Supporting Information

1. Solvent ratio effect on the coupling reaction selectivity

To further verify the effect of solvent ratio (CH_3CN/H_2O) on the coupling reaction selectivity observed in Fig. 2(a), another boronic acid compound, 4-methoxyphenylboronic acid (10 mM), was examined as an alternative reactant to the phenylboronic acid for the Suzuki coupling reaction in the presence of iodobenzene (10 mM) and one Pd-TMV chip. As shown in Table S1, the reactions were carried out under two different solvent environments with identical reaction time and temperature. In $CH_3CN:H_2O=3:2$, the final yields of 4-methoxybiphenyl (cross-coupling) and 4,4'-dimethoxy-1,1'-biphenyl (homo-coupling) are 32.7% and 10.8%, respectively. When the CH_3CN/H_2O ratio was changed to 2:3, the yield of cross-coupling product increased to 51.2%, while the homo-coupling product yield decreased to 8.2% under the same reaction conditions. This clear difference in the reaction selectivity under different solvent ratios is consistent with the one with phenylboronic acid shown in Fig. 2(a), and shows that higher water content leads to higher selectivity towards the cross-coupling pathway. Therefore, the selectivity from the solvent effect appears to be general and not limited to phenylboronic acid.

Table S1 Solvent ratio effect on selectivity of coupling reaction

Entry	Reactants ratio (mM) $IC_6H_5 : CH_3OC_6H_4B(OH)_2 : Na_2CO_3$	Solvent	Yield of cross-coupling product (C_6H_5-$C_6H_4OCH_3$), %	Yield of homo-coupling product ($CH_3OC_6H_4$-$C_6H_4OCH_3$), %
1	10:10:30	$CH_3CN:H_2O=3:2$	32.7	10.8
2	10:10:30	$CH_3CN:H_2O=2:3$	51.2	8.2

Reaction time:24h; Reaction temperature:50 °C; Stirring speed: 600 rpm

To further confirm the effect of water content on the homo-coupling pathway, reactions with only phenylboronic acid in the absence of iodoanisole were also carried out under two types of solvent mixtures ($CH_3CN/H_2O=2:3$ and 3:2). As shown in Table S2, the yield of biphenyl decreased from 31.1% to 16.8% when the CH_3CN/H_2O solvent ratio changed from 3:2 to 2:3. Apparently, in this case, higher water content in the solvent mixture also inhibited the homo-coupling pathway even in the absence of the other reactant iodoanisole, which is consistent with the trend found in the presence of iodoanisole (Fig. 2(a)).

Table S2 Solvent ratio effect on homo-coupling reaction

Entry	Reactants ratio (Mm) $C_6H_5B(OH)_2 : Na_2CO_3$	Solvent	Yield of homo-coupling product (C_6H_5-C_6H_5), %
1	10:30	$CH_3CN/H_2O=3:2$	31.1
2	10:30	$CH_3CN/H_2O=2:3$	16.8

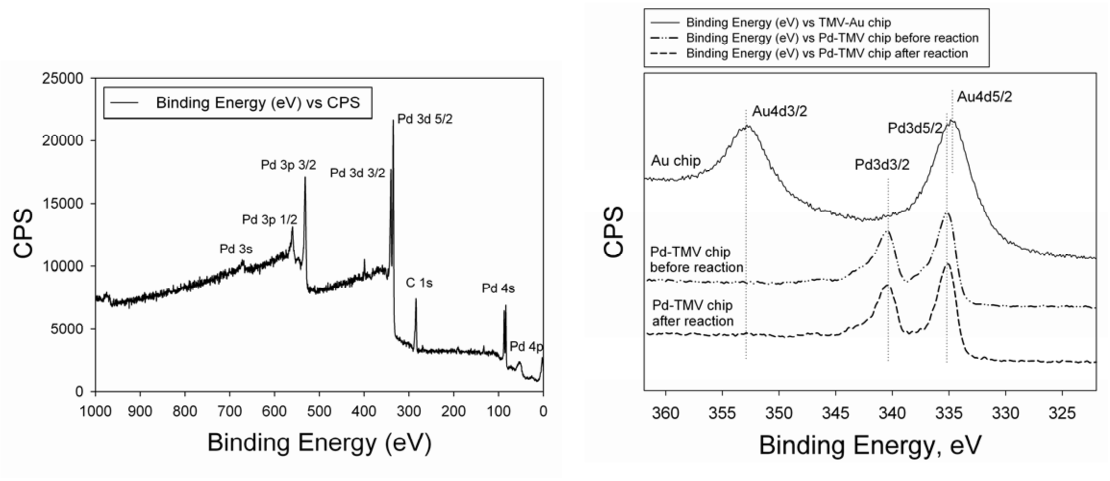
Reaction time: 24h; Reaction temperature: 50 °C; Stirring speed: 600 rpm.

