Horizon 2020 Programme

SCRREEN2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211.

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SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

GALLIUM

AUTHOR(S):

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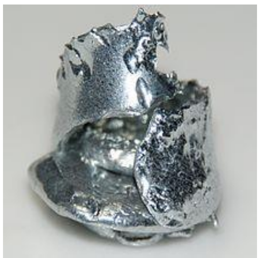
GALLIUM

OVERVIEW



Gallium (chemical symbol Ga, from Gallia) is a soft, silvery-white metal. It is an excellent conductor of both electricity and heat, has a very low melting point (30°C), and is a magnetic material. Gallium's abundance in the upper continental crust is 17.5 ppm, which is comparable to the one of lead (Rudnick and Gao 2013b). However, gallium does not occur in its elemental form in nature but mostly substitutes for other elements in certain minerals such as gallite ($CuGaS_2$) (Butcher, 2014).

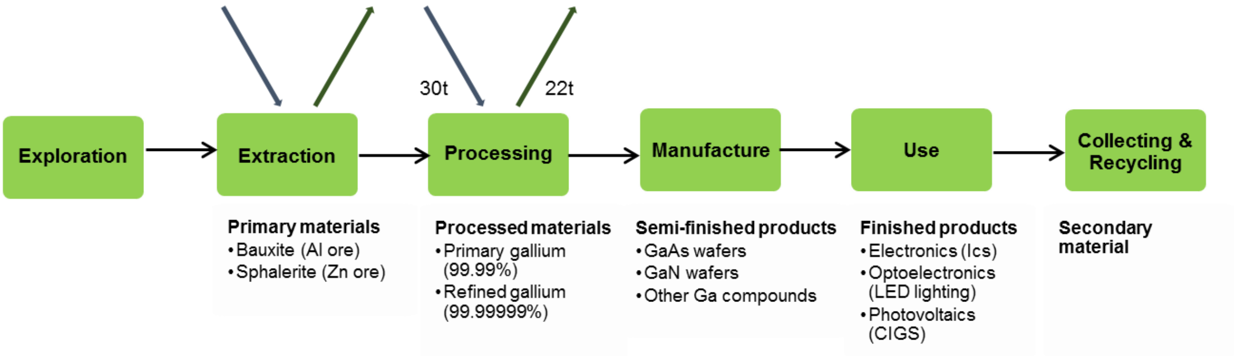


Figure 1. Simplified value chain for gallium in the EU[1]

Table 1. Gallium supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption)	EU Share	EU Suppliers	Import reliance
301	China 94% Ukraine 2% Russia 2% Other 2%	33.2	11%	China 71% USA 10% UK 9% Ukraine 3% Taiwan 3% Other 2%	98%

Prices: Gallium is not traded on any metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. Gallium prices are negotiated bilaterally on a long-term basis between suppliers and customers (Cui, Guo, Liedtke, Yin, & Huy, 2016). References for prices are obtained through averages of past deals between private parties, generally available through paid subscriptions (e.g., Asian Metal, Metal Pages). Overall, the main price driver in the past 10 years has been policies from the Chinese government related to environmental restrictions to limit pollution in the aluminium industry, especially during the winter season.

[1] JRC elaboration on multiple sources (see next sections)

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Primary supply: The production of gallium from bauxite is the primary source of supply. It would originate from minerals such as feldspar or nepheline (Deschamps et al., 2002).

Secondary supply: At present, no gallium is recovered from post-consumer scrap (Huy, D and Liedtke, M., 2016). The rate of recovery of gallium from end-of-life products is near 0% (UNEP, 2013).

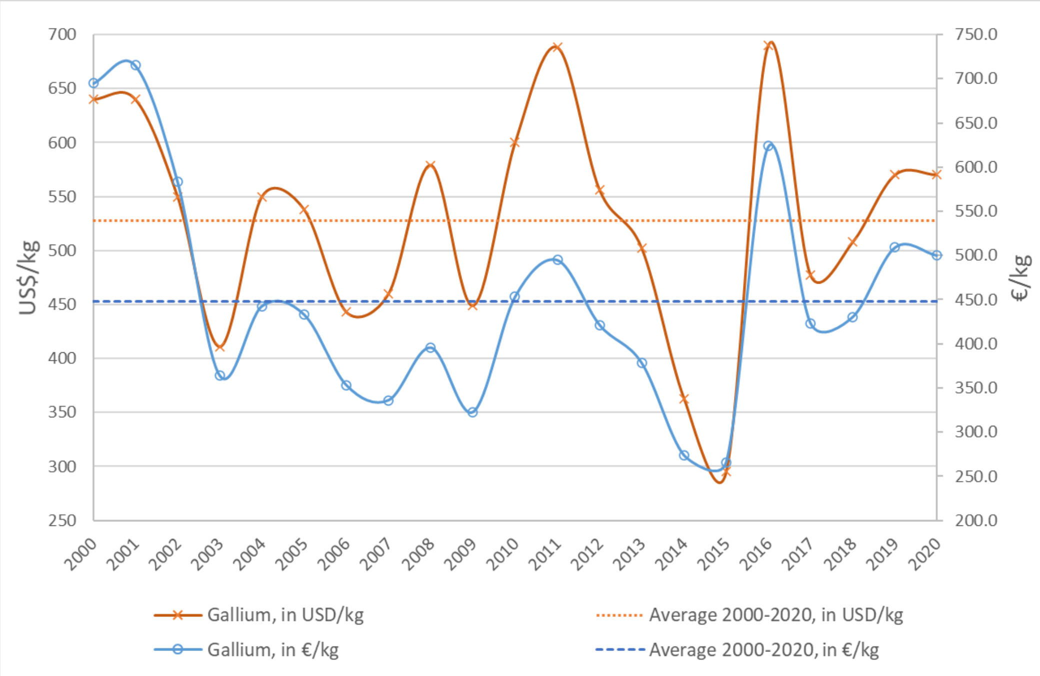

Figure 2. Annual average price of gallium between 2000 and 2020 (USGS, 2021)[2].

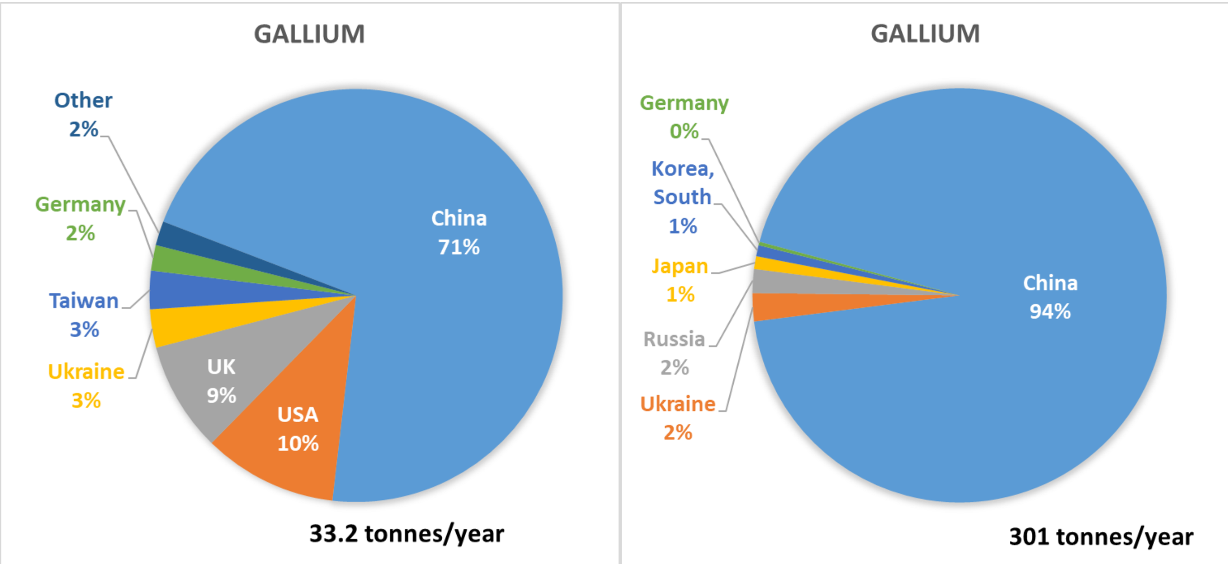

Figure 3. EU sourcing of gallium and global mine production (update)

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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Uses: Gallium is mainly used as a semiconducting material in different applications. To the best of our knowledge, the newest data on end-uses of gallium in the EU is for the timeframe of 2012-2016. Presented numbers were cross-checked for current validity in an expert consultation (SCRREEN workshop 2021). It can be estimated that 70% of gallium consumption has been in integrated circuits (ICs), 25% for lighting applications (mostly LED technology) and around 5% in the copper-indium-gallium-selenium (CIGS) photovoltaic technology (USGS, 2015; Mikolajczak, 2016),

