Heliyon 9 (2023) e17092

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Analysis of the global trade network of the chip industry chain: Does the U.S.-China tech war matter?

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ARTICLE INFO

Keywords:
Microchip industry chain
International trade
Trade characteristics
Complex network
Core-periphery structure
Robustness

ABSTRACT

Chip is the "brain" of the information industry and modern manufacturing industry, and supply chain security is the key to the sustainable development of the industrial chain. From the perspective of the industrial chain, this paper selected semiconductor silicon wafers and equipment, integrated circuits, electronic computers, and components as representative commodities in the upstream, midstream, and downstream of the chip industry chain, constructed global trade networks of the chip industry chain, and analyzed the characteristics of the networks and nodes in 2020 and the changes in China's status before and after the China-U.S. tech war. The study results indicate that the network scale and network density of the global trade network of downstream electronic computers and components are higher than those of midstream integrated circuits; the global trade network of upstream semiconductor wafers and equipment has the smallest network scale and network density, and the trade networks of all links show obvious small-world characteristics; The United States ranks first in betweenness centrality of all links, with the strongest control ability and the largest number of trading partners in all links; China has higher betweenness centrality and more trading partners in the global trade network of the two upstream commodities than that of the midstream commodities, and the lowest betweenness centrality in the global trade network of the downstream commodities; The core countries of the chip industry chain are concentrated in southeast Asia, east Asia, central and western Europe, and the United States. China's trade status of semiconductor silicon wafers and integrated circuits has declined significantly during the China-U.S. tech war. The nodes in the chip trade network have good robustness in the face of random attacks and show vulnerability under target attacks. Additionally, the trade network's robustness in the chip industry chain is the strongest for downstream commodities, ranks second for midstream commodities, and is the weakest for upstream commodities. These findings can provide references for ensuring chip supply chain security in China and other trade-participating countries.

1. Introduction

With the rapid development of China's economy, the increasing level of digitization and intelligence, and the surge in demand for chips, China has become the largest chip consumer in the world, but its domestic chip self-sufficiency rate is very low [1], China is increasingly facing a "core shortage" situation. In 2020, China's chip production capacity has reached 15%, ranking third in the world,

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https://doi.org/10.1016/j.heliyon.2023.e17092
Received 2 September 2022; Received in revised form 2 June 2023; Accepted 7 June 2023
Available online 9 June 2023

but a closer look reveals that 60% of this production capacity is contributed by foreign capital, and the production capacity of Chinese local enterprises only accounts for about 40%. In the China-U.S. tech war, the United States put Huawei and SMIC on the supply list and bans the supply of semiconductor components and related materials to them, aiming to curb the development of China's leading enterprises by completely cutting off the supply. Meanwhile, restrictions on core technologies have hindered the development of China's semiconductor industry [2]. The China-U.S. tech war not only affects China and the United States but also the sustainable development of the global semiconductor industry [3]. Under the background of economic globalization, the international trade volume of chip-related products has shown a rapid growth trend, and an increasing number of countries are participating in the international trade of chip-related products. This free trade has become an important link connecting different regions of the world, but it encounters the problem of a lack of chip supply in many countries and the weakening economic ties and interdependence between countries. At the end of 2019, chip manufacturers' productivity and China's chip imports declined due to the global epidemic. Global manufacturing has been hit hard by the epidemic, but there is a high demand for consumer electronics, which are inseparable from chips. The epidemic, such as shutdown and poor logistics, has exacerbated the shortage of chips in China, and the same situation has occurred in other countries. Chip is the foundation for the healthy development of industry, information, and other industries, and it has permeated all aspects of our lives, from national information security, economic security, and national defense security, to daily life, showing extremely high strategic significance.

Due to the above-mentioned practical problems, there are hidden dangers in the security and sustainable development of the global chip supply chain, which will not only result in a shortage of chips in China but also may lead to problems in chip supply in other countries. Therefore, investigating the global trade characteristics of typical commodities in the chip industry chain, the robustness of the trade network of each link, and the trade relationship between China and other countries (regions) can help to comprehensively reflect the trade status of each link and identify the core of link trade countries, find the differences in stability under the unexpected impact of the trade network of each link, and obtain the changing trend of China's trade status in each link. This investigation is of great practical significance to the security and sustainable development of the chip supply chain in China and even in the world.

2. Literature review

Complex networks are an abstract model that reflects the correlation topology between individuals in complex systems. They have been widely used in the fields of finance [4–7], stock [8–10], transportation [11–15], construction [16–18], healthcare [19–23], geology [[24,25]], climate [26–29], etc. Meanwhile, complex networks not only appear in the research of traditional problems but also have a wide application in some hot issues, such as sustainable development [30–34]. The characteristics and structure of any real-world systems can be described by using the structural characteristics and network functions of complex networks, so they are also applicable to the study of international trade issues. In recent years, complex networks have been gradually applied to the study of international trade issues, involving many trade fields such as mineral resources, energy, food, etc. Mineral resources and energy trade networks are current research hotspots. For instance, Du et al. constructed a world crude oil trading network based on complex networks and investigated the topological nature of the world crude oil trading network. The study revealed that the crude oil trade network follows a power law distribution, and the bilateral trade relations between countries are gradually expanding [35]. Dong et al. developed a nickel ore trade network from a supply and demand perspective. Based on the iterative algorithm model, the nickel ore trading network was optimized to reduce the trade cost by different ranges [36]. Cai et al. carried out an empirical study on international agricultural trade and trade relations between countries. The structure of global agricultural trade was quantitatively described and analyzed, and the cascade impact of the breakdown of bilateral agricultural trade relations was simulated [37].

However, the above research is limited to traditional industrial products and lacks research on high-tech products. The product value of high-tech industries is much higher than that of traditional industries, which is also the focus of great power games. The international trade network of high-tech products is less studied. For example, Li et al. used dynamic complex networks to reveal the temporal and spatial characteristics of the global industrial robot trade network and the evolution of trade conditions. The study found that Japan, Germany, and Italy are at the center of the global industrial robot trade. Though China's trade position has risen rapidly, it is mainly imported, and its exports are insufficient [38]. Hu et al. employed network analysis to study international lithium-ion batteries trade from a dynamic perspective. The study results show the trade center is transitioning from Asia to Europe. Additionally, "robust-yet-fragile" characterization and trade hidden risks were revealed [39].

The above-mentioned studies did not compare the international trade relations of products in different links of the industrial chain, and changes in one link of the industrial chain may affect the entire industrial chain. Meanwhile, the trade network analysis of a single product cannot reflect the trade relations and status differences of various countries in different links of the industrial chain, so it is significant to conduct research on various products in the industrial chain. Only a few scholars have introduced the industrial chain perspective into trade network analysis. For example, Li et al. analyzed the trade characteristics of the global copper industry chain and important countries by constructing trade networks in different links from the perspective of the copper industry chain. They established a two-dimensional evaluation index system to evaluate the comprehensive trade risks of major importing countries in all links of the industrial chain. The study found that copper processing is the link with the highest density in the global industrial chain supply chain, and it has the best connectivity and differentiation among trading countries. In the entire industry chain, the United States and China are relatively low-risk countries, Malaysia and Poland are high-risk countries, while Japan, South Korea, and Spain are the "critical" countries of trade risks, so it is necessary to focus on controlling trade supply risks [40]. Huang et al. used a complex network approach to analyze the evolution and influencing factors of international tungsten competition from the industrial chain perspective. It was found that the global tungsten competition is increasingly fierce, and the competition between Asia and Europe is the fiercest. Japan and Germany have remarkable competitiveness in the mid-downstream stages of the industrial chain. Besides, the analysis of the influencing factors shows that consumption level drives the competition for upstream and midstream products, while technological progress and China-U.S. trade frictions impede the competition for mid-downstream products [41].

In addition, there are few studies on the robustness of trade networks, and most of them focus on the robustness of energy trade networks. For example, Wei et al. investigated the robustness of the oil trade network and found that the regional aggregation of oil trade is an important factor affecting the vulnerability of the oil trade network, and the global oil trading system becomes more vulnerable after major events. To maintain the stability and security of the oil trade, economies with greater influence within the network should be considered [42]. Xie et al. also studied the robustness of the oil trade network, and they found that deliberate attacks on the bankruptcy, trade blockade, and economic sanctions of corresponding countries have a greater impact on the robustness than random attacks, and the international oil trade system is becoming more fragile [43]. Xiao et al. studied the robustness of the photovoltaic trade network and found that the global photovoltaic trading network is vulnerable to target risks and is robust to random risks [44].