Overall, results shown in Tables S1 and S2 further support the significant role of tuning water content for pathway control in the Suzuki reaction system.

2. X-ray Photoelectron Spectroscopy (XPS)

To further understand the elemental composition and chemical states of the viral-templated Pd catalysts, XPS was carried out before and after the Suzuki reaction as shown in Fig. S1. The XPS analysis was performed with XPS ESCA SSX-100 machine at the Center for Nanoscale Systems (CNS) of Harvard University (Cambridge, MA) as previously described.[1] Briefly, the chip samples were mounted on an aluminum cup prior to insertion into the ultrahigh vacuum chamber. The measurement was performed with an Al Kα monochromatic X-ray source, focused to a 600 μm diameter beam for the high resolution spectra. For the individual peak energy regions, pass energy of 100 eV across the hemispheres was used.

As shown in Fig. S1(a), the survey spectrum exhibits many typical Pd peaks (Pd3s, Pd 3p, Pd 3d, Pd 4s, Pd 4p), providing qualitative information on the presence of Pd element on the TMV templated catalyst chips.



(a) Survey spectrum (1000-0 eV) (b) Higher resolution spectra (362-322 eV)

Fig. S1 X-ray Photoelectron Spectroscopy (XPS) Spectra

Next, higher resolution XPS spectra in the range of 362-322 eV binding energy further provide information about the presence of Pd and its chemical state distribution. First, the clean Au silica chip exhibits two typical Au 4d3/2 and Au4d5/2 peaks without any Pd (top spectrum). Next, the second XPS spectrum from Pd-TMV chip before the reaction shows apparent Pd3d3/2 and Pd3d5/2 peaks with binding energy at about 340 eV and 335 eV, respectively. No Au4d3/2 peak was observed for this chip due to the full coverage of Pd nanoparticles on the densely assembled TMV chip, further confirming the observations made in Fig. 1(c)-(ii) via AFM. Finally, the bottom spectrum of a Pd-TMV chip after the reaction shows no Au peak and nearly identical Pd peaks as before reaction, confirming full Pd coverage and thus stability of Pd-TMV complexes on the chips upon reaction. Importantly, there is no significant shift of Pd3d3/2 peak position or decrease of Pd3d3/2 peak intensity from the Pd-TMV chip after the reaction (bottom spectrum), suggesting the stability and minimal change of the chemical state of the Pd nanoparticles on TMV templates.

Next to further examine the chemical state distribution of Pd nanoparticles on TMV template, a non-linear least square fitting analysis[2] was carried out by using the Casa XPS software. The relative metallic Pd content over the overall Pd species, Pd/(Pd+PdO), were determined to be 60.9 ± 2.7%, by taking average of five different samples prepared independently. Importantly, there appears to be only slight increase in the metallic Pd content (71.7 ± 1.9%) after the Suzuki reaction, indicating that most Pd species retained the original chemical state.

Overall, the XPS characterization results on the TMV-templated Pd catalysts shown in Fig. S1 demonstrate the presence of Pd on the chip surface and their stability during Suzuki coupling reaction.

3. Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)

In order to acquire further quantitative information on the amounts of Pd on each Pd-TMV chip, the catalysts were treated by acid digestion and analyzed by high performance ICP-OES.

For this, mixed standard solutions containing Pd and Au (with concentrations of 0.1, 1, 5, 50 μg/ml) were prepared by dilution of Pd and Au plasma standard stock solution (1000 μg/ml in 5% HNO_3, Alfa Aesar, MA 01835). For the sample analysis, Pd-TMV chips (before reaction) were dipped into 1 ml aqua regia solution[3] ($HCl : HNO_3$ (v:v)= 4:1) for acid digestion. Under shaking for 5 min, all Pd-TMV complexes and the thin gold layer coating on the silicon chip were dissolved completely, leaving only the silicon substrate. The acid-digested solutions were then further diluted by adding 2 ml deionized water. The mixed standards and samples were analyzed by Perkin Elmer 7300 ICP-OES (Civil and Environmental Engineering, Tufts University, Medford, MA).

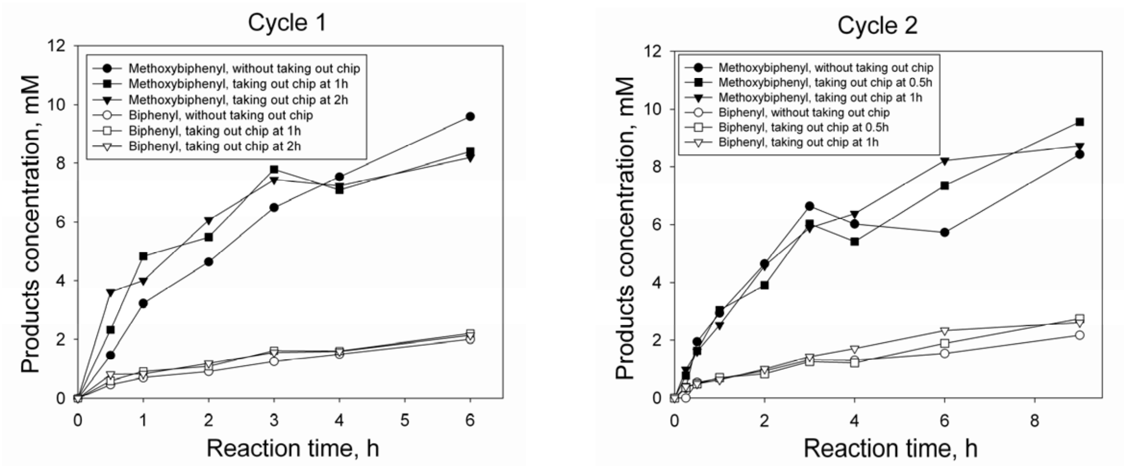
Eight Pd-TMV chips were analyzed by the procedure above, and the average Pd loading amount on each Pd-TMV chip was determined to be 8.3 ± 0.5 μg. In our previous study with Pd-TMV chips for dichromate reduction, the Pd amount was estimated to be around 14 μg at maximum, based on the assumption of completely full coverage of Pd on TMV surface[1]. In comparison, the trace amount of Pd obtained by ICP is more quantitatively reliable, suggesting slight over-estimation in our previous report.[1] Overall, the Suzuki coupling reaction of 0.05 mmol aryl halides was catalyzed by Pd-TMV catalyst chips with Pd amount of 0.078 μmole ($\frac{8.3\ \mu g}{106.42\ g/mol}$) throughout our study, as shown in the scheme of Fig. 1(a). This leads to the Pd catalyst ratio of 0.15 mol % based on aryl halide, which is lower than in other heterogeneous catalyst systems; e.g. 0.3 mol% for Pd/C[4], 2.5 mol% for Pd/zeolite[5], and 0.5 mol% for Pd/Chitosan[6].

