RSC Advances



REVIEW

View Article Online
View Journal | View Issue



Cite this: RSC Adv., 2017, 7, 9194

Recent studies of the synthesis, functionalization, optoelectronic properties and applications of dibenzophospholes

Paulina Hibner-Kulicka, ab John Arthur Joule, Joanna Skalika and Piotr Bałczewski ad

The first dibenzophospholes were described in the 1950s, but only recently have they gained greater importance, due to their use in organic electronics and the possibility of designing new π -conjugated, optoelectronic materials that incorporate these heterocycles. Our comprehensive review covering a period of 15 years (2001–2016), includes methods of synthesis of these compounds, methods for their functionalization, a description of their optoelectronic properties and their first use in optoelectronic devices. The review represents the current state of knowledge in this field and shows the great potential of simple and functionalized dibenzophospholes. The work described in this review suggests that dibenzophospholes should also be investigated more intensively as single materials, as well as in structural combinations with other π -extended conjugated aromatic and heteroaromatic systems containing phosphorus, nitrogen, silicon or sulfur atoms.

Received 4th November 2016 Accepted 23rd January 2017

DOI: 10.1039/c6ra26333j

rsc.li/rsc-advances

^aDepartment of Heteroorganic Chemistry, Centre of Molecular and Macromolecular Studies, Polish Academy of Sciences, Sienkiewicza 112, 90-363 Łódź, Poland. E-mail: pbalczew@cbmm.lodz.pl; Fax: +48 42 684 71 26; Tel: +48 42 684 71 26

^bDepartment of Molecular Physics, Technical University of Łódź, Żeromskiego 116, 90-924 Łódź, Poland. Fax: +48 42 631 32 18; Tel: +48 42 631 32 05

^cThe School of Chemistry, The University of Manchester, Manchester M13 9PL, UK
^dJan Długosz University in Częstochowa, Institute of Chemistry, Environmental
Protection and Biotechnology, The Faculty of Mathematics and Natural Sciences,
Armii Krajowej 13/15, 42-201 Częstochowa, Poland. Tel: +48 34 378 41 00

1. Introduction

Interest in π -conjugated compounds has increased greatly following the investigations of Heeger, MacDiarmid and Shirakawa,¹ that led to the award of the Chemistry Nobel Prize in 2000. There followed a period of dynamic development in the field of synthesis and studies on the properties of oligomeric and polymeric systems applicable to flexible, lightweight and low-cost electronic devices. A great deal of attention has been paid not only to structural modifications, but also to



Paulina Hibner-Kulicka received her BSc in chemistry from the Jan Długosz University in Częstochowa, Poland. Within an Erasmus program with the University of Caen-Normandy (ENSICAEN), France, she was involved in the synthesis of ladder-type heteroacenes as materials for light-emission and charge transport. She graduated (MSc) from the University of Łódź, in the area of chemistry

and nanotechnology of new materials in collaboration with the Centre of Molecular and Macromolecular Studies, Polish Academy of Science, Łódź (Prof. P. Bałczewski). Currently, she is a PhD student working on photovoltaic and OLED device fabrication at Łódź University of Technology, Poland.



John Joule grew up and went to school in Llandudno, Wales, moving to the University of Manchester for BSc, MSc, and PhD degrees, the last with Dr George F. Smith. Following post-doctoral studies with Richard K. Hill (Princeton) and Carl Djerassi (Stanford) he returned to Manchester for an academic career of 41 years. His research there produced more than 230 papers on aspects of heterocyclic

chemistry, especially indoles and quinoxalines and pteridines related to the molybdenum cofactor. His textbook 'Heterocyclic Chemistry' co-authored originally with George Smith and latterly with Keith Mills, his one-time PhD student, is now in its 5^{th} Edition.

Scheme 1

supramolecular organization of such compounds to achieve optimal properties of the final materials. The use of conjugated polyaromatic, polyacetylenic, polyolefinic compounds and fused aromatic systems, as well as their structural combinations, not only guarantees satisfactory properties and excellent stability of these compounds, but also the possibility for their easy chemical functionalization using modern synthetic tools. A disadvantage of the systems containing aromatic building blocks has often been a too high degree of aromaticity, which inhibits an easy electron delocalization along the conjugated rings when in an oxidized state.2-4

Therefore, this type of molecular system requires a beneficial incorporation of heteroaromatic rings, for example fivemembered pyrrole, thiophene or furan, possessing lower aromatic stabilization energies (ASE_{calc}: 20.57, 18.57, 14.77 kcal mol⁻¹, respectively) than a benzene ring. The aromatic character of the phosphole ring $(ASE_{calc} = 3.2 \text{ kcal mol}^{-1})$ is relatively low due to the pyramidal geometry of the phosphorus atom. Overlap between the lone pair and the diene unit is thus limited, resulting in a lower aromatic character compared with other five-membered heterocycles with nitrogen, sulfur or oxygen. The low aromatic character allows hyperconjugation of the endocyclic 4- π -electron system with the exocyclic P–R bond. Closely related dibenzophospholes I (Scheme 1) and their derivatives, being further examples of such fused heterocyclic systems, have been used successfully, alone or as building blocks, for preparation of more complex π -conjugated systems useful as electronic and optoelectronic materials. However, they are still an underestimated group of compounds in this field.

Dibenzophospholes I together with dibenzofurans II, dibenzothiophenes III and carbazoles IV belong formally to a family of heteroanalogs of fluorene V, or to be more precise, the fluorene anion (Scheme 1).

Important reviews by Réau,⁵ Baumgartner^{6,7} and Hissler^{8,9} serve as brief introductions to phospholes and other organophosphorus derivatives in the molecular electronics context. Hissler's reviews focus mainly on nonfused phospholes and diheteroaromatic derivatives of phospholes fused to thiophene, pyrrole, furan, pyridine moieties and other P-derivatives with a particular emphasis on incorporation into electronic devices while the (micro)reviews by Réau and Baumgartner focus on development of phosphole-containing oligo- and polythiophene materials. A 2015 review by Gouygou¹⁰ discussed phospholebased ligands, including dibenzophospholes, which have potential in metal and organocatalysed reactions.10

In our comprehensive review, we summarise the literature on the newest methods of synthesis and functionalisation of the dibenzophospholes as well as their applications as optoelectronic materials (Fig. 1). This work continues the comprehensive coverage in a previous review devoted to synthesis of dibenzophospholes by Aitken in 200111 and thus it deals with work from the years 2001-2016.



Joanna Skalik graduated from the Jan Długosz University in Częstochowa, Faculty of Mathematics and Natural Sciences (2008). She received her PhD with distinction at the Center of Molecular and Macromolecular Studies, Polish Academy of Sciences (CMMS, PAS) (2015). Since 2008, she has been a member of the scientific staff in the group of Prof. Piotr Bałczewski at the Department of

Heteroorganic Chemistry, CMMS, PAS. She is a co-author of several patents, original and review articles, and chapters in books (Organophosphorus Chemistry, RSC, vol. 40-42, 44, 46). She is actively involved in the realization of Polish national and European research projects.



Piotr Bałczewski studied chemistry at the Technical University of Łodź. MSc/PhD theses (P/S/Si and cyclopentanoid chemistry) were with Prof. M. Mikołajczyk at the Centre of Molecular and Macromolecular Studies (CM & MS), Polish Academy of Sciences (PAS), Łódź. Doctoral studies at the Warsaw PAS, Institute of Organic Chemistry, then a postdoctoral period at Manchester University (UK) in alkaloid

chemistry (Prof. J. A. Joule) led to habilitation and appointment as full professor at CM & MS PAS, Łódź. He currently leads materials research groups at CM & MS PAS, Łodź and the J. Długosz University in Częstochowa, and is currently Vice-President of the Polish Chemical Society.

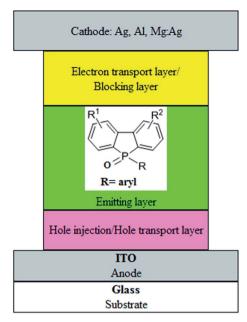


Fig. 1 The application dibenzophospholes in construction of various OLED devices.

Although the first dibenzophospholes were described in the 1950s, in recent times, these interesting compounds have gained importance due to the possibility of using them in new π -conjugated materials. The presence of the two flanking benzene rings in a dibenzophosphole gives the system several advantages over monocyclic phospholes in the context of incorporation into molecular electronics roles. The synthesis and synthetic manipulation of the tricyclic system allows adjustment of overall electronic structure by the introduction and manipulation of benzene-ring substituents. In particular, the linking of dibenzophosphole units to other electronically active components or its incorporation into polymer chains is facilitated by the benzene-ring units.

An important advantage of dibenzophospholes is their high resistance to thermal decomposition. For example, the temperature of thermal decomposition for dibenzophosphole is 365 $^{\circ}$ C, while for the phospholes and dithienophospholes thermal decomposition temperatures are between 200 and 300 $^{\circ}$ C.¹²

Dibenzophospholes and analogous tricyclic, dithienophospholes, are each well delocalized over the entire molecule and possess a smaller HOMO–LUMO gap than any of the component rings. Consequently the dibenzophospholes represent an independent class of compounds and should not be considered as classic, monocyclic phospholes. The dithienophosphole system, developed by Baumgartner *et al.*, ^{13–18} also possesses some advantages with respect to wavelength, intensity, especially tunability, as well as optical and thermal stability.

In this context, dibenzophospholes can be regarded as complementary optoelectronic materials and it is interesting to make a comparison of some selected properties of non-fused phospholes, fused dibenzophospholes and dithienophospholes, such as ranges of light absorption and light emission maxima, and luminescence quantum efficiencies. Thus for phospholes, the data are 350–450 nm, 450–620 nm, up to 0.143, for dibenzophospholes the significantly different values are 290–365 nm, 360–490 nm, up to 0.98, and for dithienophospholes the values are 330–420 nm, 415–630 nm, up to 0.90.^{17,18}

The first described dibenzophosphole (IUPAC, CAS: 5*H*-benzo[*b*]phosphindole]) was 5-phenyl substituted derivative 1,¹⁹ obtained by Wittig in 1953, in low yield from a thermal decomposition of pentaphenylphosphorane Ph_5P . Other early methods, most of which were also elaborated by Wittig and coworkers, involved reactions of Ph_5P , Ph_3P , and $Ph_4P^+X^-$ (X = Cl, Br), Ph_3P (O), with both weak (Py) and strong bases (PhMet, Et₂NMet; Met = Li, Na)^{20–23} as well as the reaction of Ph_3P with benzyne (Scheme 2).²⁴

The phosphorus atom in dibenzophospholes offers the possibility of expanding its valency and forming new bonds to O, S, Se, B, N, P, Cl, C and metals in derivatives 2, 3 and 6–8. Dibenzophospholes possessing ionic structures, like the cation 4 and the anion 9 are also known. The phosphorane structure 5 containing two dibenzophosphole units was reported for the first time by Hellwinkel in 1960.²⁵

Synthesis of dibenzophospholes

2.1. From PH₃ and derivatives

In the years 2001–2015, new methods of synthesis of dibenzophospholes have been elaborated starting from PH₃ and its derivatives. Stelzer, Sheldrick *et al.* obtained 5-phenyl-2,2'-bis(sulfonato)-5*H*-dibenzophosphole dipotassium salt **11** by reaction of primary phenylphosphine with 5,5'-bis(sulfonato)-2,2'-difluoro-1,1'-biphenyl dipotassium salt **10** in superbasic medium DMSO/KOH in 60% yield (Scheme 3).²⁶

This research group also obtained the P-unsubstituted dibenzophosphole **14** by reaction of 5,5′-bis(sulfonato)-2,2′-difluoro-1,1′-biphenyl disodium salt **12** with NaPH₂ in liquid ammonia. In this reaction, the trisodium salt **13** was formed first, which upon acidification with aqueous HCl under aerobic conditions gave the dibenzophosphole disalt **14** accompanied by its dimer **15** (Scheme 4).²⁶

Various bridged dibenzophospholes 17-21 have been obtained by a radical phosphanylation. An example of this approach is the reaction of tetrabromobiphenyls **16** (R = H, Ph) with (Me₃Sn)₂PPh in benzene or trifluoromethylbenzene, in the presence of V-40 (1,1'-azobis(cyclohexane-1-carbonitrile)) as a radical initiator followed by a subsequent oxidation of the corresponding intermediate with H₂O₂. In this process, two cis/ trans isomers 17 and 18 were formed in a ratio of 1.0:1.1 in 10% and 11% yields, in benzene and in the same ratio in 27% and 29% yields in trifluoromethylbenzene, respectively. Interestingly, the dibenzophosphole 19 precipitated pure, in 40% yield, by stirring the crude reaction mixture at room temperature overnight. The radical phosphanylation of the biphenyl 16 (R = aryl) led to formation of 4,4'-diaryl-substituted bis(phosphoryl)-bridged biphenyls 20 and 21 in 22% and 13% yields, respectively (Scheme 5).27

Review

 $\begin{array}{c} 2 \text{ PhLi} \\ \hline Ph_5P & \Delta \\ \hline low \ yield \ (ref \ 7) \\ \hline Ph_5P & Py \\ \hline 45\% \ (ref \ 9) \\ \hline Ph_4PBr & Et_2N-Li \\ \hline 87\% \ (ref \ 10) \\ \hline \end{array} \begin{array}{c} 8 & 9 & 1 \\ \hline 7 & A & B \\ \hline 7 & A$

Scheme 2

Zhou and Breit *et al.* obtained 3,7-di-*tert*-butyl substituted dibenzophospholes functionalized at the phosphorus atom by pyridin-2-(1*H*)-on-6-yl, 6-pivalamidopyridin-2-yl and iso-quinolin-1(2*H*)-on-3-yl moieties starting from 2,2'-dibromo-4,4'-di-*tert*-butylbiphenyl.²⁸

Gaunt, Girolami and Kozimor *et al.* described the reaction of PCl_3 with 2,2'-dibromo-1,1'-biphenyl that unexpectedly gave a mixture of 5-chloro- and 5-bromo-5*H*-dibenzophospholes in a 3:2 ratio as a result of halogen exchange. Both 5-halodibenzophospholes after separation behaved similarly in the

subsequent conversion into a new family of dibenzophosphole-based dithiophosphinic acids using elemental sulfur and sodium hydrosulfide hydrate.²⁹