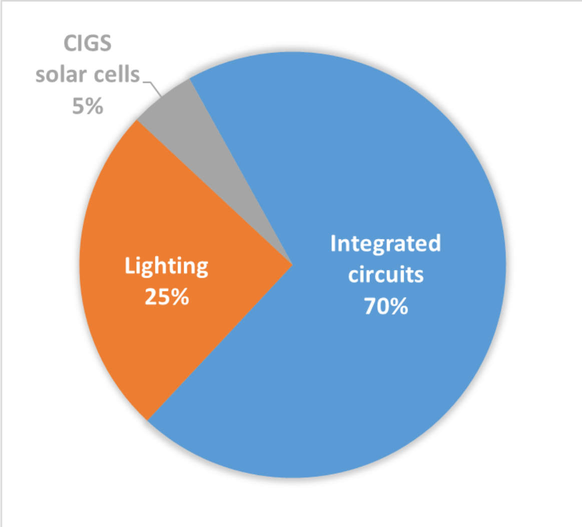

Figure 4: EU uses of gallium

Substitution: In **semiconductors,** silicon or silicon-based substrates are usually the main substitutes for GaAs or GaN substrates, such as SiGe (CRM InnoNet, 2015). But it can only be for a limited number of applications, as silicon presents a lesser electron mobility and is therefore significantly less efficient. Organic LED (OLED) could be a substitute to solid state LED but so far, they are not competitive in terms of price and durability (CRM InnoNet, 2015). In **photovoltaics**, Crystalline silicon technologies currently represent more than 90% of the market for terrestrial applications, even though conversion efficiency is reduced from 18-22% to 8-15% when silicon is used rather than CIGS in photovoltaic cells. In many **defence related applications**, GaAs-based ICs are used because of their unique properties, and no effective substitutes exist for GaAs in these applications.

Table 2. Uses and possible substitutes

Application	Share	Substitutes	SubShare	Cost	Performance
Integrated circuits	70%	Silicon	5%	Similar or lower costs	Reduced
Integrated circuits	70%	Germanium	1%	Very high costs (more than 2 times)	Reduced
Integrated circuits	70%	No substitute	94%		No substitute
Lighting	25%	Incandescent	1%	Similar or lower costs	Reduced
Lighting	25%	Halogen	6%	Similar or lower costs	Reduced
Lighting	25%	Linear fluorescent lamp (LFL)	10%	Similar or lower costs	Reduced

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Lighting	25%	Compact fluorescent lamp (CFL)	17%	Slightly higher costs (up to 2 times)	Reduced
Lighting	25%	OLED	2%	Very high costs (more than 2 times)	Similar
Lighting	25%	No substitute	64%		No substitute
CIGS solar cells	5%	No substitute	100%		No substitute

Other issues: The use of Gallium is not restricted under REACH Regulation (EC) No 1907/2006 Annex XVII (Deutsche Forschungsgemeinschaft and Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area, 2002). Dissipation ("losses") all along the gallium cycle in the economy, and in particular through extraction and beneficiation, represent a significant share of the total gallium extracted and processed (Helbig et al., 2020). This includes direct discharges of gallium to (and subsequent pollution of) the environment.

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3 Gallium supply and demand at processing stage, in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption)	EU Share	EU Suppliers	Import reliance
301	China 94% Ukraine 2% Russia 2% Other 2%	33.2	11%	China 71% USA 10% UK 9% Ukraine 3% Taiwan 3% Other 2%	98%

Along the major market dimensions (size, supply, demand and price), the global gallium market can be characterised as a relatively small market with high supply risk and historical phases of oversupply, dynamic demand (expectations) and significant price spikes.

In terms of quantities, the global gallium market is a relatively small market. For the greatest part, gallium is recovered as a by-product of bauxite processing; the rest of gallium supply comes from zinc processing, where gallium is produced as a by-product, and from new-scrap recycling (Liedtke and Huy, 2018; Riecken, 2018; USGS, 2021). Crude gallium (or low-purity gallium), which has a purity of 99.9% or 99.99%, can be processed further to obtain refined gallium (or high-purity gallium) having a purity of 99.9999% or 99.99999% (European Commission, 2020). The global capacities for production of (primary) low-purity gallium, high-purity (refined) gallium and secondary (high-purity) gallium are estimated at ca. 724 t per year, 325 t per year and 273 t per year (gallium content), respectively (USGS, 2021). World production of primary gallium amounted to ca. 351 t gallium content in 2019 (USGS, 2021; cf. Table).

The characterisation of the global gallium market as a 'high-supply-risk market' refers to high concentration of gallium supplying countries on the one hand and medium-to-high 'weighted country risk' indicated by the Worldwide-Governance-Indicator values of gallium-supplying countries on the other hand (Barazi et al., 2021). China accounts for ca. 80% of the global capacity for production of (primary) low-purity gallium and over 90% of the worldwide primary-gallium production in 2019 (USGS, 2021; cf. Table). This degree of supply concentration is the result of high capacity growth in China, in particular, in the period after 2009, when China recorded capacity-growth rates of more than 39% per year (Liedtke and Huy, 2018). At the same time, several countries have reduced or ceased the production of primary (low-purity) gallium, e.g., Korea, Russia, Germany, Kazakhstan, Hungary and Ukraine (Liedtke and Huy, 2018; USGS, 2021). In 2020, the major producers of high-purity (refined) gallium were China, Japan, Slovakia and the United States; the known producers of secondary (high-purity) gallium are Canada, China, Germany, Japan, Slovakia and the United States (USGS, 2021).

On the demand side of the gallium market, data on gallium consumption in the European Union, the United States and the world show the importance of gallium-arsenide based intermediate products and gallium-application areas 'integrated circuits' and 'optoelectronics' (European Commission, 2020; Riecken, 2018;

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Roskill, 2020; SCRREEN, 2021; USGS, 2021). Besides gallium arsenide, further gallium compounds are of industrial relevance, e.g., gallium nitride and gallium phosphide (USGS, 2021). The applications of gallium in 'integrated circuits' include radio-frequency gallium-arsenide (RF GaAS) devices and, more generally speaking, wireless communication systems; the category 'optoelectronics' includes LEDs. In particular, the gallium-arsenide wafer market has been dominated by radio-frequency and LED applications in 2019 (Yole, 2020). Further application areas of gallium are copper-indium-gallium-selenide (CIGS) solar cells and magnets among others (European Commission, 2020; Riecken, 2018).

Over the last decades, the gallium-market outcome has been affected by several events on the demand and supply sides causing peaks and lows in gallium prices. Rising gallium demand or expectations of rising gallium demand for different gallium applications have led or contributed to price peaks in 2001 (related to expectations of high demand for semi-conductors), 2007 (related to high demand for mobile phones and LEDs) and 2011 (related to expectations of high demand for CIGS solar cells and LEDs) (Liedtke and Huy, 2018). On the other hand, the fast expansion of gallium-production capacity in China contributed to oversupply and decreasing gallium prices since 2012 (Liedtke and Huy, 2018). This effect on prices has been reversed to some extent by reduction of gallium production in China and other countries over the last years (Liedtke and Huy, 2018; USGS, 2021). There are many other determinants of gallium-market dynamics; they range from macroeconomic impulses, e.g., macroeconomic crises, to regulation, e.g., environmental regulation (Liedtke and Huy, 2018).

The COVID-19 crisis is estimated to have effects on global gallium markets via impacts on the roll-out of 5G and a reduction in consumption of RF GaAs devices (Roskill, 2020; USGS, 2021; Yole, 2020). With respect to intermediate gallium products used for production of integrated circuits, there are reports of increases in delivery times, transport bottlenecks from China and increases in costs of transportation in the last two years (SCRREEN, 2021).

EU TRADE

Primary Gallium is normally recovered at 99.9% - 99.99% (3N/4N) of purity and then further refined to obtain higher purities depending on the use (Rongguo, et. Al., 2016). Globally, primary gallium is recovered as a by-product of processing bauxite and zinc ores (USGS, 2021). Gallium 4N is used for metallurgical, chemicals and solar applications while 6N to 7N purity is necessary for electronic and semiconductor applications. The trade figures are derived from Eurostat database for the period 2002-2021. Prior to 2002, the trade flow figures were not available. Moreover, since the available trade code CN 81129289 does not distinguish the different level of purity, it is currently not possible to know exactly how much and in which purity gallium was traded in the EU.

