www.oeko.de

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

ROHS Annex II Dossier for Indium phosphide. Restriction proposal for substances in electrical and electronic equipment under RoHS

Report No. 3
Substance Name: Indium phosphide
EC Number: 244-959-5
CAS Number: 22398-80-7

Version 3
25/09/2019

Head Office Freiburg
P.O. Box 17 71
79017 Freiburg
Street address
Merzhauser Strasse 173
79100 Freiburg
Tel. +49 761 45295-0

Office Berlin
Schicklerstrasse 5-7
10179 Berlin
Tel. +49 30 405085-0

Office Darmstadt
Rheinstrasse 95
64295 Darmstadt
Tel. +49 6151 8191-0

info@oeko.de
www.oeko.de

Table of Contents

List of Figures

List of Tables

Abbreviations

BATRRT	Best available treatment, recovery and recycling techniques
C	Concentration
CAS number	A CAS Registry Number, also referred to as CASRN or CAS Number, is a unique numerical identifier assigned by Chemical Abstracts Service (CAS) to every chemical substance described in the open scientific literature
CdSe	Cadmium Selenide
ChemSec	The International Chemical Secretariat
CLP	Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (REACH)
CMR	CMR substances are substances that are that are classified as carcinogenic, mutagenic or toxic for reproduction
CoRAP	Community Rolling Action Plan
CVD	Chemical Vapour Deposition
DNEL	Derived No Effect Levels
DWDM	Dense Wavelength Division Multiplexing
EC number	The European Community number (EC Number) is a unique seven-digit identifier that was assigned to substances for regulatory purposes within the European Union by the European Commission.
ECHA	European Chemical Agency
EEE	Electrical and electronic equipment
EWC	European Waste Catalogue
GaAs	Gallium Arsenide
HBT	Heterostructure Bipolar Transistors
HEMT	High Electron Mobility Transistors
IARC	International Agency for Research on Cancer
IMAT	Working group on Innovative Materials for Sustainable High-Tech Electronics, Photonics and Related Industries
InP	Indium Phosphide
IR	Infrared
ITO	Indium Tin Oxide
LCD	Liquid Crystal Display
LED	Light Emitting Diodes
LiDAR	Light Detection and Ranging
MMTA	Minor Metals Trade Association

MSDS	Material safety data sheet
n.d.	Not defined
OEL	Occupational Exposure Limit
OLED	Organic Light-Emitting Diode
PWB	printed wiring boards (also known as printed circuit boards)
PBT	PBT substances are substances that are Persistent, Bioaccumulative and Toxic
vPvB	vPvB substances are substances that are very Persistent and very Bio-accumulative (vPvB).
QD	quantum dots
RE	repeated exposure
REACH	Regulation (EU) No 1907/2006 on the Registration, Evaluation, Authorisation and restriction of Chemical substances
STOT	Specific target organ toxicity
Tb	Terabyte

1 CONTEXT and SCOPE of the DOSSIER / substance assessment

The substance assessment of indium phosphide is being performed as part of the "*Study on the review of the list of restricted substances and to assess a new exemption request under RoHS 2 – Pack 15*". With contract No. 07.0201/2017/772070/ENV.B.3 implementing Framework Contract No. ENV.A.2/FRA/2015/0008, a consortium led by Oeko-Institut for Applied Ecology, has been assigned by DG Environment of the European Commission to provide technical and scientific support for the review of the list of restricted substances and to assess a new exemption request under RoHS 2. This study includes an assessment of seven substances / group of substances[1] with a view to the review and amendment of the RoHS Annex II list of restricted substances. The seven substances have been pre-determined by the Commission for this task. The detailed assessment is being carried out for each of the seven substances in line with a uniform methodology which was developed as a part of this study[2].

In the course of the substance assessment, two stakeholder consultations were held to collect information and data for the seven substances under assessment. The first one was held from 20th April 2018 to 15th June 2018. The second one was held from 26th September to 7th November 2019 to provide specific data as to aspects on which data gaps still exist as well as to comment on the general interpretations made as to the current base of knowledge. Records of the consultations, including draft dossiers and stakeholder contributions, can be found at the Oeko-Institut's project webpage at: http://rohs.exemptions.oeko.info/index.php?id=289.

For indium phosphide, the 1st stakeholder consultation yielded a total of 16 contributions by different stakeholders. An overview of the contributions submitted during this consultation is provided in Appendix I. The contributions can be viewed at http://rohs.exemptions.oeko.info/index.php?id=292.

The 12 different stakeholder contributions[3] received during the 2nd stakeholder consultation, which was held from 26th September to 7th November 2019 generally expressed their agreement to the recommendation for not proposing InP for a restriction under RoHS. The contributions can be viewed at http://rohs.exemptions.oeko.info/index.php?id=334.

Several stakeholders provided information on volumes of InP that are expected to be placed on the market through the various applications in the future as well as an outlook on future quantum dot technologies. Therefore, various section of the dossier at hand have been adapted from the previous version 2. In particular, section 2.3 on the quantities and section 6 where several references were included concerning exposure data with having implications on section 7, the risk evaluation, and 9, the socio-economic analysis. Slight changes were also undertaken in 5.3 on recycling practices and 8.1 on alternatives. The input finally led to a slightly modified Rationale in the sense of neither proposing the substance for restriction nor for a future revision of this assessment under the same scope.

The present version 3 represents the final version of the RoHS Annex II dossier for Indium phosphide.

---

1 For the sake of better readability hereafter the term substance will be used for single substances as well as for group of substances.

2 This methodology includes a dossier template for substance assessment which had been prepared by the Austrian Umweltbundesamt GmbH in the course of a previous study. The methodology for substance assessment has been revised based on various proposals from and discussions with stakeholders. Among others, revisions have been made to clarify when the Article 6(1) criteria are considered to be fulfilled and how the precautionary principle is to be applied. The methodology has also been updated in relation to coherence to REACH and other legislation and publicly available sources of relevance for the collection of information on substances have been updated and added. The methodology is available at https://rohs.exemptions.oeko.info/index.php?id=341

3 Another six stakeholder provided the same report than already contributed by the working group of which they are members.

2 IDENTIFICATION, CLASSIFICATION AND LABELLING, LEGAL STATUS AND USE RESTRICTIONS

2.1 Identification

2.1.1 Name, other identifiers, and composition of the substance

Indium phosphide with its identifiers is summarised in the following table. The information was extracted from the Annex XV report on the proposal for harmonised classification and labelling of indium phosphide from France in 2009[4] and from the ECHA database information on substances.[5]

Table 2-1: Substance identity and composition of indium phosphide

Chemical name	Indium phosphide
EC number	244-959-5
CAS number	22398-80-7
IUPAC name	Indium phosphide indiganylidynephosphane phosphinidyneindium
Index number in Annex VI of the CLP Regulation	015-200-00-3
Molecular formula	InP
Molecular weight (range)	145.8 g/mol
Synonyms	See IUPAC names
Structural formula	In≡P
Degree of purity	No data
Remarks	-

Source: Annex XV report on the proposal for harmonised classification and labelling of indium phosphide from France (2009); ECHA information on chemicals database; https://echa.europa.eu/

2.1.2 Physico-chemical properties

Physico-chemical properties of indium phosphide are summarised in the table below and were extracted from the Annex XV report on the proposal for harmonised classification and labelling of indium phosphide from France in 2009.[6]

4 France (2009): Annex XV Dossier - Indium phosphide – CAS 22398-80-7; https://echa.europa.eu/documents/10162/7564f5ed-a09c-41a0-b8ee-7aebf4287c99; last viewed 25.05.2018

5 ECHA Information on Chemicals Database: Entry for indium phosphide (2018); https://echa.europa.eu/substance-information/-/substanceinfo/100.040.856, last viewed 25.05.2018

6 Op. cit. France (2009)

Table 2-2: Overview of physico-chemical properties of indium phosphide

Property	Value
Physical state at 20°C and 101.3 kPa	Black brittle crystals with metallic appearance
Melting/freezing point	1062°C
Boiling point	No data
Vapour pressure	No data
Water solubility	Insoluble in water (no value available). Slightly soluble in mineral acids.
Partition coefficient n-octanol/ water (log POW)	No data
Dissociation constant	No data
Vapour density relative to air	No data
Specific gravity	No data

Source: Annex XV report on the proposal for harmonised classification and labelling of indium phosphide from France (2009)

2.2 Classification and labelling status

Regulation (EC) No 1272/2008 on Classification, Labelling and Packaging (CLP)[7] ensures that the hazards presented by chemicals are clearly communicated to workers and consumers in the European Union through classification and labelling of chemicals. Annex VI of Regulation No 1272/2008 lists substances where a harmonised classification exists based on e.g. human health concerns.

Annex VI of the CLP regulation is constantly adapted by engagement of Member State Competent Authorities and ECHA where new information becomes available, where existing data are re-evaluated or due to new scientific or technical developments or changes in the classification criteria.[8]

For an explanation on the human and environmental hazards, see section 4 and 5.

2.2.1 Classification in Annex VI Regulation No 1272/2008

A harmonised classification according to Annex VI Regulation No 1272/2008 is available for indium phosphide, the classification according to Table 3.1 of Annex VI is presented in the following table. For indium phosphide, there is a harmonised classification and labelling for carcinogenicity Category 1B (H350: May cause cancer), reproductive toxicity Category 2 (H361f: Suspected of damaging fertility) and for specific target organ toxicity (repeated exposure) Category 1 (H372: Causes damage to organs through prolonged or repeated exposure. Indium phosphide induces severe effects in lungs).

[7] Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (REACH).

[8] For further information, see https://echa.europa.eu/regulations/clp/harmonised-classification-and-labelling, last viewed 19.04.2018

Table 2-3: Classification according to part 3 of Annex VI, Table 3.1 (list of harmonised classification and labelling of hazardous substances) of Regulation (EC) No 1272/2008 for indium phosphide

Index No.	International Chemical ID	EC No.	CAS No.	Classification		Labelling			Spec. Conc. Limits, M-factors
				Hazard Class and Category Code(s)	Hazard statement code(s)	Pictogram, Signal Word Code(s)	Hazard statement code(s)	Suppl. Hazard statement code(s)	
015-200-00-3	indium phosphide	244-959-5	22398-80-7	Carc. 1B Repr. 2 STOT RE 1	H350 H361f H372 (lungs)	GHS08 Dgr	H350 H361f H372 (lungs)	-	Carc. 1B; H350: C ≥ 0.01% STOT RE 1; : C ≥ 0.1% STOT RE 2; H373: 0.01% ≤ C < 0.1%

Source: Annex VI Regulation No 1272/2008; https://echa.europa.eu/de/information-on-chemicals/annex-vi-to-clp, last viewed 19.04.2018

2.2.2 Self-classification(s)

Manufacturers, importers or downstream users have to (self-)classify and label hazardous substances and mixtures to ensure a high level of protection of human health and the environment. If a harmonised classification is available, it should be applied by all manufacturers, importers or downstream users of such substances and of mixtures containing such substances.

However, suppliers decide usually independently as to the classification of a substance or mixture, which is then referred to as self-classification. Therefore, self-classification might indicate an e.g. additional hazard, which is so far not reflected by the harmonised classification. The following assessment of the self-classification therefore only refers to cases where additional hazards were notified in the self-classification.

The ECHA database Classification and Labelling (C&L) inventory contains classification and labelling information on notified and registered substances received from manufacturers and importers. With regard to indium phosphide, there is a total number of 62 companies notifying self-classifications (so called notifiers) (as of May 2018).[9] Most notifications (60 notifiers) specify the harmonised classification of Carc. 1B (H350), STOT RE 1 (H372 (lungs)) and Repr. 2 (H361(f)). Two notifiers have a deviant classification specifying only H351 (Suspected of causing cancer).