Generally, in terms of research perspectives, most of the studies on the existing world trade networks aim at a single product, and there is a lack of comparative research on different products in various links from the perspective of the industrial chain; In terms of research methods, the existing studies mainly analyze the overall characteristics of each network and node indicators, but they fail to comprehensively consider the core-periphery structure and robustness of the network; In terms of research objects, the existing international trade studies mainly focus on traditional industrial products, and there is a lack of research on high-tech industry,

Table 1
The explanation and calculation formulas of the indicators.

Indicator	Explanation	Calculation formula
Degree	Nodes are countries (regions) participating in international trade. Node degree k_i is the number of nodes connected to node *i*. In directed networks, node degree is the sum of indegree and outdegree.	$K_i = \sum_{j \in N_i} a_{ij}$ where a_{ij} is the edge of nodes *i* and *j*. If the edge exists, a_{ij} is 1; otherwise, it is 0; *Ni* refers to other nodes connected to node *i*.
Network density (ρ)	It is the ratio of the actual number of sides (the number of trade links between countries) in the network to the maximum number of possible sides. It is used to measure the tightness of the network. The greater the density, the closer the trade network, and the more frequent the trade between countries.	$\rho = m/(n(n-1))$ where *n* is the number of countries (regions) participating in trade. *m* is the actual number of network connections.
Weighted degree	Node weighting degree includes weighted outdegree and weighted indegree. In this paper, the weight is trade value.	$K_i^{out}(t) = \sum_j a_{ij}(t) w_{r_{ij}}(t)$ $K_i^{in}(t) = \sum_j a_{ji}(t) w_{r_{ji}}(t)$ where $K_i^{out}(t)$ and $K_i^{in}(t)$ are the weighted outdegree and weighted indegree of node *i* at time *t*; $a_{ij}(a_{ji})$ is the trade relationship between node *i*(*j*) and node *j*(*i*); $\omega_{rij}(\omega_{rji})$ is the trade value of node *i*(*j*) to node *j*(*i*).
Average clustering coefficient	The clustering coefficient indicates the degree of aggregation between a node and its adjacent nodes. The average clustering coefficient indicates the degree of clustering among nodes in the network. The clustering coefficient used in this paper reflects the aggregation degree of trade between countries, and it can be exploited to determine whether the network has the characteristics of a small world.	$C_i = \frac{E_i}{C_{K_i}^2}$ $C = \frac{1}{n} \sum_{i=1}^{N} C_i$ where c_i is the clustering efficient of node *i*, and *C* is the average clustering efficient.
Average geodesic distance *L*	It refers to the average distance between any two nodes in the network. In this paper, it means the average distance between exporting countries and importing countries, reflecting the efficiency in the process of trade circulation. The longer the average distance, the lower the efficiency. Also, the average geodesic distance is one of the criteria to determine whether the network has the characteristics of a small world.	$L = \frac{1}{n \times (n-1)} \sum_{i,j} d(i,j)$ where *d*(*i*,*j*) is the shortest distance from node *i* to *j*.
Betweenness centrality	It refers to the number of times a node acts as the "intermediary" of the shortest path of the other two nodes. In the trade network, the betweenness centrality reflects the control ability of a country (region) to the global trade of a commodity. The higher the centrality, the stronger the country's control ability over the commodity in global trade, and the greater the impact of the country's price or policy change on the international trade of the commodity.	$b_{mk(i)} = \frac{N_{mk(i)}}{N_{mk}}$ where N_{mk} is the number of paths between node *m* and node *k*; $N_{mk(i)}$ is the number of paths passing through point *i* between node *m* and node *k*; $b_{mk(i)}$ is the betweenness centrality, i.e., the probability that node *i* is on the path between node *m* and node *k*.
Network efficiency	It is the average of the sum of the reciprocal distances between all pairs of nodes in the network. It is used to measure the efficiency of trade circulation in the network. The higher the network efficiency, the closer the global trade connection, and the more the supply and demand of international chip-related products can be met. A very low network efficiency means that the connectivity and transmission efficiency of the network is very low, which is reflected in the small number of trade relations between countries in the chip trade network, and the chip demand of most countries cannot be met. In this case, global chip security is threatened.	$E = \frac{1}{n \times (n-1)} \sum \frac{1}{d(i,j)}$ where *d*(*i*,*j*) is the shortest distance from node *i* to *j*.

especially chip industry related products.

Aiming at the shortcomings of the existing literature, this paper extends the research object to the upstream, midstream, and downstream of the industrial chain, selects four typical commodities of the chip industry chain in the high-tech industry, and uses complex networks to investigate the international trade of the chip industry chain. Meanwhile, the global trade network characteristics and network node characteristics of typical commodities in each link of the chip industry chain are analyzed, and the core-periphery structure method is adopted to identify the core countries, and the import and export situation and the trend of coreness changes in each link of China's chip industry chain are further analyzed. Additionally, random attacks and target attacks are exploited to analyze the robustness of the product trade network in each link. The target attack includes two attack methods, one of which is based on core-periphery analysis. Through the above research process, the comparative research of products in each link from the perspective of the industrial chain has been enriched, various research methods have been organically combined, and the research gap in the international trade pattern of related products in the chip industry chain has been filled.

The rest of this paper is organized as follows. Section 3 provides the complex network research methods used in this paper, related indicators, and their implications. Section 4 is the empirical analysis part, including data sources, network overall characteristics analysis, network center node analysis, China's trade characteristics analysis, core-periphery analysis, and robustness analysis. Section 5 discusses the main conclusions of empirical analysis and provides some policy implications for the development of China's chip industry under the background of the China-U.S. tech war.

3. Model and method

The research method consists of the following steps: First, take the countries (regions) that participate in the international trade of typical commodities in each link of the chip industry chain in 2020 as the trade network node, the trade relationship between countries (regions) as the edge, and the trade value as the edge weight, to construct a directional weighted network of international trade. In this way, four directional weighted trade networks are constructed. Then, from the perspective of the overall network and node characteristics, analyze the international trade network pattern of the chip industry chain, and conduct a core-periphery analysis to identify the core countries of trade and further analyze the changing trend of China's foreign trade situation and trade status. Finally, analyze the differences in the robustness of the trade network in each link, i.e., the differences in the stability of each link in the global chip industry chain in the face of unexpected shocks. The relevant indicators and their calculation formulas, as well as the meaning of each indicator used in this paper are presented in Table 1.

4. Results and analysis

4.1. Variables and data

The whole process of the chip industry chain involves semiconductor silicon wafer manufacturing, integrated circuit manufacturing, integrated circuit packaging and testing, and downstream applications. The chip industry chain is shown in Fig. 1 (the products in the dashed box are not within the scope of this paper).

This paper selects four typical commodities in each link of the chip industry chain for research, namely, upstream semiconductor silicon wafers, upstream semiconductor equipment, midstream integrated circuits, and downstream electronic computers and components. The specific commodity name and HS code are given in Table 2. The data in this paper are all obtained from the UN Comtrade (https://comtrade.un.org/data/). The selected data are bilateral trade data of countries in the world from 2016 to 2020, including exporting countries (regions), importing countries (regions), and trade values.

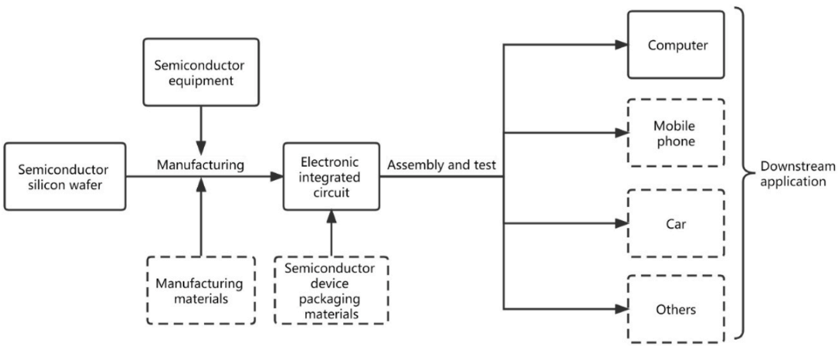


Fig. 1. Chip industry chain.

Table 2
The HS codes of the four selected commodities and their industrial chain links.

