Transition metal catalyzed element–element’ additions to alkynes

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Transition metal catalyzed element–element’ additions to alkynes

Melvyn B. Ansell a,⇑, Oscar Navarro b,⇑, John Spencer a,⇑

aDepartment of Chemistry, University of Sussex, Brighton BN1 9QJ, UK
bDivision of Biomaterials and Biomechanics, Department of Restorative Dentistry, School of Dentistry, Oregon Health & Science University, 2730 SW Moody Ave., Portland, OR 97239, USA

Abstract

The efficient and stereoselective synthesis of, or precursors to, multi-substituted alkenes has attracted substantial interest due to their existence in various industrially and biologically important compounds. One of the most atom economical routes to such alkenes is the transition metal catalyzed hetero element–element’ r-insertion into alkynes. This article provides a thorough up-to-date review on this area of chemistry, including discussions on the mechanism, range of E–E’ bonds accessible and the stoichiometric/catalytic transition metal mediators employed.

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1. Introduction

2. Transition metal mediated E–E’ additions to alkynes

2.1. Mechanism

2.2. Silicon–Silicon (Si–Si)

2.2.1. Palladium

2.2.2. Platinum

2.2.3. Gold

2.2.4. Iron

2.2.5. Nickel

2.2.6. Rhodium

2.3. Boron–Boron (B–B)

2.3.1. Platinum

2.3.2. Palladium

2.3.3. Cobalt

2.3.4. Iron

2.3.5. Iridium

2.3.6. Copper

2.3.7. Gold

2.4. Silicon–Boron (Si–B)

2.4.1. Palladium

2.4.2. Nickel

2.4.3. Gold

2.5. Tin–Tin (Sn–Sn)

2.5.1. Palladium

2.5.2. Platinum

2.5.3. Copper

* Corresponding authors.
E-mail addresses: ma462@sussex.ac.uk (M.B. Ansell), navarrof@ohsu.edu (O. Navarro), j.spencer@sussex.ac.uk (J. Spencer).
1. Introduction

Alkenes are defined as either branched or unbranched hydrocarbons that possess at least one carbon–carbon double bond (C=C) and have a general formula of C<sub>n</sub>H<sub>2n</sub> [1]. Each carbon atom in a C=C bond is sp<sup>2</sup>-hybridized, forming σ-bonds to three other atoms (Scheme 1) [2]. If the alkene has more than one substituent around the C=C bond then two geometric configurations are possible, E or Z (often termed trans or cis, respectively originating from the German words ‘entgegen’ meaning opposite and ‘zusammen’ meaning together) (Fig. 1).

The importance of alkene stereochecmistry is reflected in biologically relevant molecules and is often the difference between an active or inactive compound [3]. Furthermore, highly functionalized and stereodefined multi-substituted alkenes are found in many industrially important compounds including pharmaceuticals (Fig. 2) [4–8], dipeptide mimetics [9], and polymeric materials [10]. The stereoselective synthesis of, or precursors to, these alkenes has therefore attracted substantial attention from both academia and industry. A range of stereoselective syntheses are reported in the literature, methods include Peterson olefination [11,12], the Ramberg-Bäcklund reaction [13], the Wittig reaction (as well as the Wittig-Horner variation) [14,15], olefin metathesis [16], Julia-Lythgoe olefination [17,18], and the McMurry reaction (Fig. 2) [19,20].

Arguably, one of the most atom economical routes (maximum number of atoms of the reactants appearing in the product(s)) [21] in the synthesis of multi-substituted alkenes is alkyne reduction by its π-insertion into hetero element–element’ (E=E’, where E and E’ = H) bonds (albeit the newly formed C=E and C=E’ bonds are then further functionalized) [22]. These π-insertions result in the regio- and stereoselective formation of cis-1-element-2-ene nt’-alkenes in a single step (Scheme 1). A range of E=E’ bonds are accessible including Si=Si, Si=I, B=B, B–B, Sn–Sn, Sn=Si, Ge=Ge etc, and are mediated either stoichiometrically or catalytically by a variety of low-valent transition metal complexes.

Despite the chemical importance of this reaction and the industrial relevance of the 1-element-2-element’-alkenes as precursors to highly functionalized multi-substituted alkenes, the last thorough review on this topic was reported by Moberg and Beletskaya in 1999 (with a revised edition in 2006) [22,23]. A substantial volume of papers has since been published, and we believe there is a strong argument for an updated review that includes these more recent developments.

2. Transition metal mediated EE’ additions to alkenes

2.1. Mechanism

The main mediators in the E=E’ additions to alkenes are low-valent platinum group transition metal complexes coordinated either by phosphine or isocyanide ligand sets. The mechanism is well established, both computationally and experimentally, and consists of three major steps: oxidative addition, insertion and reductive elimination [24,25]. The first step in this catalytic cycle is the oxidative cleavage of a E=E’ bond by a M(0)L<sub>2</sub> (M = platinum...
group metal, L = phosphine/isocyanide) species to form cis-(E)(E')M (II)L₂ (MI1). MI1 is often kinetically stable and is isolated experimentally for many of the E=E' bonds discussed above (the relevant E=E' oxidative additions will be discussed in the appropriate chapters) [26–30]. A ligand exchange then occurs with decoordination of a single L ligand and coordination of the alkyne in its place to yield MI2. This is swiftly followed by an insertion of the alkyne into a M=E or M=E' bond (MI3) [31,32]. The regioselectivity of the E=E' addition is usually defined by this step and dictating factors include: the energetics of the bonds broken vs. the bonds formed, the sterics of the system and electronic stabilization effects within the resulting intermediates [33,34]. Experimental studies suggest that the insertion is often the rate-limiting step in these reaction pathways [31]. An isomerization and re-coordination of the L ligand results in the E and (E') vinyl groups adjacent to one another. This positioning is then ideally suited for stereoselective reductive elimination to yield the corresponding Z-1,2-disubstituted alkenes and consequent reformation of M(0)L₂ (Scheme 2).

This subsequent section will overview the history, state-of-the-art and scope of this field, arranged by interelement bonds activated and metals used.

2.2. Silicon–Silicon (Si–Si)

2.2.1. Palladium

The π-insertion of unsaturated moieties into Si–Si bonds is often called bis(silylation). Palladium mediated bis(silylation) of alkenes is one of the most investigated reactions within this area of chemistry [35]. The first examples were reported by Kumada...
Kumada and co-workers demonstrated that activated disilanes, of the form $X_m\text{Me}_2m\text{Si} = \text{SiMe}_3X_n$ ($X = H, F, Cl$ or $\text{OMe}$; $m = 1-2$, $n = 1-2$), added to various alkenes when catalytic quantities of $[\text{Cl}_3\text{Pd} \left( \text{PR}_3 \right)_2]$ or $[\text{Pd}(\text{PR}_3)_4]$ ($R = \text{Et}$ or $\text{Ph}$ and $R' = \text{Ph}$) were employed (Scheme 3) [36,37]. The extension of this protocol to non-activated disilanes, such as hexamethyldisilane ($\text{Me}_6\text{SiSiMe}_3$), was unsuccessful. Elsewhere, Sakurai showed that the extent of alkene bis(silylation) using the strained cyclic disilane, 1,1,2,2-tetramethyl-1,2-disilylated alkenes was favored, although significant quantities of the $E$-isomers were noted. It was observed that upon heating, $Z$ to $E$ isomerization occurred in the presence of the Pd(0) complex. This work was extended to other activated disilanes such as methoxymethyl disilanes, ($\text{MeO})_n\text{Me}_3m\text{SiSiMe}_3=\text{OMe}_n$, as well as the acetylenes, 1-hexyne and trimethylsilylacetylene [39]. Bis(silylation) with $\text{Me}_3\text{SiSiMe}_3$ was extremely sluggish even at temperatures of 140 °C.

Watanabe performed the bis(silylation) of acetylene using chlorinated disilanes, $\text{Me}_6\text{SiSiCl}_6,n$ ($n = 2-5$) [39]. The formation of the $Z$-1,2-disilylated alkenes was favored, although significant quantities of the $E$-isomers were noted. It was observed that upon heating, $Z$ to $E$ isomerization occurred in the presence of the Pd(0) complex. This work was extended to other activated disilanes such as methoxymethyl disilanes, ($\text{MeO})_n\text{Me}_3m\text{SiSiMe}_3=\text{OMe}_n$, as well as the acetylenes, 1-hexyne and trimethylsilylacetylene [40]. Bis(silylation) with $\text{Me}_3\text{SiSiMe}_3$ was extremely sluggish even at temperatures of 140 °C.

Hiyama and co-workers utilized these chlorinated disilanes in the palladium catalyzed bis(silylation) of bis(trimethylsilyl)butadiyne [41]. Subsequent treatment of the reaction mixture with $\text{MeMgBr}$ resulted in the formation of 1,1,4,4-tetakis(trimethylsilyl)butadiene (3) and/or 1,1,2,4-tetakis(trimethylsilyl)-1-butene-3-ylene (4) (Scheme 4).
Seyfert and co-workers demonstrated that the very reactive and strained Si−Si σ bond in octamethyl-1,2-disilacyclobutane was capable of bis(silylating) a number of alkenes including acetylene, phenylacetylene and dimethyl acetylenedicarboxylate when using catalytic quantities of [Cl₂Pd(PPh₃)₂]. However, extension of this protocol to other internal alkenes was unsuccessful, even at temperatures of 140 °C [44].

