Testimony

New and Critical Materials: Identifying Potential Dual-Use Areas

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Testimony of Richard Silberglitt[1]
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Before the U.S.-China Economic and Security Review Commission

June 7, 2019

Thank you Vice Chairman Cleveland, Commissioner Lee, and distinguished members of the Commission for inviting me to testify today. I have divided my comments into four sections. The first provides some basic information about new materials, focusing on nanomaterials and metamaterials, their commercial applications, and the potential for emerging dual-use applications. The second describes China's current capabilities in metamaterials compared with those of the United States. The third contains information about recent collaborations between the United States and China on materials research. The fourth and final section reviews China's continuing domination of the production and processing of critical materials. In this section, I suggest possible actions for federal policymakers to consider to increase U.S. resilience to supply disruptions or market distortions and to provide early warning for problems concerning critical materials production. This final section is based on the results of a 2013 study conducted by the RAND Corporation at the request of the National Intelligence Council,[3] taking into account relevant developments and data since the publication of that report.

Development and Applications of New Materials

Since the evolution of materials science and engineering in the latter part of the 20th century as an interdisciplinary combination of physics, chemistry, and several engineering disciplines, materials have been developed with increasing multifunctionality and ability to survive in and respond to complex and challenging environments. Instrumentation to measure materials' properties at the atomic and molecular level, combined with theoretical analyses and computer

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[1] The opinions and conclusions expressed in this testimony are the author's alone and should not be interpreted as representing those of the RAND Corporation or any of the sponsors of its research.

[2] The RAND Corporation is a research organization that develops solutions to public policy challenges to help make communities throughout the world safer and more secure, healthier and more prosperous. RAND is nonprofit, nonpartisan, and committed to the public interest.

[3] Richard Silberglitt, James T. Bartis, Brian G. Chow, David L. An, and Kyle Brady, *Critical Materials: Present Danger to U.S. Manufacturing*, Santa Monica, Calif.: RAND Corporation, RR-133-NIC, 2013.

simulations, has enabled great advances in our understanding of relationships between materials structure, processing, and properties and led to new applications.[4] Materials structured at the nanometer (one-billionth of a meter) scale are of special importance because they are very close to the molecular scale and can exhibit properties and interactions that are fundamentally different from those observed in bulk materials. For example, because of their much smaller size and much larger surface area, drugs encapsulated in or composed of nanoscale particles are significantly more easily absorbed into the bloodstream and more highly bioactive than conventional drugs, enabling therapeutic effects with lower doses and less risk of side effects.[5] Other applications in which materials of nanometer size may provide new or improved properties include wearable electronics,[6] batteries with higher energy density,[7] and energetic materials (materials with stored chemical energy that can be released, such as thermite—a mixture of powdered aluminum and iron oxide).[8] Wearable electronics and higher-energy-density batteries can be considered dual-use to the extent that they may be used by military personnel. Energetic materials are clearly dual-use.

The ability to synthesize materials with structural variations on the nanometer scale has led to the capability to develop a wide variety of metamaterials—materials with structures that are typically not found in the natural world and that vary on a scale comparable with or smaller than that of electromagnetic wavelengths. These metamaterials respond differently than ordinary materials, and in some cases exhibit properties that are not seen in nature, such as negative refraction of light.[9] Metamaterials have been shown to enable several potential dual-use applications, such as hyper-sensitive lenses;[10] perfectly reflecting[11] or completely nonreflecting[12]

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[4] For example, the U.S. Government's Materials Genome Initiative is a multiagency effort to combine experimental, theoretical, and computational methods and tools to discover and explore new materials and decrease the time to their use in commercial applications (Materials Genome Initiative, homepage, undated).

[5] See for example, the description of research on nanoparticle therapy for kidney disease at Francis Collins, "Building Nanoparticles for Kidney Disease," *NIH Director's Blog,* January 31, 2019.

[6] For a recent application that includes energy harvesting, see "Electronic Textiles Could Harvest Energy as We Move," *Nano: The Magazine for Small Science*, May 15, 2019.

[7] See Nature Reviews Materials, "Battery Materials and Technologies," September 6, 2017.