To summarise, the various self-classifications address the same types of hazards as the harmonised classification. In some cases, the level of hazard may differ, or certain hazard types have been omitted. Given that the harmonised classification is assumed to have a higher scrutiny, the differences in the self-classification compared to the harmonised classification are not further considered.

9 ECHA CL Inventory: Entry for indium phosphide (2018); https://echa.europa.eu/de/information-on-chemicals/cl-inventory-database/-/discli/details/117665, last viewed 25.05.2018

2.3 Legal status and use restrictions

2.3.1 Regulation of the substance under REACH

Indium phosphide is not regulated under REACH.

Because of being classified as carcinogen category 1B, the restrictions for substances under entry 28 of REACH Annex XVII apply for indium phosphide and prohibit the supply to the general public as a substance, as mixtures or as a constituent of other mixtures. It is noted that use of the substance in EEE would generally not be considered as a supply of the substance to the general public (neither as a substance, as a mixture or as a constituent thereof).

2.3.2 Other legislative measures

Indium is listed on the 2017 list of Critical Raw Materials for the EU (COM(2017) 490 final).[10] Materials appearing on this list have been identified as critical for the EU because possible risks of supply shortage (scarcity) and their impacts on the economy are higher than those of most of the other raw materials. Additional aspects (e.g. environmental, social) are not mentioned in the communication.

2.3.3 Non-governmental initiatives

The International Chemical secretariat (ChemSec) has developed and updates the SIN List, which identifies potential substances of concern. The list is a way for putting pressure on legislators to assess and, where, relevant address substances identified therein in the future in respect to relevant chemical legislation.[11] There are a number of categories for adding substances to the SIN List, including substances that can cause cancer, alter DNA or damage reproductive systems (CMR properties); substances that do not easily break down and accumulate in the food chain (PBT/vPvB substances); and substances of equivalent concern that give rise to an equivalent level of concern in terms of potential damage to health and environment (such as substances with endocrine disrupting properties).

Indium phosphide is listed in the SIN List because it is "*classified CMR according to Annex VI of Regulation 1272/2008*."[12]

[10] EU COM (2017), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU, Brussels, 13.9.2017, COM(2017) 490 final, available under: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2017:0490:FIN, last viewed 19.04.2018, last viewed 19.04.2018

[11] SIN List (2020a) What is the SIN List? https://sinlist.chemsec.org/what-is-the-sin-list/ , last viewed 26.02.2020

[12] SIN List (2020b) Entry for Indium Phosphide to finde under https://sinsearch.chemsec.org/chemical/22398-80-7, last viewed 26.02.2020

3 USE IN ELECTRICAL AND ELECTRONIC EQUIPMENT

Indium phosphide is employed in a wide variety of devices, products, and applications. Due to its semiconductor and photovoltaic properties, indium phosphide is used in a wide array of applications in optoelectronic devices, displays, high-speed electronics and photovoltaics. Typical applications of InP include e.g.:[13]

- Lasers, photo detectors and modulators used for global telecommunication networks;
- Spectroscopic analysers and LiDAR (Light Detection And Ranging) applications;
- High Electron Mobility Transistors (HEMT) and Heterostructure Bipolar Transistors (HBT) for high-speed electronic devices;
- Semiconductor quantum dots (QD) as a colour converting component of liquid crystal display backlit devices;
- Substrate for photovoltaic cells.

3.1 Function of the substance

As compared to other semiconductor materials such as silicon and gallium arsenide (GaAs), indium phosphide is generally characterised by superior electrical and thermal properties, higher electron mobility, higher frequency as well as higher thermal conductivity.

In optoelectronic appliances, InP-based active material produces light emission, detection, or modulation at wavelengths compatible with low dispersion or low loss in optical fibres, which enables much higher data rates (for a given distance) or much longer distances (for the same data rate) than can be achieved with other materials, like e.g. GaAs. Consequentially, the wafers have low power consumption and a low noise performance.[14]

With these functionalities, indium phosphide is considered to be the enabling semiconductor material for high power and/or high frequency performance electronic components and for various functionalities of optoelectronic devices. In these devices InP, as the gain medium[15] of generating infrared light, is responsible for the emission wavelength of laser chips and the detection wavelength of the photo-diodes at 1.30 µm or 1.50 µm ranges. The wavelength windows are determined by the minimum absorption windows of silica which is the key material of optical fibres used in telecommunications networks.[16] [17]

[13] References are included in sections 2.1 and 2.2

[14] T&M Coalition (2018), Contribution of Test / Measurement Coalition submitted on 15.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_TMC_7_Substances_response_20180615_fin.pdf, last viewed 20.12.2018

[15] A gain medium is a medium which can amplify the power of light (typically in the form of a light beam), which is needed in a laser in order to compensate for the resonator losses.

[16] Coherent (2018), Contribution of Coherent submitted on 12.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_Coherent_Indium_phosphide_Stakeholder_Response_20180612.pdf, last viewed 20.12.2018;

[17] 3SPT (2018), Contribution of 3SPT submitted during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_3SPT_Technologies_InP_1st_Stakeholder_Consultation_InP_3SPT_Participation.pdf, last viewed 20.12.2018

In the context of the RoHS directive, indium phosphide has been in the focus of discussions related to the application of quantum dot technologies in displays and in lighting. InP has been mentioned as a possible alternative for cadmium selenide in display lighting and in solid state lighting applications.[18] From past evaluations related to this application, it is further understood that the use of InP in quantum dot technologies in such products has increased.[19] In such applications, indium phosphide is used to enhance the colour gamut.[20]

3.2 Types of applications / types of materials

Basically, the application fields of indium phosphide can be classified into the following types of applications:

- Optoelectronics;
- High-speed electronics;
- Displays and lighting;
- Photovoltaic applications.

In the following these different types of applications will be briefly presented.

Optoelectronics

In optoelectronic devices indium phosphide is contained in lasers, photo detectors and modulators in the wavelength window (1550 nm) typically used for global **telecommunication networks**.[21]

These networks are operated at infrared (IR) wavelengths on the basis of dense wavelength division multiplexing (DWDM). Within this context, the properties of optical fibres are considered to be ideal for long-distance transmission with minimal loss and dispersion. The data rate of DWDM networks is in the order of terabytes/sec (Tb/s). The distance between the links may exceed 1000 km. Consequently, DWDM networks are employed world-wide for subsea and terrestrial communications

18 Further information is available in the evaluation report of RoHS exemption requests 2013-2 and 2013-5, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/20140422_RoHS2_Evaluation_Ex_Requests_2013-1-5_final.pdf, last viewed 19.04.2018

19 Oeko-Institut (2016), Assistance to the Commission on Technological Socio-Economic and Cost-Benefit Assessment Related to Exemptions from the Substance Restrictions in Electrical and Electronic Equipment: Pack 10 Final Report, prepared for the European Commission, DG Environment, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/reports/20160602_Final_Report_RoHS_Pack_10_Cd_QDs_amended.pdf, last viewed 19.04.2018

20 ANIE (2018), Contribution of ANIE submitted on 15.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_ANIE_Federation_Indium_phosphide_20180615.pdf, last viewed 20.12.2018

21 IMAT (2018), Contribution of IMAT submitted on 15.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_IMAT_InP_RoHS_Consultation_20180615.pdf, last viewed 20.12.2018

networks.[22] In order to achieve the lowest attenuation available on optical fibre (about 0.26 dB/km), the light signals require a wavelength between 1510 nm and 1600 nm.[23]

Minor Metals Trade Association (MMTA) points out that telecommunication as well as data-communication systems based on InP outperform conventional systems (e.g. based on copper) in terms of energy efficiency by "several orders of magnitude".[24]

According to IMAT,[25] concrete applications in the field of tele- and data-communication are:[26]

- Long-haul optical fibre connections over great distances up to 5000 km typically >1.25 Tb/s;
- Metro ring access networks;
- Company networks and data centre;
- Fibre optical network terminals at house connection points (so called last mile);
- Connections to wireless 3G, LTE and 5G base stations;
- Free space satellite communication.

Besides in tele- and data-communication, lasers with InP technology are also used for **sensing applications**. These refer to spectroscopic applications, where a specific wavelength is needed to interact with matter to detect certain objects, e.g. highly diluted gases. Furthermore, InP lasers are considered to be eye safe, since their radiation is absorbed in the vitreous body of the human eye and therefore cannot harm the retina. Taking this into account, another important sensing application based on InP lasers is considered to be in the field of LiDAR (Light Detection and Ranging) that may serve as the technological basis for future mobility functionalities (autonomous driving) and the automation industry.[27]

In summary, relevant examples for sensing applications are.[28]

- Gas spectroscopy for drive test equipment with real-time measurement of CO, CO_2 and NO_x;
- Stand-Off detection of traces of explosive substances on surfaces, e.g. for safety applications in airports;

---

22 Infinera (2018): Contribution of Infinera submitted on 11.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_Infinera_InP_Questionnaire_submission_with_cover_letter_20180615.pdf, last viewed 15.07.2018

23 Op. cit. IMAT (2018)

24 MMTA (2018), Contribution of MMTA submitted on 15.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_MMTA_InP_1st_Stakeholder_Consultation_Response_vf_20180615.pdf, last viewed 20.12.2018

25 IMAT's contribution was prepared by its Working Group on Innovative Materials for Sustainable High-Tech Electronics, Photonics and Related Industries. Several stakeholder participating in the consultation, e.g. UnitedMonolithic Semiconductors GmbH (UMS), VISHAY, AZURSpace Solar Power GmbH, Spectaris,Freiberger Compound Materials GmbH (FCM) and Fraunhofer HHI, are members of IMAT. In their individual contributions, these companies expressed their support for the comments submitted.

26 Op. cit. IMAT (2018)

27 Op. cit. MMTA (2018); Op. cit. IMAT (2018)

28 Op. cit. MMTA (2018); Op. cit. IMAT (2018).

- Quick verification of traces of toxic substances in gases and liquids (including tap water) or surface contaminations with analysis capabilities at the ppb level;
- Thickness measurements of polymers;
- Spectroscopy for non-destructive product control of e.g. food (early detection of spoiled foodstuff); as well as
- LiDAR applications for autonomous driving and the automation industry.

In addition to this, MMTA considers the application of InP in professional monitoring and control equipment to be critical for the continued development, qualification and manufacture of both current and next generation communications optical/photonic fibre network applications.[29]

High-speed electronics

Devices containing InP are also used to realise high-speed microelectronics. In particular, this refers to High Electron Mobility Transistors (HEMT) or Heterostructure Bipolar Transistors (HBT), which are assembled into circuits and modules for – among others – the following applications:[30]

- Robotics: Robotic vision is essentially based on high resolution imaging radar systems at millimetre-waves;
- Radiometric sensing: Almost all air constituents 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;
- 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.

Displays and lighting

In the display industry, indium phosphide is currently applied as a possible technology for colour converting components of liquid crystal display (LCD) backlit devices, including televisions and monitors. This technology utilises semiconductor quantum dots (QD) as a colour converting material. Nanoco Technologies considers InP QDs to be a safer alternative to Cd-based (e.g. CdSe) QDs, which were the first QDs that reached the market. This assessment is substantiated by pointing out that “InP QDs are typically over-coated with one or more ‘shell’ layers of another semiconductor material, such as ZnS, then integrated into a resin matrix to form a film”.[31]

Besides display applications, Nanoco anticipates that the use of QDs in specialised LED lighting products will increase in the next few years.[32]

---

29 Op. cit. MMTA (2018)

30 Op. cit. IMAT (2018)

31 Nanoco (2018), Contribution of Nanoco submitted on 15.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_Nanoco_InP_Consultation_20180615.pdf, last viewed 20.12.2018

32 Nanoco (2019). Contribution of Nanoco submitted during the stakeholder consultation conducted from 26 Sept 2019 to 7 Nov 2019 by Oeko-Institut in the course 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), see the link in the annex

Photovoltaic applications

As described by IMAT, indium phosphide is also used in ultra-high performance photovoltaic cells. Modules with efficiencies of up to 46% contain InP substrates in order to achieve an optimal bandgap combination for the conversion of solar radiation into electrical energy. Also, concentrator photovoltaics (CPV) that feature lenses and curved mirrors to focus sunlight onto small, but highly efficient, multi-junction solar cells as well as solar cells for space applications use (Ga)InP and other III-V compound semiconductors[33] to achieve the required bandgap combinations. 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.[34]

Based on a short literature review, the consultants assume that InP-based photovoltaic application are still in the research and development stage and have yet not reached the mass market, mainly due to cost restrictions.[35]

3.3 Quantities of the substance used

In this section, the quantities of Indium phosphide that are used in the application fields mentioned above are provided as far as available.

3.3.1 Wafers for optoelectronics and high-speed electronics

For the 1st stakeholder consultation, MMTA compiled an overview of the applications and quantities placed on the EU/EEA[36] market. The following figures were given for the annual EU/EEA consumption specified according to different application fields:[37]

- Photonic applications:
  - Fibre-optic networks, wireless base stations and satellite communications: **9-10 kg**
  - Other laser and sensor applications, LiDAR autonomous driving, vehicle emissions testing, spectroscopy analysis for food, chemical analysis: **6 kg**
- Electronic semiconductor applications:
  High speed (Terahertz) Hetero-junction Bipolar Transistors in measurement analysers and non-military radio frequency communications: **8 kg**

Based on these figures, MMTA estimates a total annual EU/EEA consumption of approximately **24 kg** of InP contained in the application clusters mentioned above. With the assumption that the EU/EEA market represents between 20-25% of the global market, a global consumption of between 96 and 120 kg per year is calculated accordingly.[38] In the second stakeholder consultation, Lumentum stated that it concurs with these numbers regarding the InP use in optical

33 III-V compound semiconductors are obtained by combining group III (Boron group) elements (essentially Al, Ga, In) with group V (Nitrogen group) elements (essentially N, P, As, Sb).

34 Op. cit. IMAT (2018)

35 https://photovoltaiksolarstrom.com/photovoltaiklexikon/indiumphosphid/ last viewed 26.02.2020

36 As opposed to the EU market, the EEA (European Economic Area) includes the EU28 as well as Iceland, Liechtenstein and Norway. Since the quantities used in the latter counties are relatively small, the volume difference between EU28 and EEA is understood to be negligible.

37 Op. cit. MMTA (2018)

38 Op. cit. MMTA (2018)

communication.[39] Regarding spectroscopy analysis, Lynred indicated that "*In one year, the total mass of InP processed at Lynred is less than 2,5 kg and less than 150 g can finally be found in final products*".[40]

Additionally, MMTA points out that the amounts of InP used in military applications in laser guidance systems and THz HBT transistor semiconductors in communications and decision-making applications are considered to be far greater than uses in EEE products.[41]

Due to the lack of data from independent market research institutes or from associations related to indium phosphide (InP) the Fraunhofer Heinrich-Hertz-Institute[42] conducted a survey among all supplying manufacturers. Since nearly all manufacturers responding to the survey supplied confidential figures as to their own sales, IMAT considers the total figure of 75,000 Wafers to be a robust upper limit of the InP use at the global scale. Furthermore, IMAT estimates that 75,000 InP wafers with a 2" size equal to a total mass of 268 kg. This amount will be reduced by the process step of thinning, which is a required process to produce the individual components in a very small size. According to IMAT, in a typical product, the thickness of a wafer is reduced from ca. 375 µm to 50 – 300 µm. Moreover, the yield of marketable devices is considered to be in the dimension of less than 80%. Concerning EEE, this would result in an estimated amount of max. 134 kg of InP inside products that will come on to the global market per year. Since the share of the European market is estimated to be 25%, IMAT calculates an amount based on information provided by its members of less than **33 kg** of InP material in products in Europe. Concerning the breakdown in terms of application fields, IMAT assumes the largest portion of the total amount to go into industrial or infrastructure (telecom) applications with hardly anything reaching the consumer market.[43]

According to these numbers, currently, the opto- and high-speed electronic industry consumes ~ 24 to 33 kg InP in Europe annually.

3.3.2 Displays and lighting

Besides wafers, the use of InP in QDs for displays is currently considered to be one of the largest areas of use for this material in the EU.

Figures for the amount of InP used in this application filed is provided by Nanoco citing an IHS market research report,[44] that predicts 11.6 million Cd-free displays to be sold in 2018, resulting in sales of 10.9 million m^2 of display area of QD displays. Based on an analysis carried out by Nanoco concerning commercially available InP-based display products, the amount of InP per m^2 of display area is estimated to be up to 0.03 g. Assuming that worldwide 100% of all sold QD displays were based on InP technology, approximately 0.3 tonnes of InP would be required per year for this application. According to forecasts for 2018 that predict around 20% of global 4K TV sales to be in Europe, Nanoco estimates a total of around **60 kg** per year for Europe.[45]

---

39 Lumentum (2019). Contribution of Lumentum submitted during the stakeholder consultation conducted from 26 Sept 2019 to 7 Nov 2019 by Oeko-Institut in the course 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); see the link in the annex

40 Lynred (2019). Contribution of Lynred submitted during the stakeholder consultation conducted from 26 Sept 2019 to 7 Nov 2019 by Oeko-Institut in the course 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); see the link in the annex

41 Op. cit. MMTA (2018)

42 Refered to in. IMAT (2018) as non-public. The Fraunhofer Heinrich-Hertz-Institute is member of the Working Group IMAT that submitted the contribution.

43 Op. cit. IMAT (2018)

44 IHS Wide Color Gamut & Quantum Dot Display Market Tracker – H1 2017, https://technology.ihs.com/api/binary/578908?attachment=true last viewed 26.02.2020

45 Op. cit. Nanoco (2018)

Concerning future requirements, Nanoco assumes that the InP QD technology will become more mature and applicable to different display formats (e.g. mobile phones, etc.). Against this background, the number of sold display units employing this technology is said to increase (with 23.7 million units in 2021, which roughly means a doubling within only three years). Based on this estimation, the consultant assumed in the interim report, published for commenting in the 2nd stakeholder consultation, that:

1. The current growth rate of InP QD technology with a doubling of sold units every three years will continue over the next 10 years;
2. As further assumption, the specific amount of InP required per display will not decrease;
3. This resulted in approx. **600 kg** (= 60 kg * $2^{10/3}$) of InP used in display applications per year **in Europe in 2028.**

With the technology becoming more mature, Nanoco further expects the specific material demand to decrease in the long-term: Micro-LED technology, for example, which applies QDs "on-chip", could potentially reduce the amount of QDs required per display by an order of magnitude. Overall, the assessments by Nanoco come to the conclusion that material usage of InP in QD display applications will increase in the short-term (3-5 years), but then decrease thereafter.[46] In the 2nd stakeholder consultation, Nanoco indicates that the firm finds the ~600 kg/annum in 2028 "a fair estimate" for InP QD use "on-layer". Nanosys forecasts EU InP volumes will peak at approximately **190 kilograms/annum in 2027** and shall begin to decline rapidly from there, as new, ultra-efficient, quantum dot technologies are commercialised.

The use of QDs in specialised LED lighting products is expected to increase in the next few years.[47] Besides this qualitative statement by Nanoco, however, at the time of publishing of the interim report, no data was available that estimate future volumes for such applications. Therefore, the consultant assumed the following: The market share of Cd-based QDs in lighting applications which was estimated to be 5% in 2015 and causes a CdSe consumption of 8 kg, was taken as a starting point. As a further assumption, the specific amount of InP was assumed double the amount of CdSe. By 2028, the market share for Cd-based QDs in all lighting applications is estimated to reach 80 %. Subsequently, for InP this would result in approx. **265 kg** (=8 kg * 2 * 80/5) of InP used in lighting applications per year in Europe. For these market estimations, there are at least four contributions to the 2nd stakeholder consultation (Fraunhofer IAP, OSRAM, Nanoco, Nanosys) that explain why the assumption is an overestimation and that the amounts for lighting will be much lower. Contributions by Nanoco, Nanosys and OSRAM forecast the lighting market to consume very little to zero InP in the EU over the next five to ten years due to the low InP content of lighting products that are likely to be commercialised. No further quantitative data was contributed. The consultants assume that these forecasts are more representative, seeing as the contributors are acquainted with the current status of InP QD applications and its expected future developments.

In the 2nd consultation, stakeholders were asked to provide estimations to the development of the distribution of different display configurations ("on-layer", "on-edge" and "on-chip"). Nanosys reported the "on-edge" to have been discontinued and expect the "on-chip" configuration to never be commercialised using InP QD. Also, Nanoco believes that "on-chip" technologies would be unlikely to be adopted for displays in the near future. Thus, the current and future configuration according to Nanosys is and will be "on-layer"/ "on-surface".

[46] Op. cit. Nanoco (2018)

[47] Op. cit. Nanoco (2018)

To this, Nanoco and Nanosys add that new technologies can be expected: QD-OLED and QD-µLED that would have a similar configuration to "on-chip" applications with little differences (lower light density requirements and "*far higher volume of QDs will be used for colour conversion per display*"). As the QD-OLED and QD-µLED market grow, the share of "on-layer" QD displays may decrease.[48] [49] OSRAM supports "*that "on-chip" QD-LED are suitable and acceptable for the market from our current point of view. This is due to disadvantages regarding energy and material efficiency, costs and design obstacles of "on layer" and "on edge" configurations*." According to Fraunhofer IAP, QD-OLEDs will first be ready for market from around 2021. Others are QDEF and QDEL (quantum dot Electroluminescent).[50] Nanosys sees QD-OLEDs as a bridge technology in the premium segment until QDEL would be fully commercialised. Fraunhofer IAP indicates that the commercialisation of QD-OLED and QDEL displays will strongly depend on the level of technology developments of InP-based QDs, since there are still several challenges remaining for those technologies.[51]

In its contribution, Nanoco makes a forecast for projected figures for QD-OLED/QD-µLED screens sold with corresponding QD masses used up to 2028 and thereof derives numbers for InP used in 2028: The figure of 2 tonnes was found to be a maximum amount estimate, assuming that all QD-OLED and QD-µLED displays on the EU market between 2019 – 2028 utilise InP-based QDs. However, a figure of **1.3 tonnes in 2028** may be a more realistic maximum amount estimate, again assuming that all QD-OLED and QD-µLED displays on the EU market utilise InP-based QDs. The consumption of InP would decrease if such displays did not consist only of InP-based QD but also of other types.[52] The assumption of all QD-OLED and QD-µLED displays using InP-based QDs is challenged by a statement of Nanosys[53] which forecast CdSe-based quantum dots to continue to maintain approximately 35% market share worldwide for QDEF applications.

Nanoco[54] predicts the specific amount of InP needed for lighting compared to CdSe to be lower if the industry swaps to InP-based materials. This is due to the possibility of lower material usage in the "on-chip" technology, Nanoco believes that even with an increased market share, the overall amount of QDs used in lighting applications would decrease.

3.3.3 Photovoltaic applications

Three contributions to the 2nd stakeholder consultation provided appraisals on the quantity of InP used in photovoltaic applications all attributing only little to no relevance to InP use in photovoltaic applications.[55] [56] However, no further attention will be given to these contributions as PV is not covered by the scope of the RoHS directive at the time of writing this report.

---

48 It is clear from the contributions of several stakeholders that the share of these technologies in which QD are applied shall increase on the market, However, how divided is the market between different types of QD (CeSe, InP, other …) is uncertain at present.

49 Op. cit. Nanoco (2019)

50 Nanosys (2019). Contribution of Nanosys submitted during the stakeholder consultation conducted from 26 Sept 2019 to 7 Nov 2019 by Oeko-Institut in the course 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), see the link in the annex

51 As cited by Fraunhofer IAP (2019): Donghyo Hahm, Donghyun Ko, Byeong Guk Jeong, Sohee Jeong, Jaehoon Lim, Wan Ki Bae, Changhee Lee & Kookheon Char (2019) Environmentally benign nanocrystals: challenges and future directions, Journal of Information Display, 20:2, 61-72

52 Op. cit. Nanoco (2019)

53 Op. cit. Nanosys (2019)

54 Op. cit. Nanoco (2019)

55 Op. cit. Nanosys (2019), op. cit. Lumentum (2019)

56 IMAT (2019), Contribution of six members of IMAT e.V (Fraunhofer HHI; UnitedMonolithic Semi-conductors GmbH (UMS); Vishay Semiconductor GmbH; AZURSpace Solar Power GmbH; Freiberger Compound Materials GmbH (FCM); Spectaris) submitted during the stakeholder consultation conducted from 26 Sept 2019 to 7 Nov 2019 by Oeko-Institut

3.3.4 Conclusion on InP quantities in total

The **total amount** of InP, entering the **European market** as a constituent of various EEE applications, is currently estimated to be **below 100 kg p.a.** For the further assessment within this report, an amount of 100 kg InP per annum in the EU is taken as a basis.

In general, from the four application areas, the quantum dots seem to be the application of InP with the most relevance for the next ten years while IMAT expect the consumption of InP in optoelectronics and in highspeed electronics "only" to double or to triple. InP applications in PV seem to be of nearly no relevance (though also not in scope of the RoHS Directive). In light of the expected developments in InP QD technologies, the consumption of InP could increase in the future. Data reported to the consultant within the 2nd Stakeholder Consultation ranges from below 200 kg p.a. to up to 2,000 kg p.a. An average of the range represented by the reported data, would account for **1100 kg p.a. in 2028.**

3.4 Potential for impacts of the substance on the environment and on health during the use of EEE

Concerning potential impacts on the environment and on human health during the use of InP applications, almost no information was provided by stakeholders.

However, MMTA points out that the InP applied in optical communication devices is being managed by professional users in large facilities, e.g. data-centres. Therefore, MMTA considers any risks during use to be managed proficiently. MMTA is confident that only negligible amounts would come into contact with consumers. If glass fibre in residential applications would become more widespread, domestic premises might contain miniscule amounts (approximately 1 mg) of InP, but the telecommunications box would remain the property of the provider and would, therefore, be managed by them.[57] Lumentum supports MMTA's contribution.[58]

In the case of displays and lighting applications, the consumption takes place not only at the level of professional users, but also private end users. In the view of the consultant, this opens up potential impacts on a large number of consumers.

Concerning the possibility of InP emissions during the use phase of EEE, no information has been provided by stakeholders. However, since InP is not considered to be volatile it can be assumed that hardly any emission occurs due to intended use. Furthermore, InP is usually encapsulated in wafers and quantum dot substrate. Under these circumstances, the potential for emissions during the intended use of EEE appears to be negligible.

On the other hand, based on past evaluation of exemptions related to QD technologies, it can be understood that potential emissions can be expected during fire.

in the course 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); see the link in the annex

57 Op. cit. MMTA (2018)

58 Op. cit. Lumentum (2019)

4 HUMAN HEALTH HAZARD PROFILE

The human health hazard of indium phosphide has been reviewed for the purpose of the harmonised classification. In the following the main results from the Annex XV dossier proposing the harmonised classification for indium phosphide prepared by France in 2009[59] are briefly summarised.

4.1 Critical endpoints

The substance has CMR properties as follows:[60]

Carcinogenicity: In the dossier, two cohort studies in the semiconductor industry are described: One study reports an excess of risk of melanoma and rectum cancer whereas the other study reports a significant excess of lung cancer in women and non-significant excess of stomach and breast cancer in women. Due to the limited size of the two cohorts, the limited information on exposure history and co-exposures and the lack of consistency of results between the two cohorts, it is not possible to draw a conclusion on the carcinogenic effect of indium phosphide in humans.

In animal studies, tumours of lungs, adrenal gland and other less significant tumours are induced by indium phosphide in mice, rats and hamsters. Development of tumours outside lungs after inhalation exposure suggests that the mechanism does not only rely on a local inflammatory and proliferative effect.

France (2009) concluded that indium phosphide may cause cancer, which is in line with the conclusion of the International Agency for Research on Cancer (IARC)[61] that considered indium phosphide as probably carcinogenic to humans (Group 2A) because of inadequate evidence in humans and sufficient evidence in experimental animals.

Reproductive toxicity: In an animal study, a decrease in reproductive organs is observed that was more important than the general decrease of body weight. The study provides evidence that indium phosphide induces toxic effects on the male reproductive system. Interpretation of the study is however limited by the single dose used and the absence of direct assessment of fertility function. Toxicokinetic data shows that indium can accumulate in testes after inhalation and raises a concern on potential accumulation of high concentrations due to chronic exposure. Therefore, indium phosphide was concluded as suspected of damaging fertility.

Besides the CMR properties, acute and repeated toxicity data were also reported in the dossier. The data on **repeated dose toxicity** indicated that indium phosphide causes damage to lungs by prolonged exposure through inhalation: Studies, using inhalation or intratracheal instillation, show that indium phosphide induces severe inflammation in lungs. Particles accumulate in lungs but can also be found in bronchial and mediastinal lymph nodes. Modification of the anti-oxidative potential of the cells by indium phosphide could lead to different lesions and to hyperproliferation. The proportion of the substance which passes into systemic circulation is unknown, but at higher doses, other organs can be reached, such as liver, where necrosis is observed. Severe effects (death, moribund condition and hepatic necrosis) are found in animal studies.

59 Op. cit. France (2009)

60 Op. cit. France (2009)

61 IARC International Agency for Research on Cancer (2006), to be found under http://publications.iarc.fr/104 (last accessed 10.01.2020)

4.2 Existing Guidance values (DNELs, OELs)

The Annex XV dossier does not address DNELs because of not being relevant for this type of dossier. The following occupational exposure limits for indium and indium compounds in workplace air are extracted from the IARC's Monographs on the Evaluation of Carcinogenic Risks to Humans.[62]

Table 4-1: Occupational exposure limits and guidelines for indium and indium compounds

EU country	Concentration (mg/m^3) (as indium)	Interpretation
Belgium; Finland; Netherlands; Spain Sweden	0.1	TWA (Time Weighted Average: threshold limit value based on a 8-hour workday and a 40-hour workweek)
Ireland	0.1	TWA
	0.3	STEL (Short Term Exposure Limit: threshold value based on a 15-minute average)

Source: IARC (2006)

[62] Op. cit. IARC International Agency for Research on Cancer (2006)

5 ENVIRONMENTAL HAZARD PROFILE

There is no environmental hazard assessment available for indium phosphide. The Annex XV dossier (France 2009) did not consider environmental fate properties or hazards, since the dossier was targeted at the identification of indium phosphide as a CMR substance. As indium phosphide is not regulated under REACH, there is no information via ECHA databases available.

Additional desktop research did not reveal substantial information on environmental hazards. The database of the PubChem of the US National Library of Medicine[63] provided the following information on environmental fate: "*Monovalent and bivalent indium compounds tend to disproportionate into the trivalent compounds and indium metal; the trivalent compounds are most stable. Due to the ionic nature of indium salts, volatilization from soil surfaces will not be important.*"

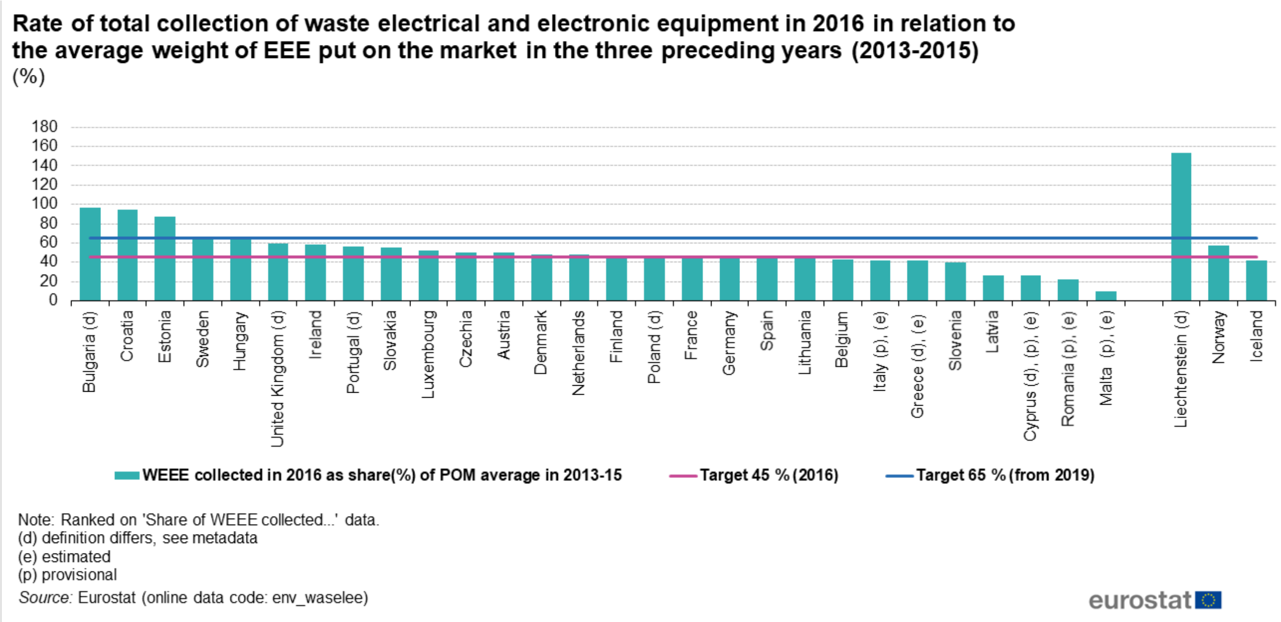
Against the lack of information, further aspects (identification of hazard potential, endpoints of concern, potential for secondary poisoning and bioaccumulation, and guidance values [PNECs]) are omitted in the dossier at hand.

[63] PubChem of the US National Library of Medicine (2020) https://pubchem.ncbi.nlm.nih.gov/compound/Indium-phosphide, last viewed 26.02.2020

6 WASTE MANAGEMENT OF ELECTRICAL AND ELECTRONIC EQUIPMENT

As described above, within the scope of RoHS, indium phosphide is used for various applications in optoelectronics, displays and high-speed electronics. The WEEE Directive requires the separate collection and treatment of all waste EEE falling in scope of the WEEE Directive. However, not all WEEE is collected and the WEEE Directive specific target rates regarding collection only require Member States to achieve a collection rate of 55% from 2016 and of 65% by 2019.[64] Despite these targets, current data suggests that these rates are still not achieved in most Member States; on the contrary, as can be seen in Figure 6-1, in most Member States, the collection rate is considered to be below 50%.

Figure 6-1: Total collection rate for Waste electrical and electronic equipment in 2015 as a percentage of the average weight of EEE put on the market in the three preceding years (%)



Source: Eurostat (2019)[65]

Against this background, two main scenarios have to be assessed - emissions from waste during waste treatment and emissions of waste that is not correctly disposed of. Moreover, in the last case, it also needs to be taken into account that incorrect disposal can occur in the form of municipal waste, but possibly also in the open environment including uncontrolled or diffuse release into the environment of the substance.

6.1 Description of waste streams

Indium phosphide may be contained in the following WEEE categories:

[64] WEEE Directive, Article 7(1) further specifies: "*From 2019, the minimum collection rate to be achieved annually shall be 65% of the average weight of EEE placed on the market in the three preceding years in the Member State concerned, or alternatively 85% of WEEE generated on the territory of that Member State*".

[65] Eurostat (2019) https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment&oldid=445263#EEE_put_on_the_market_and_WEEE_collected_in_the_EU, last viewed 26.02.2020

- Cat. 2. Screens, monitors and equipment containing screens having a surface greater than 100 cm^2, for example televisions, LCD photo frames, monitors, laptops, notebooks;
- Cat. 3. Lamps
- Cat. 4. Large equipment (any external dimension more than 50 cm), for example IT and telecommunication equipment; equipment reproducing sound or images; medical devices; monitoring and control instruments;
- Cat. 5. Small equipment (no external dimension more than 50 cm), for example equipment reproducing sound or images, medical devices; monitoring and control instruments;
- Cat. 6. Small IT and telecommunication equipment, for example mobile phones.

6.2 Applied waste treatment processes

6.2.1 Initial treatment processes applied to the WEEE containing the substance of concern

Table 6-1: Initial treatment processes applied

Initial treatment processes	The substance is present in appliances belonging to:					
	Cat1	Cat2	Cat3	Cat4	Cat5	Cat6
For WEEE collected separately						
Collection and transport		x	x	x	x	x
Dedicated treatment processes for cooling & freezing appliances						
Dedicated treatment processes for screens		x				
Dedicated treatment processes for lamps			x			
Manual dismantling		x		x	x	x
Shredding (and automated sorting)		x	x	x	x	x
For WEEE not collected separately						
Landfilling (of residual waste)		x	x	x	x	x
Mechanical treatment (of residual waste)		x	x	x	x	x
Incineration		x	x	x	x	x
Uncontrolled treatment in third countries		x	x	x	x	x

6.2.2 Treatment processes applied to wastes derived from WEEE containing the substance of concern

Table 6-2: Treatment processes for wastes derived from WEEE

Treatment processes for wastes derived from WEEE treatment	**The substance is present in the following main component/material**								
	Ferrous metals	Non-ferrous metals	Plastics	Electronic components	Cables	Glass	Powders	Fluids	Others
Under current operational conditions in the EU									
Storage of secondary wastes			x	x					
Shredding and automated sorting of secondary wastes			x	x					
Recycling of ferrous metals									
Recycling of NF metals				x					
Recycling of plastics			x						
Recycling of glass									
Recycling as building material									
Landfilling of residues			x	x					
Incineration of residues			x	x					
Co-incineration of residues			(x)	(x)					
Dedicated processes for hazardous residues			x	x					
Under uncontrolled conditions									
Acid leaching									
Grilling/desoldering									
Uncontrolled combustion			x	x					
Uncontrolled dumping of residues			x	x					

6.3 Waste treatment processes relevant for assessment under RoHS

In **optoelectronic and high-speed electronic applications**, most[66] InP based components are located on the populated printed wiring boards (PWB). The standard WEEE recovery process involves disassembling the hardware to where the PWB is separated from the chassis.[67]

66 An exemption may be QD applications besides “on-chip” technology, such as “on layer” and “on edge” configurations.

67 Op. cit. Infinera (2018)

The WEEE Directive and implementing regulations require treatment facilities to safely recycle/dispose of WEEE hazardous wastes. Member States provide further guidance on methods to employ safe WEEE disposal.[68] Since InP components are not specifically identified in this guidance or in waste classifications of the European Waste Catalogue (EWC), Oclaro assumes that these are not removed from WEEE during pre-treatment. As a result, InP chips are expected to remain on PWB or in WEEE residues after pre-treatment.[69]

The PWBs are then shredded to recover precious metals like gold, palladium and platinum and other usable materials. According to the Lumentum company, this material is treated by specialised refiners which may apply different recovery methods:[70]

- Chemical strip of surface metals;
- Smelting to separate precious metals;
- Ball-milling and smelting to separate and recover precious metals.

In order to clarify the InP material stream during waste processing, Lumentum reached out to one of its main refiners in the USA. The inquiry came to the conclusion that the refiner was not measuring the indium content in its mixed materials nor was the refiner aware of any smelter measuring indium content or recovering indium from its material. The reason is, according to Lumentum, the relatively low market price for indium (approx. $0.30 per gram of indium versus approx. $40 per gram of gold).[71] This seems to make the indium a low priority in the eyes of a metal refiner so that specific measurements are not undertaken for the element.

Besides missing economic incentives, IMAT highlights the following reasons for low recycling possibilities of InP from WEEE:[72]

- Minor concentrations in final products;
- No specialised collection system of InP containing WEEE established;
- Lack of appropriate recycling technology;
- Moreover, indium-specific detection and separation is currently not implemented in recycling processes of secondary metal fractions from WEEE.

COCIR[73] further specifies, "*Indium is a very scarce element so that its concentration in WEEE is too low for it to be economically recovered. Most indium in WEEE is available as indium tin oxide (ITO), a transparent electrically conducting coating on displays. The quantity of indium phosphide in WEEE*

---

68 As pointed out by Oclaro Inc., for instance in the UK, the 'Best available treatment, recovery and recycling techniques' (BATRRT) needs to be considered.

69 Oclaro (2018), Contribution of Oclaro submitted on 15.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_Oclaro_Indium_phosphide_CAC_15062018.pdf, last viewed 20.12.2018

70 Lumentum (2018), Contribution of Lumentum submitted on 14.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/1st_Consultation_Contributions/Contribution_1_Lumentum_Indium_phosphide_Questionnaire_1st_Cons_20180615.pdf, last viewed 20.12.2018

71 Op. cit. Lumentum (2018)

72 Op. cit. IMAT (2018)

73 COCIR (2019): Contribution of COCIR submitted during the 2nd stakeholder consultation conducted from 26.09.2019 to 07.11.2019 by Oeko-Institut in the course of the study to support the review of the list of restricted substances under RoHS (Pack 15). See the link in Annex II

will be much less than the amount of ITO so that it has no effect on WEEE processes and is not recoverable."

Display screens containing InP QDs are considered to be collected as consumer equipment (for TVs) or as IT and telecommunications equipment (for monitors). For the plastic components, including the QD film, Nanoco expects them to most likely either be shredded and incinerated, or to be disposed of in landfills.[74]

According to the database of the Toxicology Data Network (ToxNet) of the US National library of medicine, the US EPA stipulates solid waste containing indium phosphide may become characterised as a hazardous waste when subjected to testing for reactivity as stipulated in the Code of Federal Regulations for the identification and listing of hazardous waste (40 CFR 261.23), and if so characterised, must be managed as a hazardous waste.

Contrary to high-speed and opto-electric application, Nanosys believes that InP QDs „*would make an excellent candidate for recycling with sufficient incentives to set-up a recycling program to recycle indium content form QD displays as indium was added to the EU Critical Raw Materials list in 2017*".[75]

For **lighting equipment,** containing InP QDs information on the relevant waste treatment processes was not provided by the stakeholders. The consultant therefore assumes that roughly the same waste treatment approach as for the screens is applicable.

6.4 Releases from (relevant) WEEE treatment processes

During the **shredding process**, particulates are generated. Within this context, Infinera mentions a publication[76] by Oliveira and Margarido, whose measurements have shown the smallest particle size to be at about 0.04 mm (40 µm). Although there are exposure risks at the WEEE processing stage, Infinera assumes that this risk can be adequately managed through engineering controls and proper use of respiratory personal protection equipment. Standard respirators (e.g. N95) with HEPA[77] filters would help to reduce the wearer's inhalation exposure to airborne particulates. These respiratory filters have been tested and certified by NIOSH to be at least 95% efficient when tested against very "small" particles that are the most difficult size to filter (approximately 0.3 µm).[78] Hence, Infinera expects respiratory exposure of InP to be adequately controlled.[79]

Furthermore, Infinera points out that on-site audits conducted by its selected WEEE collection and processing company RENE AG confirm that the health and safety program at each recycler location is properly managed and maintained.[80] Furthermore, none of the particles from PWB shredding are considered to be in the nanoscale (<100 nm) intrinsic to quantum dots that are used in display technology. Since no nanoparticles are generated, Infinera argues that there is understood to be no

---

74 Op. cit. Nanoco (2018)

75 Op. cit. Nanosys (2019)

76 Oliveira, Paula & Taborda, Filipa & Nogueira, Carlos & Margarido, Fernanda. (2012). The Effect of Shredding and Particle Size in Physical and Chemical Processing of Printed Circuit Boards Waste. Materials Science Forum. 730-732. 653-658. 10.4028 to find under www.scientific.net/MSF.730-732.653. last viewed 26.02.2020

77 HEPA is the abbreviation for "High Efficiency Particulate Air"

78 US Food and Drug Administration. Masks and N95 Respirators. To find under https://www.fda.gov/medical-devices/personal-protective-equipment-infection-control/masks-and-n95-respirators last viewed 26.02.2020

79 Op. cit. Infinera (2018)

80 RENE AG is a German company and it is thus assumed that its statements covers recyclers in Germany and in the region.

risk of exposure to InP nanoparticles in the WEEE recovery stage attributable to PWB shredding and disassembly.[81]

When InP-based quantum dots are **burned or dissolved**, Nanoco assumes that indium and phosphorus are separated and form different compounds, such as indium oxide and phosphates, which are not classified as carcinogenic.[82]

81 Op. cit. Infinera (2018)

82 Op. cit. Nanoco (2018)

7 EXPOSURE ESTIMATION DURING USE AND/OR DURING WEEE TREATMENT

7.1 Basis of exposure estimation

According to the available figures for the different application fields, the **total volume** of indium phosphide placed on the **European market** through InP applications is estimated to be **~ 100 kg p.a.** It is understood that this amount includes both applications produced within the EU as well as imported amounts of InP (see section 3.3 for more details).

In the light of its physico-chemical properties, indium phosphide is not considered to be volatile. Furthermore, based on the available information, it is not applied as a surface material, but encapsulated in wafers and quantum dots. Even though specific information regarding release rates are not available, the potential for emissions during the use of the substance appears to be very limited (see section 3.4).

7.2 Human exposure estimation

7.2.1 Exposure of workers

7.2.1.1.1 Workers in the production of InP containing EEE

Nanosys refers in its contribution to the 2nd stakeholder consultation to the exposure of workers in quantum dot manufacturing. The company explains that InP would not be an input to the InP/ZnS QD manufacturing process. Furthermore, manufacturing InP/ZnS quantum dots would not involve transporting quantities of pre-made InP through communities where there may be some risk of spillage. In the InP QD manufacturing process the InP cores would be made and encapsulated in a shell in situ before it is ultimately incorporated into a film or device.[83]

In the IARC monograph on InP [84], some exposure data is presented for workers in the semiconductor and microelectronics industry "*where workers are involved in the production of indium phosphide crystals, ingots and wafers, in grinding and sawing operations, in device fabrication and in clean-up activities.*"

7.2.1.1.2 Workers of EEE waste processing plants

In this dossier, only the possible exposure of humans related to the handling, treatment and disposal of WEEE with contents of InP is addressed. Against this background, waste from three different product types is considered:

- Waste from use in printed wiring boards of optoelectronic and high-speed electronic applications;
- Waste from display screens containing InP QDs, and
- Waste from lighting equipment containing InP QDs.