Table 4 Relevant Eurostat CN trade codes for gallium

Processing/refining	
CN trade code	**Title**
81129289	Unwrought gallium; gallium powders

The EU is a net importer of Gallium metal (CN code 81129289 Unwrought gallium; gallium powders). The average yearly EU net import of Gallium in the period 2016-2020 was 32.44 t while the export was 6.84 t.

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Figure 5 shows that in general since 2002 there has been an increasing amount of both EU import and export of gallium, with import figure higher than the export from 2013 onwards. A decreasing trend of gallium import occurred from 2017 until 2019. Since 2011, instead, there has been a decrease in EU export. The primary production of Gallium in the EU was reported to have ceased in Germany (2013) and in Hungary (2015) (USGS, 2021). In 2020, following the increasing global Gallium Arsenide (GaAs) wafer consumption in Light Emitting Diode (LED), Radio Frequency (RF) application, and photonics applications, the EU import of Gallium increased at 60% more compared to 2019.

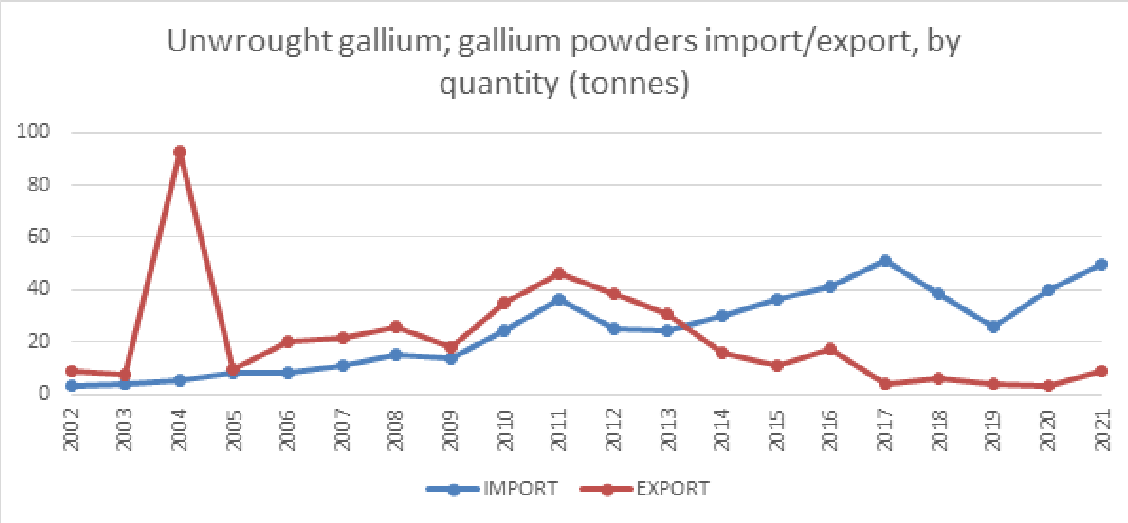

Figure 5. EU trade flows for Gallium (CN 81129289) (Eurostat, 2022)

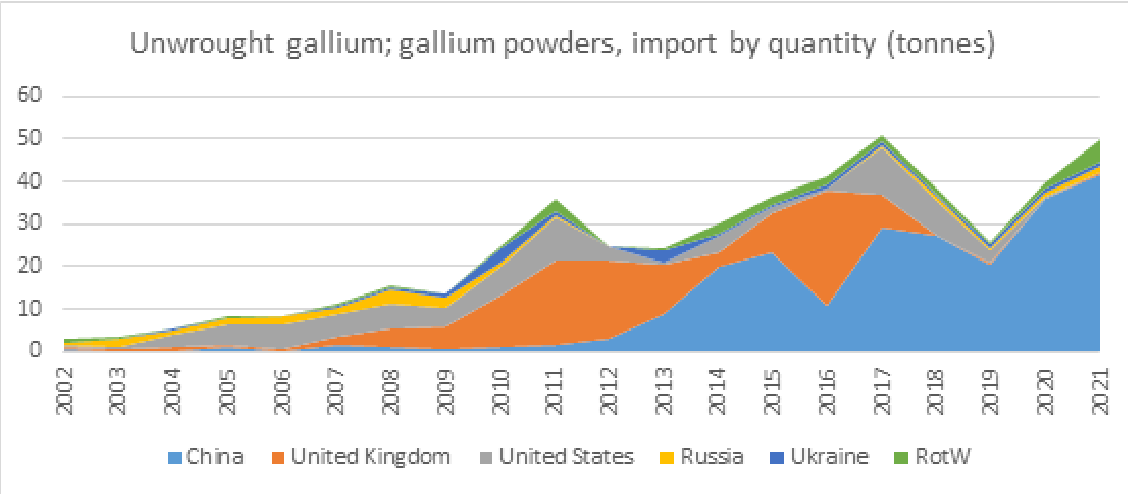

Figure 6. EU imports of Gallium (CN 81129289) in tonnes, in 2002-2021 by trade partners (Eurostat, 2022)

Figure 6 shows that, from the extra-EU perspective, Russia, the United States and the United Kingdom were the main EU suppliers of unwrought gallium and gallium in powder from 2002 until 2012. The United Kingdom supplied an average of 40% of gallium to the EU in 2016 and 2017 and stopped in 2018. The EU import from the United States was the highest in 2017 with 20% of EU import share. With the large surplus of primary gallium from China that began in 2012, the production from other countries such as Japan, South Korea (accounted in "RotW"), and Russia would most likely continue to be restricted (USGS, 2021). As reported in 2021, China had more than 80% of the worldwide low-purity gallium production capacity (USGS, 2021). Figure

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2 reflects the increasing EU import from China starting from 2012 that gradually replaced other suppliers. Since then, China has been the major supplier of gallium to the EU. The supply of gallium from China accounted for 62% of the total EU imports on the average of 2016-2020.

In terms of high purity refined gallium, Slovakia, together with China, Japan, and the United States were known as the principal producers (USGS, 2021). There was also some production of high purity refined gallium in the United Kingdom, but its production ceased in 2018 (USGS, 2021).

More than 75% of the quantity of gallium imported to the EU was destined to Germany. According to the trade flow figures reported in Eurostat, Slovakia is one of the major suppliers of gallium to Germany, together with China. Freiberger company in Germany together with Sumitomo Electric, AXT and Vital Materials were the market leader of Galium Arsenide (GaAs) wafer in 2019 (Semiconductor today, 2020). GaAs and gallium nitride (GaN) represent 94% of the use of gallium (Huy, D and Liedtke, M. ,2016). Gallium Arsenide is used in the manufacturing of devices such as microwave frequency integrated circuits, monolithic microwave integrated circuits, infrared light-emitting diodes, laser diodes, solar cells, and optical windows. However, there was no quantitative information available on the EU trade of the Gallium Arsenide wafer nor Gallium Nitride in the statistics. The specific trade codes for these commodities were not available.

The USGS estimated that the world primary low-purity gallium production capacity in 2020 was 724 t per year; high-purity refined gallium production capacity 325 t per year; and secondary high-purity gallium production capacity, 273 t per year.

PRICE AND PRICE VOLATILITY

Gallium is not traded on any metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. Gallium prices are negotiated bilaterally on a long-term basis between suppliers and customers (Cui, Guo, Liedtke, Yin, & Huy, 2016). References for prices are obtained through averages of past deals between private parties, generally available through paid subscriptions (e.g., Asian Metal, Metal Pages). Overall, the main price driver in the past 10 years has been policies from the Chinese government related to environmental restrictions to limit pollution in the aluminium industry, especially during the winter season. Due to the temporary nature of these restrictions, prices tend to increase steeply and then fall back rapidly (Roskill, 2021; Argus Media, 2021).

The price volatility of gallium (min. 99.99% fob China) was around 29% between February 2020 and January 2021 (DERA, 2021). This was an increase in the volatility compared to the period January 2016 and December 2020, where price volatility was reported to be 24%.

Gallium prices worldwide experienced a decline since 2011. Production capacity in China expanded from 140 tonnes per year in 2010 to around 600 tonnes per year since 2016 which caused an oversupply of the metal on the market. Prices picked up from € 624/kg the previous year to € 430/kg in 2018 possibly due to stockpiling by consumers in advance of the introduction of import tariffs on gallium from China into the US. In 2020, prices increased in China by an estimated 32% primarily due to a further decrease in production from China (USGS,

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2021). Covid-19 caused major disruptions in the demand for electronic metal in Europe. A reduction in market activity took place due to the various lockdowns that were imposed across the continent (Argus Media, 2021).

