Contribution by IMAT

1st Stakeholder Consultation – Questionnaire for indium phosphide InP

Part of the Study to support the review of
the list of restricted substances and
to assess a new exemption request
under RoHS 2 (Pack 15)

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Answers

Preliminary Note

Today´s microelectronic technology is dominated mostly by the chemical element silicon. This semiconductor material allows the fabrication of extremely cost-efficient electronic devices. Thus the market share is roughly around 90% worldwide. However some important functionality cannot be realized using silicon by reason of fundamental physical laws. Examples are the generation of light, or the ability to operate at very high frequencies, -voltages, -currents, and -temperatures.

In the past five decades (!) researchers worldwide explored the periodic table of the elements seeking for other materials having semiconducting properties. It turned out that only the so-called "compound semiconductors" are able to provide the desired properties. Such materials are consisting of at least two different chemical elements.

The only promising candidates identified as of today are the II-VI compounds family comprising of Zn, Cd, Hg, Se, and Te, as well as the III-V compounds comprising of Al, Ga, In, N, P, As and Sb. Today the latter category has achieved a very important market share since many products cannot be manufactured without using these materials. It has to be mentioned that these compounds are covalent bounded, so that their properties are completely different from the constitutional elements.

The III-V compound semiconductors are unique in comparison to silicon, because they can be tailored to the specific application by stacking a number of single atomic layers which differ in composition each. For instance up to 800 individual layers in nearly perfect crystalline quality are needed to fabricate a special type of semiconductor laser called Quantum Cascade Laser. The fabrication process of these layered structures is referred as "epitaxy". One may imagine which multitude of degrees of freedom in designing a layered epitaxial structure for a specific application exists. This enables the fabrication of highly sophisticated devices perfectly matching the needs of particular applications. However there are some critical limitations since the unavoidable differences in the lattice constants of the individual layers are creating tensile and compressive stress thus affecting the crystalline quality of the package. In particular optoelectronic devices are very delicate regarding imperfections of the crystalline lattice. It is obvious that this technology is quite cost-intensive regarding development, raw materials, fabrication processes, and necessary investments into fabrication plants. Hence industry will always substitute these materials immediately if an acceptable alternative in the "Silicon World" exists.

1 a) Applications

The application fields of InP splits up into two main areas. It is used as the basis

- for **optoelectronic components**
- for **high-speed electronics**
- for **photovoltaics**

N. B. there is a hitherto vastly unemployed, yet technically exiting zone in the electromagnetic spectrum between microwaves and infrared, often referred to as "Terahertz". Electromagnetic waves in this range possess hybrid properties they show high-frequency- and optical characteristics simultaneously. InP based components unlock this spectral range for important new applications.