[8] Vladimir E. Zarko and Alexander A. Gromov, eds., *Energetic Nanomaterials: Synthesis, Characterization, and Application*, Amsterdam, Elsevier, Inc., 2016. For a review of worldwide energetics activity, see M.S. Firebaugh, B.M. Rice, Y. Horie, T.M. Klapötke, J.M. Short, R.D. Lynch, R.A. Kavetsky, and D.K. Anand *Topics in Energetics Research and Development*, College Park, Md.: CALCE EPSC Press, University of Maryland, 2013.

[9] For a detailed review, see Muamer Kadic, Graeme W. Milton, Martin van Hecke, and Martin Wegener, "3D Metamaterials," *Nature Reviews Physics,* Vol. 1, 2019, pp.198–210.

[10] Dylan Lu and Zaowei Liu, "Hyperlenses and Metalenses for Far-Field Super-Resolution Imaging," *Nature Communications*, Vol. 3, 2012, p. 1205.

[11] Parikshit Moitra, Brian A. Slovick, Wei li, Ivan I. Kravchencko, Dayrl P. Briggs, S. Krishnamurthy, and Jason Valentine, "Large-Scale All-Dielectric Metamaterial Perfect Reflectors," *ACS Photonics*, Vol. 2, 2015, pp. 692−698.

[12] Mohammad J. Moghimi, Guangyun Lin, and Hongrui Jiang, "Broadband and Ultrathin Infrared Stealth Sheets," *Advanced Engineering Materials*, 2018.

materials; and optical components with specific properties, such as micro-antennas and cloaking devices.[13]

Comparison of China and United States Metamaterials Capabilities

China is pursuing a substantial research and development (R&D) effort in metamaterials. Functional nanomaterials and metamaterials were identified as priority areas of advanced materials in China's 13th 5-year plan, which calls for breakthroughs in core technologies, including new materials, and explicitly identifies key new materials research, development, and application as a project area for science and technology innovation.[14]

Analysis of patents according to the technical classification systems used by national and international patent granting authorities [e.g., the United States Patent and Trademark Office (USPTO), the World Intellectual Property Organization (WIPO), the China National Intellectual Property Administration (CNIPA)][15] provides a window into China's metamaterials efforts and its application focus. Figure 1, which was compiled for the purpose of this testimony, shows the cumulative metamaterial patent filings in China and the United States from 1989 to 2017.[16]

We see emergence in the cumulative number of filings in both countries, starting about 2005 for the United States and about five years later for China. Since filing a patent application requires an investment in time and resources with the expectation of ownership of a technology area, the increasing number of metamaterials filings is an indication that both countries regard metamaterials as an area of potential value.

While the cumulative number of metamaterials patent filings in the United States and China were roughly the same in 2017, an examination of the application focus of the two countries reveals a substantial difference. Figures 2 and 3 show the technical areas in which each country's metamaterials emergence is concentrated.

While antennas are the largest application area for each country, the concentration of focus is markedly different (41 percent of applications for China and only 19 percent for the United States). The next most important technology areas (semiconductors and optics) are similar between the two countries, both in technology and in percentage of all metamaterial applications. However, the top 80 percent of U.S. metamaterial patents are distributed over a much wider application area than the top 80 percent of China's metamaterial patents, which may reflect a greater Chinese focus on applications consistent with government R&D plans. On one hand, the

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[13] For the theory and design of optical metamaterials, see Tie Jun Cui, David Smith, and Ruopeng Liu, eds., *Metamaterials: Theory, Design, and Applications*, New York: Springer, 2010.

[14] National Development and Reform Commission, "13th Five-Year Plan for Economic and Social Development of the People's Republic of China," March 17, 2016.

[15] Patent classification analysis uses the technical classifications to which patent examiners in national and international patent granting authorities assign patents to establish a network that links patents by technology area. Emerging technologies can be identified and analyzed through variations in the cumulative number of patent filings in this network. For a description and demonstration of this approach that includes nanotechnology as an example, see Christopher A. Eusebi and Richard Silberglitt, *Identification and Analysis of Technology Emergence Using Patent Classification*, Santa Monica, Calif.: RAND Corporation, RR-629-OSD, 2014.

