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Palladium nanoparticles immobilized on polyethylenimine-derivatized gold surfaces for catalysis of Suzuki reactions: development and application in a lab-on-a-chip context†

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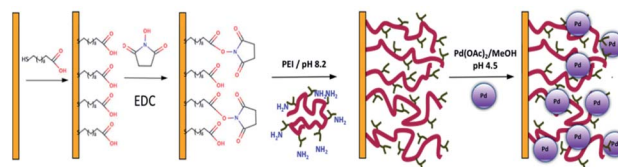
Gold surface-bound hyperbranched polyethyleneimine (PEI) films decorated with palladium nanoparticles have been used as efficient catalysts for a series of Suzuki reactions. This thin film-format demonstrated good catalytic efficiency (TON up to 3.4×10^3) and stability. Incorporation into a quartz crystal microbalance (QCM) instrument illustrated the potential for using this approach in lab-on-a-chip-based synthesis applications.

Metal and metal-oxide nanostructures and nanoparticles are often key features in materials used in separation technology, biomedical devices, and catalysis.[1,2] Poor mechanical strength and a tendency to aggregate, thus reducing the surface to volume ratio, both limit their use in real-time applications.[3,4] To overcome these shortcomings, nanoparticles are often dispersed in a matrix, such as sol–gel, biopolymers, and carbon-based materials without disturbing their innate properties at nano-scale level.[5,6] Functionalized polymers have been explored extensively in this regard due to their robustness, low cost, ease of handling, and their amenability for chemical modification.[7–9]

Recently, we have demonstrated the immobilization of hyperbranched polyethyleneimine (PEI) hydrogels on metallic surfaces for use as antifouling surfaces.[10] Owing to their hydrogelation properties, polymers of this type have proven useful in therapeutic applications, for *e.g.* bio-mineralization, and the formation of nanostructures.[11,12] PEI is a hyperbranched polymer containing very high densities of primary, secondary and tertiary amines, in a 1 : 2 : 1 ratio, and are capable of coordination with transition metals to form nanostructures.[13,14] Recent reports on amine functionalized polymer-supported heterogeneous catalysts for C–C coupling reactions (Table 1-SI†) prompted us to deploy PEI as a matrix for synthesizing surface-bound palladium nanoparticles for use as catalysts of C–C coupling reactions. For catalytic applications, a miniaturized microfluidic setup, such as a lab-on-a-chip device, can significantly reduce the consumption of chemicals, catalysts, process time and be beneficial for on-site analysis.[15,16]

In this study, we demonstrate the use of the PEI surface-supported nanoparticles for as a support for catalysis of the Suzuki reaction the possibility for using of these Pd-nanoparticle immobilized PEI-derivatized gold surfaces for performing Suzuki reactions in a microfluidics device. Catalytic surface fabrication (Scheme 1) was performed using gold sputtered quartz surfaces (Au/quartz) that were functionalized with 11-mercaptoundecanoic acid (MuDA), and then activated and derivatization with PEI. The polymer attachment was carried out at high ionic strength (150 mM NaCl), which has been found to enhance the thickness and growth of PEI brush-like structures.[10] Optimization of the Pd nanoparticle synthesis procedure was performed by varying incubation times and $Pd(OAc)_2$ concentrations (Table 1-SI†). A quartz crystal microbalance (QCM) was used to monitor the amount of Pd deposited on the PEI coated Au/quartz resonators.

The energy dispersive X-ray (EDX) spectrum confirmed the presence of Pd in the PEI film with a distinct band at 2.8 keV (Fig. 1A). XPS spectra of the Pd-bound PEI surfaces revealed the presence of the anticipated proleptic elements (C_{1s}, N_{1s}, O_{1s}, Pd_{3d} and Au_{4f}) (Fig. 1A-SI†). Deconvoluted peaks differentiated the amine N of PEI (399.8 eV) from that of the amide N (–*N–C══ O–, 400.8 eV) (Fig. 1B-SI†).[17,18] Bands around 335 and 340 eV in

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Scheme 1 Palladium immobilization on polyethyleneimine coated Au/quartz surfaces.
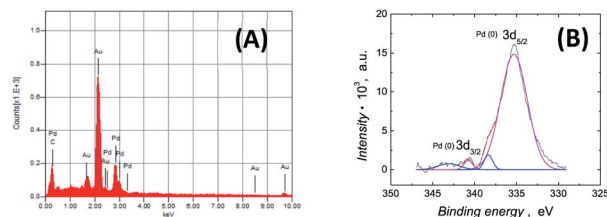
Fig. 1 (A) Energy dispersive X-ray (EDX) analysis and (B) X-ray photoelectron spectra (XPS) of the palladium nanoparticle immobilized PEI coated Au/quartz surface.