Based on these calculations, the reaction kinetics shown in Fig. 4, can be utilized to obtain "apparent" reaction efficiency per unit weight of Pd as below. In Fig. 4, the yield of target product, 4-methoxybiphenyl(4-MB), reached the equilibrium after 5 hours, and the concentration of 4-MB was almost at the maximum value, 8.2 mmol/l, within 5 hours. Thus, the apparent reaction efficiency of TMV-tempalted Pd catalyst in the first 5 hours of coupling reaction is calculated as below.

$$\frac{8.2\mathrm{mmol/l} \times 5\mathrm{ml}}{300\,\mathrm{min} \times 8.3\mu\mathrm{g}} = 0.0165\mathrm{mol}/(\mathrm{min}\cdot\mathrm{g})$$

4. Preliminary study of the reaction mechanism via chip removal during reactions

Due to the surface-assembled format, the Pd-TMV catalyst chips are good candidates to examine the nature and role of potential active species in Suzuki coupling reaction by simply removing the chips in the middle of the reaction and continuing the reaction monitoring. To identify the catalytically active species, coupling reaction of iodoanisole with phenylboronic acid with different experimental designs were carried out as shown in Fig. S2. For this, three individual experiments were conducted: (i) in the presence of Pd-TMV chip throughout the reaction, (ii) taking the Pd-TMV chip out of the reaction solution after 1 h, (iii) taking the Pd-TMV chip out after 2 h, as shown in Fig. 2S(a). After the first reaction cycle, these chips were thoroughly rinsed, then reused for the next reaction cycle without any regeneration treatment in Fig. 2S(b) under three conditions; (i) without taking the Pd-TMV chip out, (ii) taking out the chip at 0.5 h, (iii) taking out the chip at 1 h. The reaction products were then closely monitored for 8 hours.



(a) First use of Pd-TMV chip

(b) Reuse of Pd-TMV chip

Fig. S2 Mechanism investigation of Suzuki reaction

Iodoanisole : Phenylboronic acid : Sodium carbonate=10 mM: 20mM:30mM,

Acetonitrile/Water=2:3, Reaction temperature: 50 °C, Reaction time: 24h, Stirring speed: 600 rpm.

As shown in Fig. S2(a), the Suzuki reaction continued after the Pd-TMV chips were removed from the reaction mixture after 1 hour (case (ii)) or 2 hours(case (iii)), and both the cross-coupling and homo-coupling products continued increasing for 8 hours examined. The product conversion curves from the cases (ii) and (iii) are very close to the case in the presence of Pd-TMV chips throughout the reaction (case (i)). Similarly, for the second reaction cycle, the Suzuki coupling reactions upon the removal of Pd-TMV chips also proceeded with equivalent reaction rate as in the first case, as shown in Fig. S2(b). These results suggest that the coupling reaction may be catalyzed largely by Pd species in the reaction solution (presumably leached Pd molecular species or small clusters), instead of Pd nanoparticles on the chips. Importantly, our chip-based catalyst format enabled these mechanistic studies in a drastically simple manner (i.e. mechanical removal of the chips from the reaction mixture) without arduous catalysts separation procedures.

Based on these findings, ICP-OES was employed again on the reaction mixtures in order to further confirm the presence of Pd in the reaction solution, as shown in Table S3. For this, the reaction mixtures were evaporated until completely dry, and then treated with aqua regia solution for 1 hour and diluted by water, as described above.