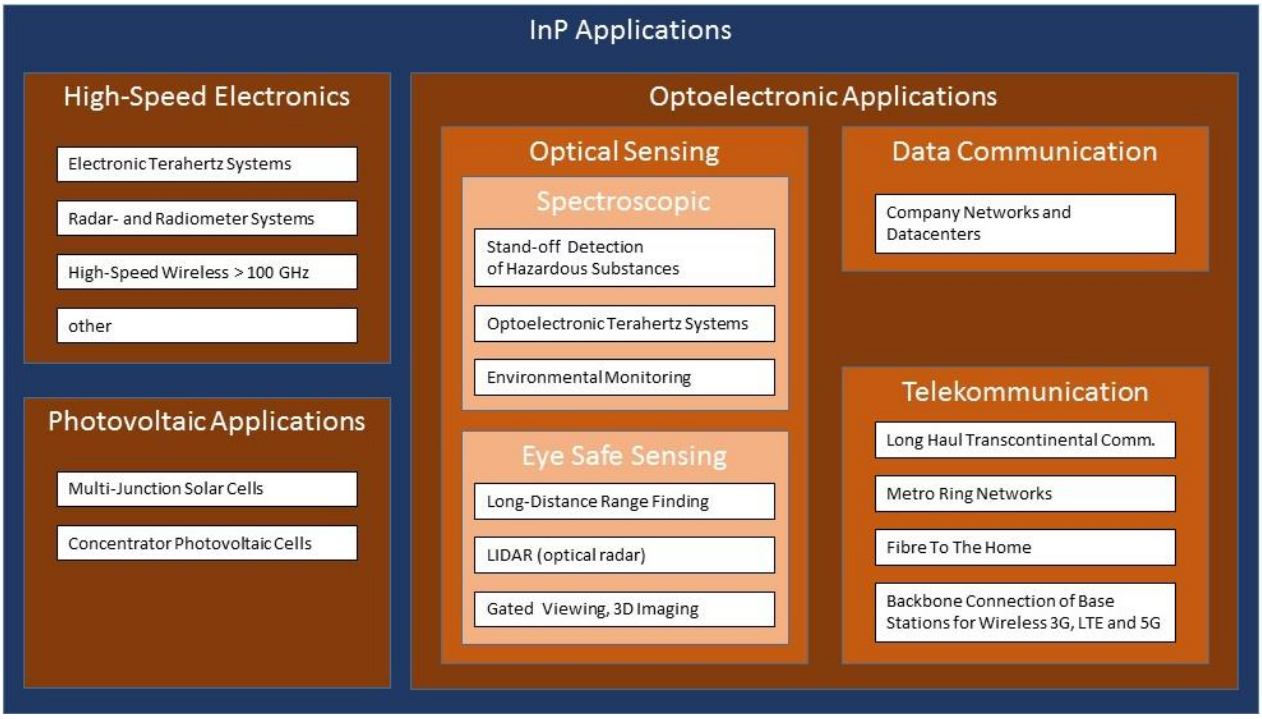

Image 1: Overview key applications for InP

<u>Optoelectronic Applications - Overview</u>

InP based lasers and LEDs can emit light in the very broad range of 1200 nm up to 12 µm. This light is used for fibre based Telecom and Datacom applications in all areas of the digitalised world. Light is also used for sensing applications. On one hand there are spectroscopic applications, where a certain wavelength is needed to interact with matter to detect highly diluted gases for example. Optoelectronic terahertz is used in ultra-sensitive spectroscopic analysers, thickness measurements of polymers and for the detection of multilayer coatings in the automotive industry. On the other hand there is a huge benefit of specific InP lasers because they are eye safe. The radiation is absorbed in the vitreous body of the human eye and cannot harm the retina. InP lasers in LiDAR (Light Detection And Ranging) will be a key component for the mobility of the future and the automation industry.

Telecom/Datacom

Indium Phosphide (InP) is used to produce efficient lasers, sensitive photo detectors and modulators in the wavelength window typically used for telecommunications, i.e., 1550 nm wavelengths, as it is a direct bandgap III-V compound semiconductor material. The wavelength between about 1510 nm and 1600 nm has the lowest attenuation available on optical fibre (about 0.26 dB/km). InP is the only relevant material for the generation of laser signals and the detection and conversion of those signals back to electronic form. Wafer diameters range from 2-4 inches.
Applications are:

- Long-haul optical fibre connections over great distances up to 5000 km typically >10 Tbit/s
- Metro ring access networks
- Company networks and data center
- Fibre to the home
- Connections to wireless 3G, LTE and 5G base stations
- Free space satellite communication