[16] Because there is an 18-month delay in publication of patent applications, 2017 is the last year with complete data.

breadth of application in the United States provides the opportunity for innovative uses of metamaterials in new areas. On the other hand, China's increased focus might lead to more advances in already identified areas. Which approach will yield greater value will depend not only on the breadth of focus, but also on the quality of metamaterials development and implementation in each country.

The company responsible for the largest number of Chinese metamaterial patents is Kuang-Chi Innovative Technology Limited, a Shenzhen-based developer of metamaterial products for the aviation industry, including "novel electromagnetic metamaterial to meet user-defined functional requirements such as wave transmission, polar rotation, radiation pattern and shielding, new meta-RF satellite communication products, near space technology."[17] The founder and president of this company, Ruopeng Liu, received his master's and doctorate from Duke University in 2009; he founded the company in 2010.[18] Liu is in a strong position to lead the development of products such as those listed above for China's aviation and space industries.

United States–China Research Collaborations

The United States and China are the two largest sponsors of R&D in the world, with estimated 2018 expenditures of $566 and 486 billion, respectively.[19] In today's global R&D environment, researchers from the two countries collaborate in a variety of areas involving new materials. One example of a current collaboration is the U.S.-China Clean Energy Research Center (CERC), which is coordinated by the U.S. Department of Energy's Office of International Affairs. CERC's objective is to use collaborations between top researchers in both countries to accelerate the development and deployment of clean energy technologies in the United States and China. It is focused on five key research areas: advanced coal technology, building energy efficiency, clean vehicles, water and energy technologies, and medium- and heavy-duty trucks.[20] One of the principal focus areas for clean vehicles is advanced batteries—an important application for nanomaterials. Another area in which U.S. and Chinese researchers are working together to advance the state of the art is wearable devices powered by energy harvested from the environment, including human activities. Devices have been developed in both countries that use nanoscale materials to generate sufficient electricity to power small electronic devices, either from piezoelectric materials (in which pressure generates electricity) or triboelectric materials (in which friction generates electricity).[21] These both appear to be productive collaborations of mutual benefit.

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[17] Bloomberg, "Aerospace and Defense: Company Overview of Kuang-Chi Innovative Technology Limited," May 30, 2019.

[18] Bloomberg, 2019.

[19] "Government and Industry Continue to Grow Global R&D," *R&D Magazine*, Winter 2019 Supplement, p. 5.

[20] See U.S.-China Clean Energy Research Center, homepage, undated.

[21] For a review of the triboelectric portion of this work, see Jianjun Luo and Zhong Lin Wang, "Recent Advances in Triboelectric Nanogenerator Based Self-Charging Power Systems," *Energy Storage Materials*, in press. Luo is at the Chinese Academy of Sciences in Beijing and Wang is at Georgia Tech. See also Professor Zhong Lin Wang's Nano Science Research Group, homepage, undated.

Another aspect of U.S.-China research collaboration is the training of Chinese nationals in U.S. academic research programs, some of whom may return to China and establish academic research programs or develop such commercial entities as Kuang-Chi Innovative Technology Limited. There is a tradeoff involved in such academic research programs. On the one hand, they support innovation in and between the two countries. On the other hand, they support transfer of technology know-how in dual-use technology areas of possible relevance to U.S. national security. These programs must be evaluated on a case-by-case basis, with the objective of ensuring that technologies that are controlled for national security reasons are not provided to prohibited countries either directly or through tacit knowledge.

China's Domination of Critical Materials Production and Processing

While the United States has extensive mineral resources and is a leading global materials producer, it is dependent on imports for many materials that are critical for manufacturing. The most well-known examples are metals of the rare earth family, which are essential to many technologies essential to both civilian and defense applications, such as chemical catalysts, lasers, high-power magnets, batteries, light-emitting diodes (LEDs), night-vision goggles, and computer hard drives.[22] However, U.S. import dependence is not limited to rare earth metals. In 2018, the United States was reliant on imports for 64 nonfuel mineral commodities—fully dependent on imports for 18 of these and more than 50 percent dependent for another 30.[23] This included such semiconductors as indium, gallium, and germanium; metals used in high-temperature alloys, such as vanadium and rhenium; antimony, which is a critical component of flame-retardant plastics and textiles; and tungsten, a critical component in materials used for drilling, cutting, and machining in industries that include mining and construction, oil and gas exploration, and tools and dies. It is these materials—critical inputs for manufacturing—that I refer to as critical materials in this testimony.