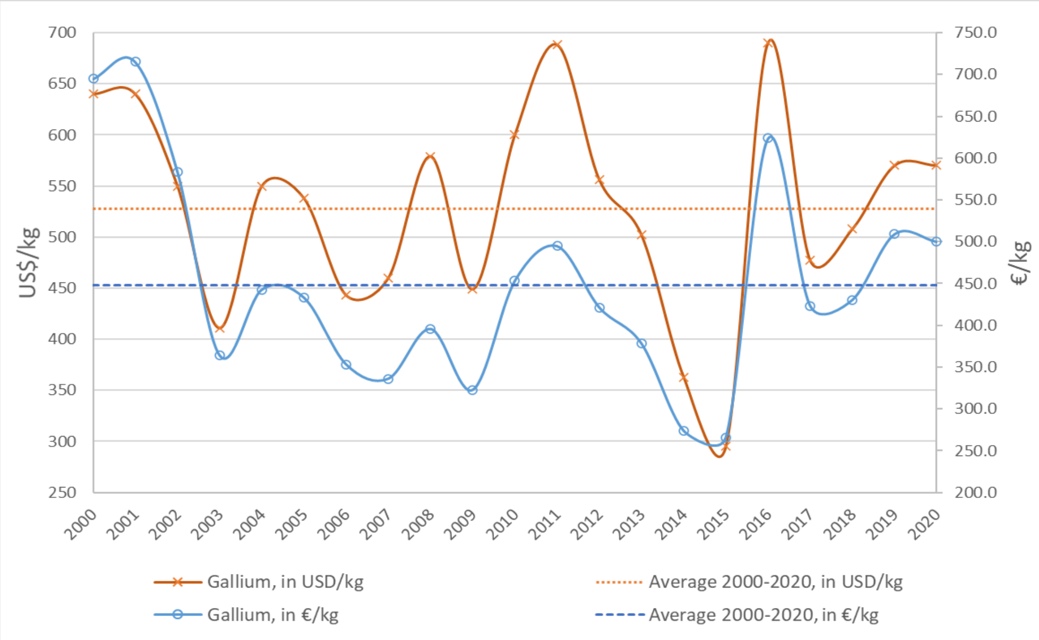

Figure 7. Annual average price of refined high-grade gallium between 2000 and 2020, in US$/kg and €/kg (based on USGS, 2021)[3]. Dash lines indicate average prices for 2000-2020.

OUTLOOK FOR SUPPLY AND DEMAND

Demand for gallium is expected to increase over the next 20 years; the integrated-circuits applications are expected to be the main driver of this growth (European Commission, 2020; SCRREEN, 2021). Radio-frequency microchips and thin-film photovoltaics have high growth potentials with respect to gallium demand (Marscheider-Weidemann et al., 2021). The gallium-arsenide wafer market is expected to grow at a compound annual growth rate of 10% in the next years (Yole, 2020). Gallium nitride may gain importance owing to potential applications in 5G-base stations (Roskill, 2020). The COVID-19 crisis can have a positive effect on gallium-demand growth in the longer run by promoting the usage of remote communication systems in different areas of social life (Roskill, 2020). The quantity of gallium produced by China is expected to be an important supply determinant in future (SCRREEN, 2021).

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Apparent consumption figures (EU production + EU imports - EU exports) are not reliable due to uncertainties related to the share of gallium produced, traded, or integrated in finished goods at all levels. CN 81129289

[3] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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Unwrought gallium; gallium powders may include secondary gallium (new scraps) for some countries like United States, Canada, Russia (European Commission, 2017). On average the apparent EU consumption of gallium at processing stage was about 33 tonnes per year between 2016 and 2020 (Eurostat Comext, 2021; WMD, 2022).

Gallium processing stage EU consumption is presented by HS code CN 81129289 Unwrought gallium; gallium powders. Import and export data is extracted from Eurostat Comext (2021). Production data of gallium is extracted from WMD (2022).

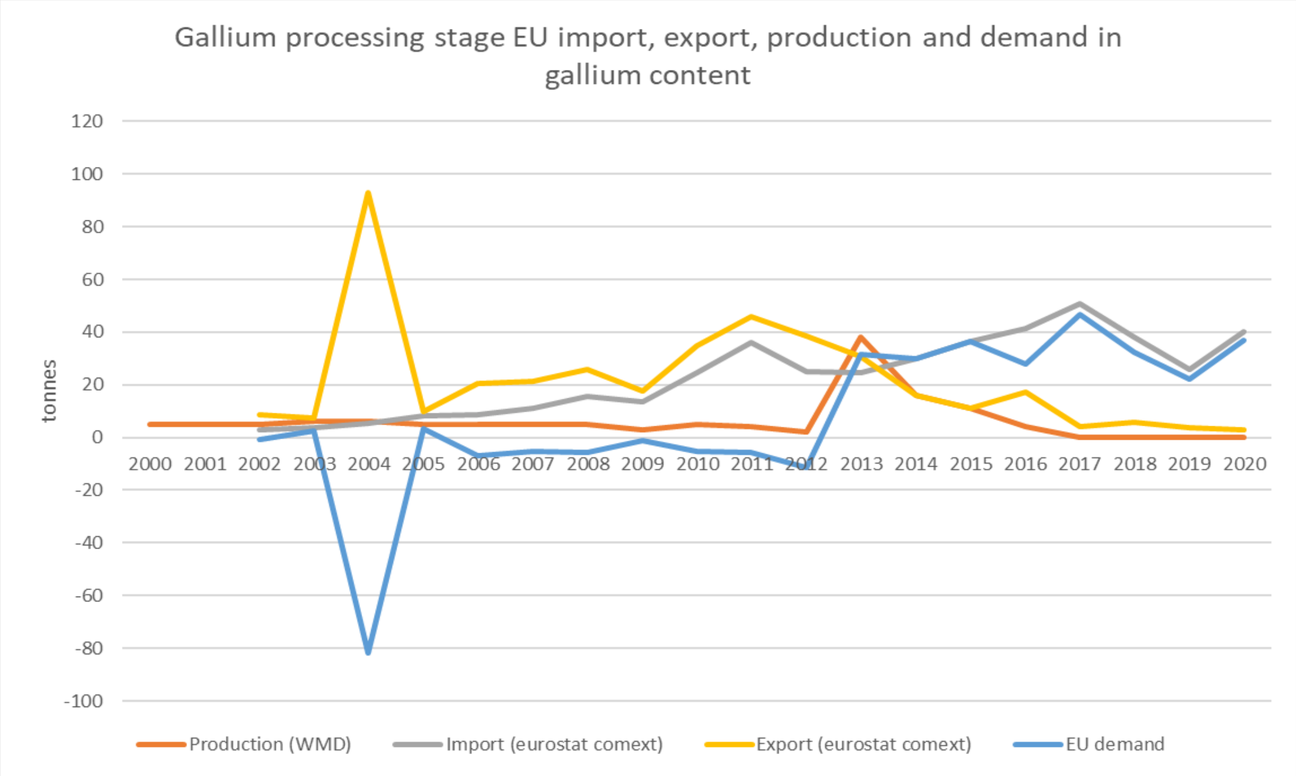

Figure 8. Gallium (CN 81129289 Unwrought gallium; gallium powders) processing stage apparent EU consumption. Production data from WMD (2022). Import and export data from Eurostat Comext (2021) for is available for 2002-2020. Consumption is calculated in gallium content (EU production+import-export).

Based on Eurostat Comext (2021) and Eurostat Prodcom (2021) average import reliance of gallium at processing stage is 98 % for 2016-2020.

EU USES AND END-USES

Gallium is mainly used as a semiconducting material in different applications. To the best of our knowledge, the newest data on end-uses of gallium in the EU is for the timeframe of 2012-2016. Presented numbers were cross-checked for current validity in an expert consultation (SCRREEN workshop 2021). It can be estimated that 70% of gallium consumption has been in integrated circuits (ICs), 25% for lighting applications (mostly LED technology) and around 5% in the copper-indium-gallium-selenium (CIGS) photovoltaic technology (USGS, 2015; Mikolajczak, 2016), as illustrated in Figure 9. Different end-uses require different qualities of substrate

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crystal, with integrated circuits (ICs) and microwave devices requiring the highest quality. In the future, gallium could additionally be used as an electrolyte for solid oxide fuel cells (SOFC) in the form of gallium oxide (Liedtke 2018).