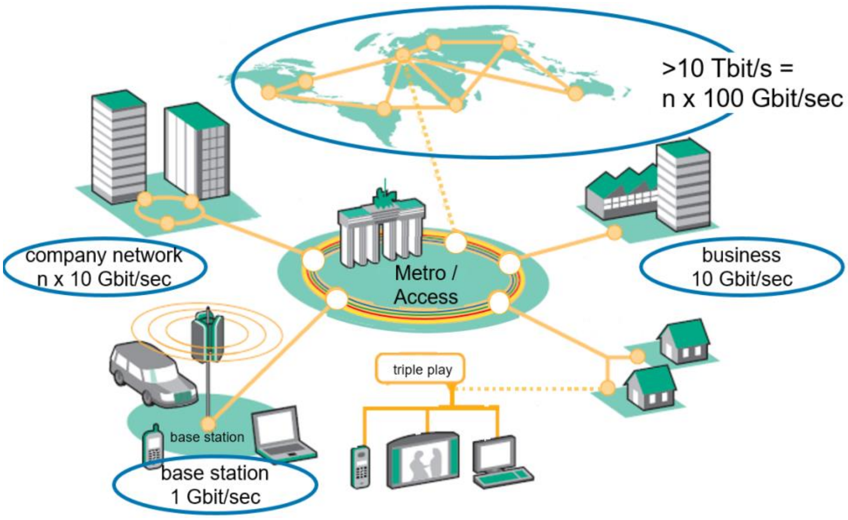

Image 2: Optical fibre Network for the Internet

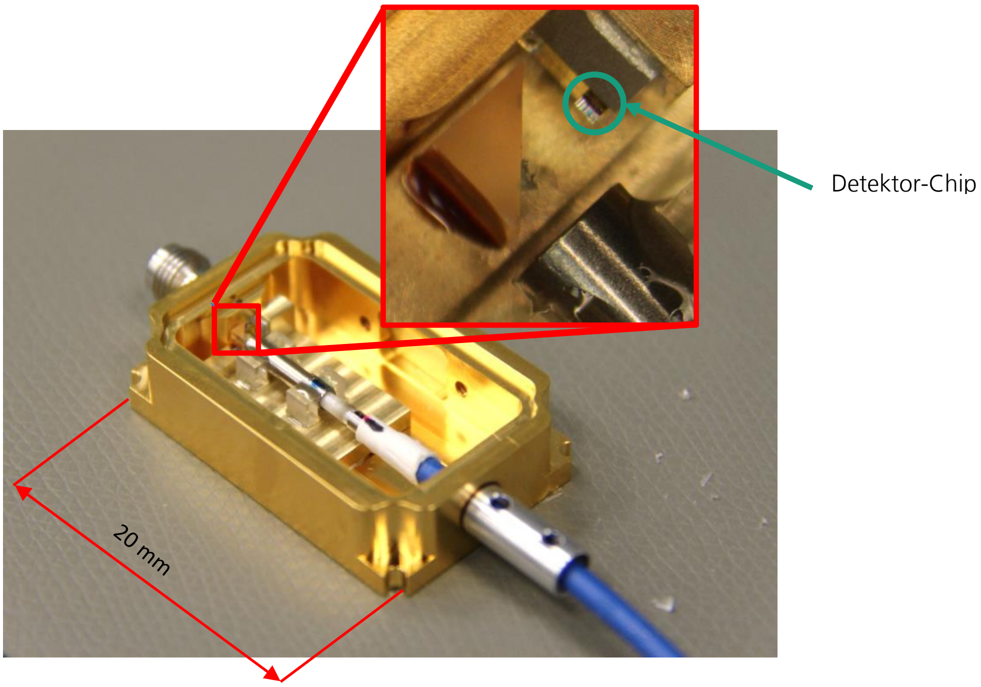

Image 3: InP Detector with a typical chip-size (450 µm x 450 µm x 150 µm) 146 µg

Image 3 shows an InP Detector mounted in a housing with a fibre connection. The housing has a footprint of 20 x 10 mm^2. The mono-mode fibre core diameter is 0,009 mm. The light is focused to the detector chip with the longest dimension of 10x of a human hair.

Optical Sensing

- Spectroscopic Sensing aiming environmental protection and identification of dangerous substances
    - A growing field is sensing based on the wavelength regime of InP. One example for Gas Spectroscopy is drive test equipment with real-time measurement of (CO, CO_2, NO_x [or NO + NO_2]). Image 4 shows a portable Emission Measurement Systems (PEMS) e. g. for Real Drive Emission (RDE) testing of vehicles powered by combustion motors.