Manners showed that the ferrocenyldisilane, [Fe(η⁵-C₅H₄)₂−(SiMe₃)]₂ inserted into acetylene or phenylacetylene to form the organometallic rings 6a and 6b, respectively (Scheme 6) [45]. The reaction of alkenes such as dimethyl acetylenedicarboxylate resulted in a mixture of mono- and di-insertion products with significant quantities of the alkyne cyclotrimination product, a common occurrence with alkenes such as dimethyl acetylenedicarboxylate and acetylene [46]. Other palladium mediated bis(silylations) of alkenes using strained disilanes have appeared in the literature: Ko’s ‘super-aromatic’ o-carborane disilane 7 [47], and Braunschweig’s [2]silachromoarenophane 8 [48], bis(silylated) terminal and internal alkenes, respectively (Fig. 3). The cyclic nature of these disilanes pre-conditioned the formation of the Z-configured 1,2-disilylated alkene products.

In 1991, a communication from Ito and co-workers revolutionised the field of alkyne bis(silylation) by the introduction of the pre-catalytic combination of [Pd(OAc)₂] and isocyanide ligands [49]. As a result, the bis(silylation) of alkenes was no longer limited to activated or strained disilanes. A combination of 2 mol% [Pd(OAc)₂]/30 mol% tert-octyl isocyanide was enough to catalyze the bis(silylation) of terminal alkenes such as 1-phenylpropyne, 1-nonyne and phenylacetylene using the non-activated disilane, Me₃SiMe₃. Reactions proceeded at 110 °C and resulted in unprecedented high stereoselectivities. Ito and co-workers extended this protocol to a range of bis(silylations) including the intramolecular bis(silylation) of alkenes in the stereoselective synthesis of 1,2,4-triols [50], cyclic tetrakis(organosilyl) ethenes as organic chromophores [51], chiral allenylsilanes [52], and enantioenriched propargyl silanes [53].

Many authors since have utilized the [Pd(OAc)₂]/isocyanide combination within their own work. For example, Strohmann...
and co-workers used the pre-catalytic combination above in a number of alkyne bis(silylations) using 1,1,2,2-tetramethyl-1,2-bis(phenylthiomethyl)disilane as the disilane source. In particular, the bis(silylation) of ethynyl[2.2]paracyclophanes resulted in the formation of 9 (Scheme 7), which have potential applications in chiral catalysis and optoelectronic materials.

The addition of Me$_3$SiSiMe$_3$ to internal alkynes is considered one of the most challenging reactions in alkyne bis(silylation) chemistry. Even Ito’s [Pd(OAc)$_2$/isocyanide] combination was catalytically inactive. Navarro, Spencer and co-workers reported the synthesis of the novel compound cis-[Pd(ITMe)$_2$(SiMe$_3$)$_2$] (10, ITMe = 1,3,4,5-tetramethylimidazol-2-ylidene), via the oxidative addition of Me$_3$SiSiMe$_3$ to [Pd(0)(ITMe)$_2$] under mild conditions. 10 was subsequently employed as a pre-catalyst in the bis(silylation) of a range of 1,2-diarylalkynes using Me$_3$SiSiMe$_3$ (Scheme 8) [57]. The resulting stilbenes 11 were synthesized with 100% Z-stereoselectivity and were either novel or previously only synthesized in a stoichiometric manner. This unprecedented protocol was also extended to the bis(silylations) of two alkynes separated by a phenyl linker, to 1-silyl-2-aryl alkynes and to terminal alkynes.

2.2.2. Platinum

In contrast, the platinum catalyzed bis(silylation) of alkynes has been investigated to a lesser extent. The most common
bis(silylation) mediator is [(η⁵-ethylenep)(PPh₃)₂]. Ishikawa detailed the bis(silylation) of a number of alkenes using 3,4-benz o-1,1,2,2,4,4-tetra(isopropyl)-1,2-disilacyclobut-3-ene [58]. The reac tivity and product selectivity using this platinum catalyst differed from the palladium analogues and depended on the alkyne used, notably employing extreme temperatures. Reactions with 1-hexyne and phenylacetylene resulted in a mixture of 12 and 13. The bulky mono-substituted alkynes mesitylacetylene and (phenylidyldimethylsilyl)acetylene formed 13 as the sole product, whereas diphenylacetylene resulted in only the 1,2-disilylated alkyne 14 (Scheme 9).

Investigations into the reactivity of 1,2-bis(dimethylsilyl)carb oane by Ko and co-workers were extended to the platinum cata lyzed bis(silylation) of alkenes. Normal 1,2-bis(silylation) was observed in the reaction with phenylacetylene, diphenylacetylene, 3-hexyne, 2-butyne and dimethyl acetylenedicarboxylate. However, the use of 1-hexyne resulted in geminal or 1,1-bis (silylation) and the formation of a five-membered disilyl ring [59]. A later report by Ishikawa described the bis(silylation) of range of terminal and internal alkenes using cis- and trans-1,2-di methyl-1,2-diphenyl-disilacyclopentane. The reactions proceeded with high stereospecificity and translation of the cis or trans nature of disilane in all cases [60].

2.2.3. Gold

The redox chemistry between gold(I)/(III) is similar to that of palladium(0)/(II), given that they are isogal. This has triggered substantial research into the development of gold catalysts that are as active as their palladium analogues [61–63]. Despite this effort, gold catalysis is very much in its infancy with the only reports of alkyne bis(silylation) in the literature being mediated by gold nanoparticles supported on titanium oxide (Au/TiO₂) [64]. Stratakis and co-workers showed that the bis(silylation) of a range of terminal alkenes using hexamethyldisilane and 1,2-diphenyl-1,2,2-tetramethyldisilane was possible [65]. In all cases, the Z-alkenes were favored with a small percentage of the E-isomers formed. The heterogeneous catalyst gave comparable activities upon recycling. Stratakis extended the protocol to 1,1,2,2-tetramethylsilane ((HMe₂Si)₄) [66]. However, two isomers (15, major, and 16, minor) were isolated (Scheme 10). Mechanistically, this observation was explained by an initial bis(silylation) followed by a dehydrogenative addition to a second alkyne [66].

2.2.4. Iron

Sunada and co-workers reacted 1,2-bis(dimethylsilyl)benzene with [Fe(mesityl)₂] (mesityl = 2,4,6-Me₃C₆H₂) in aromatic solvents under a nitrogen (N₂) atmosphere to form 17 (Scheme 11). Subsequent addition of 2-butyne or phenylacetylene resulted in the quantitative formation of the disilacarboxylenes 18a and 18b, respectively (Scheme 11) [67]. This process was made catalytic upon addition of 1,2-bis(dimethylsilyl)benzene to phenylacetylene and 20 mol% of Fe [68]. Although this is not a bis(silylation) in the traditional sense (it lacks a Si–Si ᵉ⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻彖 to the catalytic bis(silylation) of alkynes employing nickel was reported by Naka and co-workers. The reaction of 3,4-benz o-1,1,2,2-tetraethyl-1,2-disilacyclobutene with diphenylacetylene in the presence of catalytic amounts of [Ni(PEt₃)₂] formed the Z-alkene 25 [71]. As well as bis(silylation), an alkyne insertion into one of the phenylene-Si bonds occurred, with 26 isolated as a minor product (Scheme 14). This type of insertion was consistently observed on applying the methodology to other alkenes [72].

2.2.6. Rhodium

Examples of rhodium mediated alkyne bis(silylations) are rare. Tilley and co-workers carried out the stoichiometric reaction of [(Me₅P)₂RhSi(SiMe₃)₂] (27) with 2-butyne, resulting in the corresponding bis(silyl)Ni(II) complex 22 was reacted with tert butylacetylene to form the two new 1,4-disilacyclohexadienes 23 and 24, where the 'Bu groups are syn and anti, respectively (Scheme 13) [70].

The first catalytic bis(silylation) of alkenes employing nickel was reported by Ko and co-workers. The reaction of 3,4-benzo 1,1,2,2-tetraethyl-1,2-disilacyclobutene with diphenylacetylene in the presence of catalytic amounts of [Ni(PEt₃)₂] formed the Z-alkene 25 [71]. As well as bis(silylation), an alkyne insertion into one of the phenylene-Si bonds occurred, with 26 isolated as a minor product (Scheme 14). This type of insertion was consistently observed on applying the methodology to other alkenes [72].

Scheme 15. Stoichiometric bis(silylation) of 2-butyne mediated by Rh(I) species [73].

Scheme 16. Rh(I)-catalyzed intramolecular trans-bis(silylation) of alkenes [74].

