

5. Gallium

Like aluminium, gallium is a soft, silvery metal.¹ A particular concern for gallium criticality is its main use in growing and emerging markets. Gallium is almost exclusively used as III-V semiconductor material in electronics applications² that grew fast in recent years and are forecast to continue growing rapidly in the coming decades^{3,4}.

Traces of gallium can be found in the minerals diaspore, sphalerite, germanite, bauxite and coal.¹ As it is primarily obtained from the circulation liquor in the Bayer process for aluminium oxide manufacture, gallium is a by-product of aluminium production and is not extracted in its own right.⁵ After a period in which the price of gallium increased up to a peak of 688 US\$/kg[†] in 2011, the price has declined. In 2013 the price of gallium decreased continuously. Metal Bulletin #937} The leading producer is China, which has increased its production capacity by a factor of five⁶. Its competitors are Kazakhstan and Ukraine.

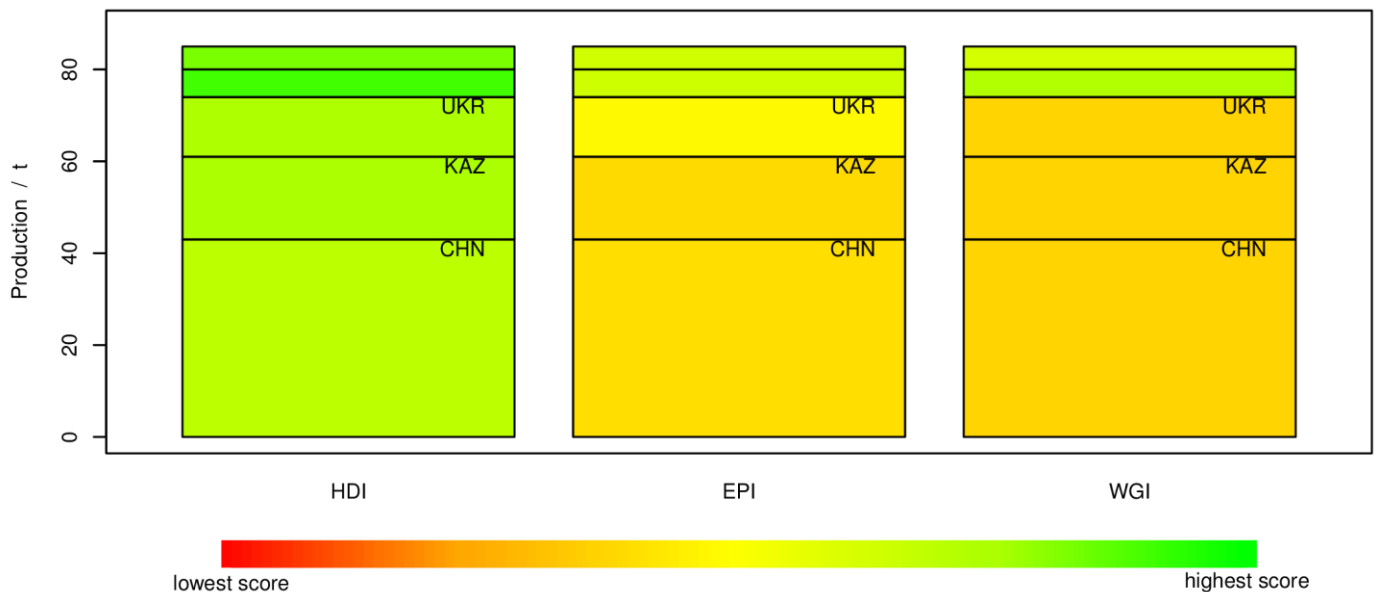


Figure 1: Distribution of gallium production⁷ and corresponding scores of the producing countries in the Human Development Index (HDI),⁸ Environmental Performance Index (EPI)⁹ and World Governance Indicators (WGI).¹⁰ Both the EPI and WGI are used to assess supply risks with the EU methodology for determining critical raw materials.¹¹ CHN = China; KAZ = Kazakhstan; UKR = Ukraine.

[†] Price, yearend, dollars per kilogram: Estimated based on the average values of U.S. imports for 99.9999% -and 99.99999% -pure gallium

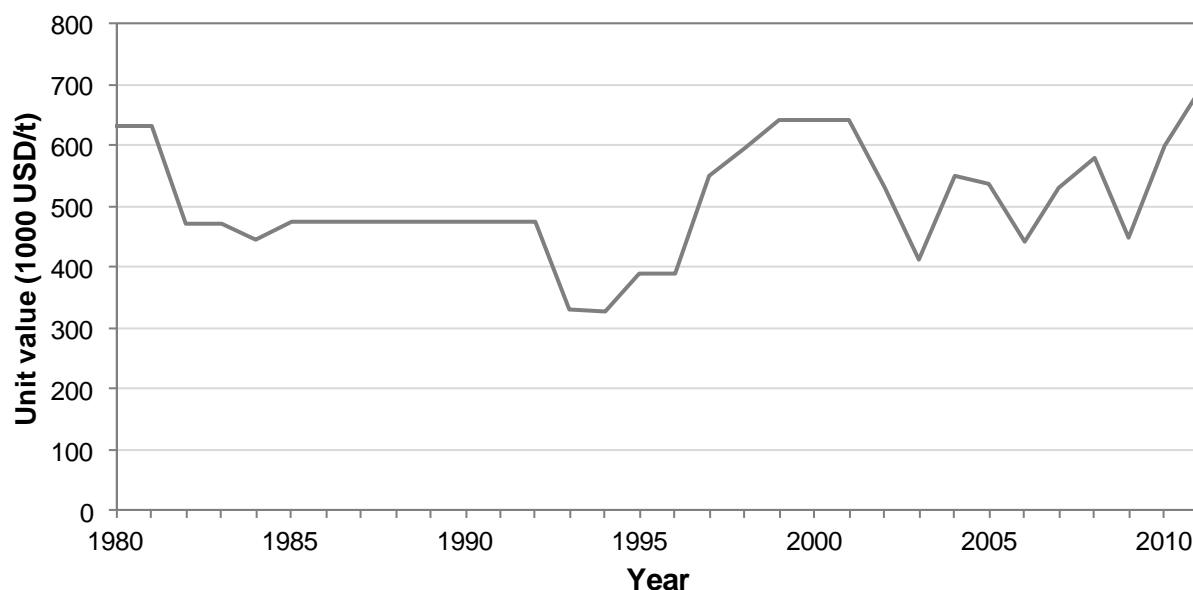


Figure 2: Gallium price development during 1980 – 2011. The unit value is defined as the value of 1 ton (t) of gallium apparent consumption (estimated).¹²

Uses and substitutability

Gallium is almost exclusively used in III-V semiconductor compounds, in particular GaAs and GaN, for two main applications fields:

- Integrated circuits
- Optoelectronic devices (LEDs, laser diodes and photo detectors, solar cells)

Integrated circuits

Semiconductor compounds used in integrated circuits (ICs) are currently the major application of gallium constituting about 70% of overall gallium use.² Integrated circuits with gallium compound semiconductors specifically GaAs and GaN, are used in high-power and high-frequency electronics, due to higher electron mobility, breakdown voltages and saturation velocity than silicon-based ICs. This faster and cleaner electron transfer enables stable high power (wireless) communication devices, such as smart phones, amplifiers, digital switches and microwave applications.^{4,13} These applications are all rapidly growing.³ Due to their high radiation and temperature resistance the gallium-based ICs are ideal for space applications, such as satellite dishes, and military use. The Ga compounds are either melt-grown wafers or thin films prepared by metal organic chemical vapour deposition (MOCVD) from trimethyl gallium precursors.

Options for substitution of gallium in integrated systems are limited because, as a minor and relative costly metal, Ga-based IC were specially develop for applications where established Si-based semiconductor and integrated circuit technology do not fulfil the applications' requirements. SiGe is a commercially available alternative to GaAs exhibiting similar properties required for high-power and high-frequency electronics.¹⁴ SiGe is able to replace GaAs wafers in some integrated circuits (high performance radio frequency applications), but it uses another critical raw material, germanium. Note that SiGe was developed as cost-effective alternative to GaAs and not because of the gallium criticality as such. Integrated circuits are core

components applied in a broad range of electronic product making component substitution instead of material substitution also not possible without function or performance loss.

In conclusion, currently substitution of gallium in integrated circuits is possible for a limited number of applications but only by materials containing another critical raw material.

Optoelectronic devices

Optoelectronics devices, such as laser diodes, photodiodes, LEDs and solar cells, constitute the other main use of gallium. LEDs are used in lighting and displays and the demand for LEDs in solid state lighting applications is growing fast due to governmental bans on the use of incandescent light bulbs. Photodiodes are used in e.g. remote controls and laser diodes are used in telecommunication optical media (CD, DVD) players. Gallium-based solar cells are exclusively used for space and military applications and concentrated solar power. Thin film copper-indium-gallium-selenide (CIGS) solar cells are an emerging technology for low-cost and high efficiency solar power generation.

As for the integrated circuits, gallium is combined with arsenic (GaAs), sulphur (GaN) or phosphor (GaP), often including indium (InGaAs) or aluminium (AlGaAs), to produce III-V semiconductor compounds. Due to their high electron velocity, compared to silicon, and their direct bandgap, Ga based semiconductors are well suited to either convert electricity to light (LEDs, laser diodes) or vice versa (solar cells, photodiodes). In multilayer stacks of these compounds a diode, created by a so-called p-n junction, functions as the active component in the optoelectronic devices. The gallium compounds are typically prepared as thin films by metal organic chemical vapour deposition (MOCVD). Hence, gallium enters the device market in the form of trimethyl gallium MOCVD precursors.

Zinc oxide (ZnO), an II-VI compound semiconductor, is being investigated as an alternative to GaN in LEDs and laser diodes. To obtain the p-n junction for the optoelectronically active diode both n-type and p-type doped ZnO is needed. However, p-type ZnO has limited stability and thus it is not (yet) a feasible substitute. Similar difficulties obtaining stable p-type compounds restrict the use of other II-VI compounds such as MgSe and ZnSe. From a component point of view, incandescent light bulbs and fluorescent light are obvious substitutes for gallium-containing solid state lighting. However, incandescent light bulbs are being phased out in the EU and other countries, because of their low energy efficiency. Fluorescent lighting relies on phosphors containing rare earth elements, which are also critical raw materials. Organic LEDs (OLEDs) are an emerging alternative technology to solid state lighting. OLED displays and light concepts have been introduced on the market by the major electronics companies. However, for now there are only a limited number of applications, because current OLEDs are not competitive with solid state LEDs on price and long-term durability. It is expected that for at least the coming 5-10 years OLEDs will remain a relative niche compared to solid state lighting.

Stacks of GaAs, (Al)InGaP/As films make so-called multijunction solar cells, which are the only solar cell types with conversion efficiency of more than 30%. Combined with a high temperature and radiation resistance they are very high performance solar cells. However gallium-based solar cells are considerably more expensive than other solar cell types, restricting their use to special applications, such as satellites and concentrated solar power.¹⁵ As a consequence the possibilities for substitution by other solar cell types, such as established silicon based solar cells, are limited without a significant loss in performance. Of the emerging second and third generation solar cell technologies copper-indium-gallium-diselenide (CIGS) thin film solar cells are potential substitutes, because of their radiation resistance and tolerance toward defects. However, the conversion efficiency is lower and they also contain critical metals gallium and indium.

Material substitution by other III-V or II-VI semiconductor compounds suffers from the same limitations as described for LEDs.

CIGS thin film solar cells are a growing application that is forecasted to attain a significant share (20%) of the fast growing photovoltaic market in the coming decades. As a thin film solar technology it holds the potential of lower manufacturing costs and better product integration compared to the state-of-the-art silicon wafer based solar modules. CIGS solar modules are manufactured on an industrial scale by around five companies world-wide. The industrial and academic CIGS community is aware of the criticality of gallium, but opinions on the need for substitution vary. A one-to-one material substitution by copper-zinc-tin-selenide/sulphide (CZTS) has become a significant R&D theme in the recent years.¹⁶ However, with record conversion efficiency (2013 figures) of only 11.1% compared to 20.4% for CIGS solar cells, commercial production of CZTS modules is not likely within the coming 10 years. Also due to the strong cost reduction in the last 3 years established silicon based solar technology is an obvious substitute for CIGS.