China is by far the most dominant producer of these critical materials, accounting for more than 50 percent of world production of 12 different critical materials—antimony, aluminum, bismuth, fluorspar, gallium, germanium, magnesium, rare earths, silicon, tellurium, tungsten, and vanadium.[24] By comparison, there is no other country that produces more than 50 percent of world production of more than one critical material. China is also in a class by itself as the only country upon which the United States is dependent for more than 50 percent of its imports of more than 18 nonfuel mineral commodities.[25]

China achieved its dominance in global raw materials production because of its large resource base, its long-term emphasis on mineral production, and its ability to produce raw

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[22] Definitions of the rare earth family of metals vary slightly. I use the definitions from K.A. Geshneider, Jr., "The Rare Earth Crisis—The Supply/Demand Situation for 2010-2015," *Material Matters*, Vol. 6, No. 2, 2012, pp. 32–37. The metals are lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, and yttrium.

[23] U.S. Geological Survey, *Mineral Commodity Summaries 2019*, Washington, D.C., 2019, p. 200.

[24] U.S. Geological Survey, 2019.

[25] U.S. Geological Survey, 2019.

materials at lower cost because of its relatively lax environmental and occupational health and safety standards. Figure 4 shows how China's dominance in materials production grew from 1990 to 2010, as mines and processing plants in other countries closed because of their inability to compete with China's low-price exports.

However, China's position as a reliable low-cost supplier of raw materials for manufacturing deteriorated as its market share and domestic consumption grew and a combination of production controls, export restrictions (e.g., quotas, tariffs), mine closings, and company consolidation contributed to significant price increases and volatility on the world market.[26] For example, prices of some rare earth metals spiked by thousands of percent between 2010 and 2013.[27]

The negative effects on competitiveness of non-Chinese manufacturers led China's trading partners to bring an unprecedented series of complaints before the World Trade Organization (WTO), beginning in 2009 and culminating in May 2015 with China's removal of export restrictions on rare earths, tungsten, and molybdenum.[28]

In 2009, the United States and the European Union (EU) brought a complaint against China's trade restrictions on various forms of bauxite, coke, fluorspar, magnesium, manganese, silicon carbide, silicon metal, yellow phosphorus, and zinc. When the WTO ruled in favor of the United States and the EU, China appealed and lost, then took full advantage of the "reasonable period of time" allowed under WTO rules before finally removing export duties on these materials on January 1, 2013, the very day the time for compliance expired.

In 2012, before China had acted on the dispute just described, the United States, EU, and Japan brought an additional complaint against China's trade restrictions on rare earths, tungsten, and molybdenum. This dispute was also settled in favor of the United States, EU, and Japan. China appealed again and lost, and finally removed export duties and export quotas, as well as restrictions on trading rights of enterprises exporting rare earths and molybdenum. China again acted on the very day the time for compliance expired (in this case, May 2, 2015).

The relatively long timeline for resolution (more than three years) of these disputes and the fact that export restrictions on three critical materials were retained for over two years after they had been ruled inconsistent with WTO rules, highlights the vulnerability of U.S. manufacturers dependent on Chinese exports of critical materials. In fact, an analysis of global industrial supply chains and trading strategies concluded that among major traders, only China pursued strong resource protection strategies, defined as export and production restrictions, consolidation of industry, and investment restrictions.[29] China continues to pursue resource protection strategies. For example, China regulates its tungsten industry by limiting the number of mining and export

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[26] Jeonghoi Kim, "Recent Trends in Export Restrictions," Paris: OECD Publishing, OECD Trade Policy Paper No. 101, 2010.