the survey spectra correspond to the $3d_{5/2}$ and $3d_{3/2}$ states of the surface bound Pd.[19] The deconvoluted bands at 335.3 and 338.2 demonstrated the presence of Pd(0) and Pd(II), respectively (Fig. 1B). Importantly, peak integration showed the immobilized Pd to be predominantly in the Pd(0) state, with less than 5% present as Pd(II).[19]

RAIR spectra confirmed the presence of the PEI on the gold surface based on the discernible vibrational bands of the –N–H–, –CH– and –CN– bending modes of the adsorbed PEI film (Fig. 2). Subtle differences can be observed in the RAIR spectra of the PEI before and after Pd immobilization. The band corresponding to –N–H– bending mode has been significantly red shifted emphasizing the interaction of the Pd particles with the amine moieties of the PEI film (Fig. 2, inset). This, together with the XPS data, provides evidence for the reduction of Pd(II) to Pd(0) and its incorporation as nanoparticles into the PEI brush layer.

SEM images (Fig. 3) showed uniform long-range coating of the palladium nanoparticles on the PEI immobilized surface (PEI/Pd). The crystallinity of the Pd coated PEI surface was evaluated with powder diffraction measurements which showed characteristic peaks for Pd(111), Pd(200) and Pd(220) with Miller indices of 40, 47.2 and 68.3° (JCPDS No. 98-004-7386), respectively, again confirming the presence of Pd nanoparticles in the (0) oxidation state (curve *a*, Fig. 2-SI†).

The possibility of using these surfaces for catalysis of the Suzuki reaction was explored using a series of phenylboronic acids and substituted aryl halides (Table 1). Pd immobilization

on the surfaces was optimized with respect to turnover numbers based upon reaction of the phenyl iodide and phenyl boronic acid (entry 1), upon incubation with 0.5 mg ml^{-1} of Pd(OAc)$_2$ in methanol for 5 h (Table 2-SI†). The amount of catalytic nano-palladium loaded was determined by QCM. Au/quartz surfaces coated with PEI/Pd were immersed in the reaction mixtures at 55 °C for 12 h (Section 1.7-SI†). Reactions of aryl halides with a series of arylboronic acids offered the corresponding products in good to excellent yield (Table 1 entry 3 to 9), except for the *ortho*-cyano substituted phenyl boronic acid, where the low yield is attributed to steric hindrance (entry 6). The biphenyl product was obtained in 93% yield from the Suzuki reaction performed in the presence of PPh$_3$ (see Section 1.4 in ESI†). This negligible effect on Pd catalyst poisoning confirms the nature of the catalytic Pd exists predominantly in the (0) oxidation state.[20] No biphenyl product has been observed when the Suzuki reaction was performed in presence of unmodified Au/quartz surface (without PEI and Pd).

The Suzuki reaction of phenyl iodide and phenyl boronic acid was also performed using shorter reaction times (6 h and 2 h), with the shorter time providing the product in an acceptable 84% and 78% yield respectively (Tables 2 and 3-SI†).

To assess the stability of the surfaces and the potential for their reuse, the surfaces were removed from the reaction mixtures and the amount of residual Pd was determined by QCM. XPS measurements revealed no significant change on the nature of the immobilized Pd (335.26 and 340.58 eV) (Fig. 3-SI†), and as reflected in the ratio of the Pd$_{3d}$ and Au$_{4f}$ bands measured before (0.45) and after (0.44) the reaction (Table 2). The stability of PEI coating during the reaction can be inferred from the N$_{1s}$ band at 399.7. Powder XRD analysis further highlighted the stability of the crystalline nature of the immobilized Pd (curve *b*, Fig. 2-SI†) with peaks for Pd(111), Pd(200) and Pd(220) comparable to those before reaction. The SEM and EDX measurements revealed that the nanopalladium had remained immobilized on the PEI matrix (Fig. 4-SI†). The amount of residual Pd was again determined by QCM after use of the surfaces in a series of reactions (Table 2), with ≈1.5% loss per cycle over four cycles. The reduced catalytic activity can be attributed to the loss (∼6%) of the immobilized Pd in due course of the reaction.

The long-term stability of the catalyst surfaces was studied by storing freshly prepared surfaces in water (Milli-Q grade water, 18.2 MΩ, UHP grade N$_2$) for three months after which catalytic activity was determined (93%).

We then explored the use of these surfaces in a lab-on-a-chip format by using them in a QCM instrument fitted with a microfluidics liquid delivery system, where the Suzuki reaction of phenyl iodide and phenylboronic acid was examined under flow injection analysis conditions. The reactants were introduced into the 2 µL volume microreactor using the instrument's peristaltic pump, and the temperature of the reaction was maintained at 40 °C. Formation of the biphenyl product was confirmed by HPLC analysis of the effluent (Fig. 5-SI†).

In comparison with other reported heterogeneous catalysts for the Suzuki reaction (Table 4-SI†), the Pd/PEI surfaces
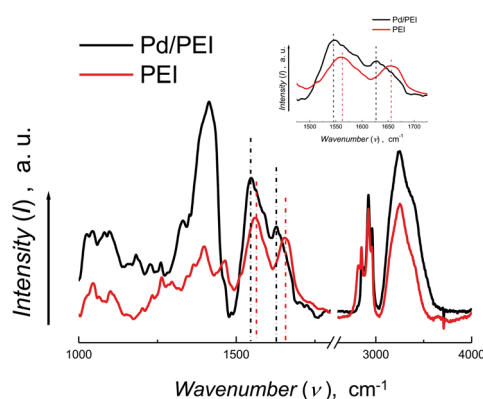

Fig. 2 RAIR spectra of PEI coated Au/quartz surface before and after Pd immobilization.

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Fig. 3 Scanning electron micrographs of (A) gold surface, (B) polyethyleneimine (PEI) film and (C) PEI-supported palladium particles fabricated on Au/quartz surfaces.

Table 1 Suzuki cross-coupling reactions of aryl halides with arylboronic acids using PEI/Pd as catalysts[a]

Entry	R_1	X	R_2	Isolated yield	TON $\times 10^3$
1	H	I	H	93%	3.1×10^3
2	H	Br	H	95%	3.4×10^3
3	H	I	$2\text{-}CH_3$	82%	2.2×10^3
4	H	I	$3\text{-}OCH_3$	57%	1.5×10^3
5	H	I	$4\text{-}OCH_3$	84%	2.4×10^3
6	H	I	$2\text{-}CN$	15%	0.4×10^3
7	H	I	$4\text{-}CN$	95%	2.8×10^3
8	$4\text{-}CH_3$	Br	H	88%	1.5×10^3
9	$4\text{-}OCH_3$	Br	H	95%	1.2×10^3
10	H	I	$3\text{-}NH_2$	n.r.	—
11	H	Cl	H	94%	10.0×10^3
12	$4\text{-}OCH_3$	Cl	H	80%	5.3×10^3
13	$4\text{-}COCH_3$	Cl	H	n.r.	—

[a] General procedure: 1.0 mmol of aryl halide, 1.2 mmol of arylboronic acid, 2.0 mmol of K_2CO_3, in H_2O/EtOH. Turnover number TON = mol product/mol Pd. n.r. = no reaction.

Table 2 Suzuki cross-coupling reaction of iodobenzene with phenylboronic acid using PEI/Pd as catalyst[a]

Entry	Run	Conc. of Pd, μg	Isolated yield	TON
1	1st	±2.3	93%	4.2×10^3
2	2nd	±2.22	89%	4.1×10^3
3	3rd	±2.22	85%	4.0×10^3
4	4th	±2.15	80%	3.8×10^3

[a] General procedure: 1.0 mmol of aryl halide, 1.2 mmol of arylboronic acid, 2.0 mmol of K_2CO_3, in H_2O/EtOH. TON = mol product/mol.

presented here have significantly lower Pd loadings (>0.001 mol%) though comparable performance, highlighting the role of the PEI matrix for facilitating mass transfer of substrates and products to and from the catalytic centers, and for avoiding aggregation of the Pd.

Conclusions

A flow microreactor for the Suzuki reaction has been developed based upon gold surface bound hyperbranched polyethyleneimine (PEI) films decorated with palladium nanoparticles and a quartz crystal microbalance instrument. The catalytic efficiency and stability of this thin film format open for the use of this approach in lab-on-a-chip-based synthesis applications.

Author contributions

Concept development (I. A. N., S. S.), experiment design (all authors), experimental studies (P. A., S. S.), analysis (P. A., S. S.), manuscript preparation (all authors).

Conflicts of interest

The authors have no conflicts of interest to declare.

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