As appears from section 6.1, the total amount of InP available for potential exposure of humans in the WEEE phase are small, in the worst case a maximum of 100 kg p.a. for the applications mentioned above. Printed wiring boards of **optoelectronic and high-speed electronic applications** contain various rare and precious metals that to a large extent can be recovered at the

[83] Op. cit. Nanosys (2019)

[84] See footnote 61

end-of-life of the products. There seems to be two main technical ways to extract the metals from the matrix:[85]

- Pyrolysis at high temperature (>1,200 ˚C) by which all the organic material will disappear leaving the metals to be extracted from the ashes, slags and possibly also collected vapour condensates;
- Shredding of the laminate from the printed wiring boards followed by extraction of the metals from the boards and disposal by incineration of the shredded laminate.

Both types of processes could lead to release to air and thereby inhalation exposure of workers. However, the potential exposure levels are assumed to be low considering that:

- The major part of InP in the EEE products is considered not to be released to the air during shredding but will remain in the product matrix until combustion / pyrolysis takes place at high temperature that destroys InP in the process (see section 7.2.3 for more details);
- Emissions of particulates can be adequately managed through engineering controls and proper use of respiratory personal protection equipment.

During shredding of **display and lighting equipment,** emissions of particulate matter are not considered to be in the nanoscale (<100 nm) intrinsic to quantum dots that are used in display technology (see section 6.4).

However, one occupational exposure study in e-waste recycling plants in Sweden[86] measured the inhalable fraction from personal air sampling of recycling workers and from static sampling representing office workers at three e-waste recycling plants in Sweden. Julander et al. (2014) analysed biomarkers from the workers and found a linear correlation between the presence of indium in the inhalable fraction and between the presence of indium in exposure biomarkers (blood, plasma and urine) as well as for other metals such as mercury, lead and also antimony. Thus, Julander et al. (2014) points out the occupational exposure to multiple metals at e-waste recycling works, even in modern plants with adequate protection routines and claims that rare metals, such as In and Sb, and not only Hg and Pb, must be monitored in these settings both in air and human samples.

7.2.2 Exposure of neighbouring residents of EEE waste processing plants

Following the considerations made above, it is concluded that the exposure levels for neighbouring residents will also be very low.

7.2.3 Consumer exposure

Due to the fact that InP is not applied as a surface material in its applications, but encapsulated in wafers and quantum dots, consumer exposure can be excluded. This is supported by a contribution of Nanosys.[87]

[85] ECB (2006), European Union Risk Assessment Report. CAS: 79-94-7, Tetrabromobisphenol-A or TBBP-A. Part II: Human Health. European Chemicals Bureau (ECB), 2006; https://echa.europa.eu/documents/10162/32b000fe-b4fe-4828-b3d3-93c24c1cdd51 last viewed 26.02.2020

US EPA (2015), Flame retardants in printed circuit boards. Final Report, August 2015. United States Environmental Protection Agency (US EPA). Publication 744-R-15-001 under the Design for the Environment programme, available under: https://www.epa.gov/sites/production/files/2015-08/documents/pcb_final_report.pdf last viewed 26.02.2020

[86] Julander, A; Lundgren, L.; Skare, L.; Grandér M.; Palma, B.; Vahter, M.; Lidéna, C. (2014): Formal recycling of e-waste leads to increased exposure to toxic metals: An occupational exposure study from Sweden; Environment International 73 (2014) 243–251.

[87] Op. cit. Nanosys (2019)

According to COCIR[88], exposure data of consumers to indium exists but the association further explains that there are many natural and anthropogenic sources of indium so that these do not provide indication as to the exposure to InP in particular.

7.3 Environmental exposure estimation

The environmental exposure resulting from handling, treatment and disposal of WEEE from **optoelectronic and high-speed electronic materials** containing InP is considered to be low, partly because the total amount available for exposure in the WEEE phase is low (total lower that 100 kg p.a.), and partly because most of the relevant waste materials will be treated either by pyrolysis at re-cycling plants or by incineration at large municipal waste incineration plants (see previous section).

When heated to decomposition, InP may emit toxic fumes of phosphorous oxides (POx)[89] that can be removed with water. With a decomposition temperature of 380°C,[90] it is considered to be very unlikely that InP will survive pyrolysis at >1,200˚C during which printed wiring boards are destroyed by pyrolysis with the aim to recover rare / precious metals. The same is applicable for the incineration at municipal waste incineration plants where the combustion temperature reaches 850˚C.

Waste water from the cleaning of gases at municipal waste incineration plants must be treated properly to avoid pollution prior to release into the aquatic environment or pre-treated prior to discharge to the public sewerage system. In the consultants' view, the amounts of InP potentially ending up in waste water are assessed to be small as the major part will be destroyed thermally prior to cleaning of the combustion gases.

As pointed out in section 6.3, waste from **display and lighting equipment** is expected either to be shredded and incinerated, or to be disposed of in landfills. Since in most Member States, the collection rate is considered to be below 50% (see section 6), landfilling is understood to be still very relevant in many cases. Against this background, as a worst-case assumption, 60% of waste from display and lighting equipment may end up in landfilling. With InP inventories of 100 kg / year (see section 3.3), a total of 60 kg / year can be estimated for this pathway.

[88] Op. cit. COCIR (2019)

[89] Op. cit. France (2009)

[90] Sun et al (2005); Optimised cleaning method for producing device quality InP(100) surfaces; http://www.slac.stanford.edu/pubs/slacpubs/11000/slac-pub-11018.pdf, last viewed 26.07.2019

8 IMPACT AND RISK EVALUATION

The estimated worst-case amounts of InP used for EEE applications in the EU that potentially could be released in the waste phase to the external environment in an untransformed form are assessed to be in the range 100 kg / annum, see sections 6.2 and 6.3. Consequently, the possible local occupational, residential or environmental concentrations will be very low.

Nanosys points out that because of their core-shell structure, manufactured InP/ZnS quantum dots pose a very low risk of toxicity to humans. Studies have shown that such core-shell InP/ZnS quantum dots are well-suited for in vivo use in humans. A recent study by the Center for Bio-Molecular Nanotechnologies and McGill University found that core-shell InP/ZnS posed a “very low” toxicity risk to humans and offered “good bio-compatibility”.[91]

Based on worst case exposure scenario assumptions, it is not found meaningful to try to establish specific risk assessment scenarios or perform risk evaluations for these scenarios. Based on the available information and the described worst-case assumptions, the overall assessment is that, if evaluated, the risk to humans and the environment would turn out to be very low / negligible.

[91] Cited by Nanosys (2019): Virgilio Brunetti et al, “InP/ZnS as a safer alternative to CdSe/ZnS core/shell quantum dots: in vitro and in vivo toxicity assessment,” Nanoscale, 2013,5, 307-317

9 ALTERNATIVES

9.1 Availability of substitutes / alternative technologies

Optoelectronics

Indium phosphide, and alloys of indium phosphide with related compounds such as InGaAsP or InGaAlAs, are considered to be unparalleled for use within transmitters or receivers in fibre optic communications systems at 1.3 µm or 1.55 µm wavelength ranges.[92]

According to SMART Photonics, InP is the only direct bandgap semiconductor with a bandgap that can be tuned to emit at a wavelength range between 1,200 and 1,700 nm. This functionality is considered to be needed for optical communications > 1km to 10,000km with no substitute available for reliable lasers in this wavelength range.[93]

At some wavelengths, however, substitution of InP by other semiconductor materials appears to be possible, but according to Coherent, this would be associated with reduced performance, higher production cost, unknown reliability, etc. Gallium arsenide could be an alternative for InP in some applications that are not sensitive to the emission wavelength of the laser.[94]

As pointed out by Infinera, early in the development of optoelectronic devices for fibre-optic communications, gallium arsenide (GaAs)-based devices, which are ideally suited to 0.85 µm transmission, were tested at 1.3 or 1.5 µm. These efforts, however, ultimately failed due to high-defect density that is inherent to highly-strained or lattice-mismatched, indium-containing alloys grown on GaAs substrates. Based on these results, indium phosphide was established as the substitute for GaAs devices and apparently offered better technical performance. In the early history of optoelectronic device development, suggestions to use devices based on II-VI semiconductors[95] (such as CdZnSe) were also made but were abandoned in the 1990s due to high defect density and poor mechanical stability inherent in these materials.[96]

Moreover, Infinera mentions that some commercial suppliers of optoelectronic components operating at 1.5 µm employ a silicon-based photonics technology. However, in Si photonics, the active devices are fabricated from InP and placed on a Si substrate for integration with other optical functions. Therefore, Infinera considers Si photonics to be a viable integration technology for InP-based devices, but not to represent a substitution path for InP. The rationale for this conclusion is that silicon by itself cannot be used for lasers or direct amplification. For Infinera, silicon appears to be ideal only for simpler, single wavelength applications, and for co-packaging with active devices in the “pluggable” market for client optics and metro transponders. Likewise, optoelectronic devices emitting at other wavelengths (IR, visible, and UV) may be fabricated from other III-V materials and may find other commercial applications. Infinera concludes however, that there is no alternative available to InP for high-capacity, long-haul networks based on DWDM technology.[97]

Photodetection devices could provide the best opportunities for substitution. According to Lumentum, for this application field, germanium would be a suitable substitute when integrated with

---

92 Op. cit. Lumentum (2018)

93 Smart Photonics (2018), Contribution of Smart Photonics submitted on 15.06.2018 during the stakeholder consultation conducted from 20 April 2018 to 15 June 2018 by Oeko-Institut in the course 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); find the link in the annex

94 Op. cit. Coherent (2018)

95 II-VI compound semiconductors are obtained by combining group II elements with group VI elements.

96 Op. cit. Infinera (2018)

97 Op. cit. Infinera (2018)

silicon nanowire waveguides on silicon substrates, because its lower absorption coefficient can be compensated by increased device length. However, substitution is considered to be limited to optical component architectures that edge-couple light from optical fibre to the waveguide. In contrast, normal incidence photodiode geometries, which are the most common solution at lower bitrates and which provide advantages in alignment tolerance, power handling capability, and polarisation independence, are not considered to be compatible with substitution by Ge-on-Si waveguide photodiodes.[98]

For **modulators**, Lumentum assumes that in limited cases, an alternative exists in silicon, but its application would be associated with performance limitations on bandwidth and insertion loss. This would limit substitution to applications where either the symbol rate is low (25 Gbaud), or where erbium-doped fibre amplifiers can be added in line to boost the signal, which increases the power dissipation and limits the compactness of the transceiver.[99]

Also in the **data centre** applications, silicon germanium technology has some limited functions according to MMTA, however, it is considered to be unsuccessful where there are greater distances between individual data centres.[100]

As **alternative technology**, gas lasers and solid-state lasers could be considered. As pointed out by IMAT, these alternatives would suffer significantly from performance data, such as output power, weight, size, energy consumption, life span, cooling requirements, and cost. Therefore, they could not be used in applications mentioned in section 3.2.[101]

<u>High-speed electronics</u>

For high-frequency electronics, InP is considered to be necessary because of its very high electron velocity. For limited applications InP, however, IMAT presumes replacement by GaAs based technologies or Silicon based technologies such as CMOS or SiGe technology.[102]