Commodities	HS code	Industrial chain
Monocrystalline silicon wafers and other crystal chips used in the electronic industry (hereinafter referred to as semiconductor silicon wafers)	381800	Upstream
Semiconductor equipment	8486	Upstream
Electronic integrated circuit	8542	Midstream
Automatic data processor and its device (electronic computer and components)	8471	Downstream

4.2. Global chip industry chain trade network analysis

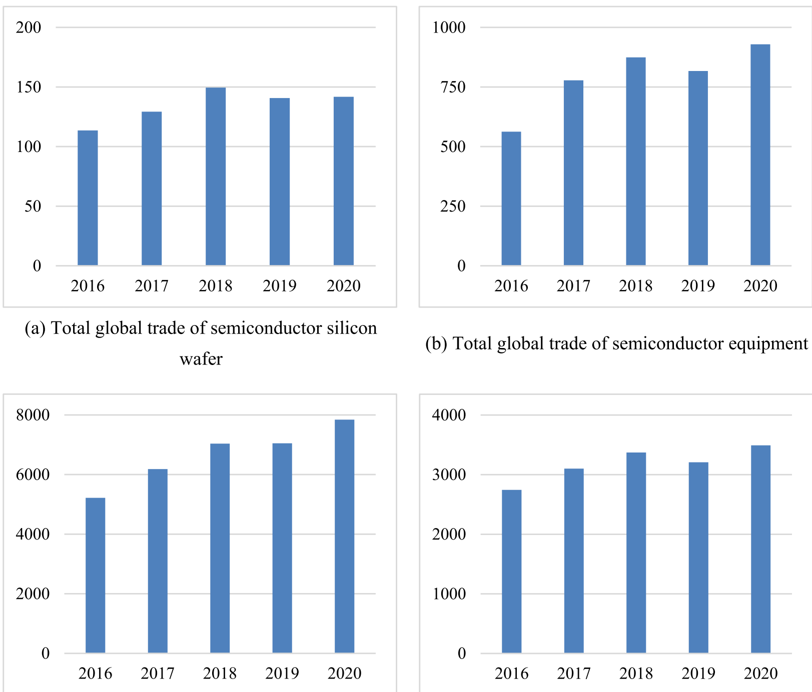
4.2.1. Analysis of global trade development trend

The global chip industry has experienced turmoil as the US has implemented a crackdown on China in the chip sector. The tech war between China and the United States in the chip field not only affects the two countries but also the global chip industry, resulting in chip shortages in many industries. The total global trade volume of the four commodities from 2016 to 2020 is shown in Fig. 2.

The total trade volume of the four typical commodities in the chip industry chain showed an overall growth trend from 2016 to 2020, except for integrated circuits, and the total trade volume of the other three groups of commodities all grew from 2016 to 2018 and picked up in 2020 after a brief decline in 2019. The growth rate of integrated circuits in the past five years is the largest, except for 2019, and the trade volume has increased significantly compared with the previous year. The trade volume of integrated circuits is the largest, followed by electronic computers and components, semiconductor equipment, and semiconductor silicon wafers, and the total trade volume of integrated circuits and electronic computers and components is much larger than that of semiconductor silicon wafers and semiconductor equipment. Integrated circuits play a crucial role in modern society and are the cornerstone of the information age. Electronic computers are also an indispensable tool in modern society and have a very wide range of applications. Semiconductor wafers and semiconductor equipment in the upstream of the chip industry chain are used as raw materials and manufacturing equipment for integrated circuits, and their total trade volume is relatively low.

4.2.2. Analysis of characteristics of global trade network

The global trade network of each link of the chip industry chain is directional. A visual method is employed in this study to map the trade network of typical commodities in the chip industry chain in 2020, as shown in Fig. 3. The larger the size of the node and the



(a) Total global trade of semiconductor silicon wafer

(b) Total global trade of semiconductor equipment

(c) Total global trade of electronic integrated circuit

(d) Total global trade of electronic computer and components

Fig. 2. The total global trade of the four commodities from 2016 to 2020 (Unit: US $100 million).

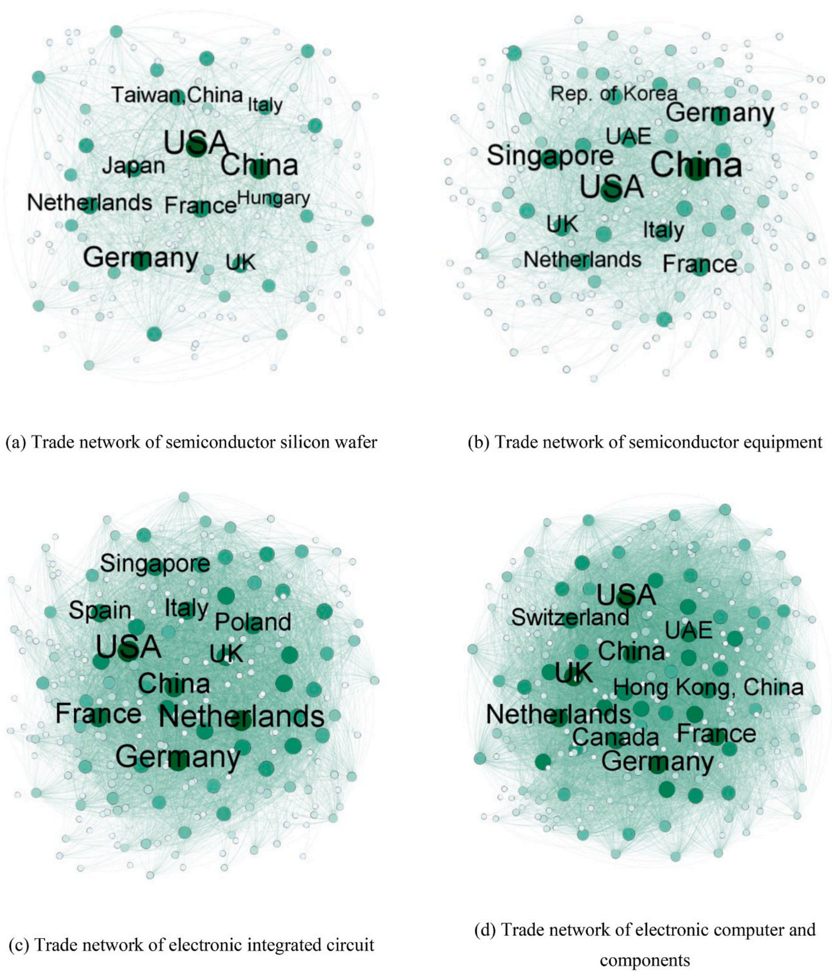
darker the color, the larger the degree of the node. Due to the large number of nodes, the top ten nodes are marked with the country name. Meanwhile, the degree value in a complex network reflects the number of trading partners of a country, and countries with a high degree value are often important importers or exporters in the trade network.

As shown in Fig. 3, the international trade network of typical commodities in the chip industry chain is very complex, and the trade relations between different countries have different positions in the entire network. For different products, the important import and export countries are different, but some countries have many trading partners in the international trade of the four commodities, such as the United States and China. Besides, compared with the midstream and downstream commodities, the trade network of the upstream two commodities is significantly sparse.

To further analyze the characteristics of the network structure, the trade network of commodities in each link of the chip industry chain in 2020 is analyzed from the aspects of network scale and network density. Specifically, the network size can be reflected by the number of nodes and the number of edges; the larger the number of nodes and the number of edges in the trade network, the larger the network size. In this paper, the number of network nodes is the number of countries (regions) participating in trade, and the number of sides is the number of trade relations. The differences in the size of the commodity trade network in each link are shown in Fig. 4.

As shown in Fig. 4, the commodity trade network of downstream commodities has the largest number of nodes and edges, i.e., the largest number of trade relations and network size, indicating these two commodities are highly valued by countries. Meanwhile, the commodity trade network of midstream commodities has the second-largest network size. The commodity trade network of downstream commodities has the smallest number of nodes and edges, i.e., the network size is the smallest, and the network size of semiconductor silicon wafers is smaller than that of semiconductor devices. Additionally, the number of trade relations between electronic computers and components is 9208, while that between the semiconductor silicon wafers is 1189. The reason for this big gap between these two commodities may be that computers are widely demanded as important downstream commodities. Overall, the trade network for downstream commodities is the largest, followed by the midstream commodities, while the trade network for upstream commodities is the smallest.

Network diameter and network density indicate the closeness of trade between countries, and the smaller the network diameter, the



(a) Trade network of semiconductor silicon wafer
(b) Trade network of semiconductor equipment
(c) Trade network of electronic integrated circuit
(d) Trade network of electronic computer and components

Fig. 3. The trade network of the four commodities in 2020.

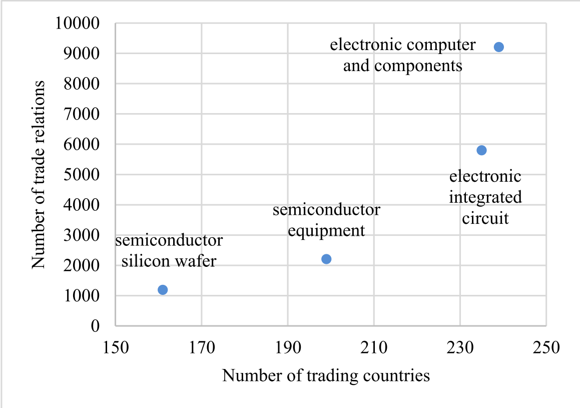


Fig. 4. The number of countries and trade relations of the four commodities in 2020.

closer the trade links between countries; the greater the network density, the closer the links between trading countries (Fig. 5). The network density is calculated by the formula listed in Table 1, and the network diameter is the maximum distance between any two points in the network.