5% (ref 12)

2.2. From ArPCl₂, Ar₂PCl or RPCl₂

Due to easy access to chlorophosphines, the synthesis of dibenzophospholes involving dilithiobiaryls constitutes a convenient source of these compounds. Using this method, Delft *et al.* obtained symmetrical dibenzophospholes **1**, **23** and **24** from the corresponding 2,2'-dibromobiphenyl precursors

F SO_3K KO_3S $PhPH_2$ DMSO, KOH $PhPH_2$ DMSO, KOH DMSO, KOH

bearing H, MeO or CF₃ groups by generation of the corresponding dianion with *n*-BuLi in Et₂O at room temperature followed by quenching the reaction mixture with

Scheme 3

dichlorophenylphosphine to give 5-phenyldibenzophosphole **1**, 2,8-dimethoxy-5-phenyldibenzophosphole **23** and 2,8-bis(trifluoromethyl)-5-phenyl-dibenzophosphole **24** in 55%, 30% and 57% yields, respectively (Scheme 6).³⁰

Gouygou, Leroux *et al.* obtained symmetrical and unsymmetrical dibenzophospholes **26–37** in 30–96% yields starting from 2,2'-dihalobiaryls *via* double halogen/lithium exchange with *n*-BuLi in THF at -78 °C followed by trapping the resulting dilithium derivatives with dichlorophenylphosphine (Scheme 7).³¹

The phosphoniafluorene **39** has been obtained according to the above procedure by dilithiation of the 5,5'-disubstituted 2,2'-dibromo-1,1'-biphenyl **38** followed by condensation of the resulting dilithio derivative with dichlorophenylphosphine PhPCl₂ and then quaternization of the dibenzophosphole phosphorus atom with MeI in THF. After exchange of the iodide

NaO₃S F NaPH₂, liquid NH₃ NaO₃S
$$\frac{13}{\text{NaO}_3\text{S}}$$
 SO₃Na $\frac{12}{\text{NaO}_3\text{S}}$ NaO₃S $\frac{13}{\text{NaO}_3\text{S}}$ SO₃Na $\frac{13}{\text{NaO}_4\text{Na$

Scheme 5

Scheme 6

Scheme 7

Br R
$$\frac{1) \, n\text{-BuLi, 2) PhPCl}_2, \, 3) \, \text{Mel, 4) } [\text{Li}(\text{OEt}_2)_n] \, (\text{BAr}_4)}{\text{THF}}$$

R $\frac{1) \, n\text{-BuLi, 2) PhPCl}_2, \, 3) \, \text{Mel, 4) } [\text{Li}(\text{OEt}_2)_n] \, (\text{BAr}_4)}{\text{CH}_2\text{Cl}_2}$

Ph $\frac{1}{\text{Me}}$

R $\frac{1}{\text{Ph}}$

R $\frac{1}{\text{Ph}}$

R $\frac{1}{\text{Ph}}$

R $\frac{1}{\text{Ph}}$

R $\frac{1}{\text{Ph}}$

R $\frac{1}{\text{Ph}}$

Scheme 8

ion to the BAr $_4$ anion, compound 39 was obtained as a red solid in 57% yield (Scheme 8). 32

This method was also used for the preparation of 2-hydroxy-substituted dibenzophosphole oxides **41–44**. After bromine/lithium exchange on the dibromobiphenyl derivative **40**, the

dilithiated intermediate was treated with either $PhPCl_2$ or (1-menthyl) PCl_2 . Then, the dibenzophospholes were oxidized *in situ* with H_2O_2 and the *tert*-butyldimethylsilyl (TBS) group was removed by reaction with tetra-*n*-butylammonium fluoride (TBAF) to give oxides **41** and **42** in 75% yields. The hydroxy groups

This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Open Access Article. Published on 30 January 2017. Downloaded on 11/8/2025 9:32:23 PM.

RSC Advances Review

Scheme 10

in the latter were converted into the corresponding triflates 43 and 44 by treatment with PhNTf₂. For $R = \iota$ -menthyl, the dibenzophosphole oxide 42 was obtained as a mixture of two epimers with opposite configuration at the stereogenic phosphorus center. The mixture was converted into triflates 44 and the two diastereomers were separated by HPLC (Scheme 9).³³

t-Butyllithium in THF, at -90 °C was also used for iodine/lithium exchange in **45** followed by reaction with PhPCl₂ and oxidation with H₂O₂ to give 3,7-dibromo-5-phenyl dibenzo-phosphole oxide **46** in 47% yield (Scheme 10).²⁷

Another method, described by Ionkin and Marshall in 2003, involved the reaction of the dichloroarylphosphine 47 with potassium in hexanes to give the 5-chlorodibenzophosphole derivative 48 in 64% yield (Scheme 11).³⁴

Scheme 11

In 2006, Wehmschulte *et al.* described the intramolecular Friedel–Crafts type reaction of the dichlorophosphines **49** or **50** initiated by $AlCl_3$ in $[d_6]$ -benzene at room temperature. In this reaction dibenzophospholes **55** and **56** were formed in 29% and 43% yields, respectively, *via* intermediates **51/52** and **53/54**, as yellow-orange oils, which were decomposed to the final products by addition of pyridine (Py) (Scheme 12).³⁵

The same research group synthesised 5-chloro disubstituted dibenzophospholes 58-60 *via* thermolysis of the aryldichlorophosphine 57 at 200-230 °C with HCl evolution (Scheme 13).³⁵

Scheme 13

$$R^{1}$$
 R^{2}
 R^{1}
 R^{2}
 R^{2}
 R^{1}
 R^{2}
 R^{2}
 R^{2}
 R^{2}
 R^{2}
 R^{3}
 R^{2}
 R^{4}
 R^{2}
 R^{2}
 R^{3}
 R^{2}
 R^{4}
 R^{4}
 R^{2}
 R^{4}
 R^{4}
 R^{2}
 R^{4}
 R^{5}
 R^{5}
 R^{5}
 R^{1}
 R^{2}
 R^{4}
 R^{5}
 R^{5}
 R^{5}
 R^{1}
 R^{2}
 R^{4}
 R^{5}
 R^{5}
 R^{5}
 R^{1}
 R^{2}
 R^{4}
 R^{5}
 R^{5

Scheme 12

2.3. From RAr₂P or Ar₃P

5-Phenyldibenzophosphole **1** has also been obtained in a two-step reaction involving addition of 1-lithio-2-diphenylphosphinylbenzene **61** to benzyne **62** followed by cyclisation of the resulting lithio adduct **63**. The starting materials **61** and **62** were obtained from 2-bromophenyl-diphenyl phosphine and **1**,2-dibromobenzene, respectively (Scheme **14**).³⁶

The next method, published by Tobisu, Chatani *et al.* in 2013, involves intramolecular cyclisation of biphenyl derivatives **64** containing PPh₂ and PMePh groups in the presence of catalytic amounts of Pd(OAc)₂ (5 mol%) in toluene through the cleavage of the C–H bond and exclusive cleavage of the P–Ph bond rather than the P–Me one. The dibenzophospholes formed first in these reactions were easily oxidized with hydrogen peroxide at room temperature which led to dibenzophosphole oxides **66** and **67** in 92%, 64% yields, respectively or

reacted with borane dimethylsulfide to give the dibenzophosphole borane **68** in 61% yield (Scheme 15).³⁷

The same reaction, carried out with 1 equivalent of Pd(OAc)₂ (in air), gave 66 in 50% yield, suggesting that the dimeric metallacycle 70 (X-ray analysis) was a plausible intermediate for the catalytic cycle. Dibenzophospholes bearing a range of functional groups (Br, F, CO₂Me, Ac, CN) and an array of fused rings (naphthalene, anthracene, furan, pyrrole) could also be synthesised using this method (Scheme 16).³⁷

The route was also successfully applied to the synthesis of a diverse array of dibenzophospholes **71–88**. The high functional group tolerance allowed access to a range of electronically different dibenzophospholes bearing alkyl **71**, **80**, **83/84**, ether **72**, alkoxyl **82**, amine **73** and **81**, acyl **74**, ester **75**, nitrile **76**, fluoride **77**, chloride **78**, and bromide **79** groups. The C–P bond formation also took place with substrates bearing *ortho* substituents to afford 1-substituted dibenzophospholes **80** and

Scheme 15

RSC Advances Review

81. Substrates with meta substituents underwent a regioselective cyclisation at the less hindered site to form 83 as a major product. This synthesis enabled various π systems including naphthalene and phenanthrene moieties, to be incorporated into the dibenzophosphole core of the compounds 85-88 (Scheme 17).37

Scheme 18

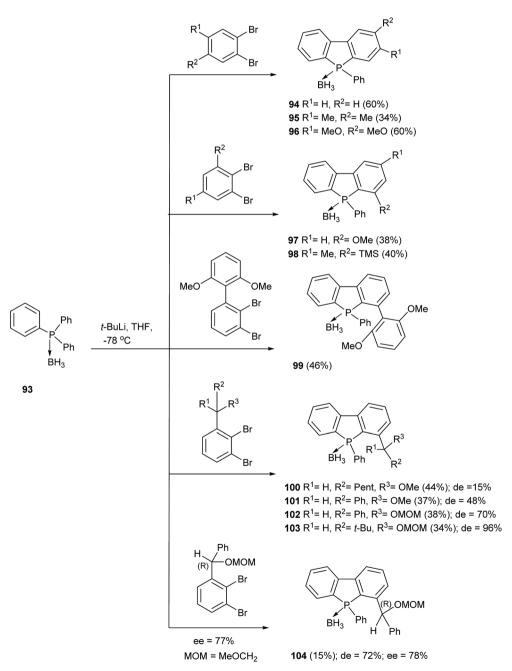
In a special case, this method could also be applied to the synthesis of 5-P-aryl substituted dibenzophosphole 90 bearing an electron-withdrawing p-trifluoromethyl on the aryl group, by cyclisation of bis(trifluoromethylphenyl)-o-(1,1'-biphenyl)phosphine 89 in the presence of $Pd(OAc)_2$, in $[d_6]$ -toluene, the final dibenzophosphole 90 being obtained in 41% yield (Scheme 18).37

In the phosphine 91, carrying one CF₃C₆H₄ group and one phenyl, a mixture of dibenzophosphole oxides 66 and 92 was obtained upon oxidation with H2O2, indicating a preference of the P-CF₃C₆H₄ bond cleavage over the unactivated P-C₆H₅ unit (Scheme 19).37

Another modification of this approach involved the synthesis of the starting phosphine via the Suzuki-Miyaura crosscoupling of o-bromophenyldiphenylphosphine with 2,4-dimethoxyphenylboronic acid, followed by cyclisation in situ, without isolation, to give the final dibenzophosphole oxide.37

Satoh and Miura et al. described the transformation of phenylphosphinothioic amides into fused dibenzophosphole

Scheme 19



Scheme 20

RSC Advances

derivatives through rhodium-catalyzed coupling with heterobicyclic alkenes and intramolecular phospha-Friedel-Crafts reactions in a one-pot manner.38

2.4. From Ar₃P-BH₃

Jugé, Leroux, Colobert et al. reported the first chemo-, regio-, and diastereoselective syntheses of P-chirogenic dibenzophosphole boranes 94-104 based on a transition metal-free, aryne cross-coupling methodology. Most of the reactions started from the tertiary phosphine-borane 93 and a variety of odibromobenzenes to simultaneously create an aryl-aryl bond and the five-membered ring of the dibenzophosphole moiety in 15-60% yields (Scheme 20).36

The use of P-modified boranes 105 in which R^3 or $R^4 = Ph$ has been replaced by tert-butyl (t-Bu), cyclohexyl (Cy) or orthoanisyl (o-An) (2-MeOC₆H₄) groups did not improve yields of these reactions (27-44%). Interestingly, in the case of 105 (R^3 Ph, $R^4 = o$ -An), preferential P-o-An cleavage occurred to give **109** $(R^3 = Ph)$ in 44% yield (Scheme 21).³⁶

2.5. From Ar₂P(O)H or Ar(R)P(O)H

Aryl or alkyl biphenyl hydrophosphine oxides have been applied successfully to the synthesis of 5-aryl and 5-alkyl substituted dibenzophosphole oxides. Thus, starting from secondary hydrophosphine oxides 110, Kuninobu et al. obtained 5-aryl substituted dibenzophospholes 111-117 via phosphinehydrogen and carbon-hydrogen bond cleavages in the presence of a catalytic amount of palladium(II) acetate (Scheme 22). This process was also carried out with [2-(2-naphthyl)phenyl]phenylphosphine oxide as a substrate to give the corresponding dibenzophosphole in 92% yield.39

The same methodology was applied to the synthesis of a mixture of 5-i-Pr substituted dibenzophospholes 120 and 121. These compounds were obtained in a ratio of 70:30, respectively, starting from a mixture of nondeuterated and deuterated phosphine oxides 118 and 119 in the ratio 1:1. Based on these results, it could be assumed that the C-H bond activation of one of the aromatic rings was the rate-determining step (Scheme 23).39

Scheme 21

Scheme 22

Terphenyl bis(hydrophosphine oxide) **122** was also applied in the same manner by Kuninobu *et al.* for the synthesis of a polycyclic, conjugated bis(dibenzophosphole oxide) **123** in 87% yield (Scheme 24).³⁹

Dibenzophospholes were also obtained by the intramolecular radical cyclisation of 2-biphenylaryl and biphenylalkylphosphine oxides **124–126** in the presence of various initiators: 2,2'-azobis-isobutyronitrile (AIBN), benzoyl peroxide (BPO) or Et_3B/O_2 under different reaction conditions. In the case of the phosphine oxide **124** (R = Ph), the use of typical initiators, such as AIBN and BPO in refluxing benzene, gave the corresponding products **127** in 48% and 41%, according to procedures A and B, respectively. Performing the reaction under milder conditions by using triethylborane and oxygen as a radical initiator gave **127** in higher yields of 73% and 87%, respectively (procedures C and D). These reaction conditions were applicable to other substrates **125** and **126** bearing *p*-anisyl and *tert*-butyl groups on the phosphorus atom, respectively to give the corresponding products **128** and **129** in good 96% and 85% yields, respectively (Scheme 25).⁴⁰