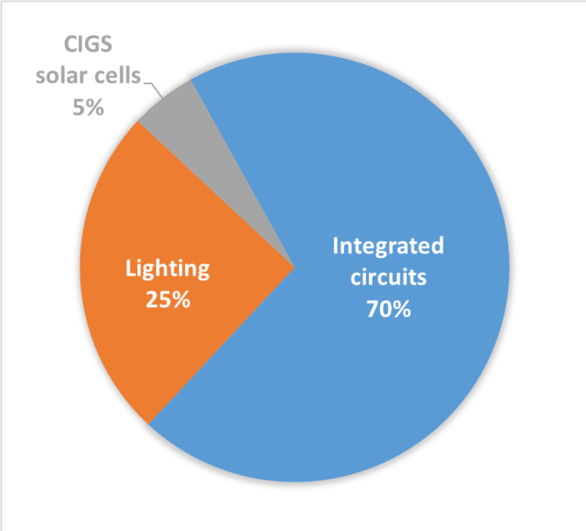

Figure 9. EU end uses of gallium average 2012-2016 (SCRREEN, 2019, no update following review by SCRREEN experts, 2022)

Figure 10 shows the global end uses of gallium taken from data sources from 2010 and 2018 (European Commission 2010, Riecken 2018). Even though comparison of two data sets from different sources has risks, some conclusions on the development of global gallium uses are drawn here since no consistent source of data is available. The share of gallium used for integrated circuits has been drastically decreasing, while the share of lighting applications more than doubled within this period. Photovoltaics are also gaining in importance. Additional applications of gallium listed only in by Riecken 2018 are the use for permanent magnets or for indium-gallium-zinc-oxide, which is used for thin-film transistors.

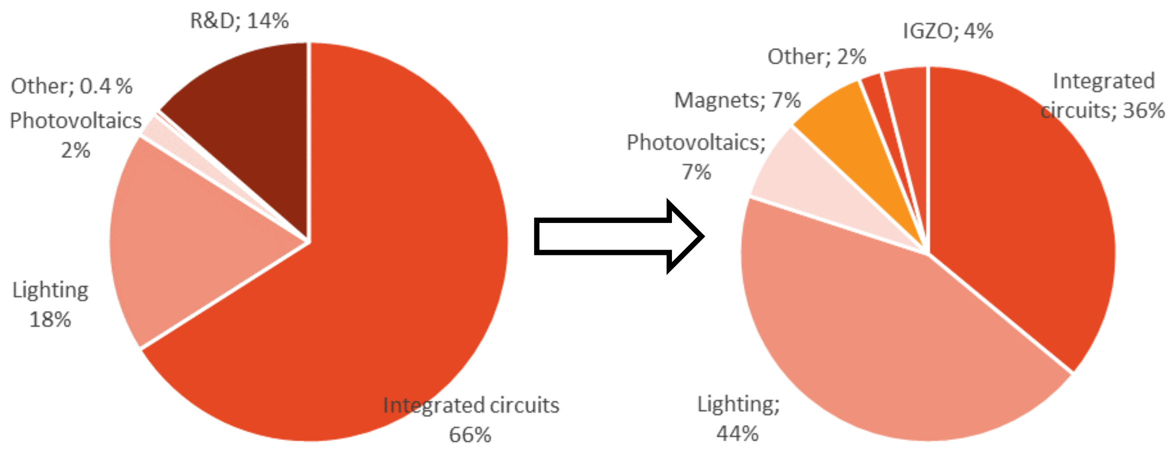

Figure 10. Global end uses of gallium. Left side: Historical end use distribution from European Commission, 2010. Right side: Industry estimate on current distribution from Riecken 2018.

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Table 5. Gallium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector for 2019 (* for 2014) (Eurostat, 2022)

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Integrated circuits	C26 - Manufacture of computer, electronic and optical products	84,074*	C2610- Manufacture of electronic components
Lighting	C27 - Manufacture of electrical equipment	97,292	C2740-Manufacture of electric lighting equipment
CIGS solar cells	C26 - Manufacture of computer, electronic and optical products	84,074*	C2610- Manufacture of electronic components

Figure 11 shows the development of the gallium consuming 2-digit NACE sectors which are defined in Table 1. It shows a continuing decrease in gross value added of C27 (Manufacture of electrical equipment), while C26 (Manufacture of computer, electronic and optical products) had a significant downfall 2008/2009 and stagnated from there on.

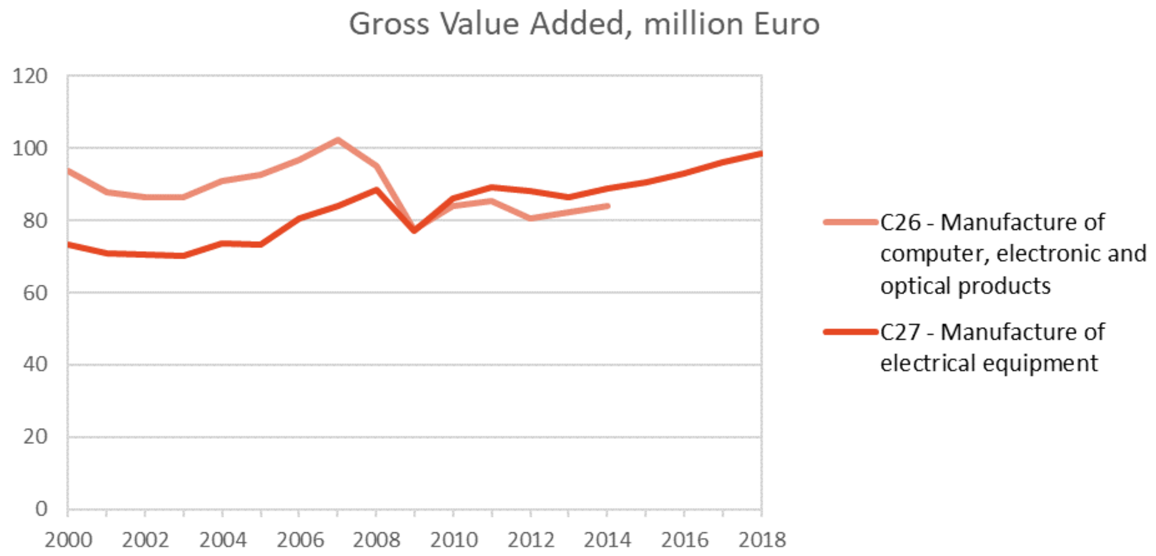

Figure 11. Value added per 2-digit NACE sector over time (Eurostat, 2021)

APPLICATIONS OF GALLIUM IN THE EU

INTEGRATED CIRCUITS

The applications of integrated circuits (ICs) are widely spread, a few examples of electronic devices include:

- Mobile phones: Use of ICs mostly in power amplifiers (PAs). The PAs in a mobile phone are vital components that amplify signals, both voice and data, to the appropriate power level for them to be

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transmitted back to the network base-station. The more advanced the generation is (4G, 5G), the more PAs are needed.
- Wireless communication systems: Semiconductors are employed in a number of different contexts (fibre optics, sensors, etc.).
- Military applications: Radar, satellite, night vision or high performance communication devices all need ICs.

The most common gallium compounds used in semiconductors for integrated circuits are gallium arsenide (GaAs) (92%) and gallium nitride (GaN) (8%) (BRGM, 2016). One of the reasons why GaN is used in lower quantities is that GaAs is composed of two metals whereas GaN is formed from a metal and a gas, which is much more difficult and costly to produce.

LIGHTING

In lighting applications, semiconductors are used in an optoelectronic capacity, because of their ability to convert electrical energy into light output. Some of their main uses are infrared emitting diodes (IREDs), laser diodes (LDs) and light emitting diodes (LEDs). The latter being one of the fastest growing markets in the past few years (Grady 2013, cf. Figure 4.1.2).

PHOTOVOLTAICS

In photovoltaics, the main use of gallium is the copper-indium-selenium-gallium (CIGS) technology. It is a thin-film technology that involves the deposition of a thin layer, only a few micrometres deep, of semiconducting material on various surfaces. However, the market for this technology has dropped since 2010. Most solar cells for terrestrial applications use crystalline silicon (c-Si, both mono- and multi-crystalline) technology. In 2020, the market share of c-Si was about 95% of global solar cell production (Fraunhofer ISE 2021). CIGS technology is preferred for specific terrestrial applications where flexibility is required and represents about 1.5% of global solar cell production (Butcher 2014, Fraunhofer ISE 2021). Thus, quantities of gallium currently used in solar-cell production remain small.

FURTHER GALLIUM USES OUTSIDE THE EU

GALLIUM METAL

Other end-uses for gallium metal include low melting alloys, substitute of mercury in thermometers or NdFeB magnets, where Ga can be added in small quantities to improve magnetic properties and corrosion resistance. All these applications remain minor in terms of overall gallium demand (Liedtke 2018).

GALLIUM CHEMICALS

Gallium chemicals include gallium nitrates, chlorides and oxides. They are used in pharmaceuticals and as catalysts or for metal-organic vapour-phase epitaxy (Liedtke 2018).