<u>Displays and lighting</u>

As pointed out by Nanoco, InP QD technology has been investigated and developed over a number of years as a safer alternative to Cd-based QDs. Hence, it would be difficult to substitute InP for a Cd-free material of the same functionality. One possible alternative could be CFQD® quantum dot material produced by Nanoco, which is an alloy of indium and other elements. According to Nanoco, alternative materials (e.g. $CuInS_2$ and halide perovskite QDs) are currently being investigated, but these materials do not provide the required performance for commercial applications. Nanosys also referred to such materials, pointing out that prototype displays with green halide perovskite quantum dots were presented recently.[103] Gallium arsenide would have a similar band gap to InP and has been developed as a possible substitute for some applications where the material is formed in a layer using chemical vapour deposition (CVD) or similar processes. However, the formation of colloidal QDs using GaAs has proved to be more difficult than using InP and the optical performance characteristics turned out to be significantly inferior. Nanoco expects it might be possible to develop

98 Op. cit. Lumentum (2018)
99 Op. cit. Lumentum (2018)
100 Op. cit. MMTA (2018)
101 Op. cit. IMAT (2018)
102 Op. cit. IMAT (2018)
103 Op. cit. Nanosys (2019)

GaAs QDs in future, but it would take many years of research, which is currently considered not to be a significant area of focus for either academic or commercial research teams.[104]

Another option for LCDs could be inorganic phosphors. Although inorganic phosphors are considered to be cheap and relatively efficient, Nanoco assumes that they are not able to give the enhanced colour reproduction increasingly demanded by consumers. Furthermore, the increased colour filtration to improve their colour performance would lead to significantly greater energy consumption.[105]

When considering alternative display **technologies**, it needs to be considered that OLED (organic light-emitting diode) displays are well established, but they are considered to be much more expensive to manufacture in large sizes, tend to have higher power consumption and are expected not to achieve the same brightness as LCD displays.[106] Nanosys summarises that OLED provide several "unique benefits" – particularly in relation to thin form factors, low black levels and good refresh rates – but OLEDs would be "*unable to meet all of the market demands for display performance*".[107]

Concerning lighting, no explicit information concerning possible substitutes was provided by the stakeholders. However, in the view of the consultant, it appears to be reasonable that the same substitutes as for displays could also apply for lighting.

Photovoltaic applications

Also concerning lighting, no explicit information concerning possible substitutes was provided by the stakeholders. Based on a short literature review, the consultant comes to the assessment that the most relevant substitute for InP in ultra-efficient photovoltaic applications is a substrate based on GaAs.

In general

IMAT explains, that worldwide InP quantities would be so low that prices remain high: "*InP wafers are five times more expensive than GaAs wafers of the same size. […] Worldwide companies and research institutes have been looking for viable alternatives to InP for more than 30 years now. If the future brings cost-saving alternatives, industry would make use of them*."

9.2 Hazardous properties of substitutes

According to ECHA InfoCard, GaAs is classified as a Carcinogen and Reproductive toxin. Therefore, Oclaro considers GaAs to be at least as hazardous as InP.[108] IMAT agrees with this statement.[109]

Nanoco states that studies on the toxicity of InP-based QDs have concluded the material to be a safer alternative to Cd-based QDs[110]. Within this context, it is mentioned that a study performed by Brunetti et al.[111] compared the cytotoxicity of CdSe/ZnS and InP/ZnS QDs in vitro and in vivo

[104] Op. cit. Nanoco (2018)
[105] Op. cit. Nanoco (2018)
[106] Op. cit. Nanoco (2018)
[107] Op. Cit Nanosys (2019)
[108] Op. cit. Oclaro (2018)
[109] Op. cit. IMAT (2019)
[110] Op. cit. Nanoco (2018)
[111] Quoted by Nanoco (2018) and Nanosys (2019) as: V. Brunetti, H. Chibli, R. Fiammengo, A. Galcone, M.A. Malvindi, G. Vecchio, R. Cingolani, J.N. Nadeau and P.P. Pompa, Nanoscale, 2013, 5, 307

(Drosophila). It was concluded in this study that InP/ZnS core/shell QDs provided a “safer alternative” to CdSe/ZnS QDs for biological applications. Cd^{2+} ions were shown to leach from the core of the QDs, despite a two-monolayer ZnS shell. The CdSe/ZnS QDs were observed to induce cell membrane damage, conditions of oxidative stress in the cells, damage of the genetic material and interference with Ca^{2+} homeostasis, which can be mainly ascribed to the presence of Cd^{2+}. Since an almost identical amount of In^{3+} ions leached from the InP/ZnS QDs, the results suggest that In-based QDs have a much lower intrinsic toxicity than Cd-based QDs.[112]

Taking into account the information of the hazardous properties given above as well as the CLP classification[113] of GaAs, the consultants can follow the assessment of Oclaro and Nanoco that GaAs is at least as hazardous as InP.

9.3 Data basis for alternatives and uncertainties

It is understood that material alternatives do exist, but they appear to be very limited to certain fields of application. For example, germanium-based substitutes are mentioned to be feasible in photo detection devices[114]. Also alternative technologies (e.g. gas lasers / solid state lasers in optoelectronics and OLED in displays / lighting application) can be considered, but are characterised to suffer significantly from reduced performance data, as well as higher energy consumption.[115]

The information specified above regarding alternatives for indium phosphide originates from various documents generated also in the context of the REACH and CLP regulations. Such documents are understood to have been subject to scrutiny and to have a relatively high certainty.

[112] See footnote 111

[113] The CLP classification of GaAs includes: ‘Carc. 1B’, ‘Repr. 1B’, STOT RE 1 (respiratory and haematopoietic systems); ‘Repr. 1B’ is higher (‘danger, may cause...’) than ‘Repr. 2’ (‘warning, suspected of...’); furthermore, the specific target organ toxicity of GaAS has also has a wider scope than just lungs.

[114] Op. cit. Lumentum (2018)

[115] Op. cit. IMAT (2018); Op. cit. Nanoco (2018)

10 DESCRIPTION OF SOCIO-ECONOMIC IMPACTS

10.1 Approach and assumptions

The scope of this assessment requires a review of possible socio-economic impacts related to a scenario in which indium phosphide as the substances under assessment was to be added to the list of restricted substances specified in Annex II of RoHS 2. This would restrict the presence of these substances in EEE to be placed on the market in the future.

In lack of quantitative data in many areas of the assessment, the following sections provide mostly provide a qualitative estimation as to possible impacts.

10.2 Impact on chemicals industry

As pointed out by IMAT, InP is produced and sold as a wafer by a very small number of companies worldwide representing at least 90% of the market. Producers of InP wafers are e.g.:[116]

- AXT, USA/China
- InPACT, France
- JX Nippon Mining and Metals Corporation, Japan
- PamXiam, China
- Sumitomo, Japan
- Vital Materials, China
- Wafer Technology, United Kingdom

InPACT, for example, according to own data the "largest Western producer" of InP substrates, is dedicated exclusively to InP.[117] Due to this specialisation, it can be assumed that a restriction of InP would have a significant impact on the continued existence of this company and, if applicable, the entire industry.

10.3 Impact on EEE producers

It is understood that InP is used as an enabling material in products with high value creation, such as global telecommunication networks (see section 3.2 for more details).

As pointed out by MMAT, European companies contribute to a global market volume of 25 billion Euros in the field of optical networking equipment and components, which supports a nearly 3 trillion Euros global industry in telecommunications services.[118]

According to SMART Photonics, the market for InP transceivers alone is estimated to be close to 10 billion Euros p.a., of which "a significant part" is produced in Europe.[119] Concerning InP based high-speed and optoelectronic hardware, IMAT estimates the market share of European manufactures to reach approximately 25% of the world market.[120]

116 Op. cit. IMAT (2018)
117 See http://www.inpactsemicon.com/companyoverview.php, last viewed 26.02.2020
118 Op. cit. MMAT (2018)
119 Op. cit. Smart Photonics (2018)
120 Op. cit. IMAT (2018)

On the level of individual enterprises, Oclaro states that "the majority" of the company's income is reliant on InP technology. In particular, the growth of the company and the related employment depends on the use of InP.[121]

3SPT states that the company would have to discontinue its semiconductor laser diode manufacturing activity in the range between 1.3 - 1.5 µm if indium phosphide would be restricted under RoHS; this would affect a turnover of more than 10 million Euros.[122]

Lynred, which explained that InP is used in its manufacturing process of InGaAs infrared detectors, a significant part of the company turnover, stated that "*40 jobs are full or partially directly concerned by InP-based activities (excluding subcontractors and suppliers)*". It is assumed that this statement refers only to jobs of employees within the company.[123]

In general, as pointed out by Nanoco, a restriction of InP entails the development of QD based on non-regulated material or new (non-QD) technologies, both involving "*significant investment of time and cost*".[124]

10.4 Impact on EEE users

Regarding the impact on EEE users, it is pointed out by Infinera[125] that elimination of InP would have serious consequences regarding the costs for long-haul (>100 km) communications networks. Alternative network technologies and architectures would be required that are expected to cause a substantial increase in the number of network nodes in a terrestrial network, with each node consisting of short-haul optical transmission equipment (GaAs-based optoelectronic devices communicating over linkages of <10 km) operating with plastic optical fibre (to be installed between nodes).

With information provided by Infinera[126], alternative laser technologies (e.g. based on GaAs) additional lasers will be required to provide the current network capabilities. The purchase of these GaAs lasers as well as the associated modules is considered to be more expensive. Additionally, these components will cause higher power consumption and the resulting hardware will also require more rack space in data centres. Based on Infinera's calculations, a network using GaAs technology will be five times more expensive than current networks with InP lasers. Furthermore, this technology would cause five times more energy demand that InP based networks and it would require five times more rack space in data-centres.

Moreover, IMAT assumes that in case of a restriction of InP the quality of infrastructure for data communication would be influenced drastically both for industry and private consumers.[127] Data market studies cited by LUMENTUM illustrate "*socio-economic losses by preventing the digital economy from growing if InP use was banned*." According to these figures, the losses in the big data market – where the supporting optical communication technology relies on InP based components – ranges from 27 to 107 billion Euro in the EU 27 by 2025.[128]

[121] Op. cit. Oclaro (2018)
[122] Op. cit. 3SPT (2018)
[123] Op. cit. Lynred (2019)
[124] Op. cit. Nanoco (2019)
[125] Op. cit. Infinera (2018)
[126] Op. cit. Infinera (2018)
[127] Op. cit. IMAT (2018)
[128] Op. cit. Lumentrum (2019)

Regarding the maintenance and repair of existing equipment IMAT further points out that replaced components should have the same properties in order to guarantee the functionality of a device. However, if adequate spare parts would no longer be available due to a restriction of InP the entire device had to be scrapped.[129]

Concerning display applications, Nanoco expects the risk of a market gap if QD manufacturers are no longer able to use InP. Until new materials or technologies become market-ready, display technology would not deliver the expected performance for the consumers. This may require higher operating costs if the device efficiency is reduced. The alternative QD material options, Cd-based and Pb-based material, have the potential for being released, e.g. in case of a house fire, so that consumers could be exposed to Cd or Pb.[130]

10.5 Impact on waste management

The various methods for treating relevant EEE waste are not understood to be a result of the use of InP. Hence it is assumed that for the most part, substitutes of InP would be similar in relation to the risk of exposure, and thus it is assumed that the waste management practices would not change. However, if Cd- or Pb-based alternatives are allowed via exemptions, "*these may have additional disposal considerations compared to InP, in order to ensure that these metals do not leach into the environment*".[131] Similarly, the main motivation for waste treatment of PWBs is understood to be the recovery of various metals. Here too the change in the use of InP is not expected to change the waste management methods. EEE containing alternative material QDs is likely to be recycled the same way as those currently used for InP QD.

10.6 Impact on administration

A change in regulation always results in a certain burden of compliance, in terms of administration of the legal change of the Directive and its transposition to national law of EU countries. If the transition period provided for the regulation change would not suffice to accompany the phase-out, it is possible that some exemptions may be requested from the substance restrictions and that these would have a further administrative burden.