Table S3. Leached Pd amount determined by ICP

		Experiment methods	Pd in reaction solution, μg/ml (ppm)	
Reaction cycle 1	Case (i)	without taking out chip	0.07	
	Case (ii)	taking out chip at 1h	0.09	
	Case (iii)	taking out chip at 2h	0.05	
Reaction cycle 2	Case (i)	without taking out chip	0.05	
	Case (ii)	taking out chip at 0.5h	0.002	Below DL
	Case (iii)	taking out chip at 1h	0.001	Below DL

First, Table S3 shows that the Pd concentrations in the solution at the end of reaction cycle 1 from three different cases were consistently low (0.05-0.09 ppm), within the same order of magnitude as the Pd detection limit (0.044 ppm) of the ICP-OES equipment. In the second reaction cycle, the Pd concentrations at the end of reaction are even less (in the ppb level), with the cases (ii) and (iii) being below the detection limit (only 1-2 ppb). While being inconclusive due to the low concentrations close to the detection limit, these ICP results suggest that such trace amounts of Pd may exist in the reaction mixtures, consistent with the chip removal results shown in Fig. S2. Several studies have shown that trace amounts of Pd in the ppm or ppb level are responsible for the catalytic activity, and sufficient to catalyze Suzuki coupling reactions.[7, 8] The chip removal and ICP results shown here thus suggest that our Pd-TMV chip-based Suzuki reaction may be catalyzed largely by the soluble Pd active species as in other nanoparticle-based systems.[9, 10] Based on these previous findings, we speculate that Pd atoms may be released/leached from the surface of Pd nanoparticles, leading to the formation of Pd(II) or Pd(0) molecular species that subsequently react with aryl halides.[11, 12] The Pd nanoparticles formed on TMV-assembled chip here can therefore be considered as a reservoir, or "pre-catalysts"[10, 11, 13] of the catalytically active species in the reaction solution. Finally, we caution that very small number of loosely bound Pd nanoparticles may detach from the chips and interfere with these experiments, despite the clear overall stability confirmed via both GISAXS and XPS in this study. Further in-depth studies employing *in-situ* SAXS in conjunction with Extended X-Ray Absorption Fine Structure (EXAFS) to elucidate the dynamic molecular and chemical behavior of our chip-based reactions are currently underway.

Notes and references

1. C. Yang, A. K. Manocchi, B. Lee and H. Yi, *Appl. Catal., B*, 2010, **93**, 282-291.
2. A. M. Venezia, L. F. Liotta, G. Pantaleo, V. La Parola, G. Deganello, A. Beck, Z. Koppány, K. Frey, D. Horváth and L. Guczi, *Appl. Catal., A*, 2003, **251**, 359-368.
3. Y. Wu, B. Hu, Z. Jiang and S. Chen, *J. Anal. At. Spectrom.*, 2002, **17**, 121-124.
4. H. Sakurai, T. Tsukuda and T. Hirao, *J. Org. Chem.* , 2002, **67**, 2721-2722.
5. L. Artok and H. Bulut, *Tetrahedron Lett.* , 2004, **45**, 3881-3884.
6. S. S. Yi, D. H. Lee, E. Sin and Y. S. Lee, *Tetrahedron Lett.* , 2007, **48**, 6771-6775.
7. N. E. Leadbeater, V. A. Williams, T. M. Barnard and M. J. Collins, *Org. Process Res. Dev.*, 2006, **10**, 833-837.
8. R. K. Arvela, N. E. Leadbeater, M. S. Sangi, V. A. Williams, P. Granados and R. D. Singer, *J. Org. Chem.*, 2004, **70**, 161-168.
9. D. Conlon, B. Pipik, S. Ferdinand, C. LeBlond, J. Sowa, B. Izzo, P. Collins, G. J. Ho, J. Williams, Y. J. Shi and Y. Sun, *Adv. Synth. Catal.*, 2003, **345**, 931-935.
10. N. T. S. Phan, M. Van Der Sluys and C. W. Jones, *Adv. Synth. Catal.* , 2006, **348**, 609-679.
11. A. Gaikwad, A. Holuigue, M. Thathagar, J. Elshof and G. Rothenberg, *Chem. Eur. J.*, 2007, **13**, 6908-6913.
12. J. Durand, E. Teuma and M. Gómez, *Eur. J. Inorg. Chem.*, 2008, **2008**, 3577-3586.
13. J. P. Simeone and J. R. Sowa Jr, *Tetrahedron*, 2007, **63**, 12646-12654.