Image 4: Mobile test equipment based on InP quantum cascade laser

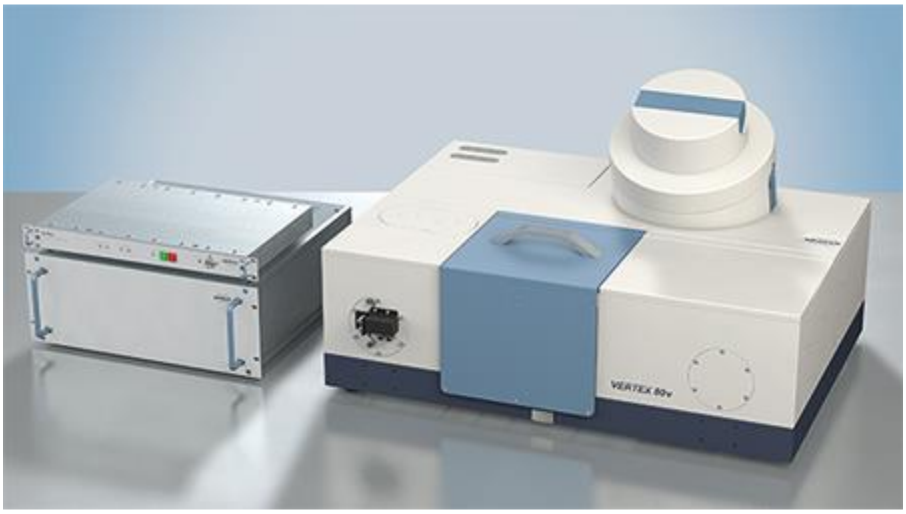

Image 5: State-of-the-Art CW THz FTIR Spectrometer with a Terahertz source based on InP (Bruker)

- Image 5 shows an FT-IR-Spectrometer VERTEX with a terahertz source. The terahertz radiation is generated from the beating signal of 2 InP lasers and an InP antenna that transforms the optical signal to the terahertz regime. The breakthrough of terahertz technology for automotive and other industries started when huge table systems with tens of mirrors were replaced by systems of shoebox size equipped with fibre lasers from the telecom arena and antennas based on InP.

- Stand-Off detection of traces of explosive substances on surfaces, e.g. for safety applications on airports or crime scene investigation after assassination attempts.
- Quick verification of traces of toxic substances in gases and liquids (including tap water) or surface contaminations down to the ppb level.
- Spectroscopy for non-destructive product control of e.g. food (early detection of spoiled foodstuff)
- Spectroscopy for many novel applications, especially in air pollution control are being discussed today and implementations are on the way.

➢ LiDAR systems for the automotive sector and industry 4.0

Widely discussed in the LiDAR arena is the wavelength of the signal. While some players have opted for 830-to-940-nm wavelengths to take advantage of available optical components, according to the report, companies (including Blackmore, Neptec, Aeye, and Luminar) are increasingly turning to longer wavelengths in the also-well-served 1550-nm wavelength band, as those wavelengths allow laser powers roughly 100 times higher to be employed without compromising public safety. Lasers with emission wavelengths longer than ≈ 1.4 µm are often called "eye-safe" because light in that wavelength range is strongly absorbed in the eye's cornea, lens and vitreous body and therefore cannot damage the sensitive retina.

- LiDAR-based sensor technology can provide a high level of object identification and classification with three-dimensional (3D) imaging techniques.
- The automotive industry will adopt a chip-based, low cost solid state LiDAR sensor technology instead of large, expensive, mechanical LiDAR systems in the future.
- For the most advanced chip-based LiDAR systems, InP will play an important role and will enable autonomous driving. (Report: Blistering Growth for Automotive Lidar, Stewart Wills). The longer eye safe wavelength is also more appropriate dealing with real world conditions like dust, fog and rain.