In the case of a restriction of a chemical substance, further administrative costs can be expected to incur in relation to enforcement of the new restrictions and the need to adapt and to operate market surveillance of compliance.

10.7 Total socio-economic impact

As explained at the onset of this chapter, the small amounts of InP potentially present in EEE products raises doubt as to the effectiveness of a possible restriction and thus as to the incurrence of actual impacts. Should a restriction be introduced, significant cost-related impacts could be expected, especially for EEE manufacturers and users. Due to the fundamental role of InP especially in the area of telecommunication, these impacts could also not be softened by longer transition period for a restriction of InP.

In addition, a restriction of InP is also not expected to generate benefits for the environment or for health (in the form of prevention of possible impacts tied with InP as a substance in general and particularly during the use and waste phase of interest for RoHS 2 Article 6(1)). The main reason for

[129] Op. cit. IMAT (2018)

[130] Op. cit. Nanoco (2018) & (2019)

[131] Op. cit. Nanoco (2019)

this assessment can be seen in the fact that in terms of total socio-economic impacts, the potential alternatives (GaAS for optoelectronic devices and Cd-based QD for displays / lighting) are not expected to have a better environmental performance than InP (see section 9.2). This suggests that a restriction of the two substances would not be proportionate, given that its costs are not expected to generate benefits for the environment or for health.

11 RATIONALE FOR INCLUSION OF THE SUBSTANCE IN ANNEX II OF ROHS

Based on the available information, it can be expected that the quantities of indium phosphide used in its main areas of application (optoelectronics, high-speed electronics, displays and lighting as well as photovoltaic applications) currently do not exceed 100 kg / year. For the time being, the estimated worst-case amounts of InP used for EEE applications in the EU that potentially could be released in the waste phase to the external environment in an untransformed form are estimated to be below 100 kg / year.

With regard to the currently available substitutes, a restriction of InP is not expected to generate substantial benefits for the environment or for health, since potential alternatives (especially GaAS for optoelectronic devices and Cd-based QD for displays / lighting) are not considered to have a better environmental performance than InP.

Should a restriction be introduced, however, significant cost-related impacts could be expected, especially for EEE manufacturers and users. Due to the fundamental role of InP especially in the area of data transfer and telecommunication, these impacts could have a substantial negative impact on Europe´s economy as a whole.

Against this background, it currently cannot be recommended to pursue a restriction under the RoHS Directive of indium phosphide.

However, there are relevant hints that the consumption of InP may increase significantly in the future. Especially the use of InP-based QD technology in displays and LED lighting equipment is expected to become a major driver in this respect. Taking into account worst case assumptions, total quantities of use of up to 2,000 kg / year cannot be excluded by 2028 (see section 3.3 for more details).

InP is at least as hazardous as GaAs and has a comparable use and toxicological profile. Based on the 10-100 tons REACH dossier of GaAs, which concluded that risks to human health and environment are irrelevant, the consultants assume that this applies also to the use of InP, even if the quantities of InP would increase up to the maximum estimate for 2028.

12 References other than contributions to the stakeholder consultation

Donghyo Hahm, Donghyun Ko, Byeong Guk Jeong, Sohee Jeong, Jaehoon Lim, Wan Ki Bae, Changhee Lee & Kookheon Char (2019) Environmentally benign nanocrystals: challenges and future directions, Journal of Information Display, 20:2, 61-72

ECB (2006), European Union Risk Assessment Report. CAS: 79-94-7, Tetrabromobisphenol-A or TBBP-A. Part II: Human Health. European Chemicals Bureau (ECB), 2006; https://echa.europa.eu/documents/10162/32b000fe-b4fe-4828-b3d3-93c24c1cdd51 last viewed 26.02.2020

ECHA Information on Chemicals Database (2018): Entry for indium phosphide; https://echa.europa.eu/substance-information/-/substanceinfo/100.040.856, last viewed 25.05.2018

ECHA CL Inventory (2018): Entry for indium phosphide; https://echa.europa.eu/de/information-on-chemicals/cl-inventory-database/-/discli/details/117665, last viewed 25.05.2018

EU COM (2017), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU, Brussels, 13.9.2017, COM(2017) 490 final, available under: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2017:0490:FIN, last viewed 19.04.2018, last viewed 19.04.2018

Eurostat (2019) https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment&oldid=445263#EEE_put_on_the_market_and_WEEE_collected_in_the_EU, last viewed 26.02.2020

France (2009): Annex XV Dossier - Indium phosphide – CAS 22398-80-7; https://echa.europa.eu/documents/10162/7564f5ed-a09c-41a0-b8ee-7aebf4287c99; last viewed 25.05.2018

HIS (2017) Wide Color Gamut & Quantum Dot Display Market Tracker – H1 2017, https://technology.ihs.com/api/binary/578908?attachment=true last viewed 26.02.2020

IARC (2006) International Agency for Research on Cancer, to be found under http://publications.iarc.fr/104, last viewed 10.01.2020

InPACT (2020) http://www.inpactsemicon.com/companyoverview.php, last viewed 26.02.2020

Julander, A; Lundgren, L.; Skare, L.; Grandér M.; Palma, B.; Vahter, M.; Lidéna, C. (2014): Formal recycling of e-waste leads to increased exposure to toxic metals: An occupational exposure study from Sweden; Environment International 73 (2014) 243–251.

Oeko-Institut (2016), Assistance to the Commission on Technological Socio-Economic and Cost-Benefit Assessment related to Exemptions from the Substance Restrictions in Electrical and Electronic Equipment (Pack 10), Final Report, prepared for the European Commission, DG Environment, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/reports/20160602_Final_Report_RoHS_Pack_10_Cd_QDs_amended.pdf, last viewed 19.04.2018

Oliveira, Paula & Taborda, Filipa & Nogueira, Carlos & Margarido, Fernanda. (2012). The Effect of Shredding and Particle Size in Physical and Chemical Processing of Printed Circuit Boards Waste. Materials

Science Forum. 730-732. 653-658. 10.4028 to find under www.scientific.net/MSF.730-732.653. last viewed 26.02.2020

Photovoltaik Solar Strom (2020) to find under https://photovoltaiksolarstrom.com/photovoltaiklexikon/indiumphosphid/ last viewed 26.02.2020

PubChem (2020), Entry for Indium phosphide, US National Library of Medicine https://pubchem.ncbi.nlm.nih.gov/compound/Indium-phosphide, last viewed 26.02.2020

SIN List (2020a) What is the SIN List? To find under https://sinlist.chemsec.org/what-is-the-sin-list/, last viewed 26.02.2020

SIN List (2020b) Entry for Indium Phosphide to find under https://sinsearch.chemsec.org/chemical/22398-80-7, last viewed 24.07.2018

Sun, Yun; Liu, Zhi; Machuca, Francisco; Pianetta, Piero; Spicer, William E. (2005); Optimised cleaning method for producing device quality InP(100) surfaces; http://www.slac.stanford.edu/pubs/slacpubs/11000/slac-pub-11018.pdf, last viewed 26.07.2019

US Food and Drug Administration. Masks and N95 Respirators (2020) To find under https://www.fda.gov/medical-devices/personal-protective-equipment-infection-control/masks-and-n95-respirators last viewed 26.02.2020

US EPA (2015), Flame retardants in printed circuit boards. Final Report, August 2015. United States Environmental Protection Agency (US EPA). Publication 744-R-15-001 under the Design for the Environment programme, available under: https://www.epa.gov/sites/production/files/2015-08/documents/pcb_final_report.pdf

Virgilio Brunetti et al. (2013), InP/ZnS as a safer alternative to CdSe/ZnS core/shell quantum dots: in vitro and in vivo toxicity assessment, Nanoscale, 5, 307-317

13 Appendix I: Contribution to stakeholder consultation hold from 20 April 2018 to 15 June 2018

The following non-confidential contributions were submitted during the 1st stakeholder consultation (see also: https://rohs.exemptions.oeko.info/index.php?id=292)

> Contribution of **Coherent,** submitted on 12.06.2018: pdf

> Contribution of the **3SPT Technologies,** submitted on 14.06.2018: pdf

> Contribution of **Infinera,** submitted on 11.06.2018: pdf

> Contribution of **Lumentum,** submitted on 15.06.2018:

>> Contribution: pdf

>> Annex: pdf

> Contribution of the **Minor Metals Trade Association (MMTA),** submitted on 15.06.2018: pdf

> Contribution of **OCLARO,** submitted on 15.06.2018: pdf

> Contribution of **MedTech Europe,** submitted on 15.06.2018: pdf

> Contribution of **Freiberger Compound Materials GmbH (IMAT),** submitted on 15.06.2018: pdf

> Contribution of **Nanoco Technologies Ltd,** submitted on 15.06.2018: pdf

> Contribution of the **SMART Photonics,** submitted on 15.06.2018: pdf

> Contribution of the **Test and Measurement Coalition (TMC),** submitted on 15.06.2018: pdf

> Contribution of **ANIE Federazione,** submitted on 15.06.2018: pdf

> Contribution of the **Association of Equipment Manufacturers (AEM),** submitted on 15.06.2018: pdf

> Contribution of the **Japanese electric and electronic (E&E) industrial associations,** submitted on 14.06.2018: pdf

> Contribution of the **AeroSpace and Defence Industries Association of Europe (ASD),** submitted on 14.06.2018: pdf

> Contribution of the **Institute of Photonic Integration Technical University Eindhoven (TUE),** submitted on 15.06.2018: pdf

14 Appendix II: Contributions to stakeholder consultation hold from 26 September 2019 to 07 November 2019

The following non-confidential contributions were submitted during the 2nd stakeholder consultation (see also https://rohs.exemptions.oeko.info/index.php?id=334):

> Contribution of **COCIR (European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry),** submitted on 22.10.2019: PDF

> Contribution of **Nanoco Technologies Ltd,** submitted on 01.11.2019: PDF

> Contribution of the **Japanese electric and electronic (E&E) industrial associations** submitted on 06.11.2019: PDF

> Contribution of **Nanosys**, submitted on 06.11.2019: PDF

> Contribution of **IMAT e.V.**, submitted on 07.11.2019: Cover letter: PDF; Contribution: PDF

> Contribution of **Fraunhofer IAP**, submitted on 07.11.2019: PDF

> Contribution of **Fraunhofer HHI**, submitted on 07.11.2019: PDF

> Contribution of **UnitedMonolithic Semiconductors GmbH (UMS**), submitted on 07.11.2019: Cover letter: PDF; Contribution: PDF

> Contribution of **Digital Europe**, submitted on 07.11.2019: PDF

> Contribution of **The European Semiconductor Industry Association (ESIA)**, submitted on 07.11.2019: PDF

> Contribution of **Vishay Semiconductor GmbH**, submitted on 07.11.2019: PDF

> Contribution of **Lumentum,** submitted on 07.11.2019: PDF

> Contribution of **LYNRED by Sofradir and ULIS**, submitted on 07.11.2019: PDF

> Contribution of **OSRAM**, submitted on 07.11.2019: Cover letter: PDF; Contribution: PDF

> Contribution of the **AZURSpace Solar Power GmbH**, submitted on 07.11.2019: Cover letter: PDF; Contribution: PDF

> Contribution of the **Zentralverband Elektrotechnik- und Elektronikindustrie e. V. (ZVEI),** submitted on 07.11.2019: PDF

> Contribution of **Spectaris**, submitted on 07.11.2019: PDF

> Contribution of **Freiberger Compound Materials GmbH (FCM)**, submitted on 07.11.2019: Cover letter: PDF; Contribution: PDF