[27] Richard Miller, "Materials Challenges for a Transforming World: Developments for a Sustainable Future: The Example of Rare Earths," *Johnson Matthey Technology Review*, Vol 61, No. 2, 2017, p. 127.

[28] WTO, *China—Measures Related to the Exportation of Various Raw Materials*, Dispute Settlement DS394, January 28, 2013; WTO, *China—Measures Related to the Exportation of Rare Earths, Tungsten and Molybdenum*, Dispute Settlement DS431, DS432, DS433, May 20, 2015.

[29] Eva Barteková and René Kemp, "Critical Raw Materials Strategies in Different World Regions," United Nations University and Maastricht University, UNU-MERIT Working Paper No. 2016-005, 2016.

licenses, imposing quotas on concentrate production, and placing constraints on mining and processing.[30]

As China's export restrictions and the WTO disputes illustrate, a dominant producer can contribute significantly to market distortions and supply disruptions that strongly affect the manufacturing sector. What is most important here is not the level of import dependence but rather the level of availability of these materials at a fair market price. It is important to note in this respect that there are dominant materials producers that eschew export restrictions and allow market forces to largely determine supply and demand of the materials they produce. One such example is Chile, producer of 55 percent of the world's rhenium.[31]

RAND's 2013 report recommended two types of actions to mitigate the influence of market distortions on the global manufacturing sector. These are: (1) actions to increase resiliency to supply disruptions or market distortions; and (2) foresight actions that can provide early warning of developing problems concerning the concentration of production.

Increasing Resiliency to Supply Disruptions or Market Distortions

Actions to increase resiliency can take two different forms: those that encourage diversified production and processing of critical materials and those that involve the development of alternative sources such as secondary production or alternative inputs to manufacturing. Market forces have already encouraged efforts at diversification, for example, new production and processing of tungsten in Vietnam, exploration and development projects for rare earths in the United States and in other countries, and renewed rare earth production from the mine in Mountain Pass, California.[32] However, the uncertainty created by a highly concentrated market is a barrier that must be overcome by actions at the local, national, regional, and global levels to create a favorable and sustainable climate for the investments and time needed to bring diversified supplies into place. Coordinated actions by importing countries can be effective here, such as the actions by the United States, EU, and Japan described earlier. Other areas in which coordination is possible include the formation and maintenance of stockpiles and the establishment of agreements about sharing limited resources in the event of supply disruptions.

Over the long term, actions to increase resiliency may include the development of new methods of extraction, processing, and manufacturing that promote the efficient use of materials; increased recovery of materials from waste and scrap (i.e., secondary production), from which the U.S. obtains approximately half of its tungsten; and research and development of alternative materials and new product designs that use smaller amounts of scarce materials.

Foresight of Developing Problems

Data on the production, processing, and trade of minerals are widely available from government organizations such as the U.S. Geological Survey and the British Geological Survey, as well as industrial organizations and the United Nations' Comtrade database. Using these data,

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[30] U.S. Geological Survey, 2019.

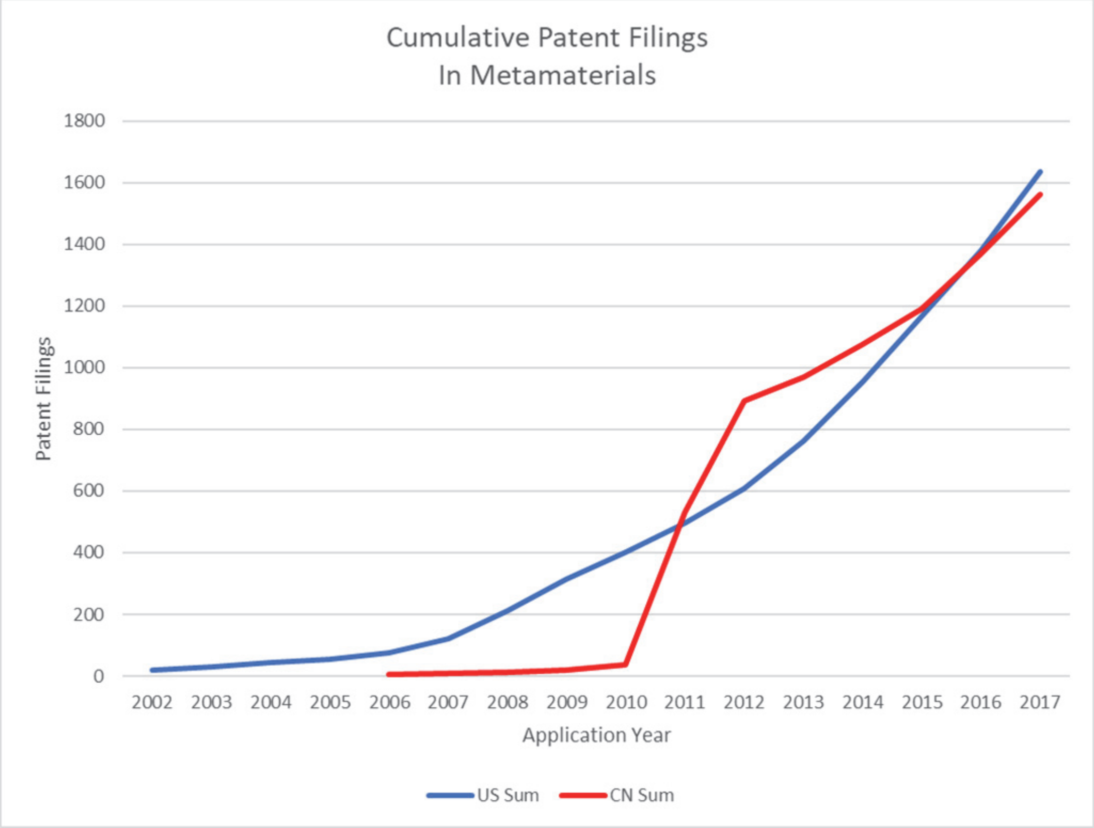
[31] U.S. Geological Survey, 2019.

[32] U.S. Geological Survey, 2019.

how might we recognize a developing pattern, such as increasing concentration of production, increasing export restrictions, two-tier pricing, price spikes, or price volatility before it creates harmful market distortions? One approach may be benchmarking of market activity with diversified commodity markets. For example, the Horizontal Merger Guidelines for firms established by the U.S. Department of Justice and Federal Trade Commission use changes in the Herfindahl-Hirschman Index of market concentration as a measure of market power.[33] When changes in the location of production of critical materials cross the threshold of these guidelines, international coordination and cooperation could prevent market concentration from reaching the level of concern that led to the WTO disputes against China. The goal of such coordination and cooperation should be to smooth market distortions while allowing for the natural economic development of producing countries.

Thank you for the opportunity to testify and I am happy to answer any questions.

Figure 1. Cumulative U.S. and China Metamaterial Patent Applications



Source: Compilation of data published by USPTO and CNIPA by Christopher A. Eusebi.

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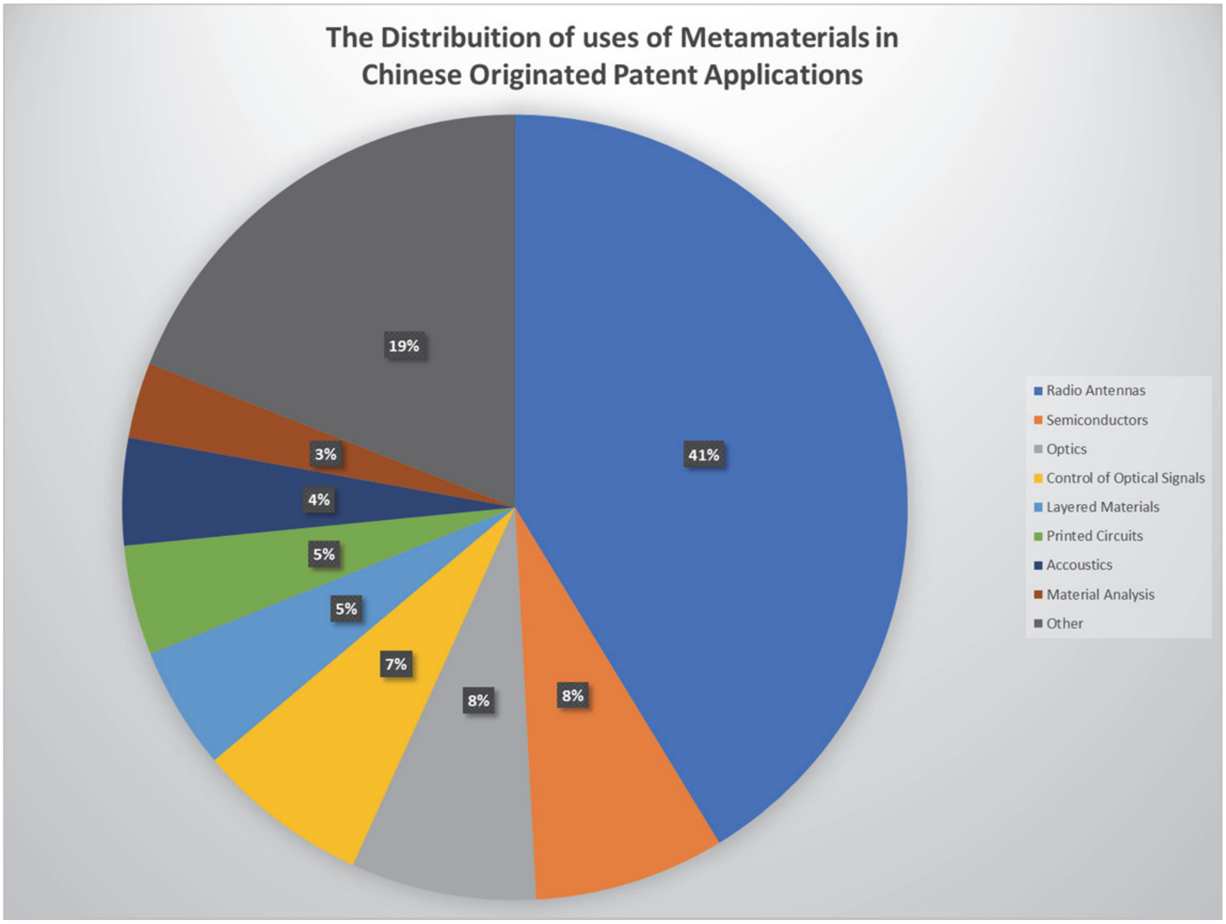
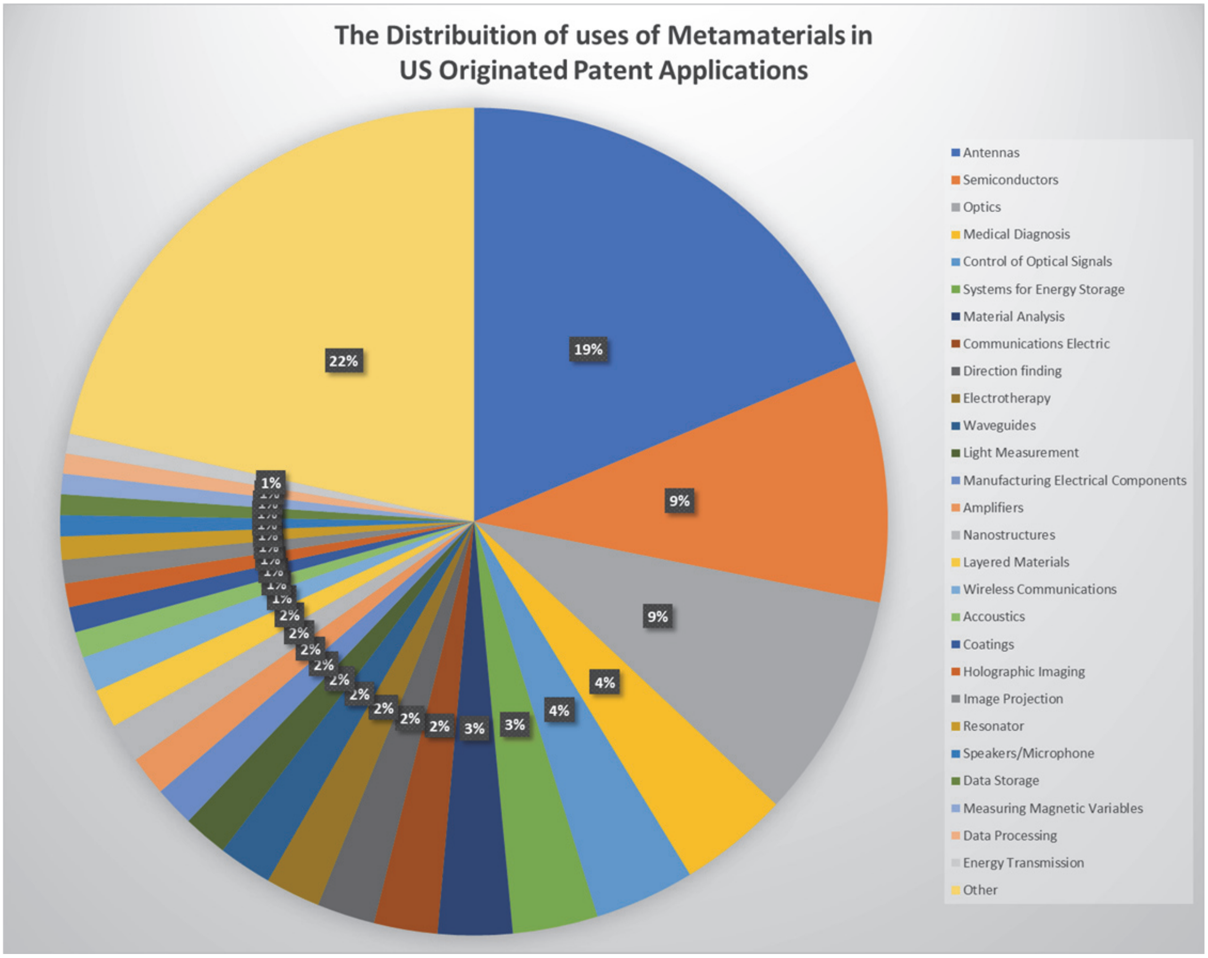
[33] U.S. Department of Justice, “Herfindahl-Hirschman Index,” webpage, undated.