Scheme 17. The first diboration of alkenes catalyzed by [Pt(PPh₃)₄] [80].
The protocol was then extended to a variety of (2-alkynylphenyl) disiloxanes affording the corresponding 3-silyl-1-benzosiloles (30) (Scheme 16).

2.3. Boron–Boron (B–B)

2.3.1. Platinum

Due to their low toxicity, high stability under atmospheric conditions and versatile reactivity, the synthesis of organoboron reagents has attracted significant interest. In particular, there is substantial focus towards 1,2-diborylated alkenes as the products of alkene diboration [75]. The resulting newly formed B–C bonds are able to participate in Suzuki-Miyaura cross-coupling reactions [76], to build more complex and useful tri- and tetra-substituted alkenes. The first source of B–B bonds investigated was diboron tetrahalides. These contain the most reactive B–B bond strengths, are now widely utilized in the stoichiometric and catalytic addition of B–B bonds to alkenes. These diboron reagents will be the main focus of this section.

Platinum is by far the most effective and widely studied mediator of alkene diboration. Seminal results by Suzuki and Miyaura [80] indicated that 1-octyne inserted into the B–B bond of bis(pinacolato)diboron (B$_2$pin$_2$) using catalytic quantities of [Pt(PPPh$_3$)$_2$] to form 31 (Scheme 17). The protocol was then extended to a range of internal and terminal alkynes with similarly high stereoselectivities obtained. The rate of diboration was drastically affected by the polarity of the solvent, with the more polar solvents (e.g. DMF) accelerating the rate. However, the authors later showed that hexane also accelerated the reaction rate and to a greater extent than most polar solvents [81]. Other transition metal complexes proved ineffective within this study, e.g. [Pd(PPPh$_3$)$_2$] and [Pd(OAc)$_2$]/isocyanide (the best catalysts in the bis(silylation) of alkynes). Suzuki-Miyaura’s coupling protocols have

Scheme 18. Platinum-mediated stoichiometric diboration of an alkyne [87].

Scheme 19. Pt(0) and Pt(II) catalyzed diboration of internal and terminal alkynes [88].

Scheme 20. Diboration-rearrangement of alkenes using 1,2-B$_2$Cl$_2$(NMe$_2$)$_2$ [89].

Scheme 21. Diboration of 1-alkynylphosphonates and 1-alkynylboronates [91].

isolation of the Rh(III) complex 28 [73]. The authors proposed that 27 undergoes a facile silyl 1,2- and 1,3-migration (F1 and F2, respectively) process in the presence of alkene resulting in a [2+2] cycloaddition and the formation of a transient metallasilacyclobutene F3. The reductive elimination of a Si–C bond in F3 gives a Rh(1)-silyl intermediate F4, which then loses one PMe$_2$ ligand. This induces an oxidative addition of a Si–Si bond in the tethered trisilyl group and subsequent formation of 28 (Scheme 15).

Matsuda and co-workers studied the rhodium(1)-catalyzed intramolecular bis(silylations) of alkenes. Initial testing and optimization were executed on the disilyl ether of a propargylic alcohol [74]. It was observed that 4-silyl-2,5-dihydro-1,2-oxasilole (29) was formed as the sole product (Scheme 16). This trans-bis(silylation) proceeded with the complete opposite stereoselectivity to the analogous palladium-catalyzed reaction.
Scheme 25. Diboration of alkenes using the diboron, pinB-Bdan [101].

Smith and co-workers carried out a stoichiometric diboration by reacting commercially available bis(catecolato)diboron (B2Cat2) with [(η2-4-octyne)Pt(PPh3)2]. This resulted in the oxidative addition bis(aryl)Pt(II) complex 32, and the Z,1,2-diborylated alkene 33 (Scheme 18) [87].

Marder and Norman extended the synthesis of bis(aryl)platinum(II) complexes to the use of other diborons including B2pin2 and B2(4-Bucat)2 (4-Bucat = 1,2-O2-2BuCaH3). [(η2-ethylene)Pt(PPh3)2] and 34 were then used as catalysts in the diboration of terminal and internal alkynes employing B2pin2 and B2Cat2 as B=O bond sources (Scheme 19). These catalysts were more efficient in the stereoselective formation of Z,1,2-diborylated alkynes than [Pt(PPh3)2], with reactions proceeding smoothly using 3 mol% of either catalyst at 80 °C. The rate and conversions were significantly affected by the choice of substituents on the alkyne and the diboron reagent. The presence of π-donating moieties on the alkyne resulted in faster reactions than π-withdrawing substituents and the fastest conversions proceeded in the order of B2Cat2 > B2pin2 > B2(4-Bucat)2 [88].

The platinum catalyzed diboration of internal and terminal alkynes using diboron 1,2-B2Cl2(NMe2)2 affords cyclic 1-azonia-2-borata-5-boroles [36] (Scheme 20). The key feature within these structures was that the boron and nitrogen atoms exhibited both a three and four-coordinated center. Although the mechanism for forming 36 was unclear, the authors proposed an initial diboration followed by a rearrangement of the B=Cl and B=NMe2 bonds [89].

Baker and co-workers developed a phosphine-free platinum catalyzed diboration of 1-octyne and di-p-methylphenylacetylene using B2Cat2 [90]. The reactions proceeded using 5 mol% of the commercially available [Cl2Pt(cod)] (cod = 1,5-cyclooctadiene) at 55 °C. This protocol was highly dependent on the choice of diboron source, no catalytic activity was observed using B2pin2, as well as the choice of halide and diene on the platinum metal. [Br2Pt(cod)] required pre-stirring for 24 h before a homogeneous catalytic mixture was obtained and even then reaction yields were lower. The use of dicyclopentadiene instead of cod as a ligand also

since been widely employed en route to, for example, enantiomerically enriched 1,2-diols [82], 5-benzylidenenbenzopiridylloxepine analogues as nuclear hormone receptors [83], 1H-phosphindoles as chiral helicenes [84], 10-mesitylborylsubstituted-dibenzo[bpin] as a photoresponsive material [85], and the pentacyclic alkaloid tylophorine [86].
resulted in the formation of the 1,2-diborylated alkenes in lower yields.

In a study into new routes for the preparation of 1,1-geminal sp2-organobismetallic derivatives, Srebnik and co-workers demonstrated the platinum catalyzed diboration of 1-alkynylphosphonates and 1-alkynylboronates afforded the Z,1,2-diborylated vinylphosphonates and trisboronated alkene products 37 and 38, respectively (Scheme 21) [91]. The reaction with alkynylboronates was extremely sensitive to the moisture content of the solvent with ‘wet’ solvents resulting in B–C bond cleavage via a hydrodeboronation. Elsewhere, Nishihara reported the platinum catalyzed diboration of phenylethynyl MIDA (MIDA = N-methylimidodiacetic acid) boronate with B2pin2 to form 1,1,2-triboryl-2-phenylethene [92].

Fernandez and co-workers reported the preparation of α,α’-difluorinated carbonyl compounds. The reactions proceeded by an initial platinum(0) catalyzed diboration of internal and terminal alkenes to form Z,1,2-diborylated alkenes. Subsequent work-up with the electrophilic fluoro-deboronation agent 1-(chloromethyl)-4-fluoro-1,4-diazoniabicyclo[2.2.2]octane dite

Scheme 26. Palladium catalyzed diboration of internal and terminal alkenes [105].

Scheme 27. Cobalt(0) catalyzed diboration of an internal alkynes [106].

Scheme 28. Iron(II) catalyzed diboration of alkenes in a symmetric and unsymmetrical manner [107].

Scheme 29. Iridium catalyzed dehydrogenative borylation/diboration of terminal alkenes [108].
Scheme 25. In the presence of phosphine-platinum catalysts, the diboration of terminal alkynes resulted in the regioselective formation of 43 with Bdan, a boryl protecting group, in the terminal position. The palladium-catalyzed Suzuki-Miyaura cross-coupling occurred chemoselectively on the more reactive internal Bpin. This was in sharp contrast to the B2pin2 based diborations, where the coupling selectively proceeds initially at the more reactive terminal Bpin group.

Escribano and co-workers showed that titania-supported platinum nanoparticles were efficient catalysts for the diboration of alkynes under solvent and ligand free conditions in air. Terminal and internal alkynes were accessible at 70 °C using 0.2 mol% of Pt/TiO2. A range of electron-donating and withdrawing aromatic or alkyl, branched and cycloalkyl substituents were accessible. Exclusively Z-1,2-diborylated alkenes were observed in all cases [102]. In contrast, when the support was magnesia (MgO), higher loadings and the use of solvent and elevated temperatures of 130 °C were required [103].

