
Surface Modification of Poly(dimethylsiloxane) (PDMS) for Microfluidic Devices

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TABLE OF CONTENTS

TABLE OF CONTENTS	I
ABSTRACT	V
DECLARATION	VIII
ACKNOWLEDGEMENTS	IX
LIST OF PUBLICATION	X
LIST OF ABBREVIATIONS	XII
LIST OF FIGURES	XVII
LIST OF SCHEMES	XXIII
LIST OF TABLES	XXV
CHAPTER 1 INTRODUCTION	1
Abstract	1
1.1 Overview.....	1
1.2 PDMS surface modification methods	9
1.2.1 Gas-phase processing.....	9
1.2.2 Wet chemical methods	15
1.2.3 Combinations of gas-phase and wet chemical methods	24
1.3 Patterned PDMS surfaces	29
1.3.1 Topographical patterning	30
1.3.2 Chemical patterning.....	31
1.4 Applications	35
1.4.1 Separation of biomolecules.....	35
1.4.2 Enzyme microreactors	50
1.4.3 Immunoassays.....	51
1.4.4 Genomic analysis.....	53
1.4.5 Capture/release of proteins in microfluidic channels	54
1.4.6 Cell culture.....	55
1.4.7 Formation of emulsions inside microfluidic channels.....	58
1.5 Summary and future perspectives.....	60
CHAPTER 2 METHODOLOGY	62

2.1	Introduction.....	62
2.2	Material and chemical.....	62
2.3	Preparation of PDMS samples.....	63
2.3.1	Thermal assisted hydrosilylation	63
2.3.2	SAM assisted templating	65
2.3.3	Combination of Soxhlet-extraction and plasma treatment	66
2.4	Surface characterization.....	67
2.4.1	WCA measurements	68
2.4.2	FTIR-ATR spectroscopy	69
2.4.3	XPS	69
2.4.4	AFM.....	70
2.4.5	Streaming zeta-potential analysis	70
2.4.6	Fluorescence labeling study.....	71
2.4.7	Stability experiments	71
2.5	DNA hybridization on PDMS surfaces.....	72
2.6	Fabrication of PDMS-based microfluidic devices.....	72
2.6.1	Fabrication of SU-8 masters	72
2.6.2	Fabrication of native PDMS-based microfluidic devices.....	73
2.6.3	Fabrication of MP2-based microfluidic devices.....	74
2.6.4	Fabrication of MP3-based microfluidic devices.....	75
2.6.5	EOF measurements.....	75
2.6.6	Fluorescence labeling in microchannels.....	76
CHAPTER 3 HYDROPHILIZATION OF PDMS BASED ON THERMAL ASSISTED HYDROSILYLATION.....		77
3.1	Introduction.....	77
3.2	Experimental section.....	78
3.2.1	WCA measurements	78
3.2.2	Stability experiment.....	78
3.3	Result and discussion.....	79
3.3.1	PDMS samples with 10:1 base/curing agent weight ratio	79
3.3.2	Comparison of MP1 samples with different weight ratio of base to curing agent in PDMS prepolymer	84
3.4	Conclusion	90
CHAPTER 4 HYDROPHILIZATION OF PDMS USING SAM ASSISTED		

TEMPLATING	92
4.1 Introduction.....	92
4.2 Experimental section.....	94
4.2.1 Stability experiment.....	94
4.3 Results and discussion	95
4.3.1 Surface characterization on PDMS surfaces.....	95
4.3.2 Application of DNA hybridization	101
4.4 Conclusion	103
CHAPTER 5 HYDROPHILIZATION OF PDMS BY COMBINATION OF SOXHLET-EXTRACTION AND PLASMA TREATMENT	104
5.1 Introduction.....	104
5.2 Experimental section.....	105
5.2.1 WCA	105
5.2.2 Stability experiment.....	105
5.2.3 AFM.....	105
5.2.4 Fluorescence labeling study.....	106
5.3 Results and discussion	106
5.3.1 Surface characterization of PDMS surfaces	108
5.3.2 Application of DNA hybridization	116
5.4 Conclusion	118
CHAPTER 6 APTAMER SENSOR FOR COCAINE USING MINOR GROOVE BINDER BASED ENERGY TRANSFER (MBET)	119
6.1 Introduction.....	119
6.2 Experimental section.....	121
6.2.1 Material and Chemical.....	121
6.2.2 PDMS Sample Preparation	121
6.2.3 MBET aptamer sensor for cocaine detection in solution.....	122
6.2.4 MBET aptamer sensor for cocaine detection on PDMS surface	122
6.3 Results and discussion	123
6.3.1 MBET aptamer sensor for cocaine detection in solution.....	123
6.3.2 MBET aptamer sensor for cocaine detection on an aptamer-modified PDMS surface	125
6.4 Conclusion	127
CHAPTER 7 FABRICATION OF PDMS-BASED MICROFLUIDIC DEVICES	128