It can be seen from Fig. 5 that, among the three links, the graph density of downstream commodities is the largest, and the network diameter is the smallest, indicating that the trading countries of downstream electronic computers and components are the most closely linked in the process of trade circulation. Meanwhile, the commodity trade networks of midstream commodities rank second in graph density and network diameter. The commodity trade network of upstream commodities has the smallest graph density but the largest network diameter, and the trade links between countries are the most alienated. Moreover, among the two upstream commodities, the trading network of semiconductor silicon wafers has a weaker graph density than that of semiconductor equipment. Generally, the trading network of downstream commodities has the highest graph density, followed by midstream commodities, and upstream commodities. In addition, the maximum network density of the commodity trade network among the four commodities is only 0.174, indicating that there is still much room for expansion in the establishment of international trade relations in each link of the chip industry chain between countries.

The average geodesic distance determines the degree of separation of countries in the trade network, and it can be used to measure the efficiency of national trade exchanges; meanwhile, the clustering coefficient reflects the degree of aggregation of national relations in the international trade network, and the average geodesic distance and average clustering coefficient determine whether the trade network has the characteristics of a small world. A small-world network refers to a subnetwork in which there is a connection between almost any two nodes in the network, and there is at least one short path between most node pairs. Most nodes are not adjacent to each other, but most nodes can access any other in only a few steps.

Usually, there are many nodes with a high number of connections in the network. These nodes play the role of public connections and reduce the length of the shortest path between other edges. In the trade network, these nodes represent the key import and export trading countries. The small-world characteristics of the trade network are reflected in the fact that most countries can be linked through some important trading countries. According to the definition of the small-world network, the average clustering coefficient and average geodesic distance of the network are calculated by the formula listed in Table 1, as shown in Fig. 6.

Fig. 6 shows that the average clustering coefficient of upstream commodities is less than that of midstream and downstream commodities, the average geodesic distance of downstream commodities is less than that of midstream commodities, and upstream

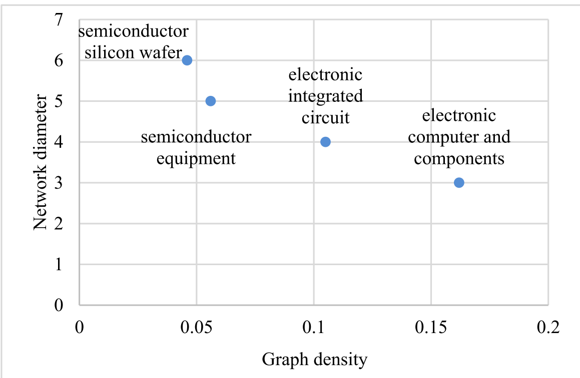


Fig. 5. The graph densities and network diameters of the four commodity trade networks in 2020.

commodities have the largest average geodesic distance. It can be seen that the degree of trade network aggregation and trade exchange efficiency of downstream commodities are the highest, followed by the midstream and the weakest upstream. The smallest clustering coefficient in the four commodity trade networks in this paper is 0.389, which is much larger than the average clustering coefficient of random networks of the same scale. The maximum average path length of the networks is 2.306, which is much smaller than the natural logarithm ln161 of the number of nodes, which is approximately 5.08. Therefore, the international trade network of each link in the chip industry chain has the characteristics of a small world network, and this is related to the existence of many directly connected paths in the network. This shows that most countries in the network can establish trade links through a very short path, and the ability of trade information dissemination and exchange between countries is strong.

4.2.3. Analysis of the characteristics of global trade network nodes in each link of the chip industry chain

The degree of access indicates the number of trading partners in a country's export (import). The higher the degree of access, the more active the country's import and export trade, and the wider the degree of trade exchanges (Table 3).

As shown in Tables 3 and in the import and export trade of the upstream, midstream, and downstream commodities, the United States ranks first in terms of export and import, and both its export trade and import trade are relatively active. For the upstream commodities, China, the United States, Germany, and other countries exhibit the most extensive trade exchanges; For the midstream commodities, the United States, Germany, and the Netherlands exhibit the most extensive trade exchanges; For the downstream commodities, the United Kingdom, the United States, Germany, and other countries exhibit the most extensive trade exchanges. This shows that the countries with the most trade exchanges of commodities in all links of the global chip industry chain are mainly the United States, China, and some European countries (Germany, the Netherlands, etc.). In the typical commodity trade network of the chip industry chain in 2020, China was one of the most active economies except that it was not in the top 5 in the import trade of downstream commodities. However, China exhibits the highest range of trade exchanges in the upstream commodities, followed by the midstream commodities, and the lowest range of trade exchanges in the downstream commodities.

In this paper, the weight represents the value of trade, and the top 10 countries in the weighted access in 2020 are selected to represent the importing and exporting countries (regions) with the largest market share in the global trade network in all links of the chip industry chain, as shown in Figs. 7 and 8.

As shown in Fig. 7, for upstream semiconductor equipment, the countries with the highest intensity include Japan, the United States, and the Netherlands; For upstream semiconductor silicon wafers, the countries with the highest intensity include Japan, China, and the United States; For midstream integrated circuits, the countries (regions) with the highest output intensity include Hong Kong, Taiwan, and China; For downstream electronic computers and components, the countries (regions) with the highest output strength include China, the United States, and Hong Kong, and the output strengths of China and United States are 170176 million US dollars and 24776 million US dollars, respectively. The difference between the two is very large, indicating that China has an absolute advantage in international computer export trade.

It can be seen from Fig. 8 that for upstream semiconductor equipment, the countries (regions) with the highest entry intensity include China, Taiwan, and South Korea; For upstream semiconductor silicon wafers, the countries (regions) with the highest entry strength include Taiwan, China, and South Korea; For midstream integrated circuits, the countries (regions) with the highest entry intensity include China, Hong Kong, and Taiwan; For downstream computers and components, the countries (regions) with the highest entry intensity include the United States, Hong Kong, and the Netherlands.

Further analysis shows that China is the largest importer of semiconductor equipment, and its export trade volume is relatively low, indicating that China has a huge demand for semiconductor equipment and highly relies on imports. Thus, more attention should be paid to domestic semiconductor equipment, and domestic semiconductor equipment enterprises should strive to break through key technical bottlenecks. Compared with the trade volume of semiconductor equipment, China's import and export trade volume of semiconductor silicon wafers are among the highest, and both occupy a large market share, which may be related to the narrowing of the technological gap between domestic and foreign semiconductor silicon wafers. Compared with the weighted output and input of typical middle and downstream commodities, China's import trade volume of integrated circuits accounts for a high proportion, while

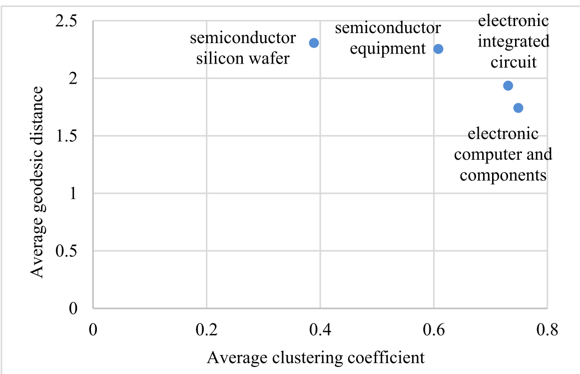


Fig. 6. The average clustering coefficients and average geodesic distance for the four commodity trade networks in 2020.

Table 3
The ranking of trade countries for the four commodities in 2020.