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INDIUM–GALLIUM–ZINC–OXIDE

Indium-gallium-zinc-oxide (IGZO) thin-film transistors are used for high performance screens. Possible applications are televisions, monitors, smartphones and tablets. The IGZO transistors allow for very high resolution and narrow frames (Hara et al. 2018).

SUBSTITUTION

Table 6. Uses and possible substitutes

Application	Share	Substitutes	SubShare	Cost	Performance
Integrated circuits	70%	Silicon	5%	Similar or lower costs	Reduced
Integrated circuits	70%	Germanium	1%	Very high costs (more than 2 times)	Reduced
Integrated circuits	70%	No substitute	94%		No substitute
Lighting	25%	Incandescent	1%	Similar or lower costs	Reduced
Lighting	25%	Halogen	6%	Similar or lower costs	Reduced
Lighting	25%	Linear fluorescent lamp (LFL)	10%	Similar or lower costs	Reduced
Lighting	25%	Compact fluorescent lamp (CFL)	17%	Slightly higher costs (up to 2 times)	Reduced
Lighting	25%	OLED	2%	Very high costs (more than 2 times)	Similar
Lighting	25%	No substitute	64%		No substitute
EU end uses of gallium average 2012-2016 (SCRREEN, 2019, no update following review by SCRREEN experts, 2022)					

SEMI-CONDUCTORS

Silicon or silicon-based substrates are usually the main substitutes for GaAs or GaN substrates, such as SiGe (CRM InnoNet, 2015). - only be for a limited number of applications, as silicon presents a lesser electron mobility and is therefore significantly less efficient. GaAs-based semiconductors also operate at higher breakdown voltages and generate less noise at high frequencies (>250 MHz). Pure GaAs substrates finally have the great advantage of being semi-insulating, whilst silicon substrates are semiconducting.

Indium phosphide components can be substituted for GaAs-based infrared laser diodes in some specific-wavelength applications, and helium-neon lasers compete with GaAs in visible laser diode applications (USGS, Gallium factsheet 2022).

LIGHTING

LEDs present many advantages such as their low-energy consumption, non-toxicity, and longevity (up to 100,000 hours). Organic LED (OLED) could be a substitute to solid state LED but so far, they are not competitive

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in terms of price and durability (CRM InnoNet, 2015). Liquid crystals made from organic compounds are used in visual displays as substitutes for LEDs (USGS, Gallium factsheet 2022).

PHOTOVOLTAICS

Crystalline silicon technologies currently represent more than 90% of the market for terrestrial applications, even though conversion efficiency is reduced from 18-22% to 8-15% when silicon is used rather than CIGS in photovoltaic cells. Other thin film technologies include cadmium telluride (CdTe) and copper indium selenide (CIS) (Fraunhofer, 2016). Reversely, Gallium has been investigated as alternative to boron doped silicon for photovoltaics (N.E. Grant et al., Solar Energy Materials and Solar Cells, Volume 206, 2020, 110299).

DEFENCE RELATED APPLICATION

Indium-gallium-zinc-oxide

In many defence related applications, GaAs-based ICs are used because of their unique properties, and no effective substitutes exist for GaAs in these applications. In heterojunction bipolar transistors, GaAs is being replaced in some applications by silicon-germanium (USGS, Gallium factsheet 2022).

SUPPLY

EU SUPPLY CHAIN

Gallium is extracted with bauxite and lead-zinc ores. It is recovered mostly during alumina production and can be refined to high level of purity (7N) by dedicated processing plants to obtain high purity gallium. Gallium products such as GaN and GaAs are also widely used, especially as semiconductors and optoelectronic devices. Europe used to have some processing capacities but most of these have recently closed owing to the poor profitability and the large Chinese overcapacities (BRGM, 2016). There is no Ga production in EU by primary resources.

The EU supply chain of gallium is quite mature; players adapt to market conditions. Eurostat data does not refer at which form Ga is imported, however, due to its low melting point (29.8 °C), it is probably imported as GaAs.

All levels of the gallium supply chain are present in the EU:

- Based on the annual production figure in World Mining Data (2019), the average EU production of primary gallium over the years 2012-2016 was estimated at 19 tonnes per year. Between 2012 and 2016, the EU production mainly took place in Germany (17 tonnes per year) and for a minor quantity (approximately 1 tonne per year), in Hungary, accounting for a total of 9% of global primary gallium supply. Inga Stade GmbH, Germany’s sole producer of primary gallium, stopped their production in 2016.The primary gallium produced by Ingal Stade was shipped to the refining in the UK and in the USA to further treat primary gallium up to 7N purity (Monnet, 2018). The production in Hungary stopped in 2013 (Huy, D and Liedtke, M. ,2016). Hungary’s production came from crude gallium

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extraction from Bayer liquor with a purity of 4N to 7N. The estimated capacity of production in Hungary reached 8 tonnes per year. In the past, there was also production of primary gallium in Slovakia, however, it stopped in 2010. According to Eurostat data (Eurostat 2020), EU appears as a significant gallium producer since 2019, however this can be attributed to the production by secondary resources. Gallium demand in EU was about 110 tonnes in 2020, while 23.3 tonnes were imported.

- At processing stage, some of the few companies in the world producing refined high-purity gallium (6N or 7N) are located in the EU, for example CMK in Slovakia and PPM Pure Metals in Germany.
- At manufacturing stage, there are processors and wafer manufacturers in Germany (e.g. Freiberger Compound Materials) and in Belgium (Umicore, which commercializes trimethylgallium). Both companies are suppliers of downstream European microelectronic and optoelectronic industrials.
- At recycling stage, some manufacturers are also active in closed-loop recycling, with facilities often located abroad. Intra-companies material transfers are frequent in this activity. Part of gallium consumption also occurs in the form of imported manufactured products.

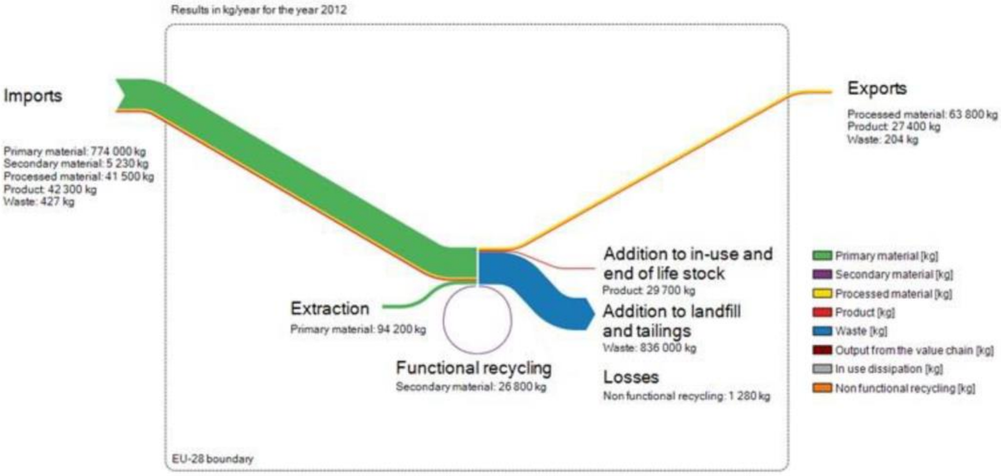

Figure 12 Simplified Sankey diagram of material system analysis of gallium (reference year 2012) (BIoIntelligence, 2015)

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF GALLIUM

GEOLOGICAL OCCURRENCE

Gallium is not found in its elemental form and does not form economically recoverable concentrations. Gallium is almost exclusively obtained as by-product during the processing of other metals, mainly aluminium and zinc (Huy, D and Liedtke, M. ,2016). Gallium is present in the Earth’s Crust at a concentration of 19 ppm.

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It is recovered as a by-product of bauxite (>80 %) and to a lesser extent zinc (< 20%). Gallium is also present in significant amounts in some phosphate rocks and coal deposits but not recovered at this point (Christmann et al. 2011). The average gallium content in both bauxite and zinc ores is around 50 parts per million. Gallium contained in world resources of bauxite is estimated to exceed 1 million tonnes, and a considerable quantity could be contained in world zinc resources. However, less than 10% of the gallium in bauxite and zinc resources is potentially recoverable (USGS, 2022).

RECOVERY AS A BY-PRODUCT OF ALUMINIUM PROCESSING

The production of gallium from bauxite, the main ore of aluminium, is the primary source of supply. Gallium is present in bauxite as a trace element. It would originate from minerals such as feldspar or nepheline (Deschamps et al., 2002). Both aluminium and gallium are released from these minerals during weathering processes and their similar geochemical properties result in the enrichment of both elements in bauxite (Dittrich et al., 2011). The ratio of gallium to aluminium, and therefore the concentration of gallium, in bauxite increases with greater intensity of weathering. Gallium also appears to be more abundant where the bauxite was derived from alkali source rocks (Weeks, 1989). The gallium content in bauxite can vary from 10 to 160 ppm (Mordberg et al., 2001; Bhatt, 2002). On average, it is reported to be 57 ppm (Schulte and Foley, 2014).

RECOVERY AS A BY-PRODUCT OF ZINC PROCESSING

Gallium concentrations in the zinc ore, sphalerite, are known to increase as the temperature of deposition decreases, although it can still be present in intermediate and higher-temperature deposit types (Stoiber, 1940; Cook et al., 2009).

In the hydrometallurgical route for zinc production, zinc oxide is first produced by roasting the zinc sulphide (sphalerite). The gallium-bearing zinc oxide is then leached with sulphuric acid to produce a zinc sulphate solution. Impurities, which include gallium, are removed through the addition of antimony or arsenic trioxide, zinc dust or proprietary reagents. The gallium is then extracted from the resulting separated solids or 'cement residues' by electrolysis (Butcher, 2014). In 2011, this source accounted for less than 1% of total gallium supply (Roskill, 2011). Global resources and reserves According to USGS (2019) estimates, gallium contained in world resources of bauxite would exceed 1 million tonnes, with a considerable quantity also potentially contained in world zinc resources. Quantitative estimates of reserves were not available (USGS, 2019)

EU RESOURCES AND RESERVES

In the Minerals4EU (2019) project, no quantitative information was reported concerning gallium in EU. Bauxite resources are reported as being present in many EU countries such as Bulgaria, France, Germany, Greece, Hungary, Italy, or Romania representing potential gallium resources. There has not been any updates of the information in Minerals4EU. The only existing estimates of EU gallium resources are provided in the 2014 criticality assessment at 21,400 tonnes, a quantity based on identified bauxite deposits (Moss R.L. et. a., 2011). This number should be interpreted with appropriate caution though, as it does not comply with international standards of reporting (UNFC) and is very likely to be overestimated, as well as being uneconomic in current market conditions.

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WORLD AND EU MINE PRODUCTION

Gallium is not systematically recovered in all bauxite and lead-zinc ores, which makes it difficult to estimate its resources. The gallium content in bauxites is between 30 and 90 ppm (USGS, 2017). Some US zinc ores bear gallium at a concentration of 50 ppm according to USGS. USGS estimates that less than 10% of the gallium contained in bauxite and zinc ores is recoverable (USGS, 2021). Based on the bauxite resources estimated between 55 and 75 Gt by USGS, and accounting for an average concentration of 50 ppm, the gallium resources would lie between 2 750 and 3 750 kt, located in Africa (32%), Oceania (23%), South America and the Caribbean (21%), Asia (18%) and elsewhere (6%). Following the same assumptions and a recovery rate of 10 %, the gallium reserves would be estimated close to 150 kt. However, these estimations do not account for other sources of recoverable gallium.

The annual global production of primary gallium exceeds 350 tonnes since 2019. gallium production is known to have increased after 2012, in large part due to major expansion of both capacity and output in China. The overcapacity from China led many producers other than Chinese to stop their gallium operations during this period (Figure 13 and Figure 14). The EU production occurred in Germany and Hungary, accounting for an average 19 tonnes per year from 2012 to 2016. According to company reports, Hungarian production stopped in 2013 (MAL Magyar Alumínium Termelő). The production in Germany (Dadco Alumina) stopped in 2016.

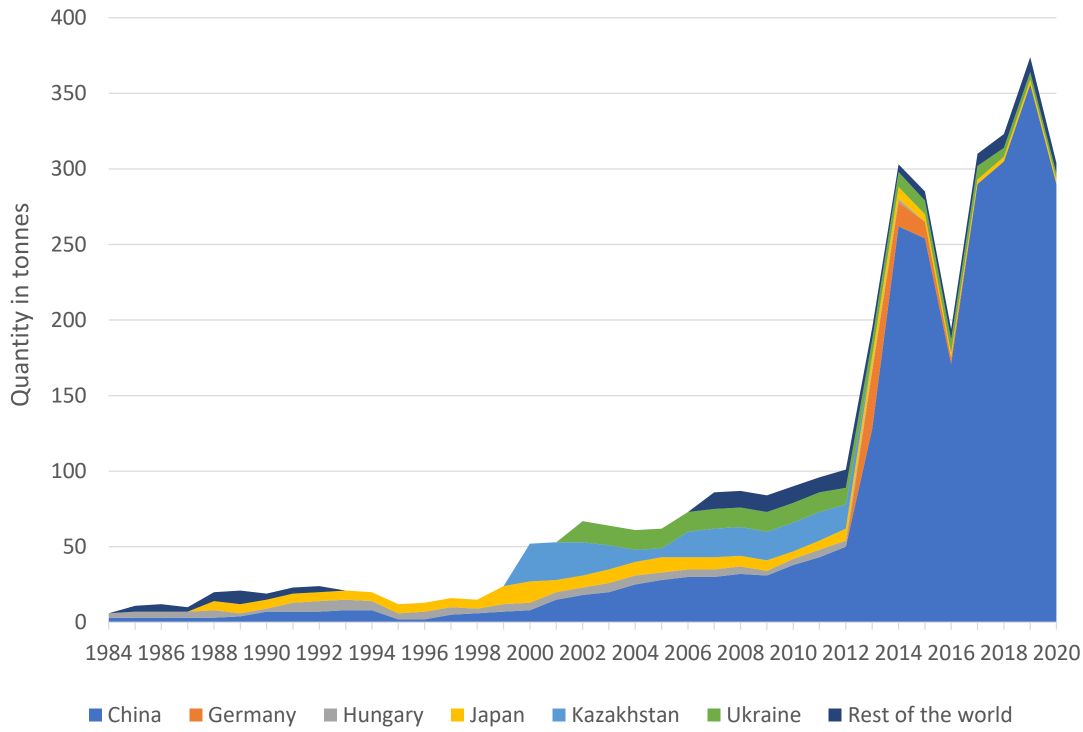

Figure 13. Global primary gallium production since 1984 (WMD, since 1984).

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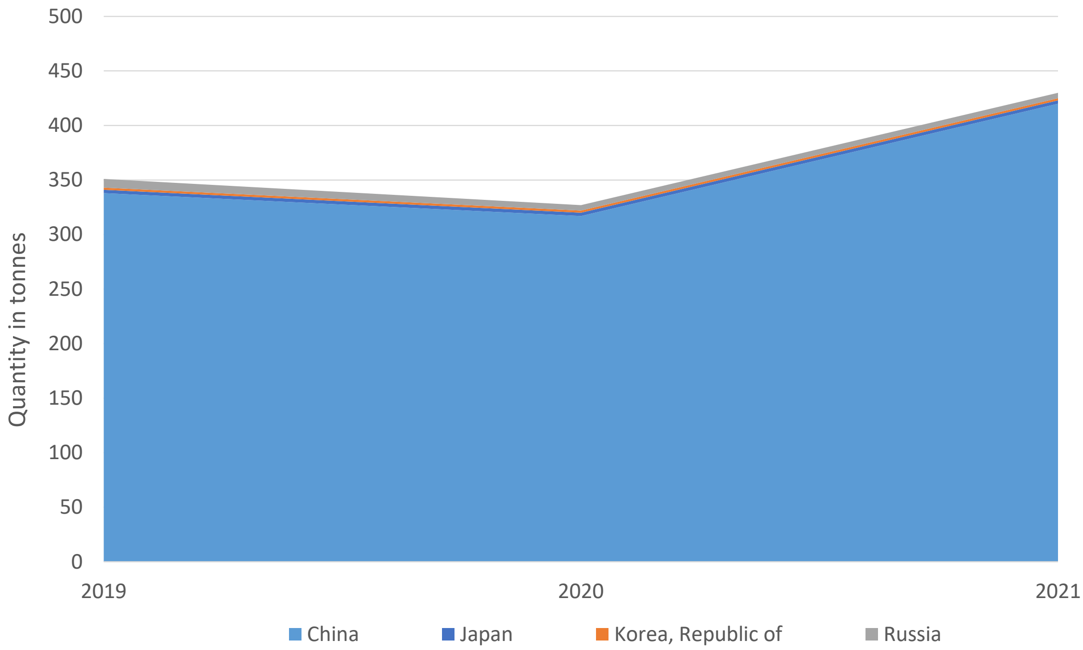

Figure 14. Global primary gallium production since 2019 (USGS, since 2000).