This radical methodology has also been applied to the synthesis of bis(dibenzophosphole oxides) having spatially extended systems of π -conjugated bonds, by using a double, intramolecular radical cyclisation of the phosphine oxide **130** in the presence of $\text{Et}_3\text{B/O}_2$, in MeOH. The products of this reaction were two diastereoisomeric bis(dibenzophosphole oxides): **131**-anti and **132**-syn obtained in 16% and 28% yields, respectively (Scheme 26).⁴⁰

2.6. From Ar₃P(O) or ArR₂P(O)

In this subsection, the syntheses of dibenzophospholes that are described start from phosphine oxides containing at least one aryl group. In 2014, Cui, Jiang *et al.* developed a new method for the synthesis of dibenzophosphole oxides **134–142**

Scheme 24

Scheme 26

Scheme 27

Scheme 28

from the readily available $\it ortho$ -halodiarylphosphine oxides 133 by use of $Pd(OAc)_2$ as a catalyst complexed with PCy_3 leading to intramolecular palladium-catalysed arylation (Scheme 27).⁴¹

An intramolecular double arylation catalysed by Pd(OAc)₂ was applied to the synthesis of polycyclic dibenzophosphole oxide **144** starting from the dibromo derivative **143** in 82% yield (Scheme 28).⁴¹

Another intramolecular version of the double arylation was realised by the same research group starting from diaryl-2,5-dibromophosphine oxide 145 and arylboronic acids or heteroarenes. Here, the phosphine complexed Pd(OAc)₂ as a catalyst brought about the intramolecular arylation and, in the same

pot, afforded further functionalised dibenzophosphole oxides **146–152** in 75–87% yields by a Suzuki–Miyaura cross-coupling (**146–148**) or direct cross-coupling with a heteroarene (**149–152**) (Scheme 29).⁴¹

Ishikawa and Manabe obtained the dibenzophosphole **154** in 35% yield by an intramolecular heteroaromatic electrophilic substitution reaction of the phosphine oxide **153** in the presence of triflic anhydride Tf₂O in pyridine. In this reaction, the oxygen atom of the phosphoryl group first reacted with triflic anhydride Tf₂O to generate an electrophilic intermediate and this was followed by electrophilic aromatic ring closure enhanced by the electron-releasing hydroxyl group; final OH/OTf conversion afforded **154** in 35% yield (Scheme 30).⁴²

Stankevič *et al.* synthesised a new group of bulky 5-*tert*-butyldibenzophosphole 5-oxides from acyclic diaryl-*tert*-butylphosphine oxides and organolithiums.⁴³

Other syntheses of dibenzophospholes starting from phosphine oxides of type $ArR_2P(O)$ and $R_3P(O)$ are described in the subsection 2.7.

2.7. From R₂P(O)CH₃ or R₂P(O)OCH₃

Tanaka *et al.* synthesized enantioenriched benzopyrano- or naphthopyrano-fused helical dibenzophosphole oxides **156**, **157**, **160**, **161**, **165** by the rhodium-catalyzed, enantioselective, double [2+2+2] cycloaddition of methyl dialkynylphophinates **155** ($\mathbb{R}^2 = \mathrm{OMe}$) with phenol or naphthol-linked tetraynes in 16–40% yields. In a similar way, dialkynyl methyl and phenyl phosphine oxides **155** ($\mathbb{R}^2 = \mathrm{Me}$, Ph) were employed to afford **158**, **159**, **162**, **163**, **164** and **165** in 30–59% yields (Scheme 31).

Synthesis of dibenzophospholes from aryl substituted phosphine oxides $Ar_3P(O)$ and $ArR_2P(O)$ has been described in the previous subsection 2.6.

2.8. From (RO)₃P(O)

Only one synthesis of dibenzophospholes has been reported starting from organic phosphates. The spirobiphosphoniafluorene **167** was obtained by the reaction of the dilithio derivative, obtained from the 2,2'-dibromo-1,1'-biphenyl **38**, with triphenyl phosphate followed by I/BAr₄ counterion exchange, in 32% yield (Scheme 32).³²

2.9. From Ar₃P=N-R

Synthesis of dibenzophospholes utilizing organophosphorus reagents containing a P=Y bond, where Y is a heteroatom (Y = N, P) other than oxygen, sulfur or selenium are also rare transformations. Nief $et\ al.$ obtained dibenzophospholes by transmetalation of the intramolecularly stabilized lithium derivative 171 to give the potassium salt 172, followed by intramolecular nucleophilic attack of the latter on the phenyl ring to form the intermediate 173. Further aromatization by deprotonation with PhK produced the potassium salt of the 5-amino-dibenzophosphole 174 (R = n-Bu) as a white, insoluble solid. The starting lithium derivative 171 was obtained $via\ NH$ and CH deprotonation of the phosphonium bromide 170 followed by ortho-lithiation of one of the phenyl rings with n-butyllithium in toluene/hexane. The phosphonium bromides

170 were synthesized from triphenylphosphine **168** and primary alkyl amines (R = t-Bu, i-Pr, n-Bu) (Scheme 33).⁴⁵

2.10. From ArP=PMe₃

Simpson, Protasiewicz *et al.* obtained a sterically hindered dibenzophosphole **176** by photolysis of the phosphorane derivative **175** in 90% yield (Scheme 34).⁴⁶

2.11. From phospholes and benzophospholes

An interesting synthesis of dibenzophospholes and their heteroaromatic analogs, in which one benzene moiety was replaced by thiophene, furan, pyrrole or indole, was presented by Mathey *et al.* using a classical 7-phosphanonorbornadiene route developed by this group. First, 3,4-dimethyl-1-cyanophosphole 177 was converted into the phospha-

Scheme 32

$$Ph_{3}P + R-NH_{2} \xrightarrow{Br_{2}, Et_{3}N} \xrightarrow{Ph_{3}P-NH-R} \xrightarrow{2 \text{ n-BuLi} \atop \text{hexane} \atop \text{toluene}}$$

$$R = \text{t-Bu, i-Pr, n-Bu}$$

norbornadiene **178** in a three-step sequence involving a replacement of the CN groups by the corresponding Ar^1-Ar^2 –Li derivative followed by metalation with $W(CO)_5$ -(MeCN) and cycloaddition of the resulting phosphole with acetylene-dicarboxylate. Next, thermolysis of **178** gave tungsten complexes of the dibenzophospholes **180–184** in 60–72% yields, as a result of insertion of the electrophilic phosphinidene intermediate **179** into a C–H bond using carbene-like chemistry (Scheme 35).⁴⁷

Nyulászi, Hissler, Réau *et al.* obtained the air-stable dibenzophosphole sulfide **186** and the dibenzophosphole oxide **187** under aerobic irradiation (320–400 nm) of dilute toluene

solutions of 1-phenyl-2,3,4,5-tetra(3-thienyl)thiooxophosphole **185** (Y = S) and 1-phenyl-2,3,4,5-tetra(3-thienyl)-oxophosphole **185** (Y = O) containing a catalytic amount of iodine, in 10% and 26% yields, respectively (Scheme 36). 48

The photocyclisation of **188**, using the Katz-modified approach, gave a mixture of the monocyclised derivative **189** and the fully cyclised target dibenzophosphapentaphene **190**, in 50% and 20% yields, respectively after separation. Then, treatment of **190** with methyl triflate afforded the phospholium salt **191** in 60% yield. The final phosphapentaphene **192** was obtained by desulfurisation of the latter with $P(NMe_2)_3$, in 50% yield (Scheme 37).⁴⁹

Another method, reported by Matano *et al.* is the cycload-dition of alkynes to biaryls containing a benzophosphole unit, catalysed by palladium(π) acetate, in the presence of pivalic acid (PivOH) and Bu₄NBr. The examples of this method are with compounds **193** (Y = S, NMe) and 4-octyne, in which the authors obtained polycyclic aromatic compounds **195** and **196** containing dibenzophosphole oxide and dibenzothiophene or carbazole units in 14% and 53% yields, respectively (Scheme 38).⁴⁴

3. Functionalisation of dibenzophospholes

Dibenzophospholes can be functionalised at the phosphorus atom and on the two peripheral benzene rings. The functionalisation can be achieved during synthesis of the dibenzophosphole rings or as a result of post-ring-synthesis modifications.

3.1. Functionalisation at phosphorus atom

One of the most important features of the phosphole ring is a low degree of aromaticity and easy availability of a free electron pair on the phosphorus atom, which enables chemical

Scheme 34

RSC Advances Review

modifications of phospholes by oxidation, sulfurization (addition of elemental sulfur), metalation or quaternization. This is due to the fact that tricoordinate phosphorus atom assumes a pyramidal geometry and the lone electron pair at the phosphorus atom has a high degree of s orbital character. These two properties limit the effective interaction between the lone electron pair and the conjugated π -electron system of the phosphole ring.

3.1.1. Oxidation. Oxidation of trivalent phosphorus in dibenzophospholes to the corresponding oxides includes direct methods with oxidizing reagents and indirect ones *via* phosphonium salts or iminophosphoranes.

Stelzer, Sheldrick *et al.* obtained 5-phenyl-2-2'-bis(sulfonato)-5*H*-dibenzophosphole-5-oxide dipotassium salt **197** directly in 92% yield by treating an aqueous solution of the salt **11** with hydrogen peroxide (Scheme 39).²⁶

The dibenzophosphole tripotassium salt **199** was obtained by reaction of 5,5'-bis(sulfonato)-2,2'-difluoro-1,1'-biphenyl dipotassium salt **10** with PH₃ using DMSO/KO*t*Bu as a basic medium. In this reaction, the tripotassium salt **198** was formed first and next reacted with hydrogen peroxide to give **199** in 41% yield (Scheme 40).²⁶

Other examples of the direct oxidation are reactions of substituted 5-phenyldibenzophospholes **200** with hydrogen peroxide in diethyl ether which gave the corresponding oxides **1, 23** and **24** in 85%, 83% and 86% yields, respectively (Scheme 41).⁵¹

The same reagent was employed in the synthesis of fully perfluorinated dibenzophosphole oxide **202** starting from the dibenzophosphole **201** in dichloromethane. Symmetrical diphenyl-, dithienyl- and diphenylethynyl-substituted hexafluorodibenzophosphole oxides **203–205**, could also be obtained in 25%, 60% and 50% yields, respectively (Scheme 42).⁵²

The conversion of P-phenyl into P-alkyl using 5-phenyl-dibenzophosphole 1 followed by P-oxidation to give the

Scheme 38

corresponding oxides has been realized by Durán *et al.* Thus, the reaction of **1** with lithium in tetrahydrofuran delivered a P-lithium derivative, which was first reacted with methyl iodide or ethyl bromide and then was oxidised with hydrogen peroxide. The final oxides **206** and **207** were obtained in 96% yields (Scheme 43).⁵³

In contrast, treatment of 1 with lithium and direct oxidation of the resulting P-lithium salt with peracetic acid $(H_2O_2/AcOH)$

at 45 °C led to the corresponding phosphinic acid **208** in 63% yield (Scheme 44).⁵⁴

Hissler, Réau *et al.* oxidized the phosphorus atom in the dibenzophosphapentaphene **192**, containing a fused dibenzophosphole moiety, with sodium metaperiodate (NaIO₄) in dichloromethane giving the corresponding oxide **209** in 70% yield (Scheme 45).⁴⁹

Chi, Chou and Chang *et al.* modified 5*H*-dibenzophosphole **211**, which was synthesised *in situ* from 5-phenyl dibenzophosphole, by the cross-coupling reaction of the P–H bond with aryl bromide **210** in the presence of CuI as a catalyst, was followed by oxidation of the resulting intermediate with H_2O_2 to give 5-[4-(carbazo-9-yl)phenyl]dibenzophosphole 5-oxide **212** in 34% yield (Scheme 46).⁵⁵

3.1.2. Reduction of P=O and P=N bonds. Diphenylsilane was used by Delft *et al.* in reduction of the P=O bond in dibenzophosphole oxides **213** in $[d_8]$ -1,4-dioxane, at 100 °C to give 5-phenyldibenzophosphole **1**, 2,8-dimethoxy-5-phenyldiben-

F SO₃K KO₃S SO₃K KO₃S

Scheme 40

Scheme 41

zophosphole 23 and 5-phenyl-2,8-bis(trifluoromethyl)-dibenzophosphole 24 in 19–55% yields (Scheme 47).⁵¹

Delft *et al.* also reduced dibenzophosphole iminophosphoranes **214**, by means of diphenylsilane in $[d_8]$ -1,4-dioxane at 101 °C producing the corresponding dibenzophospholes **1** or **23**. For the compound **23** (R = MeO), the reduction of the P=N bond was faster, than for the unsubstituted compound **1** (R = H) (Scheme 48).⁵⁶

The same research group used diphenylsilane Ph_2SiH_2 for reduction of the water-sensitive P=N bond in the dibenzophosphole iminophosphorane 215 which was obtained in the Staudinger reaction of 1 with benzyl azide. Much faster reduction was observed with $PhSiH_3$. Other alkyl, cycloalkyl, allyl and

aryl azides were also employed in the Staudinger reaction with a catalytic amount (10% mol) of the dibenzophosphole 1. This methodology was utilised practically in the synthesis of primary

Scheme 43

Scheme 44

Scheme 42

Scheme 45

Scheme 46

R
Ph₂SiH₂ (1.5 equiv.)

[d₈]-1,4-dioxane, 101 °C
Ph
NBn
1 R = H (74%)
23 R = OMe

Scheme 48

amines via intermediate iminophosphoranes 215 which could be easily hydrolysed with H₂O to the dibenzophosphole oxide 66 (Scheme 49).⁵⁷

López-Calahorra *et al.* used trichlorosilane in toluene to reduce dibenzophosphole oxides **216** to dibenzophospholes **217–219**. The dibenzophosphole **217** was isolated as a colorless oil in 93% yield while **218** and **219** were directly converted into the corresponding cyclopalladates due to a rapid oxidation in air (Scheme 50).⁵⁸

Further examples of reduction of dibenzophosphole oxides are described in subsection 3.1.5 (Schemes 57 and 59).