Figure 2. Application Areas for Chinese Metamaterial Patent Applications



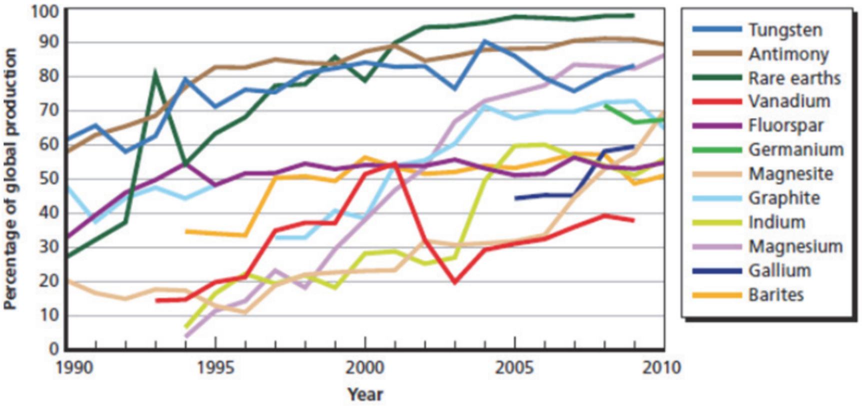
Source: Compilation of data published by USPTO and CNIPA by Christopher A. Eusebi.

Figure 3. Application Areas for United States Metamaterial Patent Applications



Source: Compilation of data published by USPTO and CNIPA by Christopher A. Eusebi.

Figure 4 Growth of China's Raw Materials Production



SOURCES: U.S. Geological Survey, 1996–2011; International Organizing Committee for the World Mining Congresses, 2011.
NOTE: Data unavailable on Chinese market share for germanium prior to 2008. Gallium data are from International Organizing Committee for the World Mining Congresses, 2011.