Rank	Semiconductor silicon wafers		Semiconductor equipment		Electronic integrated circuits		electronic computers and components	
	outdegree	indegree	outdegree	indegree	outdegree	indegree	outdegree	indegree
1	USA	USA	China	USA	Germany	USA	UK	USA
2	China	Germany	USA	Germany	USA	Netherland	USA	Germany
3	Germany	China	Singapore	China	Netherland	Germany	Germany	UK
4	Netherland	Taiwan	UAE	France	France	China	Netherland	Netherland
5	Hungary	Japan	Germany	Netherland	China	UK	China	France
6	France	France	France	Switzerland	Italy	Hong Kong	Denmark	UAE
7	Japan	UK	UK	UK	Spain	France	France	China
8	UK	India	Italy	Taiwan	Poland	Hungary	Canada	Hong Kong
9	Italy	Korea	Netherland	Italy	Singapore	Italy	Belgium	Canada
10	Belgium	Singapore	Korea	Malaysia	UK	Spain	Sweden	Italy

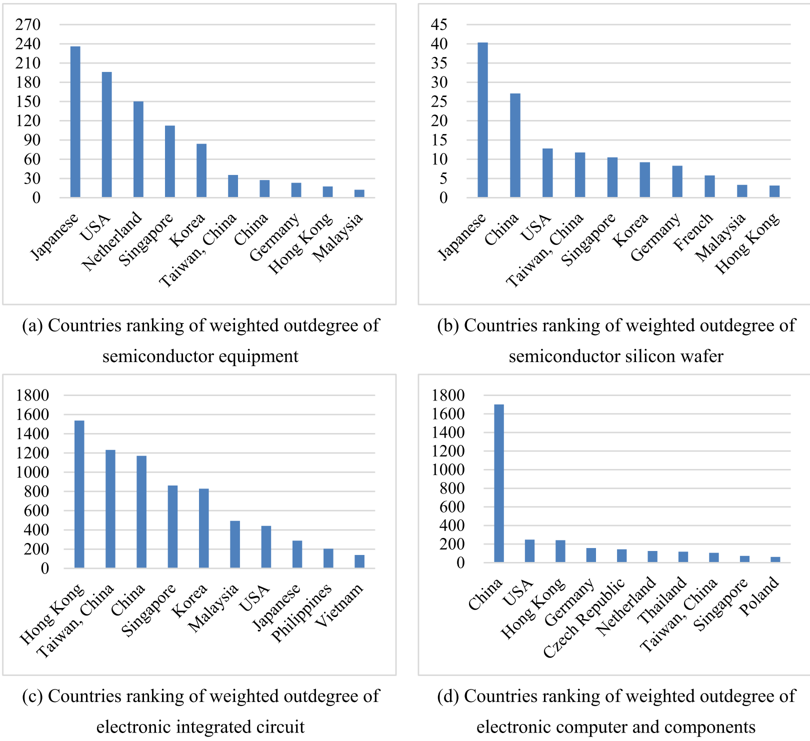
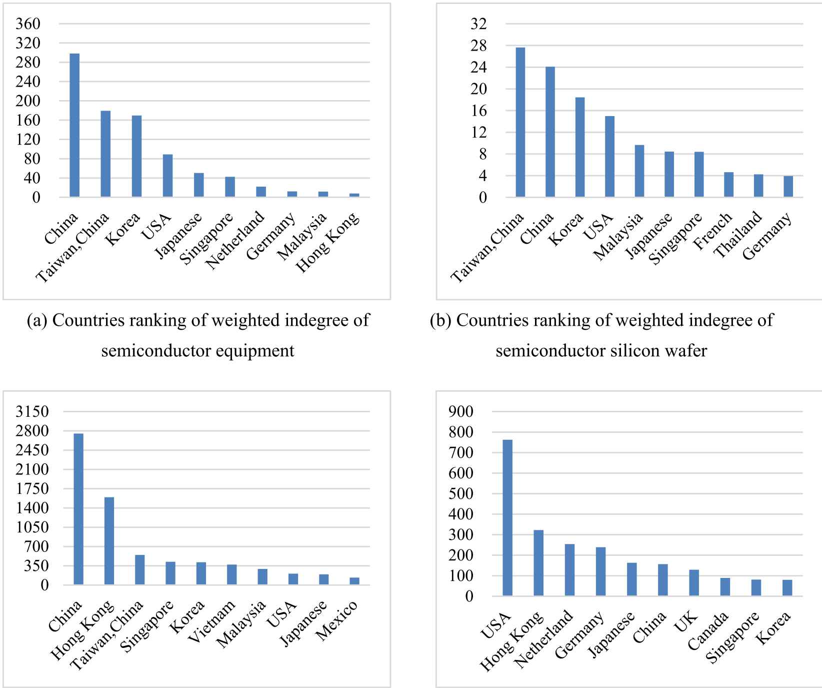


Fig. 7. The ranking of weighted outdegree of trading countries for the four commodities (Unit: US $100 million).

the export trade volume accounts for a relatively small proportion; The export trade volume of electronic computers and components accounts for a high proportion, while the import trade volume accounts for a small proportion. Thus, the main mode of China's related industries is to import electronic components such as integrated circuits for assembling and manufacturing and then export the products. For example, China remains its most important manufacturing country.

In the process of international two-way trade, if the trade relationship between countries with high betweenness centrality is broken, it may have a serious impact on other countries. So, countries with high betweenness centrality have strong control ability in trade circulation, and the world's famous chip companies are mostly distributed in these countries. In this paper, the top 10 countries with betweenness centrality in 2020 are selected to represent important transit countries in the global trade network of all links in the chip industry chain. The betweenness centrality is calculated by the formula listed in Table 1 and ranked in Table 4.

As shown in Table 4, the United States ranks first in the betweenness centrality of the trade of the upstream, midstream, and downstream commodity commodities. So, it has strong control ability and occupies the first trade control center and transit area in all links of the global chip industry chain; China's betweenness centrality in the trade of upstream semiconductor wafers and equipment is significantly higher than that of the midstream and downstream commodities. In addition, in the trade of the two upstream commodities, Germany and UAE have a high betweenness centrality; In the trade of midstream integrated circuits, the Netherlands and France have a high betweenness centrality; In the trade of downstream commodities, the UK and Germany have a high betweenness centrality. The main transit places are concentrated in the United States, some European countries (Germany, the United Kingdom, the



(a) Countries ranking of weighted indegree of semiconductor equipment

(b) Countries ranking of weighted indegree of semiconductor silicon wafer

(c) Countries ranking of weighted indegree of electronic integrated circuit

(d) Countries ranking of weighted indegree of electronic computer and components

Fig. 8. The ranking of weighted indegree of trade countries for the four commodities (Unit: US $100 million).

Table 4
The ranking of betweenness centrality for the trade of the four commodities in 2020.

Rank	semiconductor silicon wafer	semiconductor equipment	electronic integrated circuit	electronic computer and components
1	USA	USA	USA	USA
2	China	China	Netherland	UK
3	UAE	Germany	France	Germany
4	Germany	UAE	South Africa	Netherland
5	Slovenia	Singapore	Germany	France
6	Russia	Netherland	China	UAE
7	Taiwan	South Africa	UK	China
8	Hungary	UK	UAE	Canada
9	Romania	France	Hong Kong	Hong Kong
10	Austria	India	Italy	Belgium

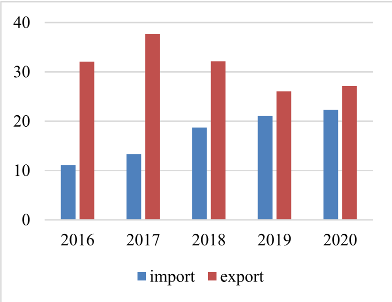
Netherlands, etc.), China, and other countries. Combined with the analysis of the degree of access and point intensity, it can be seen that although some countries (regions) do not have many trading partners and have a high betweenness centrality, they still occupy a leading position in the total trade volume, such as Taiwan, Japan, and South Korea; meanwhile, some countries have many trading partners and a high betweenness centrality, but they do not have a leading total trade volume, such as Germany. However, in general, the more trading partners a country (region) has and the higher the betweenness centrality, the easier it is to gain a leading position in total trade.

4.3. Analysis of trade characteristics of China's chip industry chain

4.3.1. Analysis of evolution of import and export trade

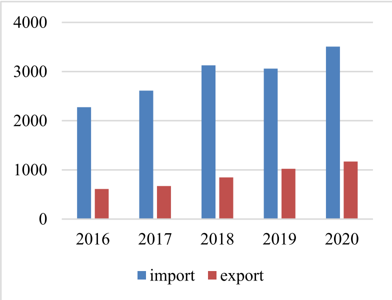
To investigate the changes in the import and export trade of China's chip industry chain, the impact of the China-U.S. tech war on the trade of the four commodities in China's chip industry chain is studied from the perspective of trade values. Fig. 9 shows the total import and export trade values of the four commodities in China from 2016 to 2020.