7.1	Introduction.....	128
7.2	Experimental section.....	129
7.3	Results and discussion	129
7.3.1	Fabrication of PDMS-based microfluidic devices.....	129
7.3.2	EOF measurements	131
7.3.3	Fluorescence labeling inside microchannels.....	133
7.4	Conclusion	135
CHAPTER 8 OVERALL CONCLUSIONS AND FUTURE WORK		136
8.1	Overall conclusions.....	136
8.2	Future work.....	138
REFERENCES.....		140

ABSTRACT

Poly(dimethylsiloxane) (PDMS) is a popular material for microfluidic devices due to its relatively low cost, ease of fabrication, oxygen permeability and optical transmission characteristics. However, its highly hydrophobic surface is still the main factor limiting its wide application, in particular as a material for biointerfaces. This being the case, surface modification to tailor surface properties is required to render PDMS more practical for microfluidic applications.

This thesis focuses on three different PDMS surface modification techniques, including 1) thermal assisted hydrosilylation; 2) self-assembled molecule (SAM) assisted templating and 3) a combination of Soxhlet-extraction and plasma treatment. The modified PDMS surfaces were then used for a series of analytical applications, including DNA hybridization and cocaine detection. Finally, the fabrication of native and surface modified PDMS-based microfluidic devices is also presented. The content in each chapter is outlined in the following.

In Chapter 1, a comprehensive review of recent research regarding PDMS surface modification techniques is presented, including gas-phase processes, wet-chemical methods and the combination of gas-phase and wet-chemical methods. In addition, topographical and chemically patterned PDMS is discussed, as well as examples of the application of modified PDMS surfaces in microfluidics.

Chapter 2 is the methodology chapter, which describes the three PDMS surface modification techniques used in this thesis. It also describes the fabrication process involved in the making of PDMS-based microfluidic devices. Moreover, details of the surface characterization techniques used for the analysis of the PDMS surfaces are described. These techniques include water contact angle (WCA) measurements, Fourier transform infrared-attenuated total reflection (FTIR-ATR) spectroscopy, X-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM), streaming zeta-potential analysis, electroosmotic flow (EOF) measurements and fluorescence microscopy. Experimental details for the experiments involving DNA hybridization on

modified PDMS are also described.

In Chapter 3, we report on a cheap, easy and highly repeatable PDMS surface modification method by heating pre-cured PDMS with a thin film of undecylenic acid (UDA) at 80 °C in an oven. A hydrosilylation reaction between the UDA and the PDMS curing agent was induced during heating. The results showed the modified PDMS surfaces became more hydrophilic compared to native PDMS and showed a more or less constant WCA for up to 30 d storage in air. In addition, the stability of the modified PDMS surface was further improved by reducing the weight ratio of PDMS base and curing agent from 10:1 to 5:1.

In Chapter 4, we present a chemical modification strategy for PDMS by curing a mixture of 2 wt % UDA in PDMS prepolymer on a pretreated gold coated glass slide. The pretreatment of the gold slide was achieved by coating the gold with a self-assembled monolayer of 3-mercaptopropionic acid (MPA). During curing of the UDA/PDMS prepolymer on the MPA/gold coated slide the hydrophilic UDA carboxyl moieties diffuse towards the hydrophilic MPA carboxyl moieties on the gold surface. This diffusion of UDA within the PDMS prepolymer to the surface is a direct result of surface energy minimization. Once completely cured, the PDMS was peeled off the gold substrate, thereby exposing the interfacial carboxyl groups. These groups were then available for subsequent attachment of 5'-amino-terminated oligonucleotides *via* amide linkages. Finally, fluorescently tagged complementary oligonucleotides were successfully hybridized to this surface, as determined by fluorescence microscopy.