3.1.3. Sulfurization. In 2012, Hissler, Réau *et al.* obtained the dibenzophosphapentaphene sulfide **190** by the reaction of σ^3 , λ^3 -dibenzophosphapentaphene **192** containing in its fused structure a dibenzophosphole unit, with S₈ in triethylamine, in 20% yield (Scheme 51).⁴⁹

The dibenzophosphole sulfides **220**-*anti* and **221**-*syn* were prepared by conversion of the corresponding oxides **131**-*anti* and **132**-*syn* with Lawesson's reagent in toluene. X-ray studies confirmed two, almost flat P-terphenyl units of the ladder-type. These compounds were obtained in 67% and 54% yields, respectively (Scheme 52). 40

Voituriez and Marinetti *et al.* obtained the phosphine sulfide 223 from the corresponding oxide 222 (R_p) by using Lawesson's reagent, in 79% yield. Photolysis of compound 223 afforded the helicene 224, with M helical configuration, as the major product in 50% yield (Scheme 53).³³

A ferrocene-containing dibenzophosphole sulfide 226 was obtained in the reaction of 5-cyanophosphole 225 with t-butyllithium followed by treatment of the resulting 5-P lithium derivative with a ferrocene (FER) derivative and addition of elemental sulfur. The final product was further converted into the corresponding aldehyde which was then reduced to a primary alcohol (Scheme 54).

3.1.4. Selenylation. A series of substituted dibenzophosphole selenides **228–232** was obtained by addition of elemental selenium to the corresponding dibenzophosphole derivatives **227.** Since the reaction was carried out in deuterated

Scheme 49

HSiCl₃ NEt₃ toluene
$$R^2$$
 Toluene R^3 R^4 R^2 R^3 R^4 $R^$

Scheme 50

Scheme 51

Scheme 52

Scheme 53

(Rp, M)-224 (50%)

Scheme 54

chloroform, at room temperature, in an NMR tube, the yields of this reaction were not determined (Scheme 55).³¹

3.1.5. Metalation. The dibenzophosphole binding with metals via the phosphorus atom requires either a direct availability of a dibenzophosphole P^{III} atom or reduction of P^{IV} to P^{III} atom prior to the binding so that the P-electron pair is available to interact with a metal. Thus, the reduction of the P-phenyl substituted helicene dibenzophosphole oxide (R_p,M) **233** with $HSiCl_3/Et_3N$ followed by reaction with a mixture of $NaAuCl_4-2H_2O$ and 2,2'-thiodiethanol as a reducing agent, afforded the gold chloride complex (R_p,M) **234** in 46% yield (Scheme 56).³³

Scheme 55

RSC Advances Review

Scheme 56

Scheme 57

Another gold chloride complex 235 was obtained in the reaction of the dibenzophosphapentaphene 192 with chloro(tetrahydrothiophene) (Tht) gold(1) in 75% yield (Scheme 57).⁴⁹

The P-menthyl substituted [6]helicene (R_p ,P) 236 was reduced under analogous conditions and reacted with [{Ir(cod) IrCl}₂] (cod = 1,5-cyclooctadiene) to give the helicene 237 in 37% yield (Scheme 58).³³

The dibenzophosphole Fe-complex 239 was obtained in the reaction of 6-substituted dibenzophosphole 238 with $Fe_2(CO)_9$ after crystallisation from benzene, in 76% yield. Analogously, the Ru-complex 240 was obtained in 68% yield after crystallization from chloroform (Scheme 59).³⁵

In 2002, Decken *et al.* obtained Fe-complexes **242** and **243** from dibenzophospholyl-Li **241** and CpFe(CO)₂X (X = Br, I) in THF, at room temperature, in 93% and 87% yields, respectively. Heating **242** or **243** in refluxing xylenes resulted in the

formation of trace amounts of **244** as well as large amounts of intractable green solids, however, in the reaction of bis(1,1'-dibenzophospholyl) **245** and $Cp_2Fe_2(CO)_4$ in refluxing xylenes a mixture of *cis*- and *trans*-isomers **244** was obtained in a 1 : 15 ratio, in 75% yield (Scheme 60).⁶⁰

The same research group obtained (μ_2 -dibenzophospholyl)-(μ_2 -bromo)-dimanganese-octacarbonyl **246** from dibenzophospholyl-Li and Mn(CO)₅Br in THF in 69% yield (Scheme 61).⁶¹

The bis(μ_2 -dibenzophospholyl)-dimanganese-octacarbonyl 247 was obtained by heating of bis(1,1'-dibenzophospholyl) 245 and Mn₂(CO)₁₀ in refluxing xylenes in 78% yield. The same compound was formed by refluxing (μ_2 -dibenzophospholyl)-(μ_2 -bromo)-dimanganese-octacarbonyl 246 in the same solvent (Scheme 62).⁶¹

A mixture of (1-phenyldibenzophosphole)-dimanganesenonacarbonyl **248** and di(1-phenyldibenzophosphole)-

Scheme 59

244-cis

Scheme 60

dimanganese-octacarbonyl 249 was obtained by reaction of 5-phenyldibenzophosphole 1 with dimanganese decacarbonyl in xylenes, in 17% and 13% yields, respectively. (η^1 -

245

Dibenzophospholyl)tris(dimethylamido)titanium **250** was formed by a reductive cleavage of the P–Ph bond in the 5-phenyldibenzophosphole **1** using potassium followed by

244-trans

Mn(CO)₅Br Li 246 (69%) 241

Scheme 61

1

a subsequent acidification with acetic acid and reaction with tetrakis(dimethylamido)titanium (Ti(NMe2)4) in 41% yield (Scheme 63).53,61

Jugé and Gouygou et al. obtained the dibenzophosphole Rhcomplex 252 by reaction of chloro-(1,5-cyclooctadiene)rhodium(1) with the dibenzophosphole 251 in dichloromethane, in the presence of silver tetrafluoroborate, in 86% yield (Scheme 64).62

The dibenzophosphole Pd-complex 254 was formed in the reaction of the dibenzophosphole 253, obtained from 211 and

chlorodibenzotropilydene (toluene, reflux), with dichloro-(1,5cyclooctadiene)palladium(II) (Pd(cod)Cl₂) in dichloromethane, at room temperature, in 95% yield (Scheme 65).63

López-Calahorra et al. synthesized the Pd-complexes 255-257 from dibenzophospholes 217-219 and an optically active dimeric cyclopalladium compound. The reaction of the dimer with the dibenzophosphole 217 gave the complex 255. In the cases of 256 and 257, a mixture of diastereomers was separated by column chromatography followed by decoordination of the dibenzophospholes by the reaction of the pure diastereomers with 1,2-bis(diphenylphosphino)ethane and oxidation of the enantiomerically pure dibenzophospholes to their oxides using H₂O₂ (Scheme 66).58

3.1.6. P-Alkylation. The dibenzophosphole sodium salt 13 obtained from 2,2'-difluoro-5,5'-disulfonato-1,1'-biphenyl 12 by treatment with NaPH2 in liquid ammonia, was utilised as a reactive intermediate in reactions with electrophiles, such as benzyl chlorides and tosylates. Thus, coupling of the sodium salt 13 with 2,2'-bis(chloromethyl)-1,1'-biphenyl in DMF afforded the bidentate ligand 258 containing sulfonated dibenzophospholes moieties in 94% yield. Bis-[2,2'-bis(sulfonato)-5Hdibenzophospholyl]-2,3-O-isopropylidene-D-threitoltetrasodium salt 259 was obtained by reaction of the sodium salt 13 with 1,4di-O-p-toluenesulfonyl-2,3-O-isopropylidene-D-threitol in 1,4dioxane or THF in 20% yield (Scheme 67).26

The reaction of the lithium derivative 261 with (chloromethyl)phosphine borane 260, in the presence of 5%

Scheme 64

Pd(OAc)₂/dppf gave 5-diphenylphosphinylmethylene dibenzophosphole borane **251** in 52% isolated yield. Direct alkylation of **261** without the presence of the Pd catalyst gave **251** in <10% yield (Scheme 68).⁶²

3.1.7. P-Arylation. P-Arylation of unsubstituted dibenzophospholes was realised by a two-step reaction starting with P–H deprotonation of the tungsten complex **180** followed by reaction with BrCN and then with PhLi afforded the tungsten P-arylated dibenzophosphole **262** in 26% yield. The final step involved removal of the W(CO)₅ tungsten moiety by heating with 1,1′-(1,2-ethanediyl)bis(1,1-diphenyl)phosphine in refluxing xylene to give 5-phenyldibenzophosphole **1** in 25% yield (Scheme 69).⁴⁷

3.1.8. P-Quaternisation. The phosphorus atom in the dibenzophosphapentaphene **192** could be quaternised *via* the corresponding dibenzophosphapentaphene sulfide by reaction with methyl triflate to give **191**, or directly with MeOTf to give **263** in 45% yield (Scheme 70).⁴⁹

3.2. Functionalisation of benzene units

The second method of functionalization of dibenzophospholes is introduction of substituents onto one or two benzene rings including functional group interconversions. An example of such a process is shown in Scheme 71. Electrophilic bromination of 5-ethyl-5H-dibenzophosphole 5-oxide 264 with bromine in acetic acid at 45 °C gave the 5-ethyl-3-bromo-5H-dibenzophosphole 5-oxide 265 in 53% yield followed by electrophilic nitration of the second benzene ring and reduction of the NO₂ to NH2 group with iron under acidic conditions. Further diazotization with sodium nitrite in a cooled mixture of sulfuric acid and water led to the corresponding diazonium salt which was decomposed by addition of copper(1) oxide in the presence of copper(II) nitrate. Subsequent reaction of the phenolic OH group so formed with (S)-2-methyl tosylate in the presence of potassium carbonate gave the chiral product 267 in 95% yield. Conversion of the bromine atom to a carboxylic group was

$$R^{1} \xrightarrow{R^{2}} R^{2} \xrightarrow{H} H$$

$$THF$$

$$255 R^{1} = H, R^{2} = H, R^{3} = Me (83\%)$$

$$256 R^{1} = CN, R^{2} = H, R^{3} = Me (85\%)$$

$$R^{1} \xrightarrow{R^{2}} R^{2} \xrightarrow{R^{3}} R^{2}$$

$$R^{2} \xrightarrow{R^{3}} R^{2} \xrightarrow{R^{3}} R^{2$$

Scheme 66

NaO₃S

NaO₃S

SO₃Na

TsO

Me

TsO

Me

TsO

Me

TsO

Me

Me

Scheme 67

SO₃Na

258 (94%)

NaO₃S

NaO₃S

realised by a cross-coupling reaction with potassium cyanide in the presence of palladium(π) acetate followed by alkaline hydrolysis with Ca(OH)₂ to give the acid **268** in 80% yield. Finally, the latter was esterified with 4-(undec-10-enoxy)phenol to give **269** also in 80% yield (Scheme 71).

Dibenzophosphole ring elongation was realised via the cross-coupling reaction of the 3-bromo dibenzophosphole 270

with (2-benzylaminophenyl)pinacolatoboron to give the biaryl derivative **271**, followed by cyclisation of the latter to afford a fused polyaromatic compound **272** in 71% yield (Scheme 72).³⁷

259 (20%)

3,7-Bis(4-diphenylamino)phenyl substituted dibenzophosphole 273 was obtained via the double Suzuki-Miyaura cross-coupling reaction of 46 with 4-(diphenylamino)phenylboronic acid in the presence of Pd(PPh₃)₄ in 80% yield (Scheme 73).²⁷

Voituriez and Marinetti *et al.* functionalised dibenzophosphole oxides by incorporating them into larger [6]- and [8]-helicenes. The triflates of the dibenzophosphole oxides 43, (S_p) 274 and (R_p) 275 were submitted to Suzuki cross-coupling reactions with a benzophenanthrene-substituted olefinic boronate. The coupling reactions were performed in the presence of $[PdCl_2(SPhos)_2]$ (SPhos = 2-dicyclohexyl-phosphino-2',6'-dimethoxybiphenyl) as the catalyst under standard conditions. The corresponding olefinic derivatives 276, (S_p) 277 and (R_p) 278 were obtained in high yields (78--87%). The photochemical cyclisation of compound 276 (R = Ph) in cyclohexane/THF led to

Scheme 69

Review

1. S₈, NEt₃

2. MeOTf

Scheme 70

the formation of a mixture of [6]- and [8]-helicenes **279** and **282**, in a 7:3 ratio, in 31% and 20% yields after purification, respectively. The cyclisation of **277** afforded a mixture of isomeric **280** from which (S_p,P) **280** was isolated in 40% yield. The oxidative photocyclisation of **278** led to a mixture of (R_p,M) **281** and (R_p,P) **283**, in a 50:42 ratio. Each isomer was isolated in 30% yield (Scheme 74).³³

4. Optoelectronic properties of dibenzophosphole derivatives

Dibenzophospholes and their derivatives belong to a group of polycyclic fused heteroaromatic compounds with spatially developed systems of π -type bonds, which play an important role in modern, lightweight and low-cost electronic elements

RSC Advances Review

such as photovoltaic cells (PV), organic light emitting diodes (OLEDs) and field effect transistors (FETs). The functionalisation of one or both benzene rings and/or derivatization of the

 $P^{\rm III}$ atom (as P^+ or P=X, where X = N, O, P, S, Se) necessarily results in modification of physicochemical properties of the dibenzophospholes such as: solubility, HOMO/LUMO energy levels, ionization potentials, energy gap, wavelength as well as intensity of absorption and emission. By careful selection of such modifications, new optoelectronic materials with improved properties can be produced.