2.3.2. Palladium

Palladium-catalyzed diborations of alkynes are rare. Examples employing [2]borametalloarenes were reported by Braunschweig and co-workers. Palladium on carbon was utilized as a heterogeneous catalytic source, however the diborations required higher temperatures and much longer conversion times than their platinum analogues [99,100]. The rarity of palladium mediated alkynedi diborations can be attributed to the energetics of the B–B bond oxidative addition at the Pd(0) center. Theoretical calculations suggest that this is both a kinetically and thermodynamically unfavorable process [104]. Despite this, Spencer, Navarro and co-workers recently accomplished the facile diboration of terminal and internal alkynes using catalytic amounts of [Pt(TiMe)2][PhC≡CPh)] (44) [105]. This represented the first examples of alkynedi diborations utilizing a homogeneous palladium catalyst. Both terminal and internal alkynes were accessible with 100% syn-stereoselective formation of the corresponding 1,2-diborylated alkynes 45 (Scheme 26). These diborations proceeded with higher yields and/or under milder reaction conditions than their platinum analogues.

A computational study to determine the mechanistic route suggested that Pd(0) catalyzed alkynedi diborations using NHC ligands followed the same catalytic cycle as phosphines (as detailed in the introduction of Section 2) [105]. An integral process in this pathway was, as in the case of phosphines, the reversible dissociation of an NHC ligand. These NHC ligands were also key to a successful oxidative addition of the B–B bond at the Pd(0) center. They destabilize the (diboron)Pd(0)L2 (L = ITMe) adduct resulting in a sufficient lowering of the free energy for oxidative addition.

2.3.3. Cobalt

In their investigations into the diboration of alkynes, Marder and co-workers described the diboration of 1,2-bis(4-(trifluoromethyl)phenyl)ethyne with B2cat (Scheme 27) using a [Co(PMe3)4] catalyst. Compound 46 was isolated as the major product of this reaction, with small quantities of the E-isomer detected [106].

2.3.4. Iron

The only example of iron catalyzed diboration of alkynes was detailed by Nakamura in 2015. Initial optimizations focused on the diboration of 4-octyne using B2pin2. Catalytic quantities of FeBr2 and LiOMe with 1.5 equivalents of MeOBpin were enough to afford 47 in high yields [107]. On extending to other Fe(II) and Fe(III) catalysts, yields dramatically decreased. The diboration of a variety of internal alkynes was possible: those with alkyl substituents proceeded in high yields, whereas aryl or bulky alkyl groups retarded the diboration. The role of the additional borating agent was also assessed. In the absence of MeOBpin the reactions still proceeded, but with lower conversions. When using MeOBnep (MeOBnep = 2-methoxy-5,5-dimethyl-1,3,2-dioxaborinane) the unsymmetrical diborylalkene 48 was isolated as the major product (Scheme 28), suggesting that the incorporation of the second boryl unit was introduced by an electrophilic substitution reaction with MeOBnep or MeOBpin.

2.3.5. Iridium

Ozerov and co-workers devised a two-step reaction to convert alkynes into trisborylalkenes. The first step transformed terminal alkynes into alkynylboronates using pinacolborane (HBpin) and iridium complex 49 as a catalyst. Degassing this reaction mixture followed by the introduction of a CO atmosphere generated the new catalyst 50, which mediated the dehydrogenative diboration of the newly formed alkynylboronate with HBpin to form 51 (Scheme 29) [108]. This reaction was extended to a range of alkyl and aryl terminal alkynes. The authors proposed the reaction to proceed via a hydroboration intermediate or via B2pin2.

2.3.6. Copper

Examples of group 11 transition metal catalyzed diboration of alkynes are very rare, with only one example of copper and one of gold described in the literature [109]. The first diboration of alkynes employing a copper catalyst was performed by Yoshida.

Scheme 30. Copper-catalyzed diboration of benzynes and tetraborylation of propargyl ethers [110].
The diboration of alkyl and aryl internal alkynes using $\text{B}_2\text{pin}_2$ in the presence of $[\text{Cu(OAc)}_2]$ and $\text{PCy}_3$ resulted in high yields of the corresponding Z-1,2-diborylated alkenes \[110\]. The authors also extended this to the diboration of benzynes to form the resulting 1,2-diborylated benzenes \[52\] (Scheme 30). Changing the phosphine to $\text{P}^1($Bu$)_3$, $\text{P}^1($Oc$)_3$ or $\text{PPh}_3$ resulted in either prolonged reaction times or lower yields. A striking feature of this copper catalysis was the diboration of propargyl ethers. In all cases the tetraborylated product \[53\] was exclusively isolated (Scheme 30).

2.3.7. Gold

Nanoporous gold (AuNPore), prepared by dealloying the monolithic $\text{Au}_{100}\text{Ag}_{70}$ alloy in a 70% nitric acid electrolyte, is a highly active catalyst in the diboration of alkynes. Jin and co-workers optimized a system with phenylacetylene and $\text{B}_2\text{pin}_2$ utilizing 2 mol% of AuNPore at 100 °C \[111\]. The AuNPore catalyst was recyclable with no notable decrease in catalytic activity over multiple cycles. The protocol was extended to a variety of terminal and internal alkynes, however other diborons were ineffective. Mechanistically, the authors proposed absorption of the $\text{B}_2\text{pin}_2$ onto the AuNPore surface. The $\text{B}—\text{B}$ bond is then cleaved at the low coordinate Au atoms to give an Au-Bpin species. The alkyne then adsorbs and reacts rapidly with two Au-Bpin species either through a simultaneous addition path to form the corresponding Z-adduct or in a stepwise manner.

2.4. Silicon–Boron ($\text{Si}—\text{B}$)

2.4.1. Palladium

Silyboranes are attractive precursors in the element–element additions to unsaturated substrates such as alkynes. According to the Pauling scale, the electronegativity difference between the Si (2.12) and B (1.88) atoms \[112\], is such that 1-boryl-2-silyl alkenes are synthesized with chemo-, regio- and stereoselective control in a single transformation \[113,114\]. The boron and silicon functionalities in these alkene adducts can subsequently undergo chemo- or stereoselective reactivity towards the preparation of more complex and unsymmetrical tri- and tetra substituted alkenes \[115,116\]. The most widely used catalysts for the silaboration of...
alkynes are group 10 transition metal complexes, specifically palladium-containing complexes.

Ito’s palladium/tert-alkyl isocyanide catalyst combination, previously detailed in alkyne bis(silylations), was effective in the silaboration of both terminal and internal alkynes to form syn-1-boryl-2-silyl alkenes (54) with high regio- and stereoselectivities (Scheme 31) [117]. The silyborane of choice was (dimethylphenylsilyl)boronic acid pinacol ester (PhMe$_2$SiBpin);

this Si–B compound is thermally stable under inert conditions and the Bpin functionality improves the stability of the subsequent organo-compounds towards hydrolysis during purification. In the case of terminal alkynes, the silaboration proceeded with the addition of the boryl group at the terminal position. Attempts at silaboration employing other metal complexes resulted in either lower yields and mixtures of regioisomers (e.g. [Pt(PPh$_3$)$_3$]) or no activity (e.g. [RhCl(PPh$_3$)$_3$]).

The authors later extended this protocol to other silyboranes (i.e. PhMe$_2$SiB(NEt$_2$)$_2$ and PhMe$_2$SiBcat) and to a larger array of

![Scheme 34. Reagent dependent stereoselective silaboration of terminal alkynes [124].](image)

![Scheme 35. Ligand controlled, stereoselective ‘abnormal’ regioselective silaboration [125].](image)

![Scheme 36. Silyborate formation and resulting external-base free cross-coupling [126].](image)

![Scheme 37. Regioselective synthesis of disubstituted siloles [127].](image)
terminal and internal alkynes, including 1,7-octadiyne to afford the double silaboration product \textit{55} (Scheme 31). The reactivity of the syn-1-boryl-2-silyl alkenes was also assessed. Suzuki-Miyaura cross-coupling and conjugate additions to methyl vinyl ketones at the alkenyl boryl group were possible, leading to \textit{56} and \textit{57}, respectively (Scheme 32) [118]. Many authors have since utilized [Pd(OAc)$_2$]/isocyanide as a mediator in the silaboration of alkynes including in the synthesis of syn-homoallylic alcohols [119], multi-arylated olefins [120], and enamides [121].

Tanaka and co-workers described the silaboration of 1-octyne employing the silylborane, 1,3-dimethyl-2-dimethylphenylsilyl-2-methylbora-1,3-diazacyclopentane. The corresponding Z-1-boryl-2-silyl alkeene \textit{58} was isolated by utilizing the pre-catalytic combination of [Pd$_2$(dba)$_3$] and epto (epto = 4-ethyl-2,6,7-trioxo-1-phosphanoclo[2,2,2]octane, P(OCH$_3$)$_2$CEt). Pre-heating the pre-catalytic combination at 80 °C for 5 min was necessary in order to generate the active catalytic species, proposed to be [Pd(epto)$_2$]. As observed in Ito’s report, the silaboration of terminal alkynes proceeds in a regioselective manner with the boryl group inserting at the terminal position. Low to no yields were observed on applying other phosphorus containing ligands such as PMe$_2$ and PPh$_3$. The protocol was also expanded to the silaboryl carbycrlization of hepta-1,6-diene to form \textit{59} (Scheme 33) [122].

Pillot and co-workers synthesized stable organosilylboranes possessing mesityl groups on the boryl atom, (diphenylmethylsilyle)dimesitylborane (PhMe$_2$SiBMe$_2$S) and (diphenyl-tert-butylosilyl)dimesitylborane (Ph$_2$BuSiBMe$_2$S). These silylboranes are not stabilized by electronegative groups on the boron atom e.g. oxygen or nitrogen, but instead through the steric bulk of the mesityl functionality. They were employed in the silaboration of terminal alkynes such as phenylacetylene, using the [Pd$_2$(dba)$_3$]/epto catalytic combination. Steric clashing between the substituents of the alkyne and the boryl moiety precluded the silaboration of internal alkynes [123].

In their investigations into the silaboration of terminal alkynes, Suginome and co-workers showed that it was possible to tune the stereoselective preference of the reaction by altering the reagent stoichiometry. The reaction parameters were assessed on treating (chlorodimethylsilyl)pinacolborane (ClMe$_2$Bpin) with 1-octyne in the presence of 1 mol\% [(\textit{t}-C$_3$H$_7$)$_2$Pd(PPh$_3$)Cl], followed by subsequent addition of isopropyl alcohol (IPA) and pyridine. When excess 1-octyne was used the \textit{Z}-isomer \textit{60} was isolated as the sole product. However, excess ClMe$_2$Bpin results in the formation of the \textit{E}-isomer \textit{61} as the major product (Scheme 34). This observation was applicable to a range of terminal alkynes, although sterically hindered substituents on the alkyne restricted \textit{E}-silaboration [124].

It was also possible to tune the regioselectivity in the silaboration of terminal alkynes. The silaboration proceeds with ‘normal’ regioselectivity in the presence of catalytic quantities of [(\textit{t}-C$_3$H$_7$)$_2$Pd(PPh$_3$)Cl]. However, using the more sterically hindered phosphine P(Bu)$_3$ (biphenyl-2-yl) an inverse or ‘abnormal’ regioselectivity was observed, with Z-2-boryl-1-silyl-1-alkenes \textit{62} isolated as the major product (Scheme 35) [125].

Suginome and co-workers also hydrolysed the ‘normal’ and ‘abnormal’ silaborated alkynes with metal hydroxides MOH (M = Na or K) instead of the IPA/pyridine mixture. This resulted in the formation of a five-membered cyclic borate \textit{63} via intramolecular attack of the resulting silanol oxygen with the tricoordinated boron atom. The potassium borates \textit{63a} and \textit{63h}}
were then subjected to external-base free Suzuki-Miyaura cross-coupling with 4-idoanisole to form 64 and 65, respectively (Scheme 36) [126].

The authors achieved a different mode of reactivity by substituting one of the substituents of the silicon atom of a silylborane for an amino group. The reaction of (Et$_2$N)Me$_2$SiBpin with aliphatic or aryl terminal alkynes resulted in the formation of 2,4- and 3,4-disubstituted siloles, 66 and 67 respectively (Scheme 37). Isomer 66 was favored in most cases and this was attributed to steric clashing within intermediates in the catalytic cycle. Deviations in the electronic and steric properties of the alkyne substituents had little influence on the regioisomer formed. However, altering the phosphine ligand to the more sterically hindered P(Ph)$_2$(2-biphenyl), resulted in a higher ratio of 66 vs. 67. The synthesis of siloles was also accompanied by the formation of the corresponding aminopinacolborane, and was extended to other silylboranes including (Me$_2$N)Me$_2$SiBpin and (pyrroldino)Me$_2$SiBpin [127].

Moberg and co-workers subjected a number of 1,3-enynes to palladium catalyzed silaborations using PhMe$_2$SiBpin. The reactions required relatively high loadings of palladium and phosphate ligand, as well as catalytic quantities of disobutylaluminum hydride (DIBAL-H). 1,2-Silaboration led to dienes 68 in all cases. Alternatively, changing the transition metal catalyst to a platinum analogue and the 1,3-enynes substituent to a sterically hindering functionality resulted in 1,4-silaboration and isolation of the corresponding allene 69 (Scheme 38) [128]. Later, Moberg altered the silaborane to OMe$_2$SiBpin and, in the presence of isopropanol and pyridine, this resulted in formation of the corresponding highly substituted 1,3-dienyl-2-silanol. Subsequent Suzuki-Miyaura and Hiyama-Danmark cross-coupling reactions yielded tri- and tetra-substituted 1,3- or 1,2-dienes in a chemo-, regio- and diastereoselective manner [129].

Most of the reports to date utilize either phosphate or isocyanide ligand sets. In their investigations into NHCS-palladium catalysis, Spencer, Navarro and co-worker observed that [Pd (TTMe$_2$)(PhC≡Ph)$_2$] (44) catalyzed the silaborations of terminal and internal alkynes with PhMe$_2$SiBpin to afford a number of known and novel 1-silyl-2-boryl alkynes 54 and 70 (Scheme 39) [130]. This protocol represented the first example of alkynylsilaborations employing NHCS ligands. All reactions proceeded with 100% syn-stereoselectivity and, in the case of terminal alkynes 100% ‘normal’ regioselectivity. High regioselectivities were also noted when using unsymmetrical internal alkynes, with the silyl moiety favoring a position that is geminal to the aryl ring. Unprecedented mild reaction temperatures for terminal alkynes, short reactions times, and low catalyst loadings were reported.

2.4.2. Nickel

Ito reported the double insertion of terminal alkynes into the Si–B bond of PhMe$_2$SiBpin to afford 2Z,1-silyl-4-boryl-1,3-butadiene derivatives in a regio- and stereoselective manner. The reactions proceeded using catalytic quantities of [Ni(acac)$_2$] and the reductant DIBALH to afford a 3:1 mixture of 71 and 72 (Scheme 40). The major product 71 was a result of head-to-head dimerization of the alkyne, whereas head-to-tail dimerization gave 72. Dimerization yields were increased by using a large excess of alkyne and were retarded by the introduction of a phosphate. This protocol was also extended to internal alkynes with the exception of diphenylacetylene, which was inert under the reaction conditions. The application to diynes resulted in intramolecular cyclization and the formation of the dimethylenecyclohexane derivatives [131].

2.4.3. Gold

The only other metal-mediated alkyne silaboration in the literature utilized gold nanoparticles supported on titania (Au/TiO$_2$). Stratakis and co-workers used 1 mol% Au/TiO$_2$ to catalyze the silaboration of terminal alkynes at room temperature to form syn-2-boryl-1-silyl-1-alkenes 73 (Scheme 41). These alkenes were

\[ \text{R} \equiv \text{H} + \text{Me}_2\text{Sn-SnMe}_3 \xrightarrow{1 \text{ mol\% Pd(PPPh}_3)_4} \text{Me}_2\text{Sn} \text{SnMe}_3 \]

\[ \text{toluene, 25-85 °C} \]

\[ \text{74a: R = H} \quad \text{74b: R = "Bu} \quad \text{74c: R = Ph} \quad \text{74d: R = PhCH}_2 \]

\[ \text{Scheme 42. The first palladium catalyzed distannation of terminal alkynes [135].} \]

\[ \text{2 Me}_2\text{Sn-SnMe}_3 \rightarrow \text{Me}_2\text{Sn} \text{SnMe}_3 \]

\[ \text{toluene, 75 °C, 30 h} \]

\[ \text{75a: R = H} \quad \text{75b: R = Me} \]

\[ \text{Scheme 43. Distillation of trimethylstannylethylene in the synthesis of tris(trimethylsilyl)ethylenes [138].} \]

\[ \text{R} \equiv \text{O} + \text{Me}_2\text{Sn-SnMe}_3 \]

\[ \xrightarrow{1-2 \text{ mol\% Pd(PhP}_3)_4} \text{Me}_2\text{Sn} \text{SnMe}_3 \]

\[ \text{THF, r.t. to 60 °C} \]

\[ \text{76} \]

\[ \text{76a: R = Me, R = OEt} \quad \text{76b: R = Et, R = OMe} \quad \text{76c: R = Pr, R = OMe} \quad \text{76d: R = cyclopentyl, R = OMe} \quad \text{76f: R = H}_2\text{C=CH(CH}_2\text{}_3 \text{R = OMe} \]

\[ \text{76g: R = H}_2\text{C=CH(CH}_2\text{}_3 \text{R = OMe} \quad \text{76h: R = I(CH}_2\text{)}_3 \text{R = OMe} \quad \text{76i: R = I(CH}_2\text{)}_3 \text{R = OMe} \]

\[ \text{76j: R = Cl(CH}_2\text{)_3 R = OMe} \quad \text{76k: R = Br(CH}_2\text{)_3 R = OMe} \quad \text{76l: R = Br(CH}_2\text{)_3 R = OMe} \]

\[ \text{76m: R = Br(CH}_2\text{)_3 R = OMe} \quad \text{76n: R = I(CH}_2\text{)_3 R = OMe} \quad \text{76o: R = I(CH}_2\text{)_3 R = OMe} \]

\[ \text{76p: R = Br(CH}_2\text{)_3 R = OMe} \quad \text{76q: R = Br(CH}_2\text{)_3 R = OMe} \]

\[ \text{MeLi, THF, -78 °C} \]

\[ \text{77a: x = Cl, R = OMe} \quad \text{77b: x = Br, R = NMe}_2 \]

\[ \text{Scheme 44. Distillation of alkylnoatoates and alkynylamides [139].} \]

\[ \text{SiMe}_3 \]

\[ \text{R} \]

\[ \xrightarrow{5 \text{ mol\% Pd(PPPh}_3)_4} \text{Bu} \]

\[ \text{dioxane, 85 °C, 4 d} \]

\[ \text{78} \]

\[ \text{Scheme 45. Transmetallation-cyclization of distannylated o-halogeno-alkenoates [140].} \]

\[ \text{Bu} \]

\[ \text{Bu} \]

\[ \text{Bu} \]

\[ \text{Bu} \]

\[ \text{Bu} \]

\[ \text{Bu} \]

\[ \text{Scheme 46. Distillation employing the backbone of poly(di(nbutyl)stannane) [142].} \]
formed with opposite or ‘abnormal’ regioselectivities with respect to the analogous palladium examples, which was attributed to the steric factors imposed by the Au nanoparticles during the 1,2-addition of the silyborane to the alkynes. Side products in this reaction were the ‘normal’ regioselective silaborated alkenes, the bis(silylated) alkenes and B₂pin₂. The presence of bis(silylated) alkene and B₂pin₂ was explained by separately stirring PhMe₃SnSiMe₂Ph and B₂pin₂ as a result of metal-catalyzed silylborane metathesis, a competing reaction in this silaboration protocol. Extension to internal alkynes resulted in mixtures of regioisomers or no yield at all [132].

2.5. Tin–Tin (Sn–Sn)

2.5.1. Palladium

Organostannanes are often utilized in the chemoselective formation of C–C bonds through Migita-Kosugi-Stille reactions [133]. The development of new methodologies in the construction of C–Sn bonds is therefore of high interest [134]. A particularly attractive example is the insertion of alkynes into Sn–Sn bonds, distannation. The resulting alkynes have two new C–Sn bonds and are frequently formed with high stereoselectivities. Low-valent palladium complexes are regularly used to catalyze the distannation of alkynes.

Some of the first investigations into distannation of alkynes were carried out by Mitchell and co-workers. Hexamethyldistannane (Me₃SnSnMe₃) and terminal alkynes were mixed in the presence of catalytic quantities of [Pd(PPh₃)₄] to form Z-1,2-distannyl alkenes 74 (Scheme 42). Aryl, alkyl and propargyl ether substituents were tolerated. Distannation of acetylene at elevated temperatures initially led to the Z-isomer, which quickly isomerized to the thermally stable E-isomer. The Z to E isomerization was also observed in the absence of catalyst under photolysing conditions [135].

Mitchell later expanded this protocol to a wider variety of terminal alkynes including functionalities such as alcohols, amides, esters and silyl groups. The Sn–Sn bond presursor was also extended to other hexaalkyldistannanes (hexaethyl and hexabutyl ditin) [136], and to 1,2,4,5-tetraastannacyclohexanes [137]. The latter were further employed in the distannation of trimethylstannylenethyne to synthesise the first 1,1,2-tristannylalkene derivatives 75 (Scheme 43) [138].

Piers and co-workers reported the distannation of alkyl-2-alkynoates using Me₃SnSnMe₃ and a [Pd(PPh₃)₄] catalyst in THF at room temperature (or reflux) to form Z-2,3-bis(trimethylstanny1)-2-alkenoates 76 (Scheme 44). A vast array of functionality was tolerated including alkenyls, ethers, silyl ethers and primary halides [139]. Alkenoates with an α-halogeno-alkyl group were treated with Meli which resulted in a transmetallation-cyclization reaction to afford 2-trimethylstannylcycloalk-1-enes 77 (Scheme 45) [140]. The distannation protocol was also extended to N,N-dimethyl-2-alkynylamides and the formation of Z-N,N-dimethylythyl-2,3-bis(trimethylstannyl)-2-alkenamide 76q. Compounds 76q were thermally labile and transferred upon heating or at room temperature to the thermodynamically stable E-isomers [139].

The weakness of the C–Sn bond meant that it was possible to use vinyltins in electrophilic substitution reactions. Mitchell and co-workers detailed the reactivity potential of the Z-1,2-bis(trimethylstannyl)-1-alkenes with the electrophiles p-tolysulphonylchlorocyanate (TSCI), dichloromethylmethyl ether (DCME), trimethylsilyl chlorosulphonates and sulfur oxides [141].

Recently, Foucher and co-workers depicted the insertion of acetylene and phenylacetylene into the backbone of poly(di(‘butoxy)stannane). This resulted in the formation of new alkene-tin polymers 78 and 79, respectively (Scheme 46) [142].
Scheme 50. Palladium(0)-catalyzed silylstannation followed by regioselective cyclization [150].

Scheme 51. Silylstannation of 1-alkoxalkynes [151].

Scheme 52. Alkyne silylstannation using ionic liquid immobilised palladium(0) [152].

Scheme 53. Silylstannation and bismetallicative cyclization of 1,3-enynes [154].

2.5.2. Platinum

The only examples of distannation of alkynes employing a platinum catalyst were carried out by Wrackmeyer and co-workers. The distannane, 1,2-distanna-[4]ferrocenophane reacted sequentially or in one pot with [Pt(PPh3)3] and a range of terminal alkynes to form the corresponding 1,4-distanna-[4]ferrocenophanes 80 (Scheme 47) [143]. Both terminal and internal alkynes were accessible. However, dimethyl acetylenedicarboxylate gave the distannation product in a side reaction while favoring cyclotrimerization to form hexamethylbenzene hexacarboxylate. Extension to analogous palladium catalysts such as [Pd(PPh3)3] and [Pd(db)3] were unsuccessful [144].

2.5.3. Copper

In 2013, Yoshiida carried out the first catalytic distannation of alkynes using a copper catalyst, [Cu(OAc)[PPh3]2] in the presence of Cs2CO3 to optimize the reaction between Me2SnSnMe2 and 1-octyne affording 81. The authors then managed to distannylate 1-hexyne, 1-decyn and branched aliphatic terminal alkynes bearing isoamyl, isobutyl and cyclopentyl, as well as chloro, amino and cyano functionalities. Alkynes that were sterically congested resulted in sluggish reactions and low yields. It was proposed that the reaction proceeded through a Cu—Sn bonded intermediate 85 derived from a CuOR complex and a base-activated distannane. Subsequent addition of 85 to a C—C triple bond afford β-stannyldialkenyl copper species 86, which is then recaptured with Me2SnOR to give the 1,2-distannylated alkene with regeneration of the CuOR complex (Scheme 48) [145].

2.6. Tin–Silicon (Sn–Si)

2.6.1. Palladium

Sn–Si bond (silylstannation) addition to alkynes results in the formation of alkynes with a new C—Sn and C—Si bond, often in a regio- and stereoselective manner. Palladium catalyzed silylstannation of alkynes are by far the most reported examples within the literature and have found application in the synthesis of natural products [146,147], and pharmaceuticals [148]. The first palladium catalyzed examples of alkynyl silylstannations were shown by Mitchell and co-workers. The authors reacted a range of terminal alkynes with (trimethysilyl)trimethylstannane (Me3SiSnMe3) in the presence of [Pd(PPh3)3] under solvent-free conditions to yield terminal alkynes, and these 1,4-distanna-[4]ferrocenophanes 80 were shown to be useful precursors for the embrace reaction.
the corresponding Z-1-silyl-2-stannyl-1-alkenes (82) (Scheme 49). In all cases the silyl moiety added regioselectively at the terminal carbon [149].

Ito extended the use of [Pd(PPh3)4] as a catalyst in the reaction of the disilanylstannane 83 with alkynes affording the (β-disilanyllkenyl)stannanes 84. The reaction proceeded with the Z-addition of the Si–Sn bond to the C–C triple bond. 84. In the presence of phenylacetylene and further quantities of [Pd(PPh3)4], the reaction underwent regioselective cyclization to form the silastannylocyclohexadiene 85 as a single isomer (Scheme 50) [150]. Ito later accomplished the silastannylation of 1-alkynylalkynes employing the pre-catalytical combination of [Pd(OAc)2]/tert-octylisocyanide. The reactions proceeded at room temperature and yielded the syn-addition products 86, with the silyl group regioselectively introduced into the carbon atom bearing the alkyne moiety (Scheme 51).

[Pd(PPh3)4] was inactive in these transformations at both room and elevated temperatures [151]. The resulting alkene adducts were then exposed to a range of reactions including Stille cross-couplings, iodination at the C–Sn bond and the formation of acylsilanes. Singer reported the silastannylation of terminal alkynes with Bu3SnSiMe2Ph using catalytic quantities of [Pd(PPh3)4] immobilised in the ionic liquid 1-~butyl-3-methylimidazolium hexafluorophosphate ([bmim][PF6]). High stereo- and regioselectivities were observed and simple ether extraction resulted in isolation of the Z-1-silyl-2-stannyl-1-alkenes 87 (Scheme 52) [152]. The palladium(0)-ionic liquid combination was recyclable with no loss of activity even after 10 cycles [153].

The bismetallative cyclization of 1,3-enynes, using Bu3SnSiMe3, is dependent on the choice of ligand and palladium source. The use of [Pd(PPh3)4] results in ‘normal’ silylstannylation of the alkyne affording 88. However, upon removing the phosphine and using [Pd2(dba)3/CHCl3] or [Pd(OH)2/C], cyclized compounds 89 can be isolated as the major products of the reaction (Scheme 53). The bismetallative cyclization can also be observed on employing nucleophilic N-heterocyclic carbene with bulky alkyl N-substituents [154].

It is possible to tune the regioselectivity of alkyne silylstannylation by changing the ligand of a palladium(II) catalyst. Treatment of fluorine containing internal alkynes with Bu3SnSiMe2 in the presence of 2.5 mol% [Cl2Pd(PPh3)2] yields the silylstannylated adducts 90. However, by switching the palladium catalyst to

Scheme 56. Palladium(0)-catalyzed borylstannylation of alkynes [157,158].

Scheme 57. Borylstannylation of 1,3-enynes followed by pinacol alcoholysis [159].

[Cl2Pd*(BuNC)2], the opposite regioselectivities 91 are observed (Scheme 54) [155].

2.6.2. Copper

The only example of a copper-catalyzed alkyne silylstannylation was carried out by Yoshida and co-workers. The authors detailed a three-component coupling reaction employing terminal alkynes, a silylborane (PhMe2SiBpin) and a tin alkoxide ("Bu3SnO′Bu) in the presence of a Cu(I) catalyst ([CuCl·P′Bu3]). The observed regioselectivities were inverse to those of conventional silylstannylation under palladium catalyzed conditions, with the stannyl moiety predominately adding to the terminal carbon as shown in 92. A range of alkyl branched and unbranched alkynes bearing cyano, bromo, hydroxyl or amino functionalities were accessible (Scheme 55). The authors proposed a similar mechanism to the distannation of alkynes mediated by a copper(I) catalyst. A silylcooper species, CuSiMe2Ph, is initially formed via a sigma-bond metathesis between a copper alkoxide and a silylborane. An alkylene would then insert into the Cu–Si bond to give a β-silylalkenylcopper intermediate, which is subsequently trapped by a tin alkoxide to furnish the silylstannylation alkene adduct and regenerated the copper alkoxide [156].

2.7. Tin–Boron (Sn–B)

2.7.1. Palladium

The borylstannylation of alkynes results in the formation of alkynes with a new C–Sn and C–B bond. The first palladium-catalyzed example was shown by Tanaka and co-workers in 1996. The borylstannane, 1,3-dimethyl-2-(trimethylstannyl)-2-bora-1,3-diazacyclopentane (Me2SnBNMe(C2H5)2NMe) was added to alkynes using catalytic quantities of [Pd(PPh3)4] (Scheme 56). The reagents were added together in benzene at 0 °C and then warmed to room temperature. Terminal alkynes yielded syn-1-boryl-2-stannyl-1-alkenes 93 as the sole product. Internal alkynes were also accessible, although a higher temperature (80 °C) was necessary [157]. Weber later extended this protocol to the more sterically hindered borylstannane, 1,3-di-tert-butyl-2-(trimethylstannyl)-2-bora-1,3-diazacyclopentane (Me2SnBNBu(C2H5)2NMeBu) [158].

RajanBabu developed Tanaka’s methodology and extended it to the borylstannylation of 1,3-enynes. This protocol resulted in the isolation of the syn-1-boryl-2-stannyl-1-alkenes (94) in chemo-, regio- and stereoselective fashions with no complications arising due to the adjacent alken. However, the boryl group in 94 was hydrolytically unstable. In situ treatment with pinacol and p-toluenesulfonic acid (PTSA) yielded the hydrolytically stable 95 (Scheme 57) [159].
alkynes with one ary1 and one alkyl substituent resulted in perfect regioselectivities with the bory1 moiety geminal to the alkyl group. In the case of terminal alkynes, the bory1 group added to the terminal carbon [160]. All reactions proceeded at room temperature with catalyst loadings as low as 1 mol%. The authors proposed that these reactions proceeded through a similar mechanism to that of the silylstannation [156].

2.8. Sulfur–Sulfur and Selenium–Selenium (S–S and Se–Se) [178]

2.8.1. Palladium

Organochalcogens are known to exhibit a range of pharmacological activity profiles including as potential anticancer [161], anti-inflammatory [162], and antibacterial agents [163]. The introduction of chalcogens into alkynes to form 1,2-bis(chalcogen) alkenes is challenging. The formation of 1,2-bis(chalcogen) alkenes often requires the use of heavy metals, high temperatures and results in a mixture of stereoisomers. Such methods include the reaction vinylidichlorides with thiolate anions [164] and radical reactivity between chalcogen species and alkynes [165]. The transition-metal catalyzed addition of dichalcogens to alkynes is a possible alternative to synthesizing 1,2-bis(chalcogen)alkenes in a stereo- and atom-economical manner.

Sonoda reported the first palladium mediated addition of diaryl disulphides and diselenides to terminal alkynes to yield the corresponding Z-1,2-bis(arylthio) and Z-1,2-bis(aryl seleno)-1-alkenes [96], respectively (Scheme 58). This protocol tolerated functionalities such as hydroxyl, trimethylsilyl and amino groups. The inclusion of a carbon monoxide (CO) atmosphere in these reactions lead instead to the isolation of the carboxylative addition adducts Z-1,3-bis(arylchalcogen)-2-alken-1-ones (Scheme 58). A stepwise approach at carbonylation with CO to yield 97 resulted in the isolation of only 96, suggesting that CO insertion was part of dichalcogen additions in the first instance [166].

Gareau and co-workers established a procedure that effectively introduced ‘dialkyl’-disulphides in the dihalogenation of alkynes. Upon protecting the disulphide with a bulky silyl group, the dihalogenation of terminal alkynes with bis(trimethylsilyl)disulphide resulted in the isolation of the corresponding Z-1,2-bis(thio) alkenes (98). Subsequent treatment with tetra-tributylammonium fluoride (TBAF) in the presence of excess methyl iodide (Mel)
de-protected/alkylated the sulfur atoms affording 99 (Scheme 59) [167].

Additionally, Gareau investigated the reactivity of 98 towards other electrophiles including halides, epoxides and acyl chlorides [168]. Furthermore, treatment of 98 with HCl in the presence of a Lewis acid ([Zn(OtBu)] or cyclo[2.2.1]heptane (100) led to the bicyclic adducts 2,5,7-trithiabicyclo[2.2.1]heptane (100) [169].

Beletskaya and co-workers reported an alternative methodology in the addition of S–S and Se–Se bonds to alkynes. Diphenyl disulphide (Ph2S2) and diphenyl diselenide (Ph2Se2) were reacted with a variety of terminal alkynes in the presence of catalytic quantities of [Cl2Pd(PPh3)2], PhEH (E = S or Se) and triethylamine (NET3) to yield the Z-1,2-bis(arylseleno)-1-alkenes. Both PhEH and NET3 were essential for the success of the reaction. The yields increased on the addition of excess PPh3, which contradicts the general trend observed for other E–E additions to alkynes within the literature [170]. It was later shown that excess PPh3 prevented the rapid polymerization to [Pd(EAr)]n and therefore the inhibition of the palladium catalyst [171].

Beletskaya also reported the dithiolation of terminal alkynes utilizing a Pd(0) catalyst supported by a triphenylphosphine resin under conventional [172], and microwave heating conditions [173]. Simple filtration resulted in the isolation of the Z-1,2-bis(thio)-1-alkenes. This approach was not applicable to diaryl diselenides. Other palladium(0) supported mediators for the dithiolation of terminal alkynes include the MCM-41-supported bidentate phosphine Pd(0) catalyst reported by Cai [174].

2.8.2. Iron

Zeni described the addition of diorganyl diselenides and disulphides to terminal alkynes in the presence of an iron(III) chloride (FeCl3) catalyst. The best results were observed using diaryl diselenides bearing neutral electron-donating and withdrawing groups. The electronic nature of the terminal alkyne substituent did not have an effect on the rate or yield of the reaction [175]. Iron catalyzed addition to 1,4-butyndiol, pentyne-1,5-diol and 4-amino butynol afforded 3,4-bis(organochalcogen)-2,5-dihydrofurans (101), 4,5-bis(organochalcogen)-3,6-dihydro-2H-pyrans (102) and 2,5-dihydro 1H-pyrrole derivatives (103), respectively, under mild aerobic conditions (Scheme 61) [176]. 1,3-Dynes in the presence of dibutyl diselenide or dimethyldisulfide and stoichiometric quantities of FeCl3 yielded symmetrical and unsymmetrical 3,4-bis(buty1 selanyl)chalcogenophanes (104). In the synthesis of the 104, the cyclization was stereoselective providing exclusively the desired E-selenoynynes as intermediates. The selenophanes then formed via an intramolecular 5-endo-dig cyclization [177].

2.8.3. Copper

The addition of the catalytic mixture of Cu, zinc dust and glycerol resulted in the stereoselective addition of diaryl dichalcogenides to form a variety of E-1,2-bis-chalcogen alkynes (105) (Scheme 62). Zinc and glycerol were essential to the reaction; Zn reduced Cu(I) to Cu(0) while glycerol acted as a solvent, but also as a possible reducing agent for the reduction of Zn(II) to Zn(0) [178].

2.8.4. Nickel

The only examples of nickel-catalyzed addition of diaryldisulphides to alkynes were developed by Beletskaya and co-workers.
The use of 3 mol% $[\text{Ni(acac)}_2]$ and 30 mol% PMePh$_2$ at 100 °C under solvent-free conditions resulted in the stereoselective dithiolation of both internal and terminal alkynes to form 2-dithiolated alkene products. The reaction temperature was important: too low meant incomplete reactivity and too high led to a mixture of stereoisomers [179].

2.8.5. Rhenium

The stoichiometric reaction between the tetrathiometallate anion $[\text{ReS}_4]^{2-}$ and diphenylacetylene, 2-butyne and bis(trimethylsilyl)acetylene in the presence of elemental sulfur afforded the corresponding 2-bis(alkylthio)alkenes (107) (Scheme 64). A range of functionality at the terminal alkynyl substituent was accessible including hydroxyl, tert-butyldimethyisiloxyl and nitrile. However, internal alkynes were not accessible with this protocol [181].

Yamaguchi and co-workers extended their studies to the addition of disulphides and diselenides to alkynes in cross-over experiments. A 1:1 mixture of diaryl disulphides and diaryl diselenides were reacted with terminal alkynes using the same Rh complex and 1,1'-bis(diphenylphosphino)ferrocene (dpff). This resulted in the formation of Z-1-aryl seleno-2-arylthio)-1-alkenes (108) as the major product (Scheme 65). The amounts of minor by-products Z-2-aryl seleno-1-arylthio)-1-alkene, Z-1,2-bis(arylthio) alkene and Z-1,2-bis(aryl seleno)alkene were insubstantial. However, the minor product ratio became significant upon removal of trifluorosulfonic acid or when increasing the steric hindrance surrounding the alkynes [182].

2.9. Sulfur–Silicon ($S$–$Si$)

2.9.1. Gold

Nakamura and co-workers developed the AuCl-catalyzed cyclization of $o$-alkynylphenylthio)silanes (109) to form the corresponding 3-silylbenzo[b]thiophenes (110). The reaction was proposed to proceed initially by coordination of the gold species to the alkynyl moiety. The sulfur atom then acts as an intramolecular nucleophile, attacking the electron deficient alkyne which results in a silylsulfonium intermediate. Subsequently, $[1,3]$-migration of the silyl group and elimination of AuCl yielded 110 (Scheme 66). The yield was highly dependent on the natural of the alkynyl substituents with electron rich aromatic rings producing higher yields than electron poor or bulky groups (which inhibited the reaction) [183].

2.10. Sulfur–Boron ($S$–$B$)

2.10.1. Palladium

Suzuki and Miyaura employed 9-alkylthio)-9-borabicyclo[3.3.1]nonane in the palladium(0) catalyzed thio boration of terminal alkynes to produce 9-[Z-2-(alkylthio)-1-alkenyl]-9-borabicyclo[3.3.1]nonane derivatives. These reactions were highly regio- and stereoselective with the boryl group adding to the terminal carbon in all cases. The reactions were sufficiently mild that a variety of functionalities were tolerated [184].

2.11. Germanium–Germanium ($Ge$–$Ge$)

2.11.1. Palladium

In contrast to Si–Si and Sn–Sn bonds, the insertion of alkynes into Ge–Ge bonds has been investigated to a much lesser extent. The resulting compounds are expected to have a reactivity profile somewhere in-between their Si–Si and Sn–Sn analogues. The majority of alkyl digermymations in the literature are palladium catalyzed. The first example was reported by Ando and co-workers. In their work, a strained cyclic digermirane was reacted with acetylene and dimethyl acetylenedicarboxylate in the presence of 10 mol% $[\text{Pd(PPh}_3]_2$ in formation of the digermacyclopentene 111. When X was a sulfur atom, it was possible to selectively cleave the Ge–S bond to afford 112 (Scheme 67) [185].

Mochida and co-workers reacted 1,2,2,3,3,4,4-octaisopropyl trig ermetane ([(Pr$_2$Ge)$_4$] with various terminal alkynes in the presence of palladium complexes to synthesise $1,2,3,4$-tetrahydro-1,2,3,4-tetragermirins (113), $\Delta^2$-1,2,3-trigermolene (114) and $IH$-germroles (2,4-, 3,4- and 2,3-disubstituted) (115). The yields of 114 and 115 increased with time, a fact attributed to the thermolysis of 113 in the presence of excess alkyn. The formation of 114 from 113 suggested extrusion of disopropylgermylene (iPr$_2$Ge),

![Scheme 68. Addition of a tetragermetane to internal alkynes [186].](image)

![Scheme 69. Digermylation, reductive cyclization employing dichlorodicermanes and terminal alkynes [186].](image)
which was readily trapped by two equivalents of alkyne to give 115 [186] (Scheme 68).

In 1991, Tanaka used linear non-strained digermanes in the digermylation of alkenes. 1,2-Dichloro-1,1,2,2-tetramethyldigermane was reacted with phenylacetylene in the presence of a palladium(0) catalyst to form 116 (Scheme 69). The extension of the protocol to hexamethyldigermane resulted in very low conversions [187]. Following studies accomplished the conversion of 116 to 1,2-digermacyclobut-2-enes (117) by reductive cyclization in the presence of sodium metal. The treatment of 117 with alkenes in the presence of palladium catalysts resulted in the digermylation and the formation of the corresponding 1,4-digermacyclohex-2,5-dienes 118 and 119 (Scheme 69) [188].

2.11.2. Platinum

The digermylation of terminal with hexamethyldigermane has only been accessible employing a platinum catalyst at 120 °C, affording the corresponding Z-[2,3-bis(trimethylgermyl)]ethylenes (120) (Scheme 70). Lowering the temperature resulted in deterioration of the yields [189]. Internal alkenes were unreactive.

2.12. Germanium–Tin (Ge–Sn)

2.12.1. Palladium

Piers and co-workers reported the germylstannation of α,β-acyleneic esters with Bu₃SnGeMe₃ to afford E-2-(tri(alkylstannyl)-3-[(trimethylgermyl)alk-2-enoes (121) as the major product. The reactivity of the resulting germyl and stannyl groups were separately assessed. 121 was treated with BuLi and an alkyl halide to form 122 via the transmetallation of Bu₃Sn. The germyl moiety was also transformed into a C–I bond upon addition of iodine (Scheme 71) [190].

Nakano synthesized Z-1-aryl-2-germyl-1-stannylethenes (123) by adding tributyl(triethylgermyl)stannane to aryl terminal alkenes in the presence of catalytic amounts of [Pd(dba)₂] and 4-ethylnyl-1-phospha-2,6,7-trioxabicyclo[2.2.2]octane (Scheme 72). This protocol was extended to ethynylthiophene and 2-methyl-3-butyln-2-ol. The regioselective addition of the germyl moiety at the terminal carbon was favored in all cases [191].

2.13. Germanium–Boron (Ge–B)

2.13.1. Nickel, palladium and platinum

In their investigation into the elaborative dimerization of alkynes catalyzed by nickel complexes, Ito and co-workers developed the analogous germylborane reaction. The product/s obtained in the germylboration of 1-hexyne were highly dependent on the metal catalyst used. In the presence of [Ni(acac)₂]/DIBALH, the germylborated dimerized product 124 was obtained. By altering the catalyst to [Pd(OAc)₂]/isocyanide, a 1:1 mixture of 124 and the germylboration adduct 125 was isolated, whereas catalytic-quantities of Pt(PPh₃)₄/(C₂H₄) resulted in exclusively 125 (Scheme 73) [131].
3. Conclusions

This review presents the state-of-the-art in homo- and hetero-
genous transition metal catalyzed hetero element–element additions to alkenes. These reactions yield highly functionalized multi-substituted alkenes with high regio- and stereoselectivities. The early literature was limited to reactive or unstable E–E bonds, and reactions were primarily mediated by platinum group transition metal complexes with phosphine or isocyanide ligands. Developments over the past decade made it possible to employ other transition metal complexes such as coinage metal complexes, and utilize commercially available E–E bonds that are air and moisture stable. Furthermore, the application of NHCs as ligands has vastly improved conditions in an unprecedented manner. However, E–E bonds are still restricted in their application and the state-of-the-art catalysts remain flawed. Continuing efforts are likely to focus on earth abundant transition metal complexes and new E–E bonds that improve current regio- and stereo selectivities.

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References