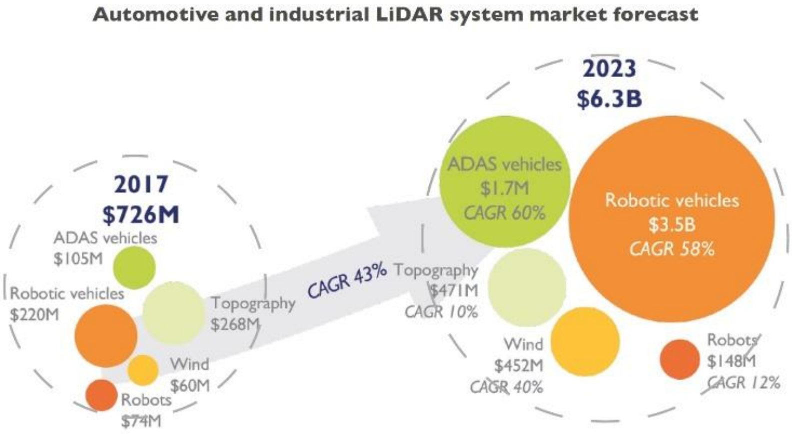

Image 6: Automotive and industrial LiDAR system market forecast

Photovoltaic applications

Photovoltaic cells with highest efficiencies of up to 46% (Press Release, Fraunhofer ISE, 1. December 2014) implement InP substrates to achieve an optimal bandgap combination to efficiently convert solar radiation into electrical energy. Today, only InP substrates achieve the lattice constant to grow the required low bandgap materials with high crystalline quality. Research groups all over the world are looking for replacements due to the high costs of these materials. However, up to now all other options yield lower material qualities and hence lower conversion efficiencies. Further research focusses on the re-use of the InP substrate as template for the production of further solar cells.

Also today's state-of-the-art high-efficiency solar cells for concentrator photovoltaics (CPV) and for space applications use (Ga)InP and other III-V compounds to achieve the required bandgap combinations. Other technologies, such as Si solar cells, provide only half the power than III-V cells and furthermore show much stronger degradation in the harsh space environment. Finally, Si-based solar cells are also much heavier than III-V solar cells and yield to a higher amount of space debris. One way to significantly increase conversion efficiency also in terrestrial PV systems is the use of similar III-V solar cells in CPV systems where only about one-tenth of a percent of the area is covered by high-efficiency III-V solar cells.

High-speed electronics

Today´s semiconductor technology allows the creation and detection of very high frequencies of 100 GHz and higher. Such components find their applications in wireless high-speed data communication (directional radio), radars (compact, energy-efficient and highly resolving), and radiometric sensing e. g. for weather- or atmospheric observations.

InP is also used to realize high-speed microelectronics and such semiconductor devices are the fastest devices available today. Typically, microelectronics on InP is based on High Electron Mobility Transistors (HEMT) or on Heterostructure Bipolar Transistors (HBT). The sizes and volumes of both transistors based on InP material is very small: 0.1 µm x 10 µm x 1µm. Typical substrate thicknesses are < 100 µm. These transistors are assembled into circuits and modules for the following applications:

- Security scanning systems: Imaging systems for airport security imaging and scanners for civil security applications.
- Wireless communications: High-speed 5G wireless communications will explore InP technology due to its superior performance. Such systems operate at frequencies beyond 100 GHz in order to support high data rates.
- Biomedical applications: Millimeter-wave and THz spectrometers are employed for non-invasive diagnostics in medical applications from cancer tissue identification, diabetes detection, to medical diagnostics using human exhaled air.
- Non-destructive testing: Industrial applications employ scanning systems for quality control in e.g. automotive paint thickness applications and defects in composite materials in aerospace.
- Robotics: Robotic vision is essentially based on high resolution imaging radar systems at millimetre-waves.
- Radiometric sensing: Almost all components and pollutions in the atmosphere show characteristic absorptions/emissions (fingerprints) in the microwave range. InP allows to fabricate small, lightweight and mobile systems to identify such substances.

ii.) To substitute InP it would be necessary to find a semiconductor with the same bandgap in order to address the same wavelength window. For high-frequency electronics, InP is also necessary because of its very high electron velocity.

InP based devices are the fastest devices available today. For limited applications InP can be replaced by GaAs based technologies or Silicon based technologies such as CMOS or SiGe technology.

1 b.) With respect to the extremely low volume of InP and a strong focus on non-consumer markets the reintroduction into the material cycle by recycling can be neglected.

1 c.) In the applications indicated above InP remains as the constitutive material for device operation.

2 Quantities

<u>Preliminary note:</u>

In many publications information is not appropriately separated between indium metal and indium phosphide in terms of their quantities, uses and possible alternatives. Unfortunately this is also the case in the background document of this questionnaire. Please be aware that there is as well a huge difference in all fields between indium phosphide and indium tin oxide

In ≠ InP ≠ ITO.

Only in a very limited number of industrial companies InP is part of the processes. Wherever this is the case appropriate measures for occupational health and safety have been established for many years. Their efficiency is monitored accordingly. The staff is regularly trained and skilled in the proper handling of this material. Exposure risk is adequately controlled.

Only very small quantities of InP are encapsulated in various components of an EEE (please see examples above). Thus, there is no direct contact of industrial users with this material possible.

Image 7: Typical supply chain in semiconductor industry

<u>Technology:</u>

a. InP is produced starting with raw material indium metal and phosphorus. From these the stoichiometric compound InP has to be synthesised, followed by a process to grow a single-crystalline ingot. For use in semiconductor industry wafers have to be provided made from this material.
b. InP is sold and produced solely as a wafer by a very small number of companies worldwide representing at least 90% of the market. Producer of InP wafers are e.g.
    - AXT, USA/China
    - InPact, France
    - JX Nippon Mining and Metals Corporation, Japan
    - PamXiam, China
    - Sumitomo, Japan
    - Wafer Technology, United Kingdom
    - Vital Materials, China

   There is no data from independent market research institutes or associations on indium phosphide (InP). Therefore, in May 2018, the Fraunhofer Heinrich-Hertz-Institute conducted its own survey among all supplying manufacturers. The survey asked about their sales and their estimated own market share. All wafer sizes were weight converted into 2" wafers. Since nearly all manufacturers have supplied the confidential figures of their own sales, the figure of 75000 Wafers is a robust upper limit. The estimated market size, which results from sales and the estimated own market share on average, is only 57000 wafers. 75000 wafers in 2" size correspond to a weight of 268 kg. Due to edge losses, faulty components and thinning, a significant share of the originally used input of InP wafers does not go into the finished product. For wafer manufacturing this loss during the production process goes into material cycle; faulty components and waste by thinning is disposed off according to legal regulations.

c. Thinning is a required process step to be able to singularise (= wafer dicing) the very small components. For a typical product the thickness of a wafer is reduced from ca. 375 µm to 50 – 300 µm. In addition, the yield of marketable devices is in the dimension of less than 80%.

d. As part of an EEE this results in an estimated amount of max. 134 kg of InP inside products that will come into the global market per year. The share of the European market is about 25 % resulting in less than 33 kg of InP material in products in Europe. From this amount of material, the largest portion goes into industrial or infrastructure (telecom) and hardly anything reaches the consumer market.

3 Potential emissions in the waste stream

As mentioned above the very small amount in weight of InP per component in the end equipment targeted by RoHS is negligible and will not contribute significantly to the main waste stream.
On the contrary, the majority of waste is originated only in companies where InP is processed in form of crystals and wafers, respectively.
There Indium phosphide is managed in the waste phase according to typical semiconductor processing rules as hazardous chemical waste. Based on the legal regulations already for many years efficient measures for Occupational Health and Safety as well as for environmental protection have been established. No emissions into the environment are observable after semiconductor process completion of InP.
Most of InP is lost during

- cutting of crystals into wafers
- polishing of final wafer surface
- back-grind of wafers during chip manufacture

During the industrial processing internal material cycles have been already optimized in order to achieve the most possible benefit of this expensive material. Starting with the synthesis of InP

crystals only < 5% of InP ends in the final electronic devices. However, the remaining small quantities of waste are disposed off by an accredited specialised waste company.
The most significant aspect with regard to the target of RoHS is the end of life process and how equipment is recycled safely in the EU. But according to the "Study on the Review of the list of Critical Raw Materials" published by EU COM in 2017 the same reasons for low recycling possibilities of electronical devices containing InP can be applied

- minor concentrations in final products
- lack of appropriate technology
- low economic incentives

Additionally there is no collecting system of such end of life devices established.

4 Substitution

Not applicable as indicated above

Beside the physical properties of InP which cannot adequately provided by other materials substitution is not feasible in terms of

- Cost efficiency: InP wafers are very expensive. If other material would be available it would have been introduced already by industry.
- Intended additional value for reduced risk: Alternative semiconductor materials with similar physical properties own the same or even higher risk for human health and environment due to their hazardous potential.
- Regulatory obligations: The obligation to substitute wherever it is possible is already existing given in the CMD → no additional regulation is necessary; regarding the alternative semiconductor materials the same legal basis has to be applied as for InP.