In Chapter 5, the surface modification of PDMS was carried out by using a 2-step plasma modification with Ar followed by acrylic acid (AAc). The stability of the modified PDMS surface was further improved by Soxhlet-extracting the PDMS with hexane prior to plasma treatment. 5'-amino-terminated oligonucleotides were covalently attached to the PAAc modified PDMS surface *via* carbodiimide coupling. Results show that the covalently tethered oligonucleotides can successfully capture fluorescein-labeled complementary oligonucleotides *via* hybridization, which were visualized using fluorescence microscopy.

In Chapter 6, we report on an optical aptamer sensor for cocaine detection by first using minor groove binder based energy transfer (MBET) technique. First, a

carboxyl-functionalized PDMS was prepared using SAM assisted templating as described in Chapter 4. A cocaine sensor was then fabricated on this carboxyl-functionalized PDMS surface by covalently immobilizing DNA aptamers *via* amide linkages. The cocaine sensitive fluorescein isothiocyanate (FITC)-labeled aptamer underwent a conformational change from partial single-stranded DNA to a double stranded T-junction in the presence of the target. The DNA minor groove binder Hoechst 33342 selectively bound to the double stranded T-junction, bringing the dye within the Förster radius of FITC. This process initiated MBET, thereby reporting on the presence of cocaine. In addition, this aptamer sensor was also implemented for cocaine detection in solution.

In Chapter 7, the fabrication of microfluidic devices based on the native PDMS and/or the modified PDMS is described. First standard soft-lithography was used to produce PDMS microchannels. Then, the sealing of the microchannels was achieved with the assistance of thermal treatment or an O₂ plasma. Finally, for the modified PDMS-based devices, the presence of reactive carboxyl groups from the initial UDA or AAc plasma treatment were verified by the immobilization of Lucifer Yellow CH dye in modified PDMS microchannels.

In Chapter 8, an overall comparison between the three different PDMS surface modification methods is provided and the future perspectives are outlined.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed 周錦雯 Date 29/11/2012

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LIST OF PUBLICATION

Papers arising from Chapter 1

1. Zhou, J. W., Ellis, A. V., Voelcker, N. H., Recent developments in poly(dimethylsiloxane) surface modification for microfluidic devices. *Electrophoresis* 2010, *31*, 2-16.
<http://onlinelibrary.wiley.com/doi/10.1002/elps.200900475/abstract>
2. Zhou, J. W., Khodakov, D. A., Ellis, A. V., Voelcker, N. H., Surface modification for PDMS-based microfluidic devices. *Electrophoresis* 2012, *33*, 89-104.
<http://onlinelibrary.wiley.com/doi/10.1002/elps.201100482/abstract>

Papers arising from Chapter 3

3. Zhou, J. W., McInnes, S. J. P., Mutalib Md Jani, A., Ellis, A. V., Voelcker, N. H., One-step surface modification of poly(dimethylsiloxane) by undecylenic acid. *Proceedings of SPIE* 2008, *7267* (726719), 1-10.
http://spie.org/x648.html?product_id=810101

Papers arising from Chapter 4

4. Zhou, J. W., Voelcker, N. H., Ellis, A. V., Simple surface modification of poly(dimethylsiloxane) for DNA hybridization. *Biomicrofluidics* 2010, *4*, 046504.
http://bmf.aip.org/resource/1/biomgb/v4/i4/p046504_s1
5. Zhou, J. W., Ellis, A. V., Kobus H., Voelcker, N. H., Aptamer sensor for cocaine using minor groove binder based energy transfer (MBET). *Analytica Chimica Acta* 2012, *719*, 76-81.
<http://www.sciencedirect.com/science/article/pii/S0003267012000797>

Papers arising from Chapter 5

6. Zhou, J. W., Ellis, A. V., Voelcker, N. H., Poly(dimethylsiloxane) surface modification by plasma treatment for DNA hybridization applications. *Journal of Nanoscience and Nanotechnology* 2010, *10*, 7266-7270.
<http://www.ingentaconnect.com/content/asp/jnn/2010/00000010/00000011/art00061>

Papers arising from Chapter 6

7. Zhou, J. W., Ellis, A. V., Kobus H., Voelcker, N. H., Aptamer sensor for cocaine using minor groove binder based energy transfer (MBET). *Analytica Chimica Acta* 2012, *719*, 76-81.