In conclusion currently substitution of gallium in optoelectronic devices (LEDs, laser diodes, photodetectors and solar cells) is limitedly possible and only at a loss of performance.

Summary

Prime examples for the utility of gallium are the use of gallium arsenide (GaAs) integrated circuits for wireless communication (e.g. smart phones) and of gallium nitride (GaN) in solid state lighting (LED). Substitution of gallium is limited because, as a minor and relative costly material, gallium is primarily used in applications where there are no comparable alternatives.

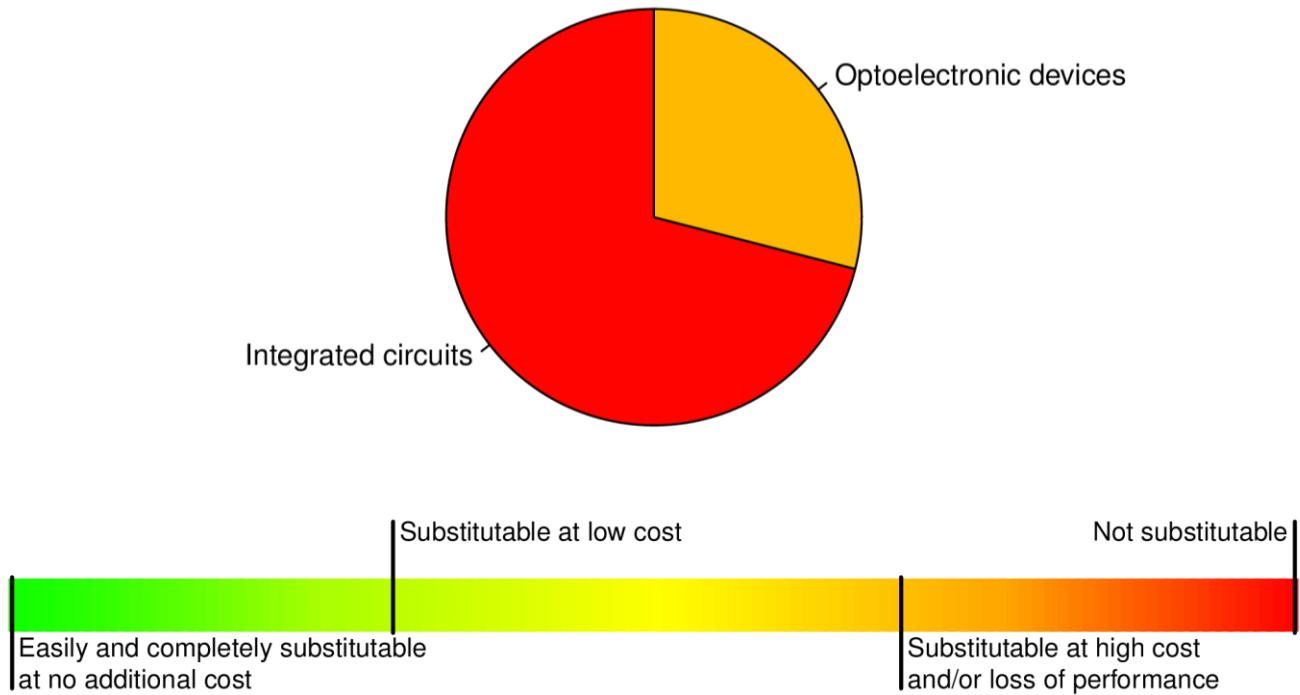


Figure 3: Distribution of end-uses and corresponding substitutability assessment for gallium. The manner and scaling of the assessment is compatible with the work of the Ad-hoc Working Group on Defining Critical Raw Materials (2010).

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