<u>Note:</u>

The only alternative semiconductor material class for the fabrication of efficient tuneable laser sources in the mid- and longwave infrared region consist of II-VI compound semiconductor materials, that contain cadmium, mercury or lead. Therefore the use of such lasers is limited to classified defence applications.

Lasers that are not semiconductor lasers e. g. gas lasers and solid state lasers suffer significantly from performance data. (Output power, weight, size, energy consumption, life span, cooling requirements, and cost). Therefore they cannot be used in the before mentioned applications.

5 Socio economic impact of a possible restriction

Potential restriction of InP would lead to a total collapse of optical data transmission based on optical fibres as well as to unacceptable burden in high-speed electronics. In this case the so-called Key Enabling Technologies (KETs) defined by EU COM and their important strategic role as a key element of European industrial policy would be jeopardized. EU COM states: "The KETs provide the basis for innovation in a range of products across all industrial sectors. They underpin the shift to a greener economy, are instrumental in modernising Europe's industrial base, and drive the development of entirely new industries."

Reading the RoHS directive as it is already in place you find the requirement "that there should be coherence between those objectives and other Union environmental legislation."

Microelectronics and photonics are explicitly named among the 6 defined KETs. A restriction of InP would eliminate this small but important part of the semiconductor industry and research in Europe. Possible consequences would be:

- No more core products made in Europe for the digitalisation. Consequently, all InP based products and systems would have to be imported from the US or Asia.
- Keeping in mind, that telecommunication and network equipment made by Chinese manufacturer HUAWEI is not allowed in the US, Europe would have to surrender to all hidden backdoors or the suspension of deliveries for essential imported hardware! This would mean the total loss of control in the digital world.
- Europe's industry would no longer be able to participate in the supply chain of electronic equipment due to the lack of own production and processing of InP material, respectively.
- Regarding the use of electronic devices a long service life period is foreseen. Given this frame in case of maintenance and repair replaced components should have the same properties to guarantee the functionality of a device as it was originally the case. If spare parts don't comply the entire device has to be scrapped instead of only replace a certain component. This means if InP has to be substituted
    - Adequate spare parts are no longer available.
    - Replacement of only a certain component avoids the scrapping of complex electronic equipment and helps to reduce the quantity of waste in total.
- In case of a restriction of InP the quality of infrastructure for data communication would be influenced drastically as well for industry and private consumers.

6 Further information and comments

Economic relevance of industrial use of InP:

The value of a processed wafer lies in regime of 40000 €. The value of the product is about 20 times higher than the contained semiconductor. This leads to a market of 46 Billion € in Europe. Europe is holding a strong position of approximately 25% of the world market in InP – based on high-speed and optoelectronic hardware.

Summary

- InP cannot be replaced by any other semiconductor material even after decades of intense research worldwide. The total volume introduced into the market via EEE is extremely low.
- The periodic table of the elements provides only a limited number of semiconducting elements and compounds. This is the finding of decades of intense research.
- There is no "universal" semiconductor material which can fulfil all requirements with respect to crucial physical properties and less hazardous potential.
- Silicon is by far the semiconductor material used with highest quantities, however not capable to generate light by reason of fundamental physical laws.
- The semiconductor industry is extremely price sensitive therefore expensive compound semiconductors are used only if no alternative exists. Hence, no additional regulation is necessary to foster substitution.
- Often compound semiconductor (e.g. InP) devices are key components in complex high-tech systems for industrial applications → almost no consumer use of InP semiconductor materials
- Because of dual-use properties sometimes such essential devices for products with high value creation are subject to foreign export regulations e. g. ITAR. Therefore it is of key importance for the European industries to have an independent supply of such components. For this reason EU is funding pilot-line activities like MIRPHAB (InP based lasers) or PIXAPP (InP Photonics).
- Double regulation should be avoided → interface between existing legislation should be improved.
- There should be coherence between objectives of RoHS and other Union environmental legislation.
- In case of further regulation of InP by RoHS directive the technological sovereignty of Europe would be lost.