<http://www.sciencedirect.com/science/article/pii/S0003267012000797>

Other papers

8. Mutalib Md Jani, A., Zhou, J. W., Nussio, M. R., Losic, D., Shapter, J. G., Voelcker, N. H., Pore spanning lipid bilayers on silanised nanoporous alumina membranes. *Proceedings of SPIE* 2008, 7267 (2670T), 1-10.

LIST OF ABBREVIATIONS

AA	ascorbic acid
AAc	acrylic acid
AAm	acrylamide
AFM	atomic force microscope
AHPCS	allylhydridopolycarbosilane
Ala	alanine
AMPS	2-acrylamido-2-methyl-1-propanesulfonic acid
4-AP	4-aminophenol
AP	alkaline phosphatase
APDMES	3-aminopropyldimethylethoxysilane
APTES	3-aminopropyltriethoxysilane
APTMS	3-aminopropyltrimethoxysilane
Arg	arginine
Asn	asparagine
Asp	aspartic acid
ATRP	atom transfer radical polymerization
BAS	1-butyl-3-methylimidazolium dodecanesulfonate
BGE	background electrolyte
BMImBF ₄	1-butyl-3-methylimidazolium tetrafluoroborate
BODIPY® FL CASE	<i>N</i> -(4,4-difluoro-5,7-dimethyl-4-bora-3a,4a-diaza-s-indacen e-3propionyl)cysteic acid, succinimidyl ester
BP	benzophenone
BSA	bovine serum albumin
CAD	computer-aided design
CE	capillary electrophoresis
CEC	capillary electrochromatography
Chit	chitosan
COMOSS	collocated monolith support structure
CPTCS	3-chloropropyltrichlorosilane

CTMS	chlorotrimethylsilane
CVD	chemical vapor deposition
Cys	cysteine
3D	three dimensional
DA	dopamin
DBA	dobutamine
DDAB	didodecyldimethylammoniumbromide
DDM	n-Dodecyl- β -D-maltoside
DNA	deoxyribonucleic acid
DOC	sodium deoxycholate
dsDNA	double stranded deoxyribonucleic acid
ECM	extracellular matrix
EDAC	<i>N</i> -(3-dimethylaminopropyl)- <i>N'</i> -ethylcarbodiimide hydrochloride
EDTA	ethylenediaminetetraacetic acid
μ_{eo}	electroosmotic mobility
EOF	electroosmotic flow
EP	epinephrine
ER α	estrogen receptor α
FAM	6-carboxyfluorescein
FITC	fluorescein isothiocyanate
FRET	fluorescence resonance energy transfer
FTIR-ATR	Fourier transform infrared-attenuated total reflection
Gln	glutamine
Glu	glutamic acid
Gly	glycine
GMA	glycidyl methacrylate
GPTMS	3-glycidoxypropyltrimethoxysilane
HA	hyaluronic acid
HEPES	4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid
His	histidine
HPGs	hyperbranched polyglycerols
h-PSMA	hydrolyzed poly(styrene- <i>co</i> -maleic anhydride)

HQ	hydroquinone
HSA	human serum albumin
5-HT	5-hydroxytryptamine
Ig	immunoglobulin
Ile	isoleucine
IPA	isopropyl alcohol
LBL	layer-by-layer
LPEI	linear polyethyleneimine
Lys	lysine
MA	maleic anhydride
MAAc	methacrylic acid
MALDI	matrix-assisted laser desorption/ionization
MBET	minor groove binder based energy transfer
Met	methionine
2-MP	2-mercaptopyridine
MPA	3-mercaptopropionic acid
mPEG	methyl-poly(ethylene glycol)
MPTMS	3-mercaptopropyltrimethoxysilane
MS	mass spectrometry
NHS	<i>N</i> -hydroxysuccinimide
O/W	oil-in-water
PA	phosphatidic acid
PAAc	poly(acrylic acid)
PAAm	Poly(acrylamide)
PAH	poly(aromatic hydrocarbon)
PAS	poly(4-aminostyrene)
PBS	phosphate buffered saline
PDDA	poly (diallyldimethylammonium chloride)
P(DMA- <i>co</i> -GMA)	poly(dimethylacrylamide- <i>co</i> -glycidyl methacrylate)
PDMS	poly(dimethylsiloxane)
PE	poly(ethylene)
PEG	poly(ethylene glycol)
PEGMEM	poly(ethylene glycol) methyl ether methacrylate

