTD, KUNARNOR CORP | 2002 |
| 3 | 288 | Magneto resistive element for magnetic memory has ferromagnetic double junction with a stacked structure | TOSHIBA KK | 2000 |
| 4 | 287 | Programmable conductor random access memory for computer system, reads out binary values stored in memory elements as resistance values | MICRON TECHNOLOGY INC | 2001 |
| 5 | 279 | Nonvolatile memory cell has resistance switching element having resistivity-switching metal oxide or nitride compound layer, connected in series with diode | SANDISK CORP | 2005 |
| 6 | 228 | Magnetic random access memory for mobile personal computer, has memory cell with bit line connected to common node of series connected tunnel magnetoresistive elements through transistor | TOSHIBA KK | 2000 |
| 7 | 216 | Magnetic tunnel junction device for a non-volatile magnetic random access memory array has a free ferromagnetic layer having two ferromagnetic films | INT BUSINESS MACHINES CORP | 1999 |
| 8 | 204 | Magnetic element, used in magnetic memory, comprises pinned layer, non-magnetic spacer layer, and free layer having out-of-plane demagnetization energy and high perpendicular anisotropy | GRANDIS INC | 2004 |
| 9 | 204 | Magnetic memory cell fabrication method e.g. for MRAM, involves depositing dielectric layer comprising aluminum oxide on ferromagnetic layer by atomic layer deposition technique | ASM AMERICA INC | 2000 |
| 10 | 202 | Spin-transfer switched magnetic random access memory device for e.g. wireless communication, has alternating current source producing magnetic field on free magnetic layer, and transistor causing spin transfer torque in layer | GRANDIS INC | 2005 |

**Figure 5** The following list shows **(Top)** the most cited articles in the Spintronics field from the Web of Science and **(Bottom)** most cited patents from the Derwent Patent Index.

# VIII. About this Publication

Referenced work in this publication does not constitute endorsement by the United States Department of Defense (DoD) of the linked web sites, nor the information, products or services contained therein. In addition, the content featured does not necessarily reflect DoD's views or priorities. To provide feedback or ask questions, contact us at asdre-st-bulletin-reply@sainc.com. This publication is authored and distributed by: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- **Artjay Javier, Ph.D.**, ONTA S&T Analyst
- **David Byrd**, ONTA S&T Analyst


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# X. APPENDIX

## A. Scientometric Methodology

TechSight is an open-resource, cloud-based ecosystem developed and maintained by ONTA. As of this writing, it consists of an ElasticSearch database infrastructure with a Kibana front-end and some commercial and custom-written plugins. The databases used for this analysis were global scientific publications using the Web of Science and global patent applications using the Derwent Patent Index, both provided by Clarivate, Inc. All of the figures generated in this report come from visualizations generated by Techsight.

More dashboards for this specific report are available on the ONTA TechSight system and contain additional visualization elements not included in this report since their dynamic nature is not compatible with static reporting. These include network visualizations that allow for a finer-grained analysis and allow the user to delve into specific information on top performing universities, companies, authors and inventors. To access it, sign up for a free account at:

https://registration.761link.net/accountRequest-ZoneB/accountRequest/techsight.

You must be either a DoD employee, or a contractor supporting DoD, and register using your .mil e-mail address.

A search query is manually developed by an analyst to capture best capture the field of this report. Development of this query is directed at improving precision (by eliminating non-relevant documents from the results) and recall (by collecting as many relevant documents as possible) through the use of Boolean operators and unique terms. Since ElasticSearch is being used, differences in term suffixes are automatically accounted for and require no additional specification.