OUTLOOK FOR SUPPLY

There are no precise data concerning the supply trend of gallium as this directly depends on the growth of aluminum and zinc industries.

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

At present, no gallium is recovered from post-consumer scrap (Huy, D and Liedtke, M. ,2016). The rate of recovery of gallium from end-of-life products is near 0% (UNEP, 2013).

The low recovery rate of gallium is due to the difficulty and cost to recover gallium in items where it is highly dispersed. Gallium in its major application, semiconductor devices such as integrated circuits (ICs) and light emitting diodes (LEDs), is used in a few microns thick deposition layer on top of a much thicker substrate and therefore require very little gallium per device (Weimar, 2011). Current recycling processes of waste of electrical and electronic equipment in which they are contained rather favour the recovery of precious metals or copper, while gallium ends up as an impurity in recycled metals or in waste slags (UNEP, 2013).

However, as for many other metals, pre-consumer recycling (i.e. from industrial scrap) is more common source of secondary supply for gallium. The manufacture processes of gallium arsenide (GaAs) and gallium nitride (GaN) wafers are estimated to be the metal's most important secondary source, with some 60% scrap generated and recycled in a 'closed loop' (Butcher, 2014). As for gallium used in thin film photovoltaic production, CIGS technology in particular, material yields assuming sputtering deposition is typically 30-60%, which also allow material recovery and recycling (Marwede, 2014).

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Worldwide production capacity of secondary gallium is estimated at 200 t (Huy, D and Liedtke, M. ,2016). In the United States, high/purity gallium new scrap is known to be recovered from GaAs-based devices (USGS, 2019). There are a few companies in the EU with operations for Ga recycling, for example CMK in Slovakia, who refined from low purity primary gallium (3N, 4N) and from recycled waste material containing gallium (gallium arsenide, chloride, oxide). The recycling and refining capacities were reported at 25 tonnes per year for the years 2006 – 2009 (Huy, D and Liedtke, M. ,2016).

Gallium is recovered in new scraps during fabrication processes, notably in Canada, China, Japan, and the United States, but also inside Europe, in Slovakia and Germany. End-of-life recycling of gallium is almost inexistent. USGS estimates secondary high-purity gallium production capacity at 273 t/yr.

REFINING AND PURIFICATION OF GALLIUM

Gallium is extracted from bauxite through the following process: Bauxite is treated by the Bayer process in order to extract alumina. Bauxite ore is heated in a pressure vessel along with a sodium hydroxide solution (caustic soda) at a temperature of 150 to 200 °C. Aluminium and gallium are separated from iron oxides and silica, which gives the "red mud". After a series of precipitation of aluminium hydroxides, gallium compounds are concentrated, then gallium is extracted by different techniques: solvant extraction, ion exchange, and electrolysis. Impurities are filtered out of liquid gallium and hydrochloric acid washing. For microelectronic applications, gallium is refined to high levels of purity such as 6N or 7N. In this case, gallium is refined by fractional crystallization or electrolytic refining of gallium trichloride (Elementarium).

Optoelectronic applications generally require gallium (and arsenic) of at least 6N purity (99.9999%) and electronic applications require 7N purity metal. Purities of 6N or 7N are achieved by gradual crystallization of liquid gallium. Two methods exist and rely on the fact that impurities tend to remain in the liquid phase and cannot contaminate the growing crystal. There are many impurities of concern such as Ca, C, Cu, Fe, Mg, Ni, Se, Si, Sn, Te. Concentrations of these elements should be less than 1 ppb in the gallium (and arsenic) used for GaAs semiconductors manufacture. Lead, mercury and zinc concentrations must also be lower than 5 ppb. Mass spectrometry is used to analyse final high purity gallium for such impurities (Roskill, 2011).

The capacity for refining gallium into high-purity gallium (6N or 7N) worldwide is estimated at around 160 tonnes according to USGS and it is and less concentrated in China. It is only mastered by a few companies, some of them located in the EU, for example, CMK97 in Slovakia and PPM Pure Metals in Germany.

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Gallium is classically neither extracted from artisanal mining nor associated with Acid Mine Drainage (German Environment Agency, 2020). Paragenesis with radioactive substances may be of medium concern (German Environment Agency, 2020). Yet, there is no consensus on this issue: whereas the German Environment Agency (2020) mentions "slightly elevated concentrations of uranium and/or thorium" in Chinese bauxite

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deposits, Evans (2016) instead considers that “most bauxites will contain low levels of radioactive elements, […], and this is normally doubled in the bauxite residue” (Evans, 2016).

The use of Gallium is not restricted under REACH Regulation (EC) No 1907/2006 Annex XVII (Deutsche Forschungsgemeinschaft and Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area, 2002).

ENVIRONMENTAL ISSUES

Dissipation (“losses”) all along the gallium cycle in the economy, and in particular through extraction and beneficiation, represent a significant share of the total gallium extracted and processed (Helbig et al., 2020). This includes direct discharges of gallium to (and subsequent pollution of) the environment, e.g. Ga concentrations in groundwater are much larger near a semiconductor manufacturing area of Taiwan than in other districts (Chen et al., 2006). Such pollution could have potential ecological and human health impacts through food-chain contamination (Chang et al., 2017), yet to be further explored.

Moreover, there are only limited studies in the literature regarding the environmental impacts of gallium production from a life cycle perspective. Nuss and Eckelman (2014), building on ecoinvent 2.2 data, report that environmental impacts of gallium, per mass unit of production, are in the medium range compared to other metals when considering the impact on global warming, cumulative energy demand, terrestrial acidification, freshwater eutrophication, and human toxicity (cancer and non-cancer). Yet gallium is in the lower range when considering impacts of global yearly production compared to other metals, instead of impact intensity per unit of production.

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF GALLIUM FOR EXPORTING COUNTRIES

In 2021, there were no countries for which the economic value of gallium product exports represented more than 0.1 % of the total value of their exports.

SOCIAL AND ETHICAL ASPECTS

No specific issues were found to be reported for gallium in this context.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- **Photovoltaics (TRL 9)**

Also, copper indium gallium selenium sulfide (CIGS) is recognized as the next generation of promising new solar cells due to the high performance, wide applicability, and efficient photoelectric conversion

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efficiency (Shen et al., 2018). PV systems are known for their very low carbon emissions or GHG emissions. Generally, the solar modules require no fossil fuels to operate, however some manufacturing processes are still slightly depending on fossil fuels. These processes are also known for a relatively less payback time compared to other conventional and renewable energy sources (Rabaia et al., 2020). Up to now substitution possibilities for Ga in solar cell are very limited (John et al. 2021). Comparing different solar cell materials (silicon, cadmium telluride, and gallium arsenide) gallium arsenide is the optimum material for solar cell design as it possesses very good light absorption capability. This ensures that GaAs solar cell exhibits higher efficiency than the former two materials. In addition, GaAs based solar cell design gives better performance than other types. Regarding CISG solar cells, some studies have attempted to replace indium and gallium with lower-priced elements, such as zinc and tin. However, the efficiency of alternative solar cells is likely to be affected due to the unique optoelectronic properties of indium and gallium (Ma et al., 2020).

OTHER RESEARCH AND DEVELOPMENT TRENDS

- GaNSpector[4] project: Automated inspection tool to unveil defects in raw Gallium Nitride (GaN) crystals (EU, 2021 – 2023)

The aim is to develop an automated non-destructive inspection tool to help semiconductor manufacturers to get insight into raw GaN crystal quality. Such a scanner will help to improve the growth process, as well as to assess the defectiveness of GaN crystals before processing. It will save resources on slicing and polishing initially defective crystals, and thereby time and costs to fabricate epi-ready wafers.

- EleGaNT[5] project: Transistor Integrated Circuits (EU, 2021-2023)

The EU-funded EleGaNT project aims to demonstrate a higher level of integration between GaN and integrated circuits. The project will demonstrate improved designs of GaN integrated circuits and passive devices and of point-of-load converter boards.

- ICG68-PROG[6] project: Imaging of c-Met aberrant cancers with Gallium-68 chelators for positron emission tomography (EU, 2020 – 2022)

The overall aim of the project is to create a library of novel molecular agents able to effectively target c-Met and to efficiently bind gallium-68, and therefore to be exploited as c-Met PET imaging tracers. The expected results are to select the most promising and effective tracers among the library of synthesized compounds for further preclinical development.

[4] See https://cordis.europa.eu/project/id/101033102
[5] See https://cordis.europa.eu/project/id/101004274
[6] See CORDIS EU research results: https://cordis.europa.eu/project/id/893784

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