It can be seen from Fig. 9 that the total trade volume of all upstream, midstream, and downstream commodities in China has shown an increasing trend, but except for the imports of semiconductor silicon wafers and the exports of integrated circuits, the rest have declined significantly in 2019 and picked up in 2020. This may be due to the impact of the U. S.-China technology war. Affected by this, the problem of chip shortage in China is very serious. Today's world is a community of interests, so it is not only China that is affected

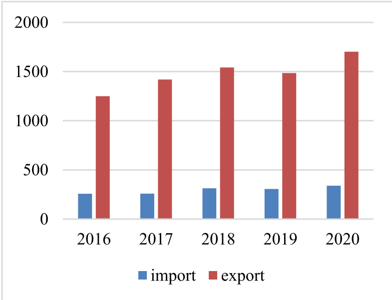


(a) Total import and export trade value of semiconductor equipment

(b) Total import and export trade value of semiconductor silicon wafer



(c) Total import and export trade value of electronic integrated circuit



(d) Total import and export trade value of electronic computer and components

Fig. 9. The total import and export trade value of the four commodities in China (Unit: US $100 million).

by the war. This has caused turmoil in the entire global chip industry chain, resulting in losses in many countries, including domestic companies in the United States, and there is also chip a shortage in the United States. Meanwhile, today's world dependents more on an intelligent, informatized lifestyle due to the impact of the epidemic, so the demand for chips is increasing. In this case, many countries support China, which stimulates China's determination to innovate independently and makes China more aware of the importance of the chip industry in the current era. Meanwhile, the impact of the trade war also shows that China needs to strengthen its competitiveness and reduce its dependence on external markets to cope with external uncertainties and risks.

4.3.2. Analysis of import and export trade partners

To identify China's important trade partners in import and export, the trade value of China's import and export with other countries is ranked, and the trade status between China and other countries and its important import and export trade partners are analyzed. Tables 5 and 6 present the ten countries (regions) with the highest trade value of China's import and export of the four commodities in 2020.

It can be seen from Table 5 that Japan ranks first among the major countries that import semiconductor wafers from China, and Taiwan and South Korea have the highest trade value in China's import of semiconductor wafers; Among the major importers of semiconductor equipment from China, Japan ranks first, and Taiwan and South Korea rank second and third, indicating that Japan is an important importer of upstream commodities in China's chip industry chain. Meanwhile, Hong Kong ranks first in the trade value of importing midstream and downstream commodities, indicating that Hong Kong is an important importer of upstream and midstream commodities in China's chip industry chain. Additionally, Taiwan and South Korea are major importers of Chinese integrated circuits,

Table 5
The ten countries (regions) with the highest trade value of China's imports 4 commodities in 2020.

	semiconductor silicon wafer	semiconductor equipment	electronic integrated circuit	electronic computer and components
1	Japan	Japan	Hong Kong	Hong Kong
2	Taiwan	Korea	Taiwan	Thailand
3	Korea	USA	Korea	USA
4	Hong Kong	Singapore	Singapore	Philippine
5	USA	Netherland	USA	UAE
6	Singapore	Taiwan	Malaysia	Taiwan
7	Germany	Hong Kong	Viet Nam	Singapore
8	Russia	Germany	Ireland	Germany
9	Malaysia	Austria	Japan	Malaysia
10	UK	UK	Philippine	France

Table 6
The ten countries (regions) with the highest trade value of China's exports of the four commodities in 2020.

	semiconductor silicon wafer	semiconductor equipment	electronic integrated circuit	electronic computer and components
1	Malaysia	Hong Kong	Hong Kong	USA
2	Korea	Singapore	Taiwan	Hong Kong
3	Viet Nam	Taiwan	Korea	Netherland
4	Taiwan	USA	Viet Nam	Japan
5	Thailand	Korea	Malaysia	Germany
6	Japan	Japan	Singapore	UK
7	Hong Kong	Viet Nam	Japan	Korea
8	Singapore	Malaysia	Philippine	Singapore
9	India	Turkey	India	India
10	USA	Thailand	USA	Australia

and Thailand and the United States are major importers of Chinese electronic computers and components. These countries play an important role in China's chip industry, providing necessary materials and equipment support for China's chip manufacturing industry. Meanwhile, it also shows that China still relies on imports, and needs to further strengthen its independent R&D and production capacity, and increase the chip self-sufficiency rate.

As shown in Tables 6 and in terms of China's export trade of semiconductor wafers, China's export trade to Malaysia ranks first; Meanwhile, Korea and Vietnam are also major exporters of China's semiconductor wafers. In terms of China's export trade of semiconductor equipment, China's export trade volume to Hong Kong ranks first. Singapore and Taiwan are also major exporters of China's semiconductor equipment. In terms of China's export trade of integrated circuits, Hong Kong, Taiwan, and South Korea are the top three, and they are the main exporters of China's integrated circuits. In terms of the export trade of downstream computers and components, the United States is China's largest computer exporter, followed by Hong Kong, and the Netherlands. Overall, China's international trade and cooperation in the field of semiconductors is very complex, and it needs to give full play to its own advantages and strengthen cooperation with countries and regions to ensure the country's information security and economic development.

4.3.3. *Core-periphery analysis*

The purpose of performing core-periphery analysis is to divide the nodes in the network into core regions and edge regions, and the nodes that occupy an important position in the network are those in the core region. Only analyzing the transaction situation of various countries is not enough to fully show the complexity of the trade of various countries, nor can it reveals the importance of China in the international market structure. Therefore, this paper carries out a core-periphery analysis to describe the degree of participation of various countries in the international trade network of commodities in all links of the chip industry chain. The degree of participation is reflected by coreness. The greater the coreness, the higher the degree of participation of the country in international trade, the more important its position in the entire trade network, and the change in the coreness can reflect the change in the country's status. In this paper, countries with a coreness exceeding 0.05 are classified as core regions, and the changing laws of countries in core regions are illustrated. After the bilateral trade data are converted into matrix form, ucinet is employed to calculate the coreness of each country, and the ranking is shown in Table 7.

As shown in Table 7, the number and membership of core countries vary for different commodities, with the lowest number of core countries for downstream computers and components. The trade between core countries accounts for a large share of the total trade, which indicates that fewer countries have the highest trade flows. The large number of core countries for the other three commodities in the midstream and upstream demonstrates that many countries have great participation in international trade. It can be seen that the traditional trading countries (regions) in the chip industry have a high position in the network, such as the United States, China, Taiwan, etc., and they are at the core of the trade network of the four commodities; There is a large number of core countries in the middle east and south Asia, indicating the important position of Southeast Asia in the global chip industry chain; In addition, the United States, central and western Europe, and east Asia, including China, Japan, and South Korea, are also key areas of the global chip industry chain. This can be attributed to the long-standing technological capabilities and infrastructure of these countries, and their strategic investments in the semiconductor industry.

Based on the above analysis, the position of China in the international chip industry chain can be further discussed. Fig. 10 shows the trend of China's coreness change.

As illustrated in Fig. 10, in the past five years, China's coreness in the international trade of downstream computers and components is the lowest at 0.874 and the highest at 0.888, indicating a stable variation trend. As one of the world's largest electronic computer manufacturing centers and consumer markets, China occupies a large share of the world's electronic computer market,

Table 7
The countries (regions) with the four commodities in the core region in 2020.

Commodities	Core countries
Semiconductor silicon wafer	China, Hong Kong, Japan, France, Germany、 Malaysia, Taiwan, Korea, Singapore, USA
Semiconductor equipment	China, Austria, Japan, Netherlands, Taiwan, Korea, Singapore, Switzerland, USA
Electronic integrated circuit	China, Hong Kong, Japan, Malaysia, Taiwan, Philippines, Korea, Singapore, USA, Viet Nam
Electronic computers and components	China, Hong Kong, Taiwan, Philippines, Singapore, the USA, Thailand

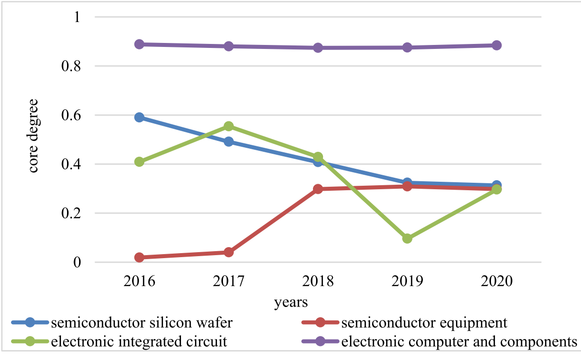


Fig. 10. The variation trends of China's coreness for the four commodities.

which is much higher than that of other countries (regions). China's coreness in the international trade of midstream integrated circuits has fluctuated significantly in the past five years, declining since 2017, falling to its lowest level in 2019, and picking up in 2020, and this is probably due to the impact of the U.S.-China technology war on China's integrated circuit industry. However, the rebound of China's coreness in 2020 shows that China's emphasis on the integrated circuit industry has increased in this background, and this industry has become the focus of attention of the whole country, gradually gathering more policies and resources. Many American companies rely heavily on China's integrated circuit market, and this is an important factor affecting the trend of trade conflicts. In the upstream of the chip industry chain, China's coreness in the international trade of semiconductor silicon wafers is declining year by year, and this is also related to the "stuck neck" by the United States in related fields of China. China's coreness in the international trade of semiconductor equipment showed an overall upward trend, where the coreness in 2017 and 2018 was 0.019 and 0.04 respectively; due to this, China did not enter the core countries, but its coreness began to increase significantly and remained stable in 2018. In recent years, China has made great progress in developing semiconductor silicon wafers and equipment, but Japan and the United States are still the main monopolies of upstream commodities, especially semiconductor equipment. In general, China's coreness changes in the international trade of the four commodities are different. Among them, semiconductor silicon wafers and integrated circuits are greatly affected by the China-U.S. technology war. At present, all four types of commodities in China are in the core area and occupy the core position. In a strategic sense, the global chip industry has become one of the important areas for countries to compete for technological and economic leadership. In these 1 areas, the United States has been leading, and China is actively catching up. Therefore, for the United States and China, strengthening the development and control of the chip industry is of great strategic significance to realize the dominant position of the global semiconductor industry.