## B. How large is a research field or area of innovation? (Frequency Analysis)

The size of a research field can be estimated in terms of total aggregated knowledge, for which the metric cumulative document counts is a suitable proxy. Under the assumption that every article is unique and therefore constitutes a single unit of knowledge, the sum of all the articles in a research field approximates the total knowledge accumulated in the field. Another suitable metric is total community size, for which the number of unique authors is a suitable metric since these are the workers that generate knowledge. A larger workforce tends to correlate to a greater capacity to produce knowledge and therefore grows proportionately with aggregated knowledge. Some fields exhibit differing productivity (i.e. documents per unique worker) depending on ease of publishing, difficulty in carrying out experiments and field-dependent variables. Fields like particle physics and clinical medicine tend to have articles with a large number of authors due to the difficulty of the experiments. Fields such as nanoscience and nanotechnology tend to have higher productivity due to the ease of publishing new results. Fields like mathematics tend to have only a single author due to the nature of the work, and fields in computer science tend to have generally low publication rates relative to their research production. Similar factors affect patent indicators and are notably shaped by key differences between the two corpora, such as motivations for publishing versus patenting, the differences between peer review and patent examination, and the choice of technical terminology. Field sizes and influence are based on analyst observations and experience in a semi-quantitative rough order of magnitude sense: very small fields <10 articles, small fields <100 articles, medium fields <1,000 articles, large fields <10,000 articles, very large fields >100,000 articles. For influence: poorly cited <1 citation/article, medium citation rate ~1 citation/article, high citation rate >10 citations/article.

## C. How influential is a research field? (Citation Analysis)

Scientific articles contain a list of references that cite previously published articles. The number of times an article has been referenced by other articles is called its citation count. Over time, an article's citation count tends to increase as subsequently published articles cite that article. Citation count tends to correlate with an article's influence, indicating the article's content has influenced other articles. Citation is also a suitable proxy for quality, as more articles describing the first reports of original work tend to have higher citations. An exception to this rule are review articles which tend to have very large citation counts and contain no original work but are cited typically to point new readers to a compact source for their further education in the field. Despite this exception, it is not inappropriate to include review articles in a citation analysis because the articles tend to be more widely read, and are a demand signal that a field has aggregated enough knowledge that a convenient repository for that knowledge is desirable. Since citation counts provide a usable proxy for "quality", this analysis provides a counterbalance to the "quantity" metric of document counts.

## D. How fast is the research field or area of innovation growing? (Trend Analysis)

Scientific fields grow over time as researchers publish related articles, building on early seminal works. Emerging and potentially disruptive research areas typically display rapid, exponential-like growth early in their lifecycle.

### E. What are the key areas of research, development and innovation? (Semantic Analysis)

The content of a research field can be understood from a hierarchical framework. Understanding the parentage of the field creates awareness of the nature and character of the field relative to the context of current scientific organization. As a proxy, we use the Web of Science's Subject Categories field, which are inspired by OECD's Field of Science (FOS) categories (OECD Cateogry Scheme, n.d.). While a field tends to localize around a specific section of this hierarchy, outliers sometimes exist arising from relevant articles in unrelated research fields indicating this field has influenced work or been adopted by these other fields. Similarly, patents in the Derwent Patent Index (DWPI Classification System, n.d.) are inspired by the WIPO classification and section scheme and lend themselves to similar visualization schemes. Research topics can often be conceptually subdivided into sub-topics. These sub-topics are often differentiated by specific keywords which are indicative of the content of these subtopics and represent segments of research focusing on research drivers such as key questions or specific innovations. Quantitatively tracking these keywords indicates the relative popularity of these sub-topics.

### F. What are the leading countries? (Country Cross-Analysis)

Authors and inventors are affiliated with organizations whose addresses are in specific countries. By subdividing the data according to country, we can produce analyses at the national level that broadly indicate a country's participation level in a research field. Top 10 Countries by Publications are determined by the address of the affiliation of the author in the Web of Science. Note that an author can have multiple affiliations, thus belong to multiple countries. Top 10 Countries by Patent Application are determined by the address of the affiliation of the assignee in the Derwent Patent Index. An alternative approach is to use the inventor affiliation, which results in larger country counts since a patent can have multiple inventors, but only one assignee. Patent protection can be granted by applying to nation-specific authorities (i.e. U.S. Patent and Trademark Office), regional authorities (i.e. European Patent Office) or international authorities (World Intellectual Property Organization). It is often useful to compare which countries patents in a specific technology are granted and comparing that to where those companies are affiliated as it indicates whether one country is seeking IP protection in another country, or worldwide, for its products.