4.1. Non-fused dibenzophospholes

4.1.1. Simple dibenzophospholes. Several promising compounds for optoelectronics have been reported and include dibenzophospholes **1**, **66**, **228**, **284–291** containing various substituents on the phosphorus atom. These have potential applications in sundry optoelectronic elements including photovoltaic cells, organic light-emitting diodes (OLEDs), bio-and chemical sensors and nonlinear optical devices NLOs (Scheme 75).^{12,65}

Chen and Huang et al. presented a theoretical study on the optical and electronic properties of dibenzophospholes 1, 66, 228, 284-290, involving calculations of the highest occupied molecular orbitals (HOMO), the lowest unoccupied molecular orbitals (LUMO), triplet energies (${}^{3}E_{g}$), energy gaps (E_{g}) as well as other calculations leading to: ionization potentials (IPs), electron affinities (EAs), including calculations of the reorganization energies (λ) and singlet exciton generation fractions (χ_s) , together with radiative lifetimes and emission spectra. Optoelectronic properties of these compounds were compared with carbazoles 292, which are currently one of the most commonly used chemical units in optoelectronic devices. The dibenzophospholes 1, 66, 228, 284-290 had lower levels of the HOMO and LUMO than the carbazoles 292. However, the compounds 1 and 284 had a wider range of energy gaps, relative to carbazole analogues due to the nonplanar molecular structures and stronger electron-donating ability of the phosphorus atom. Chemical modifications of the PIII atom through oxidation, sulfurization and selenylation led to a gradual increase of the HOMO levels in the following order: -6.26 eV (287) < -5.83 eV (288) < -5.43 eV (286), -6.23 eV (66) < -5.86 eV (285) <-5.51 eV (228), while the LUMO decreased to around -1.55 eV, which was far below the LUMO levels of 1 and 284. This correlation showed that introduction of electron-withdrawing substituents (O, S, Se atoms) enhanced the injection and electron-transport abilities of the dibenzophospholes 66, 228, 285-286 and 288. For the ionized compounds 289 and 290

(P+Me and P+Ph), the positively charged phosphorus atom reduced the hole injection, but enhanced the electron-accepting ability of these compounds. The energy gap decreased in the following order: 4.95 (284) > 4.94 (1) > 4.80 (287) > 4.75 (66) > 4.52 (290) > 4.51 (289) > 4.33 (285) > 4.28 (288) > 3.97 (228) >3.88 eV (286). The triplet energies (${}^{3}E_{g}$) of the dibenzophospholes 1, 66, 228, 284-288 showed their potential applications as host materials, as well as revealed that dibenzophospholes 1 and 284 could be promising building blocks for the host materials. For the dibenzophospholes 1, 66, 284 and 287, the calculated singlet and triplet exciton-formation cross section σ_s $\sigma_{\rm t}$ and corresponding singlet exciton generation fractions ($\chi_{\rm s}$) suggested their potential as highly efficient fluorescent-lightemitting materials. The chemical modification of the PIII atom with S and Se atoms, in the dibenzophospholes 228, 285, 286 and 288 caused a slight decrease of the χ_s values in the range of 15–20%. The calculated values of the ionization potentials (IPs) and electronic affinities (EAs) showed that dibenzophospholes could be used simultaneously as electron-transport and holetransport materials according to different substitutions on the P atom. The abilities to create holes and to accept electrons were improved by the introduction of strong electron-withdrawing substituents or replacement of P-methyl for P-phenyl. For the dibenzophospholes 66 and 287, smaller hole transport reorganization energies (λ_{hole}) were calculated than their electron transport reorganization energies ($\lambda_{\text{electron}}$), which means faster hole transport than electron transport in these compounds. The **RSC Advances**

opposite correlation occurred in the dibenzophospholes 228 and 286 for which values of λ_{hole} were bigger than their values of $\lambda_{electron}$ and indicated a slower hole transfer, than the electron transfer. The time-dependent density functional theory (TD-DFT) calculations showed electron transitions for dibenzophospholes 1, 66, 284-285, 287-288 as well as their effect on the emission spectra in both vacuum and solvent (THF) as shown in Fig. 2.65

Based on the theoretical emission spectra, the dibenzophospholes 1, 66, 284-285, 287-288 may constitute deep blue light emitting materials in the range of $\lambda_{em} = 327-419$ nm. The Stokes shifts of 1 and 284 were calculated to about 45 nm, and the shifts of their derivatives 66, 285, 287 and 288 were all

around 65 nm relative to carbazoles 292, the Stokes shifts of which were within 10 nm. The calculated emission spectra of dibenzophospholes 66, 285, 287 and 288 in vacuum, were red shifted and thio-modified dibenzophospholes 285 and 288 showed a small intramolecular charge-transfer emission at $\lambda =$ 415 nm. The solvent effects led to larger Stokes shifts of dibenzophospholes 284, 287 and 288 in comparison to the carbazole analogues 292. For the compounds 284 and 287, THF stabilized their excited states, causing small red shifts (4-10 nm) of the emission spectra in comparison with those in vacuum. The opposite correlation was observed in the dibenzophosphole 288, where the solvent effects stabilized the ground state and induced the blue shift of the emission spectra.

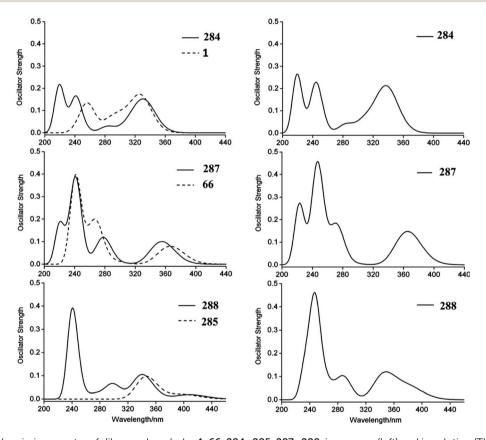


Fig. 2 The simulated emission spectra of dibenzophospholes 1, 66, 284-285, 287-288, in vacuum (left) and in solution (THF, right)⁶⁵ (reprinted with permission from the American Chemical Society).

Table 1 Wavelengths of maximum absorption (λ_{abs}), half-wave potential ($E_{p1/2}$), wavelengths of maximum emission (λ_{em}), quantum yields of photoluminescence (ϕ_{PL}), decomposition temperature (T_d) and molar absorption coefficient (ε) of the compounds 66, 285 and 291, in CH₂Cl₂

	UV-Vis absorption		Photoluminescence	e (PL)	Electrochemical properties	Thermal properties
Compound	$\lambda_{\rm abs}[nm]$	$\log \varepsilon$	$\lambda_{em}\left[nm\right]$	$\phi_{ m PL}$	$E_{\mathrm{p1/2}}\left[\mathrm{eV}\right]$	$T_{\rm d}^{\ a} \left[{}^{\circ}{ m C} \right]$
66 285	332 330	2.9 2.9	366 366	0.042 0.002	-1.93 -1.92	213 220
291	330	3.0	366	0.134	-1.80	220

^a TGA, 10% weight loss.

The radiative lifetimes were calculated by using Einstein transition probabilities for the compounds 1, 66, 284–285, 287 and 288. The dibenzophospholes 285 and 288 showed longer lifetimes than commonly used carbazoles 292, whereas the dibenzophospholes 1, 66, 284 and 287 had similar radiative lifetimes in comparison to the commonly used carbazoles 292.

In addition to this theoretical study, further investigations with thermogravimetric analysis (TGA) showed that the derivatives **66**, **285** and **291** possess good thermal stabilities. This is important for the fabrication of OLEDs, because low-molecular weight species are often deposited as thin films by vacuum evaporation. The derivatives **66**, **285** and **291** emitted in the UV region and were photoluminescent. The Stokes shifts of these compounds were relatively small (about 32–36 nm), which suggested a minimal rearrangement of molecules during photoexcitation. The quantum yields were dependent on the nature of the groups attached to the phosphorus atom. Selected photophysical, electrochemical and thermal data for these compounds are presented in Table 1.¹²

In 2011 the group of Anzenbacher Jr *et al.*⁶⁶ investigated solid-state interactions, fluorescence and phosphorescence properties of dibenzophospholes **66**, **228** and **285** as single crystals and the mixed crystals of **228** and **285** acquired in CH₂Cl₂/MeOH glass at 77 K. Moreover, an X-ray diffraction analysis was carried out, which indicated that the mixed crystal of **228** and **285** showed a larger number of intermolecular interactions such as π - π and Se-H, than each of them in the single crystals. The fluorescence maxima of the dibenzophospholes **66**, **228**, **285** in a glass corresponded to the wavelength at $\lambda = 363$ -364 nm. However, in the compounds **228** and **285** the fluorescence was strongly suppressed due to the higher spin-orbit coupling of selenium **228** and sulfur **285**.

Additionally, these compounds exhibited comparable emission spectra with broad phosphorescence at $\lambda=450$ –660 nm. The phosphorescence lifetimes $(\tau_{\rm ph})$ of the dibenzophospholes **66**, **228** and **285** were $\tau_{\rm ph}=312$ ms, 0.54 ms and 21 ms, respectively. The emission and phosphorescence spectra of the single crystal of **66** were red-shifted compared to the spectrum reported in the glass, due to the intermolecular interactions in the solid state, however, the lifetime of **66** was shorter when compared to the glass. Similar red-shifts were observed for single crystals of **228** and **285**, in the fluorescence and phosphorescence spectra. Furthermore, the mixed crystals of **228** and **285** exhibited only phosphorescence and presented carrier transport and emission properties. This advantage may be applied in the light-emitting single crystal organic field-effect transistors (SC-OFETs). ⁶⁶

Chi, Chou and Chang *et al.* obtained 5-[4-(carbazo-9-yl) phenyl]dibenzophosphole-5-oxide **212**, which was used in the construction of the three-layer OLEDs as a bipolar host material.

This compound consisted of carbazole and dibenzophosphole moieties, which served as electron donor and acceptor, respectively. The carbazole derivatives are known as hole-transporting materials, with high triplet energy gap, which makes them efficient host materials for the phosphorescent dopants. Moreover, the phosphine oxide moiety facilitates the

Scheme 77

Table 2 Selected properties of the compound 212^a

Photophysical properties Electrochemical properties					Thermal properties			
$\lambda_{abs}\left[nm\right]$	$\lambda_{\mathrm{Ph}}\left[\mathrm{nm}\right]$	$\lambda_{PL}\left[nm\right]$	$E_{1/2}^{\mathrm{ox}}\left[\mathrm{V}\right]$	$E_{1/2}^{\mathrm{red}}$ [V]	HOMO [eV]	LUMO [eV]	$E_{\rm s}$ [eV]	$T_{ m d} \ [^{\circ}{ m C}]$
292	425	458	0.98	-2.33	-5.78	-2.33	3.55	365

^a The oxidation and reduction experiments were conducted in CH_2Cl_2 and THF solution, $E_{1/2}$ (V) refers to $[(E_{pa} + E_{pc})/2]$, where E_{pa} and E_{pc} were the anodic and cathodic peak potentials referenced to the Fc⁺/Fc couple, $E_s = |HOMO - LUMO|$ from the redox data.

RSC Advances

electron injection and transport without lowering of the triplet energy gap (Scheme 76).55

The selected electrochemical, thermal and photophysical characterisation of the dibenzophosphole 212 is presented in Table 2.

Additionally, thermogravimetric analysis (TGA) of the dibenzophosphole 212, which decomposed at 365 °C, showed that this compound is capable of forming stable films upon thermal evaporation.

Other potential optoelectronic materials are dibenzophospholes 39 and 167. These compounds exhibited strong acceptor

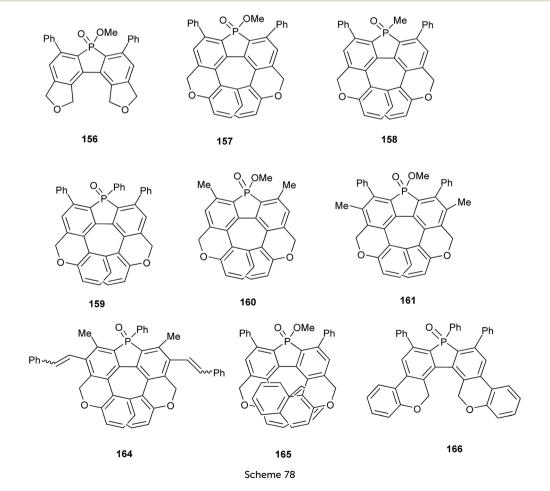
Table 3 Selected optical properties of the dibenzophospholes 39 and 167 and their silicon analogues, in CH₂Cl₂ (ref. 32)^a

UV-Vis absorption		Fluorescence		Two photon absorption (TPA)	
Compound	λ _{max} [nm]	$\varepsilon/10^5 \mathrm{\ M}^{-1}$ $\mathrm{[cm}^{-1}]$	$\lambda_{\mathrm{em}}\left[\mathrm{nm}\right]$	$\phi_{ m F}$	$\lambda_{\mathrm{max}}^{2} [\mathrm{nm}]$
39	464	0.57	647	0.52	932
167	496	1.03	715	0.04	932
293	376	0.76	464	0.16	752
294	395	2.37	492	0.28	775

 $^{^{}a}$ $\sigma^{(2)}$ divided by the molar mass (MW).

properties and showed enhanced two-photon absorptions at $\lambda =$ 932 nm, therefore these compounds should be useful as longwavelength emissive materials (Scheme 77).32

The absorption and emission maxima of the dibenzophospholes 39 and 167 showed bathochromic shifts compared with their silicon analogues 293 and 294, due to the strong acceptor properties of the phosphonium cores. The effect of solvents on optical properties in toluene, acetone and dichloromethane was also investigated for these compounds. The longest absorption wavelengths of the dibenzophospholes 39 and 167 were at $\lambda = 460$ and 495 nm, respectively in toluene and were almost the same as those in CH2Cl2. However, in acetone, the dibenzophospholes 39 and 167 exhibited blueshifted absorption maxima at $\lambda = 430$ and 467 nm, respectively. The dibenzophosphole 39 exhibited higher fluorescence quantum yield, than its spirocyclic analog 167, which emitted much weaker fluorescence. The opposite trend was observed for the silicon compounds, in which spirocyclic framework of 293 improved the quantum yield. Another important difference was reported for fluorescence properties of dibenzophospholes and their silicon analogues. The emission bands of silicon derivatives 293 and 294 exhibited maxima at $\lambda = 464$ and 492 nm, while dibenzophospholes 39 and 167 were bathochromically shifted to $\lambda = 647$ and 715 nm, respectively, in CH₂Cl₂. The twophoton absorption (TPA) showed maxima for the silicon



analogues **293** and **294** at $\lambda = 752$ and 775 nm, respectively. However, for the dibenzophospholes **39** and **167**, the TPA maxima were in accordance with the bathochromic shifts and were red-shifted. Photophysical characterisation of the investigated compounds is summarized in Table 3.