PEI	poly(ethyleneimine)
PEMEA	propylene glycol methyl ether acetate
PEMs	polyelectrolyte multilayers
PEO	poly(ethylene oxide)
PGA	poly(L-glutamic acid)
PGMA	poly(glycidyl methacrylate)
Phe	phenylalanine
PHMA	poly(hydromethylsiloxane)
PLLA	poly(L-lactic acid)
PMAAc	poly(methacrylic acid)
PNIPAAm	poly [<i>N</i> -isopropyl acrylamide]
P(NIPAAm- <i>co</i> -AAc)	poly(<i>N</i> -isopropyl acrylamide- <i>co</i> -acrylic acid)
p-PDA	p-phenylenediamine
PPEGMA	poly(poly(ethylene glycol)methacrylate)
PPO	poly(propylene oxide)
Pro	proline
PSCA	prostate stem cell antigen
PSS	poly(sodium 4-styrenesulfonate)
PTX	paclitaxel
PVA	poly(vinyl alcohol)
PVA- <i>g</i> -GMA	poly(vinyl alcohol)- <i>g</i> -glycidyl methacrylate
PVC	poly(vinyl chloride)
PVP	poly(vinylpyrrolidone)
PVP- <i>g</i> -GMA	Poly(vinylpyrrolidone)- <i>g</i> -glycidyl methacrylate
QD	quantum dot
RB	rhodamine B
RGDS	Arg-Gly-Asp-Ser
RMS	root mean square
RSD	relative standard deviation
SAMs	self-assembled monolayers
SDS	sodium dodecyl sulfate
SELEX	systematic evolution of ligands by exponential enrichment
Ser	serine

SP-PCRs	solid phase-polymerase chain reactions
STB	sodium tetraborate
TAPS	<i>N</i> -tris(hydroxymethyl)methyl-3-aminopropanesulfonic acid
TBE	Tris-borate-EDTA
TEOS	tetraethyl orthosilicate
TFOS	trichloro(1H, 1H, 2H, 2H-perfluorooctyl)silane
Thr	threonine
TOF	time of flight
Tris	tris(hydroxymethyl)aminomethane
Try	tryptophan
TTE	Tris-TAPS-EDTA
Tyr	tyrosine
UDA	undecylenic acid
UV	ultraviolet
UVO	ultraviolet/ozone
Val	valine
WCA	water contact angle
W/O	water-in-oil
W/O/O	water-in-oil-in-oil
W/O/W	water-in-oil-in-water
XPS	x-ray photoelectron spectroscopy

LIST OF FIGURES

- Figure 1-1.** PDMS microchip with injected electrode pads for generating localized plasma in main channel. (a) Chip design, showing the injected electrodes, the main channel and the localized plasma. (b) Injected gallium electrodes adjacent to main channel. (c) PDMS microchip with patterned gallium electrodes adjacent to main channel. Cross-section of main channel and gallium electrodes is shown in the inset [36]..... 11
- Figure 1-2.** Schematic illustration of the bonding process between two complementary reactive CVD coatings 1 (poly(4-aminomethyl-*p*-xylylene-*co*-*p*-xylylene)) and 2 (poly(4-formyl-*p*-xylylene-*co*-xylylene)) [40].....13
- Figure 1-3.** Schematic of a PDMS microchannel modified with LPEI and citrate-stabilized gold nanoparticles using LBL assembly [46].17
- Figure 1-4.** Scanning electron micrographs of cross-sections of (a) uncoated and (b) coated PDMS channels by mixture of TEOS and methyltriethoxysilane using the sol-gel method [59].19
- Figure 1-5.** Schematics of the process of surface modification of PDMS with Pluronic F127. (a) The microchannel based on Pluronic F127 embedded PDMS; (b) when the microchannel based on Pluronic F127 embedded PDMS was filled with water, Pluronic F127 molecules migrated to the water interface with hydrophilic PEO towards to water and hydrophobic PPO towards to PDMS [124].....21
- