DOI: 10.1002/adsc.200800356

Benzimidazolium-Pyrazole-Palladium(II) Complexes: New and Efficient Catalysts for Suzuki, Heck and Sonogashira Reactions

Fuwei Li[a] and T. S. Andy Hor[a,*]

[a] Department of Chemistry, National University of Singapore, 3 Science Drive 3, Singapore 117543
Fax: (+65)-6873-1324; e-mail: andyhor@nus.edu.sg

Received: June 8, 2008; Published online: October 6, 2008

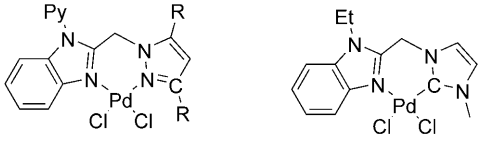
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.200800356.

Abstract: Three unsymmetrical benzimidazolium-pyrazole N-N ligands 2-(1-propylbenzimidazolylmethyl)-3,5-di-R-pyrazole (R = H, Me, *t*-Bu) have been conveniently prepared and structurally analyzed. The solid lattice packing of the R = Me compound at 223 K reveals one-dimensional "zig-zag" water chains stabilized by organic molecular channels through N···H–O and O–H···O bonding. These hybrid ligands add to palladium(II) to give high yields of air-stable complexes that are fully characterized by NMR, ESI, and X-ray single-crystal crystallography. They are active Suzuki catalysts at room temperature towards cross-coupling of unactivated aryl bromides and 5- or 6-membered heteroaryl bromides with arylboronic acids with turnover frequencies (TOF) reaching as high as 60,000 h^{-1}. Their catalytic efficiency is significantly better than that of the C–N carbene-imidazole analogue. These catalysts are also active in Heck and Sonogashira cross-coupling reactions of aryl bromides giving the desired products in good yields. These results suggested that these Pd(II) complexes with N-based hybrid ligands are versatile and efficient catalysts for different types of cross-coupling reactions under aerobic conditions.

Keywords: cross-coupling; hybrid ligands; N-heterocyclic carbenes; palladium; water channel; X-ray structure determination

Introduction

Palladium-catalyzed C–C bond forming reactions such as the Suzuki–Miyaura,[1] Mizoroki–Heck[2] and Sonogashira[3] reactions have been recognized as powerful methodologies in the synthesis of natural products and a variety of complex organic molecules used in pharmaceutical and materials processes. It also provides a focus of our recent work in C–C cross-coupling reactions.[4] Phosphine is generally the ligand of choice due to its superior donor capability and stabilization effects.[5] However, many phosphines are air- and moisture-sensitive, obnoxious, toxic and therefore difficult to handle. They are also prone to dissociation, oxidation and hydrolysis. These have prompted the vigorous research on phosphine-mimics such as N-heterocyclic carbenes (NHCs).[6] NHC complexes are largely stable, but many of them are also handicapped by the lack of coordinative flexibility. This subsequently led to the emergence of carbene-hybrids, a recent example of such is found in the benzimidazole-functionalized imidazolium-based NHC in Pd(II) (Scheme 1).[7] We herein advance a new class of "carbene-mimic" hybrid ligands (**2**–**4**) prepared from 2-chloromethyl-1-propylbenzimidazole (**1**) and pyrazole, through the use of unsymmetrical bidentate benzimidazole-pyrazole N,N chelates (**5**–**7**) as a contrast to the benzimidazole-carbene C,N chelate (**8**) (Scheme 1).[7] These two difunctional motifs share a common skeletal framework with similar steric encumberance. However, the replacement of a carbene with a presumably weaker σ-donor, stronger π-acceptor and more labile pyrazole N-donor is expected to have a catalytic benefit.[8] The use of N,N- as alterna-



5, R = H
6, R = CH_3
7, R = $C(CH_3)_3$

8

Scheme 1. Structures of benzimidazole supporting N-N (**5**–**7**) and C-N (**8**) bidentate Pd(II) complexes.

tives to P,P-type ligands could also favor oxidative addition and promote an array of C–C cross-coupling reactions.[9]

Results and Discussion

Synthesis and Characterization of Benzimidazolium-Pyrazole Unsymmetrical N-N Ligands (2–4)

The ligands 2-(1-propylbenzimidazolylmethyl)-3,5-di-R-pyrazole (R = H, **2**; Me, **3**; *t*-Bu, **4**) have been conveniently prepared in good yields by N-alkylation of the pyrazolyl compounds with 2-chloromethyl-1-propylbenzimidazole (**1**) (Scheme 2). The latter is obtained as a pink solid in a one-step procedure from commercially available sources.[7] All the ligands have been characterized by ^{1}H NMR, ^{13}C NMR and high-resolution mass spectroscopy. The solid-state structures of the ligands **3** and **4** have been established by X-ray single-crystal crystallography [Figure 1; depository numbers: CCDC 690474 (**3**) and CCDC 690475 (**4**)]. They show the expected imidazole and pyrazole moieties with a methylene bridgehead. A remarkable feature of **3** is revealed in its hydrate structure at 223 K with a unidirectional "zig-zag" water cluster encapsulated in the extended lattice channels (see Supporting Information).

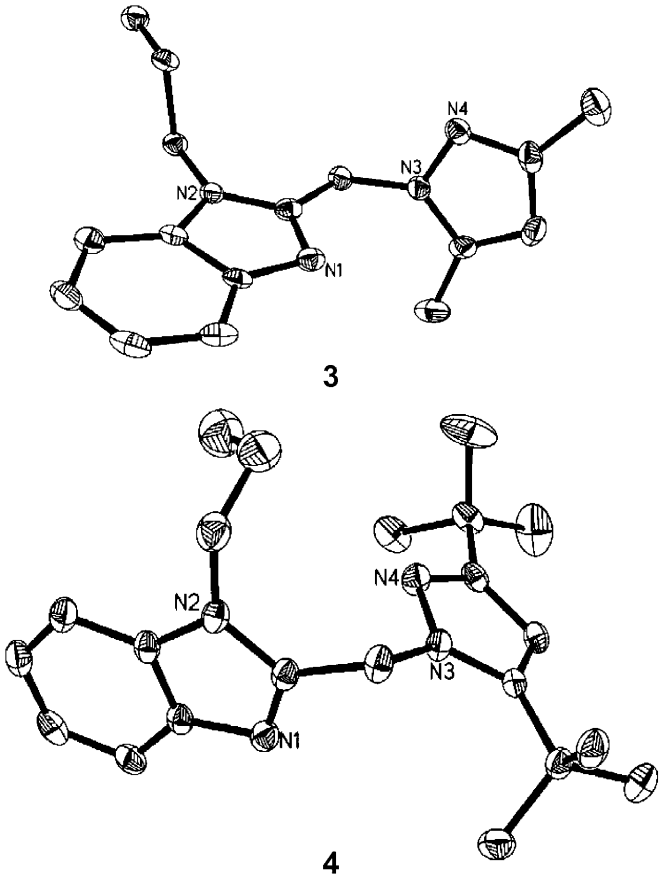
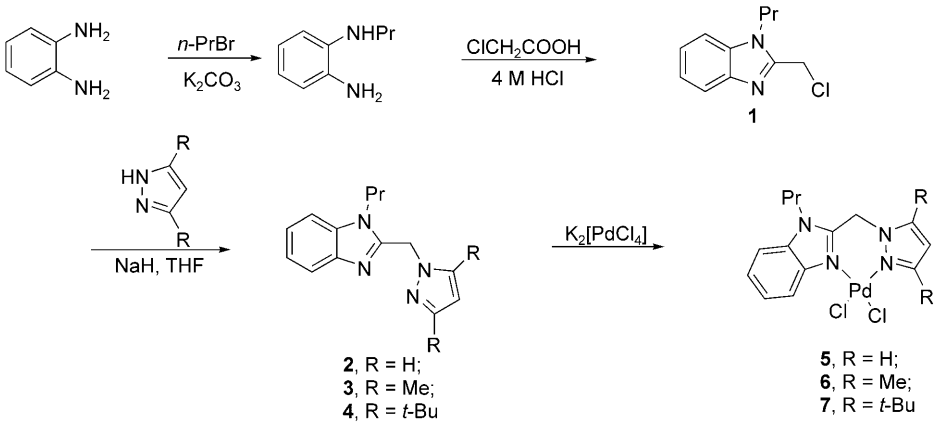


Figure 1. ORTEP view of ligand **3** and **4** (ignoring the proton and water solvate in **3**) (thermal ellipsoids at the 30% level).

Synthesis and Characterization of Benzimidazolium-Pyrazole-Based Difunctional Pd(II) Complexes (5–7)

The new Pd(II) complexes **5**–**7** were obtained in 76–82% yields as yellow to orange crystals from an aqueous methanolic solution of $K_2[PdCl_4]$ with the ligands **2**–**4** at room temperature (Scheme 2). These mononuclear complexes with an N,N-chelate have been fully characterized by NMR, ESI-MS and elemental analysis. The ESI data suggest that for **5** and **6**, peaks corresponding to the cationic dinuclear chloride-bridged species are present. This is not unexpected and can be explained by chloride dissociation followed by dimerization under the charged conditions in ESI. For **7**



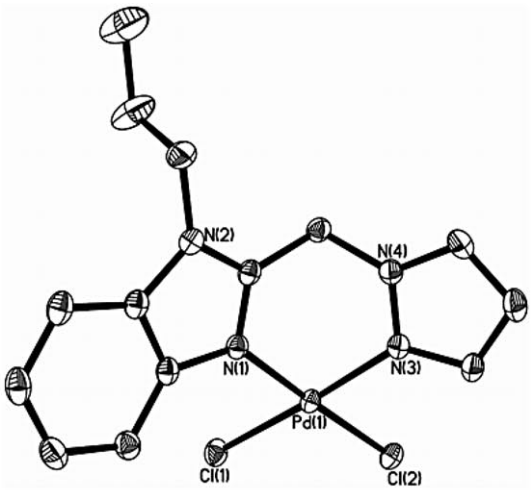
Scheme 2. Synthesis of benzimidazolium-pyrazole ligands (**2**–**4**) from **1** and their corresponding Pd(II) complexes (**5**–**7**).

there is an additional singlet resonance ($\delta = 6.16$ ppm) in its ^{1}H NMR spectrum, apart from the expected double doublets ($\delta = 6.40$ and 5.92 ppm), of the CH_2 bridgehead between the benzimidazole and the pyrazole. This points to the presence of a secondary species, which is tentatively identified as $PdCl_2(\eta^1\text{-N-N})_2$, with a free-rotating bridgehead arising possibly from the opening up of the N-N chelate ring. ESI-MS analysis gives the expected $[Pd(N\text{-}N)(CH_3CN)Cl]^+$ (m/z=536), but also $[Pd(N\text{-}N)_2Cl]^+$ (m/z=847). The latter arises from migration of the N-N ligand (**4**). The ease of chelate dissociation, and subsequent ligand scrambling, of **7** possibly provides a means to remove unfavorable interaction between the butyl substituent and coordinated chloride. Crystals suitable for X-ray diffraction analysis were obtained by slow diffusion of Et_2O into CH_3CN or DMSO solutions of the samples. Similar to **8**, whose structure has been reported,[7] the structures of **5**–**7** are square planar with difunctional N,N chelation giving a 6-membered metallo-heterocylic ring [Figure 2; depository numbers: CCDC 690476 (**5**), CCDC 690477 (**6**) and CCDC 690478 (**7**)].

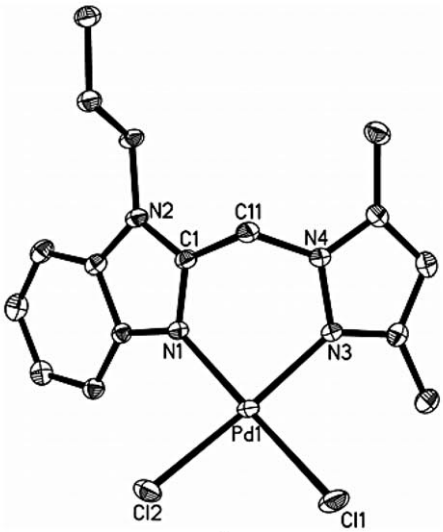
Suzuki–Miyaura Coupling of Aryl Halides with Arylboronic Acids at Room Temperature

Visentin et al. recently reported that the chelating phosphinocarbene ligand (P-C) of a Pd(II) complex shows a significantly slower rate in amination compared to its phosphinopyrazole (P-N) analogue.[10] This prompted our investigation to compare the Pd complexes of benzimidazolium-pyrazole (N-N) (**6**) and benzimidazolium-carbene (C-N) (**8**). The coupling reaction of unactivated 2-bromoanisole with phenylboronic acid is significantly enhanced by **6** compared to **8** (Table 1, entries 1 and 2). Replacement of the carbene by pyrazole possibly lowers the electron density of the metal, thereby promoting nucleophilic attack by the boronic acid and easing the transmetallation.

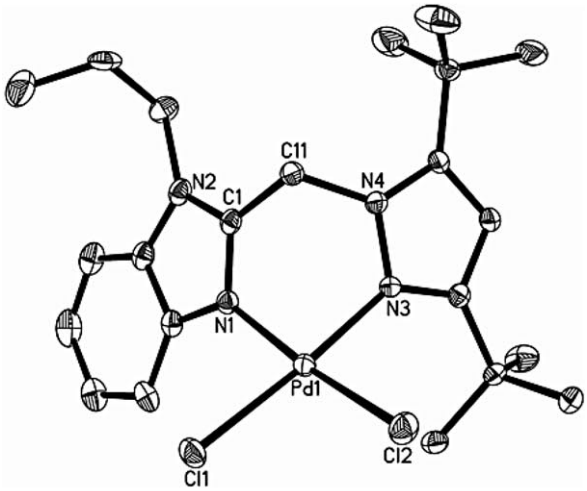
Both Fu et al. and Buchwald et al. reported the steric and electronic influences of the P ligands on the formation of the catalytic intermediates.[11] We have accordingly studied the effect of the R substituent of the pyrazolyl ring on the activity. The use of **5**, with the least strerically demanding **2** as the ligand, gives a modest 56% yield (Table 1, entry 3). It is remarkable that the use of a bulky and electron-rich CMe_3 group (compared to Me or H) results in a quantitative yield with the reaction being completed within 10 min at room temperature (entry 4). A near quantitative yield is achieved within 20 min even when the catalyst load is reduced to 0.05 mol%, and when unactivated aryl bromide is used (entry 5). This points to a marked influence of the substituent on the heteocyclic ring on



5



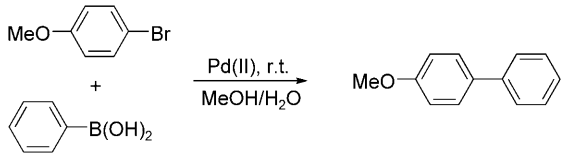
6



7

Figure 2. Molecular structures of **5**–**7** showing 30% probability ellipsoids (hydrogen atoms omitted for clarity).

Table 1. Screening of the catalysts and solvents on the Suzuki coupling of 2-bromoanisole with phenylboronic acid.[a]



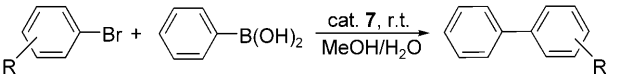
Entry	Catalyst	Solvent	Time [min]	Yield [%][b]
1	**8**	$MeOH/H_2O$	20	35
2	**6**	$MeOH/H_2O$	20	73
3	**5**	$MeOH/H_2O$	20	56
4	**7**	$MeOH/H_2O$	10	>99
5[c]	**7**	$MeOH/H_2O$	20	97
6	**7**	DMF/H_2O	10	>99
7	**7**	DMA/H_2O	20	>99
8	**7**	THF/H_2O	20	81
9	**7**	NMP/H_2O	20	82
10	**7**	$EtOH/H_2O$	10	>99
11	**7**	$MeCN/H_2O$	20	73

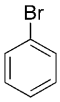
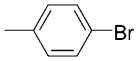
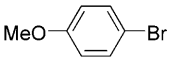
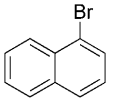
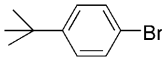
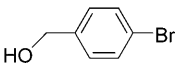
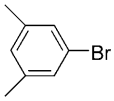
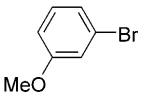
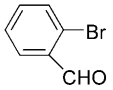
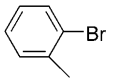
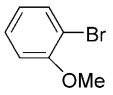
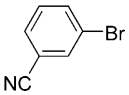
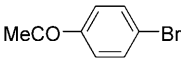
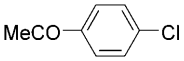
[a] *Reaction conditions*: 0.5 mol% catalyst, 0.5 mmol of 4-bromoanisole, 0.6 mmol of phenylboronic acid, 1.2 mmol of K_2CO_3, 2 mL of MeOH, 1 mL of H_2O, room temperature.
[b] GC-MS yield.
[c] 0.05 mol% catalyst.

catalytic reactivity. The higher activity of **7** could be related to the NMR observation of the open-up of the N,N chelate, which would create a vacant site for easier substrate attack. The solvent effect is similar to that observed for **8** – aqueous MeOH or EtOH gives the highest output, perhaps attributed to better solubility of the reagents and easier reduction of Pd^{2+} to Pd(0) and hence facile entry to the catalytic cycle.[12]

Under the above optimized conditions, complex **7** was applied to a representative range of aryl halides (Table 2). In the presence of K_2CO_3, it is effective towards the coupling of various aryl bromides with phenylboronic acid in $MeOH/H_2O$ at room temperature within a short reaction duration. Use of deactivated or electron-rich aryl bromides (entries 1–10) proceeds smoothly with high turnover frequencies (TOF) (entries 1 and 3), even when the catalyst loads are reduced to 0.05 mol%. The sterically hindered *ortho*-substituted substrates could also couple efficiently at low catalyst loads giving $\geq$90% yields within 40 min at room temperature (entries 11–15). The coupling reaction of 4-acetylphenyl bromide with phenylboronic acid can be promoted even with minimum catalyst (0.01 mol% of **7**) to give quantitative conversion within 10 min, achieving a TOF of 60,000 h^{-1} (entry 17). It is also effective towards activated aryl chlorides. In the presence of 0.2 mol% of **7**, a 32% yield of the cross-coupled product is obtained from 4-acetylphenyl chloride (Entry 18). The yield improves to 52% with higher catalyst load without the use of a cocatalyst such as TBAB at room temperature (entry 19).

Table 2. Palladium-catalyzed Suzuki cross-coupling of aryl halides and phenylboronic acid in aqueous methanolic solution at room temperature.[a]



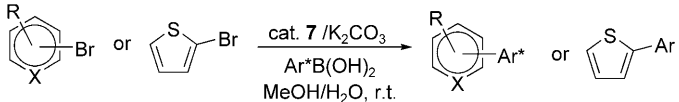
Entry	ArBr(Cl)	Pd [mol%]	Time [min]	Yield [%][b]	TOF [h^{-1}]
1		0.05	10	>99 (92)	12000
2		0.05	20	>99 (95)	6000
3		0.05	10	>99 (96)	12000
4		0.05	20	56	3360
5		0.5	30	>99 (89)	400
6		0.05	30	68	2720
7		0.5	60	98 (89)	196
8		0.5	15	>99 (90)	800
9		0.5	30	91 (86)	364
10		0.05	15	>99 (97)	8000
11		0.05	40	63	1890
12		0.5	30	>99 (90)	400
13		0.05	30	90 (79)	3600
14		0.05	30	76	3040
15		0.05	40	90 (82)	2700
16		0.05	10	>99 (95)	12000
17		0.01	10	>99 (98)	60000
18		0.2	20	32	960
19		2.0	180	52	17

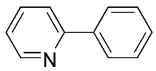
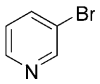
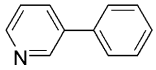
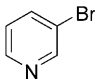
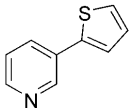
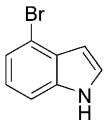
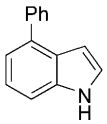
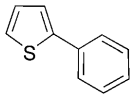
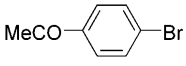
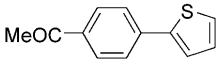
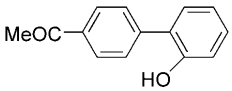
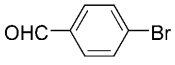
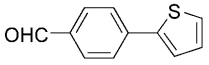
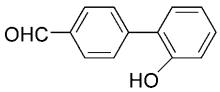
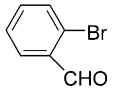
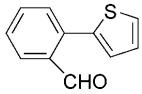
[a] *Reaction conditions*: 0.5 mmol of aryl halide, 0.6 mmol of phenylbronic acid, 1.2 mmol of K_2CO_3, 3.0 mL of $MeOH/H_2O$ (2:1).
[b] GC-MS yield (Isolated yields are indicated in parenthesis).

Suzuki–Miyaura Coupling of Heteroaryl Bromides or Heteroarylboronic Acids at Room Temperature in the Presence of Complex 7

Compared to advances in the coupling of aryl halides, the use of heterocyclic substrates has been plagued with problems especially when palladium catalysts are used. Some representative successful systems have been reported by Guram,[5b] Buchwald,[5c] Plenio,[5d] Fan[5g] etc. and their co-workers who commonly used phosphorus-containing ligands in reactions carried out under an inert atmosphere or at a high temperature. The present N(sp^2)-N(sp^2) chelating complexes can be applied to Suzuki coupling of selective N- or S- containing heterocycles and free-OH containing arylboronic acid, resulting in the desired cross-coupling products in generally good yields with considerably lower catalyst loads at room temperature (Table 3). The reactions of pyridyl bromides with phenylboronic acid proceed readily at room temperature to give high yields of the desired products (entries 1 and 2). The coupling between 3-bromopyridine and 5-membered heteroarylboronic acid also gives the desired product in 78% yield within 15 h (entry 3). The catalyst is also effective towards the coupling of a heteroaryl species with an unprotected -NH group, giving the corresponding product in 94% yield within 2 h (entry 4). In addition, the coupling of aryl bromides and OH-containing arylboronic acid could also be carried out smoothly with high reactivity (entries 7 and 9). The

Table 3. Room temperature Suzuki cross-coupling of heteroatom-containing substrates by using catalyst **7**.[a]



Entry	Ar-X	Product	Cat. Loading [mol%] (time, [h])	Yield [%][b]
1			0.25 (3)	91 (84)
2			0.25 (2)	81 (77)
3			0.5 (15)	78 (69)
4			0.25 (2)	94 (90)
5			0.5 (15)	67 (60)
6			0.5 (5)	67 (61)
7			0.25 (6)	95 (87)
8			0.5 (5)	72 (65)
9			0.25 (6)	98 (90)
10			0.5 (11)	62 (60)

[a] *Reaction conditions*: 0.5 mmol of aryl halide, 0.6 mmol of phenylbronic acid, 1.2 mmol of K_2CO_3, 3.0 mL of MeOH/H_2O (2:1).

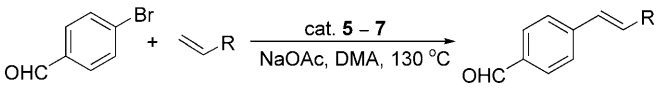
[b] GC-MS yield (Isolated yields are indicated in parenthesis).

reactions of thiazolyl derivatives and aryl halides or boronic acids give moderate yields (entries 5, 6, 8 and 10).

Mizoroki–Heck Coupling of Aryl Bromides with Styrene or *n*-Butyl Acrylate

The catalytic differences of complexes **5–7** were examined in the Heck reaction of 4-bromobenzaldehyde with styrene or *n*-butyl acrylate. They generally give good yields in dimethylacetamide (DMA) at 130 °C within 1–2 h under a low catalyst loading of 0.5 mol%. Complex **6** shows the best activities toward these two reactions (Table 4).

Table 4. Screening catalyst on Mizoroki-Heck reaction of 4-bromobenzaldehyde with styrene and *n*-butyl acrylate.[a]



Entry	Catalyst	R	Time [h]	Yield [%][b]	*E/Z*
1	**5**	Ph	2	90	9
2	**5**	CO_2-*n*-Bu	1	78	98/2
3	**6**	Ph	2	92	10
4	**6**	CO_2-*n*-Bu	1	99	99/1
5	**7**	Ph	2	89	10
6	**7**	CO_2-*n*-Bu	1	92	99/1

[a] *Reaction conditions*: Aryl bromide 1.0 mmol, olefin 1.5 mmol, 0.5 mol% complex, DMA 3 mL, NaOAc 2.0 mmol, temperature 130 °C.
[b] GC-MS yield.

The Heck reaction of selected aryl bromides proceeds smoothly with only 0.25–0.004 mol% of **6** under aerobic conditions. As given in Table 5, electron-withdrawing (entries 1–4), electron-donating (entries 6–9) and *ortho*-substituted aryl bromides (entries 10 and 11) could smoothly couple with styrene or *n*-butyl acrylate in excellent yields. It is noteworthy that the Heck reaction of 4-acetylphenyl bromide with styrene can be facilitated even with very low catalyst loading (0.004 mol% of **6**) to give quantitative conversion with a TON of 25,000 (turnover number, mol product/mol catalyst) (entry 12).

Sonogashira Coupling of Aryl Bromides with Phenylacetylene

All three complexes are active in the Sonogashira reaction of 4-acetylphenyl bromide with phenylacetylene without a copper additive (entries 1–3, Table 6). Complex **6** gives the best performance with quantitative conversion under very low catalytic loading (0.2 mol%) within a few hours (entry 4). All representative electron-poor, electron-neutral and electron-rich aryl bromides react with phenylacetylene smoothly to generate the corresponding cross-coupling products in excellent yields under standard aerobic conditions (entries 5–7). The catalyst is also tolerant of *ortho*-substituted 2-bromobenzaldehyde giving a near quantitative yield of the desired coupling product in 20 h (entry 8). Use of 1-bromonaphthalene gives a moderate yield (entry 9).

Conclusions

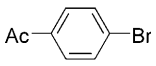
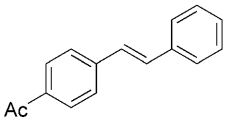
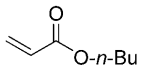
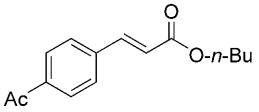
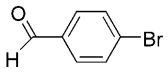
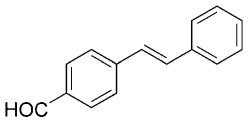
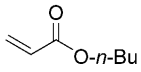
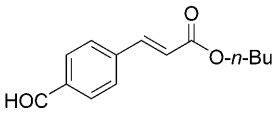
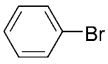
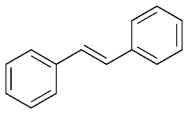
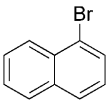
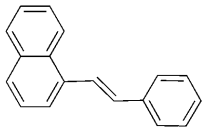
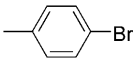
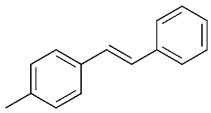
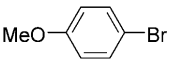
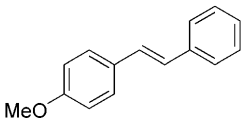
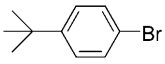
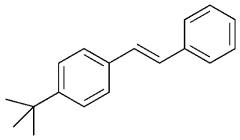
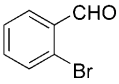
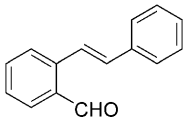
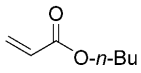
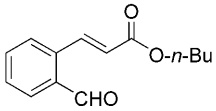
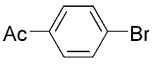
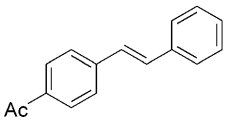
In summary, we have prepared a series of unsymmetrical benzimidazolium-pyrazole N-N ligands (**2–4**) with one of them (**3**) showing one dimensional H-bonded water chains in the solid lattice at 223 K. These (N-N)Pd(II) complexes with hybrid ligands are among the most efficient phosphine-free catalytic systems towards Suzuki cross-couplings of aryl and heteroaryl bromides in terms of conversions, yields and the ambient conditions used. Their utility can be extended to Heck and Sonogashira couplings of aryl bromides in high yields. These air-stable complexes can be easily prepared and used under aerobic conditions. The higher activities shown by the use of the benzimidazolium-pyrazole ligand compared to the related NHC analogue demonstrates the potential of N,N difunctional heterocyclic chelates in promoting cross-coupling catalysis. It also points a way forward to design NHC-carbene mimics in a similar manner that carbene could mimic phosphines. Current experiments in our laboratory are directed at these heterocyclic ligand designs.

Experimental Section

General Remarks

All the chemicals and solvents were used as received without purification except THF. *N*-Propylbenzene-1,2-diamine was prepared according to the literature procedures.[13] NMR spectra were measured on Bruker ACF300 300 MHz or AMX500 500 MHz FT NMR spectrometers. ESI-mas spectra were obtained on a Finnigan Mat 95XL-T spectrometer. Elemental analyses were performed by our microanalytical laboratory. High-resolution mass spectra were obtained in the ESI mode on a Waters Micromass Q-Tof Premier Mass Spectrometer. Melting point (mp) measurements were recorded on a Büchi B-540. The crystals were mounted on quartz fibers and X-ray data collected on a Bruker AXS APEX diffractometer, equipped with a CCD detector at −50 °C, using Mo KR radiation ($\gamma = 0.710\ 73$ Å). The data were corrected for Lorentz and polarization effects with the SMART suite of programs and for absorption effects with SADABS. Structure solution and refinement were carried out using the *SHELXTL* 97 programs.[14] The structures

Table 5. Mizoroki–Heck reaction of aryl bromides with olefin catalyzed by complex **6**.[a]

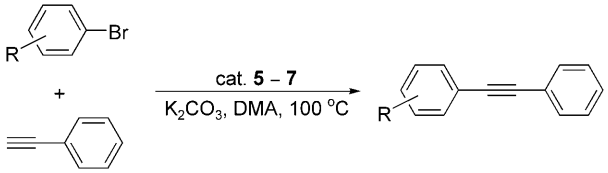
Entry	Aryl bromide	Olefin	Time [h]	Product	Yield [%][b]
1			3		97
2			4		99
3			4		98
4			4		99
5			20		99
6			24		99
7			24		94
8			24		99
9			24		90
10			24		96
11					85
12[c]			15		99

[a] *Reaction conditions*: Aryl bromide 0.5 mmol, olefin 0.75 mmol, 0.25 mol% complex **6**, DMA 3 mL, NaOAc 1.0 mmol, temperature 130 °C, *E/Z* ratios are similar to those recorded in Table 4 when the same olefin was used.

[b] GC-MS yield.

[c] Catalyst loading is 0.004%.

Table 6. Benzimidazolium-pyrazole Pd complexes-catalyzed Sonogashira coupling reaction.[a]



Entry	Catalyst	R	Time [h]	Yield [%][b]
1	**5**	4-Ac	3	78
2	**6**	4-Ac	3	85
3	**7**	4-Ac	3	72
4	**6**	4-Ac	4	99
5	**6**	4-CHO	4	99
6	**6**	H	20	99
7	**6**	4-Me	19	97
8	**6**	2-CHO	20	98
9[c]	**6**	$C_{10}H_7$	20	78

[a] *Reaction conditions*: Aryl bromide 0.5 mmol, phenylacetylene 0.75 mmol, 0.20 mol% complex, DMA 3 mL, K_2CO_3 1.0 mmol, temperature 100 °C.
[b] GC-MS yield.
[c] Aryl bromide is 1-bromonaphthalene.

were solved by direct methods to locate the heavy atoms, followed by difference maps for the light non-hydrogen atoms.

Preparation of 2-Chloromethyl-1-propylbenzimidazole (1)

Monochloroacetic acid (8.0 g, 85 mmol) and *N*-propylphenyl-1,2-diamine (7.50 g, 50 mmol) were refluxed in 4 M HC1 (50 mL) for 7.5 h. The reaction mixture was kept overnight and then neutralized with aqueous K_2CO_3 slowly. The precipitated product was collected by vacuum filtration, washed several times with water and dried to give a pink solid **1**; yield: 8.35 g (80%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.82–7.41 (m, 1H), 7.40–7.27 (m, 3H), 4.86 (s, 2H), 4.22 (t, J = 7.5 Hz), 2.01–1.91 (m, 2H), 1.03 (t, J = 7.4 Hz, 3H); ^{13}C NMR (75.47 MHz, $CDCl_3$): δ = 149.39, 142.86, 136.03, 124.12, 123.17, 120.90, 110.62, 46.51, 37.42, 23.75, 12.05.

Preparation of Benzimidazolium-Pyrazole Ligands (2–4)

Pyrazole (10 mmol) was added to a stirred suspension of NaH (480 mg, 12 mmol) in anhydrous THF (30 mL) under nitrogen. When H_2 evolution was complete, a solution of **1** (2.08 g, 10 mmol) in THF (50 mL) was added slowly. The mixture was then refluxed for 6 h, cooled and filtered. The filtrate was evaporated and resultant solid was purified by column chromatography using hexane/ethyl acetate (4:1) to give a colorless solid.

2-(1-Propyl-benzimidazolylmethyl)-pyrazole (2): yield: 2.3 g (96%); mp 79.0–79.5 °C; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.80–7.79 (m, 1H), 7.54 (d, J = 1.9 Hz, 2H), 7.36–7.27 (m, 3H), 6.29 (t, J = 2.2 Hz, 1H), 5.66 (s, 2H), 4.18 (t, J = 7.6 Hz, 2H), 1.62–1.54 (m, 2H), 0.91 (t, J = 7.6 Hz, 3H); ^{13}C NMR (125.77 MHz, $CDCl_3$): δ = 149.06, 142.96, 140.10, 136.11, 130.00, 123.91, 123.02, 120.79, 110.72, 107.61, 49.64, 46.35, 23.60, 11.83; HR-MS: m/z = 241.1444, calcd. for $C_{14}H_{17}N_4$: 241.1453.

2-(1-Propylbenzimidazolylmethyl)-3,5-dimethylpyrazole (3): yield: 2.5 g (93%); mp 102.0–102.5 °C; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.75 (d, J = 7.6 Hz, 1H), 7.32 (d, J = 7.6 Hz, 1H), 7.29–7.24 (m, 2H), 5.80 (s, 1H), 5.54 (s, 2H), 4.23 (t, J = 7.6 Hz, 2H), 2.25 (s, 3H), 2.22 (s, 3H), 1.52–1.45-(m, 2H), 0.91 (t, J = 7.6 Hz, 3H); ^{13}C NMR (125.77 MHz, $CDCl_3$): δ = 149.38, 148.46, 142.89, 141.12, 136.25, 123.65, 122.85, 120.70, 110.64, 106.84, 48.19, 46.44, 23.66, 14.05, 11.95, 11.76; HR-MS: m/z = 269.1767, calcd. for $C_{16}H_{21}N_4$: 269.1766.

Crystal data for 3: formula $C_{16}H_{22}N_4O$, colorless crystal, monoclinic space group Cc; a = 10.784(3), b = 29.897(9), c = 4.885(1) Å; β = 101.458(6)°; V = 1543.7(8) Å^3; Z = 4; crystal size 0.52 × 0.08 × 0.04 mm^3; GOF = 1.151; reflections collected: 4322; independent reflections: 2299 [R_{int} = 0.0352]; R_1 = 0.0616; wR_2 = 0.2260. Depository number: CCDC 690474.

2-(1-Propylbenzimidazolylmethyl)-3,5-di-*tert*-butylpyrazole (4): yield: 3.2 g (91%); mp 93.0–94.0 °C ; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.80–7.78 (m, 1H), 7.79–7.35 (m, 1H), 7.31–7.26 (m, 2H), 5.94 (s, 1H), 5.71 (s, 2H), 4.29 (t, J = 7.6 Hz), 1.65–1.57 (m, 2H), 1.33 (s, 9H), 1.30 (s, 9H), 0.92 (t, J = 7.3 Hz, 3H); ^{13}C NMR (125.77 MHz, $CDCl_3$): δ = 159.98, 152.69, 149.56, 142.21, 135.88, 122.74, 122.02, 120.00, 109.92, 101.02, 49.75, 45.67, 31.96, 31.62, 30.53, 30.25, 22.81, 11.42; HR-MS: m/z = 353.2690, calcd. for $C_{22}H_{33}N_4$: 353.2705.

Crystal data for 4: formula $C_{22}H_{32}N_4$, colorless crystal, monoclinic space group $P2_1/c$; a = 23.951(3), b = 15.735(2), c = 11.217(1) Å; β = 94.487(3)°; V = 4214.5(8) Å^3; Z = 8; crystal size 0.50 × 0.34 × 0.26 mm^3; GOF = 1.067; reflections collected: 23710; independent reflections: 7423 [R_{int} = 0.0507]; R_1 = 0.0682; wR_2 = 0.1468. Depository number: CCDC 690475.

General Procedure for the Preparation of Benzimidazolium-Pyrazole-Based Palladium Complexes 5–7

To an MeOH solution (5 mL) of the corresponding benzimidazolium-pyrazole ligand **2–4** (1 mmol) was added slowly a water solution (5 mL) of a molar equivalent of $K_2[PdCl_4]$ and the mixture stirred for 12 h at room temperature. The yellow to orange precipitate was collected by filtration and washed several times with water, then dried in vacuum to give the respective yellow to orange solid product.

5: yield: 318 mg (76%); mp 314.0–315.0 °C ; ^{1}H NMR (300 MHz, CD_3SOCD_3): δ = 8.30–8.24 (m, 2H), 7.86–7.78 (m, 2H), 7.45–7.35 (m, 2H), 6.51 (t, J = 2.5 Hz, 1H), 6.27 (s, 2H), 4.48 (t, J = 7.2 Hz, 2H), 1.85–1.73 (m, 2H), 0.89 (t, J = 7.3 Hz, 3H); ^{13}C NMR (75.47 MHz, CD_3SOCD_3): δ = 146.33, 142.78, 138.27, 134.69, 133.08, 124.48, 123.56, 119.64, 112.03, 107.11, 45.82, 23.04, 10.73; anal. calcd. for $C_{14}H_{16}N_4PdCl_2$: C 44.0, H 4.22, N 14.66; found: C 44.01, H 4.12, N 14.44; MS (ESI): m/z = 422 {[Pd(N-N)Cl]$^+$ + CH_3CN}, 798 [Pd_2(N-N)$_2Cl_3$].

Crystal data for 5·DMSO: formula $C_{16}H_{22}Cl_2N_4OPdS$, yellow crystal, monoclinic space group $P2_1/c$; a = 11.896(4), b = 7.953(3), c = 21.606(8) Å; β = 102.075(1)°; V =

1998.9(1) Å^3; $Z=4$; crystal size $0.44\times0.18\times0.16$ mm^3; GOF = 1.052; reflections collected: 13783; independent reflections: 4587 [$R_{int}=0.0215$]; $R_1=0.0304$; $wR_2=0.0779$. Depository number: CCDC 690476.

6: yield: 366 mg (82%); mp 331.0–332.0 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.11$ (d, $J=7.2$ Hz, 1H), 7.86–7.79 (m, 1H), 7.46–7.37 (m, 2H), 6.30 (d, $J=16.4$ Hz, 1H,), 6.18–5.99 (m, 2H), 4.72–4.42 (m, 2H), 2.62–2.46 (m, 6H), 1.83-1.70 (m, 2H), 0.94 (t, $J=7.2$ Hz, 3H); ^{13}C NMR (75.47 MHz, CD_3SOCD_3): $\delta=152.46$, 147.24, 143.96, 138.20, 133.40, 124.79, 124.00, 119.60, 112.61, 108.15, 46.27, 44.04, 23.73, 15.11, 11.81, 11.11; anal. calcd. for $C_{16}H_{20}N_4PdCl_2$: C 43.12, H 4.52, N 12.57; found: C 43.00, H 4.53, N 12.61; MS (ESI): $m/z=452$ {[Pd(N-N)Cl]$^+$ + CH_3CN}, 854 [Pd_2(N-N)$_2Cl_3$]$^+$.

Crystal data for 6: formula $C_{16}H_{20}Cl_2N_4Pd$, yellow crystal, monoclinic space group $P2_1/c$; $a=9.341(5)$, $b=19.782(1)$, $c=9.950(5)$ Å; $\beta=112.542(1)°$; $V=1698.3(2)$ Å^3; $Z=4$; crystal size $0.40\times0.30\times0.06$ mm^3; GOF = 1.060; reflections collected: 11897; independent reflections: 3895 [$R_{int}=0.0253$]; $R_1=0.0267$; $wR_2=0.0633$. Depository number: CCDC 690477.

7: yield: 419 mg (79%); mp 246.0–247.0 °C; ^{1}H NMR (300 MHz, CD_3SOCD_3): $\delta=8.29$–8.21 (m, 1H), 7.85–7.74 (m, 1H), 7.49–7.44 (m, 2H), 6.40 (d, $J=14.8$ Hz, 0.4H), 6.16 (s, 1.2H) 6.13 (s, 0.4H), 6.06 (s, 0.6H), 5.92 (d, $J=14.5$ Hz, 0.4H) 4.31–4.10 (m, 2H), 1.63–1.44 (m, 9H), 1.15–1.06 (m, 9H), 0.87–0.75 (m, 3H); ^{13}C NMR (125.77 MHz, CD_3SOCD_3): $\delta=159.72$, 152.56, 149.75, 142.00, 125.68, 124.68, 124.01, 119.93, 112.34, 101.14, 49.13, 46.76; anal. calcd. for $C_{22}H_{32}N_4PdCl_2$: C 49.87, H 6.09, N 10.57; found: C 48.36, H 6.15, N 10.15; MS (ESI): $m/z=536$ {[Pd(N-N)Cl]$^+$ + CH_3CN}, 847 {Pd(N-N)$_2$Cl}.

Crystal data for 7·CH$_3$CN: formula $C_{24}H_{35}Cl_2N_5Pd$, yellow crystal, triclinic space group P-1; $a=9.543(2)$, $b=11.805(2)$, $c=12.659(2)$ Å; $\alpha=76.419(4)$, $\beta=102.075(1)$, $\gamma=71.520(3)°$; $V=1310.5(4)$ Å^3; $Z=2$; crystal size $0.36\times0.20\times0.10$ mm^3; GOF = 1.071; reflections collected: 11838; independent reflections: 3777 [$R_{int}=0.0421$]; $R_1=0.0349$; $wR_2=0.0802$. Depository number: CCDC 690478.

General Procedure for Suzuki–Miyaura Cross Coupling Reaction

Water (1.0 mL), aryl or heteroaryl halide (0.5 mmol), boronic acid (0.6 mmol), and K_2CO_3 (1.2 mmol) were introduced into a 15-mL tube. An MeOH solution of the Pd-NN complex of interest with a specified catalyst loading (see Table 1, Table 2, and Table 3) was injected. The reaction mixture was stirred at room temperature for 10 min-15 h (see tables). The resultant mixture was diluted with CH_2Cl_2 (10 mL) and washed with water (10 mL). The water phase was extracted by CH_2Cl_2 (5 mL) two times. The organic extracts were combined and dried over $MgSO_4$, filtered, and concentrated in vacuum. The product was analyzed by GC-MS and also isolated by column chromatography (silica gel, hexane/ethyl acetate 20:1).

General Procedure for Mizoroki–Heck and Sonogashira Coupling Reactions

Aryl bromide (0.5 mmol), olefin or phenylacetylene (0.75 mmol), and NaOAc or K_2CO_3 (1.0 mmol) were placed in a 15-mL tube. A DMA solution of Pd-NN complex (3 mL) was then added in the given quantity (see Table 4, Table 5, and Table 6). The reaction mixture was stirred at 130 °C or 100 °C for the specified duration. After cooling to room temperature, the reaction mixture was diluted with CH_2Cl_2 (10 mL) and washed with water (10 mL). The organic extract was dried over $MgSO_4$, filtered, and the resultant mixture analyzed by GC-MS.

Acknowledgements

This work was supported by the Agency for Science, Technology & Research (Singapore) (R143–000–277–305 and R143–000–364–305) and the National University of Singapore. We thank the staff at the CMMAC of NUS for technical assistance.

References

[1] Some representative reviews for the Suzuki cross-coupling and its applications, see: a) A. Suzuki, N. Miyaura, *Chem. Rev.* **1995**, *95*, 2457; b) A. Suzuki, *J. Organomet. Chem.* **1999**, *576*, 147; c) S. R. Chemler, D. Trauner, S. J. Danishefsky, *Angew. Chem. Int. Ed.* **2001**, *40*, 4544; d) S. Kotha, K. Lahiri, D. Kashinath, *Tetrahedron* **2002**, *58*, 9633; e) F. Bellina, A. Carpita, R. Rossi, *Synthesis* **2004**, 2419; f) A. Suzuki, *Chem. Commun.* **2005**, 4759; g) N. T. S. Phan, M. van der Sluys, C. W. Jones, *Adv. Synth. Catal.* **2006**, *348*, 609.

[2] Some representative reviews for the Heck reaction and its applications, see: a) W. Cabri, I. Candiani, *Acc. Chem. Res.* **1995**, *28*, 2; b) G. T. Crisp, *Chem. Soc. Rev.* **1998**, *27*, 427; c) I. P. Beletskaya, A. V. Cheprakov, *Chem. Rev.* **2000**, *100*, 3009; d) N. J. Whitcombe, K. K. Hii, S. E. Gibson, *Tetrahedron* **2001**, *57*, 7449; e) A. B. Dounay, L. E. Overman, *Chem. Rev.* **2003**, *103*, 2945; f) P. J. Guiry, D. Kiely, *Current Org. Chem.* **2004**, *8*, 781; g) N. Miyaura, *Adv. Synth. Catal.* **2004**, *346*, 1522; h) M. Shibasaki, E. M. Vogl, T. Ohshima, *Adv. Synth. Catal.* **2004**, *346*, 1533; i) V. Farina, *Adv. Synth. Catal.* **2004**, *346*, 1553; j) A. M. Trzeciak, J. J. Ziolkowski, *Coord. Chem. Rev.* **2005**, *249*, 2308; k) F. Alonso, I. P. Beletskaya, M. Yus, *Tetrahedron* **2005**, *61*, 11771.

[3] Some representative reviews for the Sonogashira reaction and its applications, see: a) K. Sonogashira, *J. Organomet. Chem.* **2002**, *653*, 46; b) R. R. Tykwinski, *Angew. Chem. Int. Ed.* **2003**, *42*, 1566; c) E. Negishi, L. Anastasia, *Chem. Rev.* **2003**, *103*, 1979; d) R. Chinchilla, C. Nájera, *Chem. Rev.* **2007**, *107*, 874.

[4] a) Z. Q. Weng, S. H. Teo, L. L. Koh, T. S. A. Hor, *Organometallics* **2004**, *23*, 3603; b) S. H. Teo, Z. Q. Weng, T. S. A. Hor, *Organometallics* **2006**, *25*, 1199; c) Z. Q. Weng, S. H. Teo, T. S. A. Hor, *Acc. Chem. Res.* **2007**, *40*, 676; d) S. K. Yen, L. L. Koh, H. V. Huynh, T. S. A. Hor, *Dalton Trans.* **2007**, *35*, 3952.

[5] Some latest references for phosphine ligands applied in the C–C cross-coupling reactions, see: a) M. J. Burns, I. J. S. Fairlamb, A. R. Kapdi, P. Sehnal, R. J. K. Taylor, *Org. Lett.* **2007**, *9*, 5397; b) A. S. Guram, X. Wang,

E. E. Bunel, M. M. Faul, R. D. Larsen, M. J. Martinelli, *J. Org. Chem.* **2007**, *72*, 5104; c) K. Billingsley, S. L. Buchwald, *J. Am. Chem. Soc.* **2007**, *129*, 3358; d) C. A. Fleckenstein, H. Plenio, *Green. Chem.* **2007**, *9*, 1287; e) A. T. Lindhardt, M. L. H. Mantel, T. Skrydstrup, *Angew. Chem. Int. Ed.* **2008**, *47*, 2668; f) B. H. Lipshutz, B. R. Taft, *Org. Lett.* **2008**, *10*, 1329; g) L. Wu, Z. W. Li, F. Zhang, Y. M. He, Q. H. Fan, *Adv. Synth. Catal.* **2008**, *350*, 846; h) C. A. Fleckenstein, H. Plenio, *Green. Chem.* **2008**, *10*, 563.

[6] Some representative reviews for N-heterocyclic carbene-palladium catalysts in the C–C coupling reactions, see: a) W. A. Herrmann, *Angew. Chem. Int. Ed.* **2002**, *41*, 1290; b) K. J. Cavell, D. S. McGuinness, *Coord. Chem. Rev.* **2002**, *248*, 671; c) F. E. Hahn, *Angew. Chem. Int. Ed.* **2006**, *45*, 1348; d) E. A. B. Kantchev, C. J. O'Brien, M. G. Organ, *Angew. Chem. Int. Ed.* **2007**, *46*, 2768; e) A. T. Normand, K. J. Cavell, *Eur. J. Inorg. Chem.* **2008**, *18*, 2781.

[7] F. W. Li, S. Q. Bai, T. S. A. Hor, *Organometallics* **2008**, *27*, 672.

[8] J. P. Collman, L. S. Hegedus, J. R. Norton, R. G. Finke, *Principles and Applications of Organometallic Chemistry*, 2nd edn., University Science Books, Mill Valley, CA, **1987**.

[9] For recent representative applications of N-N bidentate palladium complexes in C–C coupling reactions, see: a) P. H. Li, L. Wang, *Adv. Synth. Catal.* **2006**, *348*, 681; b) C. Nájera, J. Gil-Moltó, *Adv. Synth. Catal.* **2006**, *348*, 1874; c) S. H. Li, Y. J. Lin, J. G. Cao, S. B. Zhang, *J. Org. Chem.* **2007**, *72*, 4067; d) S. Haneda, C. Ueba, K. Eda, M. Hayashi, *Adv. Synth. Catal.* **2007**, *349*, 833; e) M. Trilla, R. Pleixats, M. Wong Chi Man, C. Bied, J. J. E. Moreau, *Adv. Synth. Catal.* **2008**, *350*, 577; f) V. Montoya, J. Pons, V. Branchadell, J. Garcia-Anón, X. Solans, M. Font-Bardía, J. Ros, *Organometallics* **2008**, *27*, 1084.

[10] F. Visentin, A. Togni, *Organometallics* **2007**, *26*, 3746.

[11] a) A. F. Littke, C. Dai, G. C. Fu, *J. Am. Chem. Soc.* **2000**, *122*, 4020; b) E. R. Strieter, D. G. Blackmond, S. L. Buchwald, *J. Am. Chem. Soc.* **2003**, *125*, 13978.

[12] S. W. Kim, J. N. Park, Y. J. Jang, Y. H. Chung, S. J. H. Wang, T. Hyeon, *Nano Lett.* **2003**, *3*, 1289.

[13] P. Chattopadhyay, R. Rai, P. S. Pandey, *Synth. Commun.* **2006**, *36*, 1857.

[14] G. M. Sheldrick, *SHELXL-97*, *Program for crystal structure refinement*, University of Göttingen, Germany, **1997**.