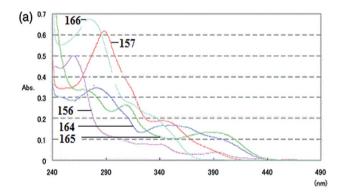
4.1.2. Helicene type dibenzophospholes. Structurally unique benzopyrano- and naphthopyrano-fused helical dibenzophospholes **156–161** and **164–166** are also interesting candidates for organic semiconducting materials (Scheme 78).⁴⁴

Optical data for the dibenzophospholes **157–161** and **164–166** compared with the dibenzophosphole **156**, which does not

Table 4 Photophysical properties of the fused helical dibenzo-phospholes 156-161 and 164-166 in CHCl₃ (10^{-5} M)

	UV absorption	$\frac{\text{Emission}^a}{\lambda_{\text{max}} [\text{nm}]}$	
Compound	$\lambda_{\max}\left[nm\right]$		
156	259, 341	375	
157- (-)	288, 341	477	
158-(-)	288, 344	471	
159-(-)	289, 337	474	
160-(-)	281, 338	469	
161-(-)	285, 343	464	
164-(+)	$281, 348^b$	482^b	
165- (+)	308, 386	490	
166	275	406	

^a Excited at 280 nm. ^b Measured for a E/Z mixture.



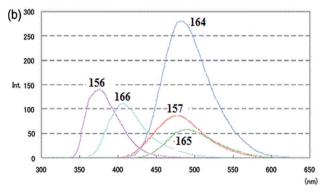


Fig. 3 UV-Vis absorption and emission spectra of compounds 156–157 and 164–166, in CHCl₃ $(10^{-5}\text{M})^{44}$ (reprinted with permission from the American Chemical Society).

contain the 2-alkoxyphenyl group, showed large red-shifts of absorption and emission maxima. The substituents on the phosphorus atom showed a small impact on the absorption and emission maxima in dibenzophospholes **157–159**, which oscillated around at $\lambda=288$ nm and 475 nm, for the absorption and emission maxima, respectively. The same effect was observed for substitutions at the 2- and 7-positions in dibenzophospholes **161** and **164**. Compound **160** exhibited absorption maximum at a similar wavelength as **164**, but the emission was less shifted. The farthest red-shifts for the absorption and emission maxima were observed for the dibenzophosphole **165** (Table 4 and Fig. 3).⁴⁴

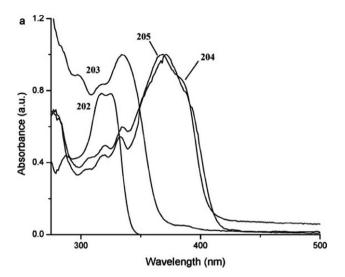
4.1.3. Perfluorinated dibenzophospholes. Interesting examples of benzene ring functionalisation are perfluorinated derivatives **202–205**. The fluorine atoms in the aromatic systems stabilised LUMO energy levels and improved electron transport and cofacial packing. The dibenzophospholes **202–205** have a potential application as n-type electronic components with useful electron transport properties what makes them interesting candidates for devices based on electro- and photoluminescence (Scheme 79).⁵²

The absorption and emission spectra of the derivatives **203–205** were slightly red-shifted in comparison to the dibenzophosphole **202**. The photoluminescence spectra of all

Table 5 Wavelengths of absorption (λ_{abs}) , emission maxima of photoluminescence (λ_{em}) , quantum yields (ϕ_{PL}) of the compounds 202–205, in solution and solid state

	UV-Vis absorp		Photoluminescence			
Compound	$\lambda_{ m abs} \ [m nm]$	$\log \varepsilon$	λ _{em} [nm] solution	$\phi_{ ext{PL}}$ solution	$\lambda_{\rm em}$ [nm] solid	
202	325	3.6	365	0.18^{a}	378	
203	338	3.8	395	0.60^{a}	428	
204	385	_	424	0.54^{b}	_	
	369		443			
205	380	3.7	414	0.98^{b}	472	
			432			

 a Referenced to 1,4-bis-(5-phenyl-2-oxazolyl) benzene (POPOP) in THF ($\phi_{\rm F}=0.9$). b Referenced to 9,10-diphenyl anthracene in THF ($\phi_{\rm F}=0.9$).



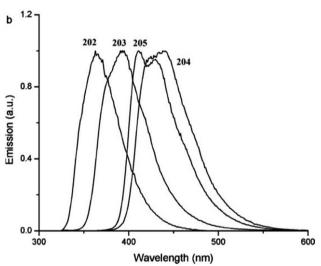


Fig. 4 UV-Vis absorption (a) and emission (b) spectra of the compounds **202–205** in THF⁵² (reprinted with permission from the American Chemical Society).

investigated compounds **202–205** showed maxima between $\lambda_{\rm em}=365$ to 432 nm. These values were in the ultraviolet to violet range and corresponded to blue light emission, for the solution and solid states. The quantum yields of dilute solutions varied significantly with the nature of the 3,7-substituents. The highest value was observed for the derivative **205**. The optical properties of these compounds are presented in Table 5 and Fig. 4.⁵²

Tilley *et al.* investigated electrochemical properties of dibenzophospholes **202–205**. Selected results are summarized in Table 6.

The 3,7-thienyl and alkynyl disubstituted derivatives 204 and 205 exhibited a decrease of LUMO values by 0.1–0.3 eV compared to the dibenzophosphole 202, due to their slightly longer conjugation length. Additionally, the thienyl dibenzophosphole 204 exhibited higher HOMO energy level, than the alkynyl derivative 205. The derivative 203 had the widest range of the energy gap. The low values of LUMO levels in

Table 6 Values of HOMO, LUMO energy levels and energy gap ($E_{\rm g}$) of the compounds 202–205 in acetonitrile (0.1 M n-Bn₄N⁺PF₆ $^-$ in CH₃CN)

Compound	$HOMO^a$ [eV]	$LUMO^a$ [eV]	$E_{\rm g}$ [eV] solution
202	_	-3.0^{b}	_
203	-6.7	-3.0^{b}	3.7
204	-6.2	-3.1^{b}	3.1
205	-6.5	$-3.3^{b,c}$	3.2

 $[^]a$ Referenced to Fe/Fe $^+$. b Reversible reduction. c Three drops of toluene was added to improve solubility in CH $_3$ CN.

dibenzophospholes 202–205, suggested that these compounds could be useful as n-type conducting materials.⁵²

4.2. Fused dibenzophospholes

4.2.1. Linearly fused dibenzophospholes. Several dibenzophospholes have been reported that are attractive prospects for optoelectronic uses, including **129**, **131**-*anti*, **133**-*syn*, **220**-*anti*, **221**-*syn*. These compounds attract increasing attention due to relatively small HOMO-LUMO energy gaps and the possibility to tune their properties through diverse functionalisations at the phosphorus atom (Scheme 80).⁴⁰

The dibenzophosphole oxide 129 showed absorption maximum at $\lambda_{abs}=340$ nm and emission at $\lambda_{em}=382$ nm, for the CH₂Cl₂ solution. The absorption and emission maxima of the dibenzophospholes 131-anti and 133-syn were red-shifted compared to the derivative 129 related to π -expansion through the $\sigma^*-\pi^*$ conjugation of the π -framework to the σ^* orbital of the exocyclic P-C bonds. The dibenzophosphole oxides 131-anti and 133-syn exhibited high fluorescence quantum yields of 0.89 and 0.79, in solution. In the solid state, the quantum yield of both compounds were somewhat lower. In this state, the quantum yield of 133-syn ($\phi_F=0.63$) was larger than that of 131-anti ($\phi_F=0.46$), indicating that interactions in the solid state were different for both diastereomers due to conformational difference.

Scheme 80

Table 7 The values of absorption and fluorescence maxima of the compounds 129, 131-anti, 133-syn, 220-anti and 221-syn, in CH₂Cl₂

	UV-Vis absorp	tion	Fluorescence					
Compound	$\lambda_{\mathrm{abs}}\left[\mathrm{nm}\right]$	$\log \varepsilon$	λ_{em} [nm] solution	$\phi_{ ext{F}}{}^a$ solution	$\lambda_{\mathrm{em}}\left[nm\right]$ solid	$\phi_{ ext{F}}^{a}$ solid		
129	340	3.19	382	0.67	_	_		
131 -anti	391	3.68	426, 438	0.89	454	0.46		
133 -syn	391	3.61	426, 438	0.79	476	0.63		
220 -anti	385	3.73	430	0.004	437, 471, 501	0.12		
221-syn	386	3.72	431	0.004	476, 500	0.04		

^a Absolute quantum yield determined by an integrating sphere system.

The dibenzophosphole sulfides **220**-anti and **221**-syn revealed different photophysical properties compared with the dibenzophosphole oxides **131**-anti and **133**-syn. The absorption maxima of the sulfides had almost the same values of $\lambda_{\rm abs}=385~{\rm nm}~(\log~\epsilon=3.73)$ and $\lambda_{\rm abs}=386~{\rm nm}~(\log~\epsilon=3.72)$ for **220**-anti and **221**-syn, respectively. These electronic properties led to blue-shifted absorption maxima of the dibenzophospholes sulfides in comparison with those of the dibenzophosphole oxides. The fluorescence quantum yields of the sulfides **220**-anti and **221**-syn, in solution dramatically dropped down to 0.004 in comparison to oxides **131**-anti and **133**-syn, but in the solid state increased to 0.12 and 0.04 for **220**-anti and **221**-syn, respectively. The selected photophysical properties of the investigated compounds are summarized in Table 7.40

The linearly fused dibenzophospholes **195** and **196** are also promising for optoelectronics devices, in which optical properties were highly dependent on the combination of benzo [b](thiophene or pyrrole) subunits (Scheme 81).⁵⁰

The UV-Vis absorption and emission spectra of the dibenzophospholes **195** and **196** were significantly blue shifted relative to the corresponding non-fused biaryl substrates **193** (see subsection 2.11). The Stokes shifts of the rigid fused structures of **195** (3829 cm $^{-1}$) and **196** (4810 cm $^{-1}$) were smaller than those of the biaryl substrates **193** (R = S) (4250 cm $^{-1}$) and **193** (R = NMe) (7000 cm $^{-1}$).

Table 8 The optical characterisation of the compounds 195 and 196 and their precursors 193 (R = S, NMe), in CH_2Cl_2 (ref. 50)

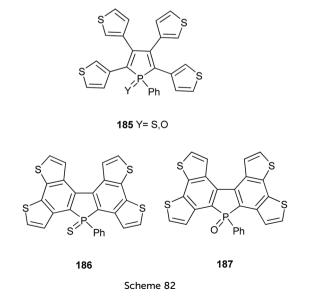
	UV-Vis absor	psorption Fluorescence		
Compound	$\lambda_{abs}\left[nm\right]$	$\log \varepsilon$	$\lambda_{\mathrm{em}}\left[nm\right]$	$\phi_{ ext{F}}{}^a$
193 (R = S)	377	4.31	450	0.17
193 $(R = NMe)$	393	4.07	542	0.44
195	344	3.96	396	0.13
196	355	4.08	431	0.24

^a Excited at λ_{abs} 400 nm for the ϕ_{F} measurements.

Density functional theory (DFT) calculations at the B3LYP/6-31G* level showed widening of the HOMO-LUMO gap upon acetylene fusion. The energy gaps were changed from 3.53/3.34 eV for 193 (R = S, NMe) to 4.10/3.85 eV, for 195 and 196, respectively.

The fluorescence decay curves of the compounds **195** and **196** in CH_2Cl_2 were fitted as a single exponential with lifetimes of 2.2 and 7.9 ns. More photophysical properties of **195** and **196** including quantum yields are displayed in Table 8.⁵⁰

4.2.2. Thiophene modified fused dibenzophospholes. The compounds **186** and **187** obtained from **185** (Y = S, O) possess



a considerable dibenzophospholes character based on optical properties in the solid state (Scheme 82).⁴⁸

The dibenzophospholes **186** and **187** compared to the respective nonfused precursors **185** (Y = S, O) showed blue-shift absorption maxima, higher oxidation and lower reduction potential values, which indicated the less efficient electron π -delocalization over the sp²-C atoms of **186** and **187** and typical for the dibenzophospholes, increased localization of the π -electrons within aromatic subunits. Although, the dibenzophospholes **186** and **187** were emissive materials with $\lambda_{\text{max}} = 475$ and 477 nm, respectively, their quantum yields oscillated at around **1%**. Photophysical properties of these compounds are presented in Table 9.⁴⁸

Table 9 The optical data of the dibenzophospholes 186 and 187 and their precursors 185 (Y = S, O) in CH_2Cl_2

	UV-Vis absorpt	Fluorescence	
Compound	$\lambda_{max}\left[nm\right]$	$\log \varepsilon$	$\lambda_{\rm em} [nm]$
185 $(Y = S)$	413	3.48	484
185 $(Y = O)$	411	3.83	_
186	391	3.56	475
187	389	3.63	477

4.2.3. Benzene modified fused dibenzophospholes. Fused benzene modified dibenzophospholes **190–192**, **209**, **235** and **263**, which have the same fused aromatic C skeleton but different P moieties, have been successfully utilized as organic materials for optoelectronics (Scheme 83).⁴⁹

The optical and electrochemical properties of these dibenzophospholes were investigated to evaluate the impact of the P modifications on their electronic properties. The absorption spectra of the all investigated fused dibenzophospholes 190-192, 209, 235 and 263 varied over a wide range covering the entire visible spectrum. In the absorption spectrum of the dibenzophosphole 192, an intense characteristic band at λ_{max} = 472 nm was observed. The absorption maxima of the σ^4 -P derivatives 190, 209 and 235 were shifted towards higher wavelengths. A larger bathochromic shift was observed for Palkyl and P-S phospholium salts 263 and 191. Addition of a phenyl group to phosphorus in the dibenzophosphole 192 resulted in a shift of its maximum absorption towards higher wavelengths. All of these dibenzophospholes were fluorescent in solution, with gradual red shifts of the λ_{em} in the compounds 190-192 and 263. The Stokes shifts for rigid structures in the compounds 192, 190, and 263 were relatively small (737, 1072, 1355 cm⁻¹, respectively). Furthermore, the emission bands indicated a small rearrangement of these molecules upon photoexcitation and for this reason their quantum yields were

Scheme 83

Table 10 Wavelengths of absorption maxima (λ_{abs}) , logarithm of the molar absorption coefficient (log ε), wavelength of emission maxima (λ_{em}) , fluorescence quantum yields (ϕ_F) , oxidation potentials (E_1^{ex}) , reduction potentials (E_1^{ex})

	UV-Vis abso	orption	Fluorescence		Redox potentials	
Compound	$\lambda_{\rm abs}^{a}$ [nm]	$\log \varepsilon^a$	$\lambda_{\mathrm{em}}{}^{a} [\mathrm{nm}]$	$\phi_{ m F}^{\ \ a,b}$	$E_1^{{ m ox}b}$	$E_1^{\mathrm{red}c}$
190	514	4.04	544	0.21	0.71	-1.70
191	569	3.95	669	0.03	1.01	-1.04^{d}
192	472	4.34	489	0.80	0.44	-2.10^{d}
209	524	4.11	549	0.52	0.77	-1.71^{d}
235	508	4.14	537	0.08	0.75	-1.67^{d}
263	554	4.00	599	0.19	0.97	-1.31^{d}

 a In dichloromethane (10 $^{-5}$ M). b Measured relative to fluorescein (NaOH, 0.1 M, $\phi_F=0.9$). c In dichloromethane and $Bu_4N^+PF_6^-$ (0.2 M). d Reversible process.

relatively high (>0.20), as opposed to the derivative **191**, which presented a larger Stokes shift (2875 cm⁻¹) accompanied by a decrease in the fluorescence quantum yield to 0.03.

Cyclic voltammetry measurements of these compounds showed that the chemical functionalisation of the P center in the dibenzophospholes 190–192 and 263 led to a gradual increase in the oxidation and reduction potentials as well as indicated that the phospholium salts 191 and 263 had high electron affinities. Moreover, the dibenzophospholes 190, 209, 235 and 263 presented reversible reduction waves, which suggested stability in their reduced state, under the measurement conditions. It is noteworthy that the evolution of the redox potentials within the compounds 190–192 and 263 were consistent with the decrease in the optical gap. Accurate photophysical and electrochemical data of these compounds are presented in Table 10 and Fig. 5.⁴⁹

Time-dependent density functional theory (TD-DFT) calculations were performed to gain more insight into the electronic properties of the dibenzophospholes **190–192**, **209**, **235** and **263**. These results showed that the long-wavelength UV-Vis absorption of these dibenzophospholes resulted from HOMO–LUMO transitions. The frontier molecular orbitals were comparable in **190–192**, **209** and **263**. These π molecular orbitals were delocalized on the sp²-carbon skeletons with a contribution of the respective orbitals of the phosphole ring.

The HOMO with a nodal plane on the P^{III} was influenced by the inductive effects of the substituents on the phosphorus atom. Additionally, both experimental and theoretical data showed that the local chemical modifications around P had a great significance on the gap fine-tuning.⁴⁹

4.2.4. Bridged dibenzophospholes. Notable organic compounds for optoelectronic devices are bridged dibenzophospholes **17–18**, **20** and **21**, which were obtained by Yamaguchi and Studer *et al.* These compounds exhibited electronaccepting character and could find many applications as building blocks in molecular electronics (Scheme 84).²⁷

The UV-Vis absorption spectra of the dibenzophospholes 17-cis and 18-trans showed an absorption band with the maxima

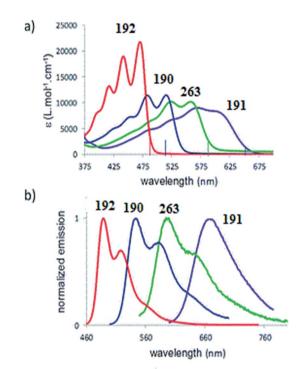


Fig. 5 UV-Vis absorption spectra (a), normalised emission spectra (b) of the compounds 190-192 and 263 in dichloromethane (10^{-5} M)⁴⁹ (reprinted with permission from the American Chemical Society).

wavelength at $\lambda_{abs}=347$ nm and logarithms of the molar absorption coefficient 2.52 and 2.56 for 17-cis and 18-trans, respectively. Additionally, both isomers presented essentially identical spectra irrespective of the stereochemistry. The fluorescence spectra of 17-cis and 18-trans showed a violet fluorescence with the maximum wavelength at $\lambda_{em}=387$ nm in both cases, whereas the quantum yield was low ($\phi_{F}=0.03$).

Notably, the absorption and fluorescence spectra of 17-cis and 18-trans were in the longer wavelength range, than those of the dibenzophosphole oxide 66. These results were attributable to the small HOMO-LUMO gap of isomers 17-cis and 18-trans. The compounds **20**-trans and **21**-trans showed absorption at λ_{abs} = 375 and 399 nm, and fluorescence bands at $\lambda_{\rm em} = 422$ and 547 nm, respectively, which were related to the effective extension of π conjugation. Whereas the dibenzophospholes 17-cis and 18-trans showed only a faint fluorescence, the π -extended derivatives 20-trans and 21-trans presented more intense emission with $\phi_{\rm F}$ values of 0.20 and 0.34, respectively. Remarkably, the λ_{em} value of the dibenzophosphole 21-trans was longer than that of compound 20-trans in CHCl3. To compare the electronaccepting properties of the bridged compounds 20-trans and 21-trans, the non-bridged dibenzophosphole 273 was also prepared and measured in various solvents. For the compounds 21-trans and 273, the fluorescence spectra presented considerable bathochromic shifts with increasing polarity of a solvent, whereas the absorption maxima showed small solvent dependence. These facts demonstrate that the compounds 21-trans and 273 had more polar structures in the excited state than in the ground state. The use of the Lippert-Mataga equation to This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Open Access Article. Published on 30 January 2017. Downloaded on 11/8/2025 9:32:23 PM.

RSC Advances Review

compare the degree of polarity of the structures in the excited state, showed that extension of the electron-accepting character of the bridged dibenzophospholes 20 and 21-trans was larger than the non-bridged dibenzophosphole analogue 273. Noteworthy is that the dibenzophosphole 21-trans retained fluorescence quantum yield in the solid state of $\phi_{\rm F}=0.30$, in contrast to the non-bridged analogue 273 which exhibited a much smaller fluorescence quantum yield than in solution ($\phi_{\rm F}=0.18$ for solid, 0.89 for solution). Individual results of the investigated compounds are summarized in Table 11.²⁷

Yamaguchi and Studer et al. presented the cyclic voltammograms of the dibenzophospholes 21-trans and 273, showing

Table 11 UV-Vis absorption and fluorescence characterisation of the compounds 17-cis, 18-trans, 20-trans, 21-trans, 66, 273, in CH₂Cl₂

	UV-Vis absorption		Fluorescence	2
Compound	$\lambda_{\mathrm{abs}}{}^{a}\left[\mathrm{nm}\right]$	$\log \varepsilon$	$\lambda_{\mathrm{em}}^{b} [\mathrm{nm}]$	${\phi_{ m F}}^c$
17 -cis	347	2.52	387	0.03
18-trans	347	2.56	387	0.03
20-trans	375	3.54	422	0.20
21-trans	399	4.57	547	0.34 (0.30)
66	332	2.89	366	0.042
273	396	4.63	499	0.89(0.18)

^a Only absorption maxima at the longest wavelengths were shown. ^b Emission maxima upon excitation at the absorption maximum wavelengths. ^c Absolute fluorescence quantum yields determined by a calibrated integrating sphere system within $\pm 3\%$ errors.

the first reversible reduction waves with reduction potentials of -2.15 and -2.36 V, respectively. These observations indicated that the dibenzophosphole **21**-*trans* might serve as a material to enhance the electron-accepting character.

5. Application of dibenzophospholes for organic electronic devices

We believe that dibenzophospholes, as organic π -conjugated compounds, have enormous potential as optoelectronic materials for example in light-emitting diodes, organic field-effect transistors, nonlinear optical devices and organic solar cells.39 However, in the years 2001-2016, only limited testing of dibenzophospholes and their derivatives as materials in these types of device took place. In the 15 years since the review by Aitken11 in 2001, only two simple dibenzophospholes 66 and 212 were used in Organic Light-Emitting Diodes (OLEDs) in various configurations. These devices were fabricated in typical layered structures on indium-tin-oxide (ITO)-coated glass substrates ($\leq 15 \Omega$) with multiple organic layers between the transparent bottom ITO anode and the top metal cathode. The organic and metal layers were deposited by thermal evaporation under high vacuum conditions with a base pressure of $<10^{-6}$ Torr. The active areas of the devices were $2 \times 2 \text{ mm}^2$ as defined by the shadow mask for cathode deposition.

Chi, Chou and Chang *et al.* applied the dibenzophosphole **212** in the three layer OLEDs with 4 wt% of Os complex as an emitter. The dibenzophosphole **212** served as a bipolar host material with electron-donor properties due to the carbazole

moiety, as well as electron-acceptor properties by reason of the presence of phosphoryl moiety. The configurations of these devices were as follows: ITO/3DTAPBP-[2,2'-bis(3-(N,N-di-p-tolylamino)phenyl)biphenyl] (40 nm)/the dibenzophosphole **212** with Os complexes **A** or **B** (Scheme 85) (30 nm)/BP4mPy-[3,3',5,5'-tetra[(3-pyridyl)-phen-3-yl]biphenyl (40 nm)]/LiF (0.8 nm)/Al (150 nm) (Fig. 6). 55

3DTAPBP with a wide triplet gap of around 2.68 eV, was employed as the hole-transport or a host material in redemitting OLEDs. The second material BP4mPY served as an electron transport layer. These devices exhibited a bright

emission of dopants due to good transfer energy between the host and guest materials. Below are presented the $Os(\pi)$ complexes used in these red-emitting OLEDs (Scheme 85).

The efficiencies of OLEDs in this configuration were as follows: cf. 14.3%, 34.8 cd A^{-1} and 45.2 lm W^{-1} for the complex **A** and 9.9%, 15.7 cd A^{-1} and 20.5 lm W^{-1} for the complex **B**. The luminance maxima of 52.6 and 23.7 cd m^{-2} were achieved for the complexes **A** and **B**, through applying relatively low voltages of 2.5 and 2.6 V, respectively. Moreover, the internal quantum efficiency amounted to nearly 100% in both devices.

The resulting device parameters for the phosphorescent OLED containing as host dibenzophosphole **212** can be compared to the parameters of an OLED containing the standard bipolar host material CBP-4,4'-N,N'-dicarbazolebiphenyl in the following configuration: ITO/3DTAPBP (40 nm)/CBP (or dibenzophosphole **212**) doped with 4% Os complexes **A, B** (30 nm)/BP4mPy (40 nm)/LiF (0.8 nm)/Al (150 nm) or with other commercial materials, such as BP4mPy/3DTAPBP in the following configurations: ITO/3DTAPBP (40 nm)/3DTAPBP doped with 4% Os complexes **A, B** (10 nm)/BP4mPy doped with 4% of Os complexes **A, B** (20 nm)/BP4mPy (40 nm)/LiF (0.8 nm)/Al (150 nm).

The parameters obtained for the standard host material (CBP, BP4mPy/3DTAPBP) doped with Os complexes **A** and **B** were lower than those obtained for the host dibenzophosphole **212** doped with the Os complex **A** (14.3%, 34.8 cd A^{-1} and 45.2

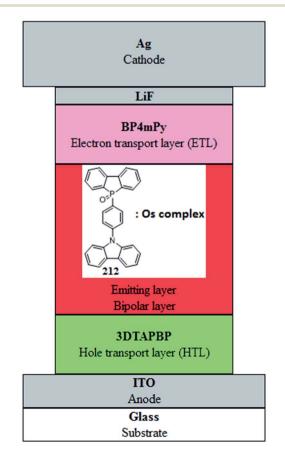


Fig. 6 Three-layer OLED.

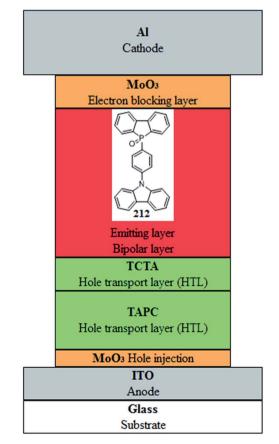
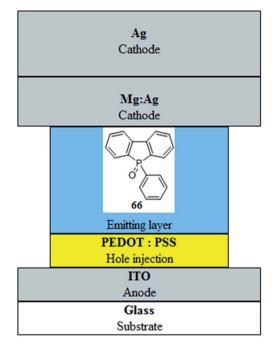


Fig. 7 The hole-only device.

RSC Advances

 $lm W^{-1}$): for CBP, efficiencies of 10.9% (21.7 cd A^{-1} and 11.9 lm W^{-1}) and 10.1% (13.7 cd A^{-1} and 10.0 lm W^{-1}) for the Os complexes A and B were achieved, respectively, whereas, efficiencies for the devices with BP4mPy/3DTAPBP in the second configuration of 12.9% (27.9 cd A^{-1} and 21.8 lm W^{-1}) for the complex **A** and 10.7% (18.5 cd A^{-1} and 19.3 lm W^{-1}) for the complex B, were obtained.55

The compound 212 was also used in the only-hole device in the following configuration: ITO/MoO₃ (1 nm)/TAPC-[di-[4-(N,N-



Single-layer OLEDs.

ditholylamino)-phenyl cyclohexane (30 nm)/TCTA-[4,4',4"tris(carbazol-9-vl)-triphenylamine] (30 nm)/the compound 212 (100 nm)/MoO₃ (20 nm)/Al (110 nm), for which MoO₃ was applied as a hole injection/electron blocking layer, while TAPC and TCTA were used as dual hole-transport layers for providing a smooth hole-injection into the tested material as shown in Fig. 7.55

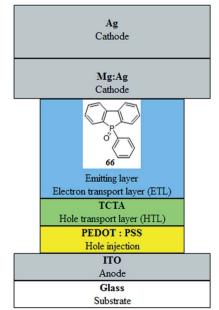
Analogously, an only-electron device was also prepared in the following configuration: ITO/Al(20 nm)/the dibenzophospholes 212 (100 nm)/TmPyPB-[1,3,5-tri[(3-pyridyl)-phen-3-yl]benzene] (10 nm)/TmPyPB doped with 10 wt% of n-type cesium carbonate Cs₂CO₃ (10 nm)/Al (110 nm), where TmPyPB was used as the electron transport layer.

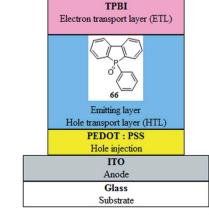
Current density-voltage (J-V) characteristics of the only-hole and only-electron devices exhibited the excellent hole and electron transport capability of the dibenzophosphole 212. Summarizing, the dibenzophosphole 212 possesses superior carrier transport properties for both positive and negative charges.

In contrast, the dibenzophosphole 66, which was used in 2006 by Wu and Réau et al. as an electron transport layer, hole transport layer as well as an ambipolar material for OLEDs, turned out to be an unsuitable component for single- and two-layer OLEDs. The configuration of the single-layer OLED used was the following: (poly(3,4-ethylenedioxythiophene):polystyrene ITO/PEDOT:PSS sulfonate) (25 nm)/organic layer (100 nm)/Mg:Ag (80 nm)/Ag (150 nm) as shown in Fig. 8.12

Light emission was observed for a turn-on voltage of 4 V. However, the device was unstable and its electroluminescence characteristics (brightness, emission wavelength) varied rapidly with applied driving current.

The dibenzophosphole 66 was also tested in the two-layer OLEDs as an electron-transporting material (n-type) as well as hole-transporting material (p-type) in the two following





Cathode

Mg:Ag

Cathode

Fig. 9 Two-layer OLEDs.

ITO/PEDOT/TCT-[tris(4-carbazoyl-9-ylphenyl) configurations: amine]/the compound 66/Mg:Ag/Ag and ITO/PEDOT/dibenzophosphole 66/TPBI-[2,2',2"-(1,3,5-benzinetriyl)-tris(1-phenyl-1H-benzimidazole)]/Mg:Ag/Ag. Thus, the compound 66 was mixed with the known p-type hole-transporting material TCTA-[tris(4-carbazoyl-9-ylphenyl)amine and with the commonly known n-type electron transporting material TPBI-[2,2',2"-(1,3,5-benzenetriyl)-tris(1-phenyl-1*H*-benzimidazole)] to provide two unstable bulk-hetero junctions, respectively (Fig. 9).12 A comparison of the opposite results obtained with dibenzophospholes 66 and 212 as materials for OLEDs, shows that more intensive investigations should be undertaken in this area with other representatives of dibenzophospholes, as reviewed in this article.

Conclusions 6.

Dibenzophosphole and its derivatives are an underestimated group of heterorganic compounds which may serve as electroluminescent materials for optoelectronic devices due to easy synthesis (subsection 2) and functionalization (subsection 3), high thermal stability and the possibility of fine-tuning their electronic properties through various structural modifications both on phosphorus and the benzene rings (subsections 3.1 and 3.2). Other areas of optoelectronics are open for exploration of dibenzophospholes and their derivatives. The ³¹P-NMR technique may be a very useful tool for the rapid monitoring of progress in chemical synthesis and in testing chemical purity and stability of these compounds. Since, so far, only two dibenzophospholes 66 and 212 were used in construction of emitting diodes, 12,65 more intensive research with other dibenzophosphole representatives should certainly be investigated in the future.

This review shows the great potential of both simple and functionalized dibenzophospholes that should be tested more intensely as single materials, as well as in structural combinations with other π -extended conjugated aromatic and heteroaromatic systems containing phosphorus, nitrogen, silicon or sulfur atoms. The promising results obtained so far with closely related phospholes12 may outline possible directions of further improvements in optoelectronic materials based on organophosphorus compounds.

Acknowledgements

This work was financed by the National Science Centre (NCN), Poland on the basis of the grant number 2013/11/B/ST5/01610 and by Statutory Funds from the Ministry of Science and Higher Education in Poland.

References

- 1 H. Shirakawa, E. J. Louis, A. MacDiarmid, C. Chiang and A. J. Heeger, J. Chem. Soc., Chem. Commun., 1977, 16, 578.
- 2 U. Mitschke and P. Bauerle, J. Mater. Chem., 2000, 10, 1471.
- 3 M. J. S. Dewar and N. Trinajstic, J. Am. Chem. Soc., 1970, 92, 1453.

- 4 B. El Hamaoui, L. Zhi, J. Wu, J. Li, N. T. Lucas, Z. Tomovic, U. Kolb and K. Mllen, Adv. Funct. Mater., 2007, 17, 1179.
- 5 T. Baumgartner and R. Reau, Chem. Rev., 2006, 106, 4681.
- 6 M. G. Hobbs and T. Baumgartner, Eur. J. Inorg. Chem., 2007,
- 7 T. Baumgartner, Acc. Chem. Res., 2014, 47, 1613.
- 8 D. Joly, P.-A. Bouit and M. Hissler, J. Mater. Chem. C, 2016, 4,
- 9 M. P. Duffy, W. Delaunay, P.-A. Bouit and M. Hissler, Chem. Soc. Rev., 2016, 45, 5296.
- 10 K. Fourmy, D. Nguyen, O. Cabaret and M. Gouygou, Catal. Sci. Technol., 2015, 5, 4289.
- 11 R. A. Aitken, Sci. Synth., 2001, 10, 817.
- 12 H. Su, O. Fadhel, C. Yang, T. Cho, C. Fave, M. Hissler, C. Wu and R. Réau, I. Am. Chem. Soc., 2006, 128, 983.
- 13 T. Baumgartner, T. Neumann and B. Wirges, Angew. Chem., Int. Ed., 2004, 43, 6197.
- 14 T. Baumgartner, W. Bergmans, T. Karpati, T. Neumann, M. Nieger and L. Nyulászi, Chem.-Eur. J., 2005, 11, 4687.
- 15 S. Durben, Y. Dienes and T. Baumgartner, Org. Lett., 2006, 8, 5893.
- 16 Y. Dienes, S. Durben, T. Karpati, T. Neumann, U. Englert, L. Nyulászi and T. Baumgartner, Chem.-Eur. J., 2007, 13, 7487.
- 17 Y. Matano and H. Imahori, Org. Biomol. Chem., 2009, 7, 1258.
- 18 C. Romero-Nieto and T. Baumgartner, Synlett, 2013, 24, 920.
- 19 G. Wittig and G. Geissler, Justus Liebigs Ann. Chem., 1953, 44, 580.
- 20 S. Ogawa, Y. Tajiri and N. Furukawa, Bull. Chem. Soc. Jpn., 1991, 64, 3182.
- 21 G. Wittig and A. Maercker, Chem. Ber., 1964, 97, 747.
- 22 S. Affandi, R. L. Green, B. T. Hsieh, M. S. Holt, J. H. Nelson and E. C. Alyea, Synth. React. Inorg. Met.-Org. Chem., 1987, 17, 307.
- 23 G. Wittig and E. Kochendoerfer, Chem. Ber., 1964, 97, 741.
- 24 G. Wittig and E. Benz, Chem. Ber., 1959, 92, 1999.
- 25 D. Hellwinkel, Chem. Ber., 1966, 99, 3642.
- 26 O. Herd, D. Hoff, K. W. Kottsieper, C. Liek, K. Wenz, O. Stelzer and W. S. Sheldrick, Inorg. Chem., 2002, 41(20), 5034.
- 27 A. Bruch, A. Fukazawa, E. Yamaguchi, S. Yamaguchi and A. Studer, Angew. Chem., Int. Ed., 2011, 50, 12094.
- 28 Q. Ruan, L. Zhou and B. Breit, Catal. Commun., 2014, 53, 87.
- 29 J. A. Macor, J. L. Brown, J. N. Cross, S. R. Daly, A. J. Gaunt, G. S. Girolami, M. T. Janicke, S. A. Kozimor, M. P. Neu, A. C. Olson, S. D. Reilly and B. L. Scott, Dalton Trans., 2015, 44, 18923.
- 30 H. Kalkeren, S. Leenders, C. Hommersom, F. Rutjes and F. Delft, Chem.-Eur. J., 2011, 17, 11290.
- 31 A. Oukhrib, L. Bonnafoux, A. Panossian, S. Waifang, D. H. Nguyen, M. Urrutigoity, F. Colobert, M. Gouygou and F. R. Leroux, Tetrahedron, 2014, 70, 1431.
- 32 T. Agou, M. D. Hossain, T. Kawashima, K. Kamada and K. Ohta, Chem. Commun., 2009, 44, 6762.
- 33 K. Yavari, P. Retailleau, A. Voituriez and A. Marinetti, *Chem.*-Eur. J., 2013, 19, 9939.

- 34 A. S. Ionkin and W. J. Marshall, Heteroat. Chem., 2003, 14(4), 360.
- 35 A. A. Diaz, J. D. Young, M. A. Khan and R. J. Wehmschulte, Inorg. Chem., 2006, 45, 5568.
- 36 V. Diemer, A. Berthelot, J. Bayardon, S. Juge, F. R. Leroux and F. Colobert, J. Org. Chem., 2012, 77, 6117.
- 37 K. Baba, M. Tobisu and N. Chatani, Angew. Chem., Int. Ed., 2013, 52, 11892.
- 38 Y. Unoh, T. Satoh, K. Hirano and M. Miura, ACS Catal., 2015, 5, 6634.
- 39 Y. Kuninobu, T. Yoshida and K. Takai, J. Org. Chem., 2011, 76, 7370.
- 40 S. Furukawa, S. Haga, J. Kobayashi and T. Kawashima, Org. Lett., 2014, 16, 3228.
- 41 Y. Cui, L. Fu, J. Cao, Y. Deng and J. Jiang, Adv. Synth. Catal., 2014, 356, 1217.
- 42 S. Ishikawa and K. Manabe, Tetrahedron, 2010, 66, 297.
- 43 M. Stankevič, J. Pisklak and K. Włodarczyk, Tetrahedron, 2016, 72, 810.
- 44 N. Fukawa, T. Osaka, K. Noguchi and K. Tanaka, Org. Lett., 2010, 12(6), 1324.
- Martinez-Arripe, F. Jean-Baptiste-dit-Dominique, A. Auffrant, X. F. Le Goff, J. Thuilliez and F. Nief, Organometallics, 2012, 31, 4854.
- 46 S. Shah, M. Cather Simpson, R. C. Smith J. D. Protasiewicz, J. Am. Chem. Soc., 2001, 123, 6925.
- 47 X. Wei, Z. Lu, X. Zhao, Z. Duan and F. Mathey, Angew. Chem., Int. Ed., 2015, 54, 1583-1586.
- 48 O. Fadhel, D. Szieberth, V. Deborde, C. Lescop, L. Nyulászi, M. Hissler and R. Réau, Chem.-Eur. J., 2009, 15, 4914.
- 49 P. Bouit, A. Escande, R. Szucs, D. Szieberth, C. Lescop, L. Nyulászi, M. Hissler and R. Réau, J. Am. Chem. Soc., 2012, 134, 6524.
- 50 Y. Hayashi, Y. Matano, K. Suda, Y. Kimura, Y. Nakao and H. Imahori, Chem.-Eur. J., 2012, 18, 15972.
- 51 H. Kalkeren, S. Leenders, C. Hommersom, F. Rutjes and F. Delft, Chem.-Eur. J., 2011, 17, 11290.

- 52 K. Geramita, J. McBee and T. D. Tilley, J. Org. Chem., 2009, 74, 820,
- 53 Y. J. Ahn, R. J. Rubio, T. K. Hollis, F. S. Tham and B. Donnadeiu, Organometallics, 2006, 25, 1079.
- 54 N. Dubrovina, H. Jiao, V. Tararov, A. Spannenberg, R. Kadyrov, A. Monsees, A. Christiansen and A. Borner, Eur. J. Org. Chem., 2006, 11, 3412.
- 55 C. H. Lin, C. W. H. Su, J. L. Liao, Y. M. Cheng, Y. Chi, T. Y. Lin, M. W. Chung, P. T. Chou, G. H. Lee, C. H. Chang, C. Y. Shih and C. L. Ho, J. Mater. Chem., 2012, 22, 10684.
- 56 H. A. van Kalkeren, C. Grotenhuis, F. S. Haasjes, C. A. Hommersom, F. P. J. T. Rutjes and F. L. van Delft, Eur. J. Org. Chem., 2013, 31, 7059.
- 57 H. A. Kalkeren, J. J. Bruins, F. P. J. T. Rutjes and F. L. Delft, Adv. Synth. Catal., 2012, 354, 1417.
- 58 E. Durán, E. Gordo, J. Granell, M. Font-Bardía, X. Solans, Velasco and F. López-Calahorra, Tetrahedron: Asymmetry, 2001, 12, 1987.
- 59 J. G. L. Cortés, S. Vincendeau, J. C. Daran, E. Manoury and M. Gouygou, Acta Crystallogr., Sect. C: Cryst. Struct. Commun., 2006, 62, m188.
- 60 A. Decken, M. Neil, C. Dyker and F. Bottomley, Can. J. Chem., 2002, 80, 55.
- 61 A. Decken, M. Neil, C. Dyker and F. Bottomley, Can. J. Chem., 2001, 79, 1321.
- 62 D. H. Nguyen, H. Lauréano, S. Jugé, P. Kalck, J. C. Daran, Coppel, Urrutigoity and Gouygou, Organometallics, 2009, 28, 6288.
- 63 C. Thoumazet, L. Ricard, H. Gruützmacherb and P. Le Floch, Chem. Commun., 2005, 12, 1592.
- Duran, D. Valasco, F. Lopez-Calahorra and 64 E. H. Finkelmann, Mol. Cryst. Liq. Cryst., 2010, 381, 43.
- 65 J. Yin, R. F. Chen, S. L. Zhang, Q. D. Ling and W. Huang, J. Phys. Chem. A, 2010, 114, 3655.
- 66 R. Kabe, V. M. Lynch and P. Anzenbacher, CrystEngComm, 2011, 13, 5423.