4.4. Robustness analysis of trade network

The robustness of complex networks refers to the network's ability to maintain stable and effective when the network is deliberately attacked or random failures occur. This is reflected in the trade network's ability to maintain normal operation and circulation in the face of certain external environmental impacts or changes under the trade policies of certain countries. When evaluating the robustness of a network, network efficiency (E) is often adopted as an evaluation index, which can well reflect the network's topological performance, especially the connectivity between nodes and the overall efficiency. Network efficiency has been applied to the robustness evaluation of transportation networks and energy networks by scholars. Therefore, this paper selects network efficiency as the evaluation index of the trade network.

A node attack in a complex network indicates that when a node is attacked, the node and all edges connected to the node are removed to form a new network. Usually, there are two types of node attacks: random attacks and target attacks. Specifically, random attack refers to the random destruction of nodes in the network with some probability, regardless of the position and importance of the network nodes. In the international trade network, random attacks show that some countries or regions may be affected by international economic and trade turmoil and other factors, making the chip in a certain year fail to be exported, and this situation is accompanied by uncertainty. Target attack refers to the targeted destruction of nodes in the network. This attack is based on the importance of the nodes, so its harm to the network is often greater. It may be performed on a certain country or region in the trade network. The import and export policies of the country have undergone tremendous changes, causing the country's chip supply or demand to be interrupted. Under the background of the U.S.-China tech war and the epidemic, the policies introduced by some countries or regions to stop international trade can be regarded as supply disruptions caused by targeted attacks.

In this paper, target attacks and random attacks are adopted when simulating and destroying nodes in the network. When the target attack is carried out, the nodes in the network are deleted according to their degree and importance, and the network efficiency changes of the whole network are observed. The targets of attacks by node importance are the core countries of trade in each link obtained through core-periphery analysis. The random attack is performed by using a Python program to generate random sequences to attack network nodes randomly. Due to the uncertainty of random attacks, the average of ten random attack results is taken for study in this paper. All three attacks are carried out through the Python program, and the simulation results under different attack methods are shown in Figs. 11 and 12 and Table 8.

As shown in Figs. 11 and 12, when attacking a network node, the impact of target attacks and random attacks on the node is different. The network efficiency under a random attack decreases more slowly than that under a target attack. Taking the trade network of integrated circuits as an example, when the network efficiency drops below 0.1, the number of network nodes attacked by the target attack according to the degree value only accounts for 22% of the number of nodes attacked randomly. Therefore, the trade network has better robustness in the face of random attacks. Meanwhile, it shows that in the trade network, a country with more partners is located close to the network center, and it has an indispensable role in trade. When chip security problems occur in these countries, it will affect the normal operation of the global chip trade. Additionally, when the global semiconductor wafer trade network is subjected to random attacks, the number of nodes attacked accounts for 81% of the nodes in the network, and the network efficiency drops below 0.1. In the semiconductor equipment trade network, when the number of nodes attacked accounts for 90% of the nodes in the network, the network efficiency drops below 0.1. However, in the trade networks of integrated circuits and electronic computers, when the network efficiency drops below 0.1, the number of nodes attacked accounts for 96% and 97% of the number of nodes, respectively. When the trade networks of the four commodities are attacked by targets according to degree values and the network efficiency drops below 0.1, the number of nodes attacked accounts for 11.8%, 13%, 21%, and 33% of the total number of nodes, respectively. It can be seen that in the face of random attacks and degree attacks, the network efficiency of the two upstream commodities is higher than that of the midstream and downstream commodities, i.e., the robustness of the trade network of downstream commodities in the chip industry chain is the highest, that of the midstream commodities ranks second, and that of upstream commodities is the weakest.

The target attack method is employed to perform node attacks on the core countries of each link obtained above, and the attack order is the order of the countries listed in Table 7. Table 8 shows that the network efficiency of each trading network changes differently after a deliberate attack on the core country, with the network efficiency of the upstream commodities decreasing more than that of the midstream and downstream commodities. Meanwhile, the network efficiency of each commodity trade network changes differently after target attacks are performed at core countries, with the network efficiency of the upstream commodities decreasing more than that of midstream and downstream commodities. This is reflected in international trade as follows: when the supply or demand of chip-related products in a few core trading countries is interrupted, the trade network of upstream commodities in the industrial chain will be more severely impacted, while the trade networks in the midstream and downstream will be less impacted, and the network robustness is higher. This again verifies the results of the first two attacks.

5. Conclusion and policy implications

In this paper, complex networks are used to construct a weighted network of international trade for four typical commodities in the upstream, midstream, and downstream of the chip industry chain. Then, the overall characteristics and node characteristics of the network in 2020 are analyzed, and core countries are identified. In addition, this paper investigates the coreness of China's trade network and the situation of import and export trade from 2016 to 2020. The main conclusions are as follows:

1) In 2020, the global trade network of the downstream electronic computers and components in the chip industry chain was the largest, followed by midstream integrated circuits, and the two upstream commodities. This situation is the same as the copper industry chain trade [40]. Meanwhile, the trade network of upstream commodities has the lowest complexity than that of the midstream commodities and the downstream commodities, which is consistent with the cobalt industry chain trade [45]. The trade network of downstream commodities is tighter and the efficiency of trade exchange is higher than that of the midstream, and the upstream is the weakest. The typical commodities in each link show obvious "small-world" characteristics, and this is consistent with the trade of the energy industry [46]. Moreover, the trade of the four commodities has relatively low network density, i.e., the network is relatively loose, and there is much room for expansion in the establishment of trade relations between countries.
2) In 2020, the United States ranked first in the betweenness centrality of the trade network of the four typical commodities in the global chip industry chain, indicating that it has a strong control ability in all links of commodity trade and is also the most important transit area. This is consistent with the international trade of rare earths [47]. Thus, the United States has an important position not only in the trade of high-tech products but also in the trade of precious strategic resources. China's betweenness centrality of upstream commodities ranks second only to the United States, while the betweenness centrality of the trade network of the midstream and downstream commodities is relatively low. In terms of trading partners, the United States has a leading number of import and export trading partners in 2020, and its trade is very active and extensive. The trade breadth of China is the highest in the upstream commodities, followed by the midstream commodities, and the lowest in the downstream commodities. China is the largest importer of semiconductor equipment, with a huge demand for semiconductor equipment and a strong dependence on imports for the three categories of commodities in the upstream, midstream, and downstream. China's import and export trade of semiconductor silicon wafers has a large market share, which is consistent with the research results of the international polysilicon trade [48]. The main mode of China's chip industry is still to import electronic components such as integrated circuits to assemble and manufacture and then export the products, e.g., China is still the most important manufacturer of electronic computers.
3) From 2016 to 2020, the total trade volume of China's upstream, midstream, and downstream commodities showed an overall increasing trend. It shows that China's semiconductor industry is gradually developing and becoming one of the priorities of China's trade. However, except for the import of semiconductor silicon wafers and the export of integrated circuits, which have risen year by year, the rest have declined significantly in 2019 and picked up in 2020. This is mainly due to the U.S.-China tech war. This is inconsistent with the continuous increase in the import and export trade volume of Chinese traditional medicine products [49]. The reason may be that the chip industry is a high-tech industry, which is the focus of China-U.S. trade. In 2020, Japan was the

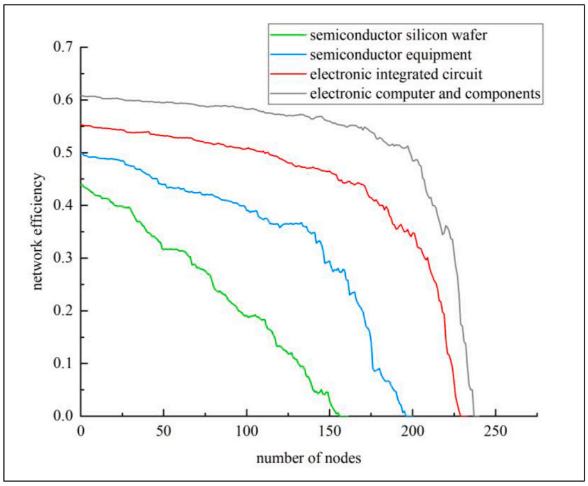


Fig. 11. The efficiency of the trade networks of the four commodities under random attacks.

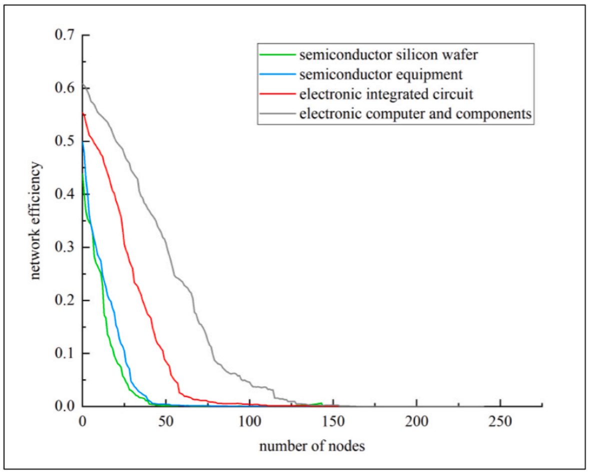


Fig. 12. The efficiency of the trade networks of the four commodities under the target attack.

Table 8
The changes in the network efficiency of the four commodities after attacks on core countries.

The number of attacks	Semiconductor silicon wafer	Semiconductor equipment	Electronic integrated circuit	Electronic computers and components
0	0.438498965	0.4992	0.553731316	0.608478615
1	0.416953616	0.47811	0.550937329	0.597927874
2	0.417992198	0.476606	0.552396637	0.599673203
3	0.414714182	0.474628	0.551385988	0.596247825
4	0.41116419	0.46801	0.549733139	0.595684577
5	0.396797629	0.463248	0.545994667	0.593568528
6	0.395219941	0.468048	0.537493665	0.585953071
7	0.388898792	0.466051	0.536234022	0.584696118
8	0.394015881	0.441936	0.532787698	
9	0.391987626	0.440241	0.517680306	
10	0.376301692	0.380223	0.516748812	
11	0.315786726			

main importer of China's upstream commodities, while Hong Kong and Malaysia were the main exporters of China's upstream commodities. Hong Kong was the main region for China to import midstream integrated circuits and downstream electronic computers, and it was also the main region for China to export integrated circuits. Besides, the United States was China's main exporter of electronic computers and components.

4) Core-periphery analysis indicates that the core countries of the global chip industry chain in 2020 were mainly concentrated in Southeast Asia, East Asia, Midwest Europe, and the United States, which are different from the core countries of international coal trade [50]. The reason may be that coal is an energy mineral, and the core countries of trade are mostly countries with rich coal resources. From 2016 to 2020, China's trade in downstream electronic computers and components of the chip industry chain was the highest and remained stable. China's coreness of midstream integrated circuits rebounded in 2020 after a continuous decline in 2018 and 2019, the coreness of downstream semiconductor wafers continued to decrease, and the coreness of semiconductor equipment was on the rise. The reduction of China's coreness may be caused by the China-US tech war, and the tariffs involving the chip industry in the China-U.S. trade war also have adverse effects. Such effects exist in many fields, such as the international plastic resin trade [51]. Generally, the coreness changes of the four commodities in China are different. Among them, semiconductor silicon wafers and integrated circuits exhibited a significantly declined trade volume during the China-U.S. trade war, but they are currently in the core position.
5) By analyzing the network robustness of the typical commodities in the international chip industry chain in 2020, it is found that the trade network of downstream commodities in the chip industry chain is the strongest, followed by that of the midstream commodities, and that of the upstream commodities is the weakest. The trade network of upstream commodities is fragile, and in the face of turbulence in international trade, even a small impact will interrupt the normal operation of the network. When the network nodes are attacked randomly, they can maintain high stability, and the network is more vulnerable when attacked by the target, which is consistent with the analysis results of Xiao et al. on the photovoltaic trade network [44]. Therefore, the trade interruption of a few countries in the world often does not cause great harm to international chip trade security, but when the number of countries attacked exceeds a certain number, it may lead to the collapse of the entire trade network, thus threatening the world chip trade security.

Based on the above research results, the following suggestions are given:

1) Continuously expand the import channels of upstream and midstream commodities. China still has a high dependence on semiconductor equipment and technology, and needs to focus on the development of the domestic semiconductor industry to strengthen its position in the industrial chain. In the context of the China-U.S. tech war, we should ensure the stable supply and security of chip raw materials and manufacturing equipment. The multi-dimensional development of import channels should be facilitated to realize the balance and sustainable development of foreign trade. Meanwhile, we should promote the localization of raw materials and equipment, especially the domestic substitution of high-end products. In addition, trading nations need to be aware of the potential impact of geopolitical tensions and trade wars on the semiconductor industry and diversify their supply chains to reduce dependence on a single country or region.
2) Focus on breaking through the core technology related to the chip industry, to transform the low-end industrial chain into a high-end one. The total trade volume of electronic computers and components in China's integrated circuits and downstream commodities continues to lead, but the main mode is still processing and manufacturing. Therefore, efforts should be made to develop leading chip design enterprises in the world by strengthening key core technologies. Meanwhile, we should give full play to the role of leading enterprises, optimize the allocation of scientific and technological resources, and strive to achieve more major disruptive innovations. Countries around the world have jointly built a global layout and perfect industrial chain system in their respective semiconductor markets, and countries play a distinct role in the industrial chain. However, only the development of multinational companies that span the entire industry and occupy the core technology can truly occupy the core position in the global industrial chain.
3) Focus on developing the export markets of countries along the "The Belt and Road", especially the export of downstream electronic computers and component commodities. China is a major global producer of electronic computers, but it has relatively few trading partners. The countries along the "Belt and Road Initiative" route run through Central Asia, Southeast Asia, South Asia, West Asia and even parts of Europe. Most of them are emerging economies and developing countries, and they are export markets with great potential, especially ASEAN, India and other countries. Strengthening trade exchanges with those countries and promoting trade cooperation are of great significance to improving China's international competitiveness of downstream commodities in the chip industry chain and preventing international trade risks. In addition, the "Belt and Road" initiative not only contributes to the economic development of China and countries along the route, but also opens up markets for other countries in the world. It is a public platform for promoting the common development and prosperity of all countries.
4) Reduce the dependence on foreign countries. Under the background of the China-U.S. tech war, to prevent the supply crisis caused by malicious trade interruption, China can adopt the strategy of diversified import and export trade, decentralize chip imports, and focus on the uncertainty of international trade network of upstream commodities in the industrial chain. Besides, China plays an important role in the international chip industry chain, so China's chip security is closely related to the world's chip security. Under the influence of the epidemic, China should actively promote the normal progress of international chip trade, establish various trade relations, and increase the robustness of the international chip trade network. Meanwhile, all countries should pay attention to the volatile factors in the environment and international trade, identify potential risks, and adjust the chip import and export trade relations to ensure chip security.
5) Continue to pay attention to emergencies affecting international trade, with particular attention to policy changes in major trading countries of upstream raw materials. In international trade, with the increase of trade wars and political conflicts between countries, the trade between various nodes in the chip industry chain has become more unpredictable and unstable. In the face of international trade turbulence and other factors leading to the limited international trade of chips, countries should strengthen

trade exchanges and cooperation. The trade core countries of the chip industry chain have strong control ability in the international trade of chips, and their foreign trade policies will affect the global trade network security of chips. Therefore, the core trading countries should play an active role and provide mutually beneficial foreign trade policies, which is of great significance to ensure the security and stability of international chip trade.

However, the study of the overall characteristics of the trade network in this paper focuses on the vertical comparative study of each link from the perspective of the industrial chain. Therefore, this paper analyzes the changes in the status of China's chip industry trade network from 2016 to 2020, only the global chip industry trade network in 2020 is investigated, and the time evolution analysis of the global chip industry trade network is lacking. Additionally, due to the limited space, this paper only selects the representative commodities of each link in the chip industry chain, failing to include all commodities in the industry chain. Therefore, future research can be expanded on this basis to conduct a broader analysis of the time evolution of the global chip industry trade network, and to examine more products in the industry chain. In addition, since this paper mainly focuses on trade issues, there is less strategic analysis of the results, but it is undeniable that the topic has wider importance in the international arena, which can also be one of the goals of future in-depth research.

Author contribution statement

Yongli Zhang: Conceived and designed the experiments; Contributed reagents, materials, analysis tools .
Xianduo Zhu: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper was supported by The National Social Science Fund of China (Grant No. 21BTJ049).

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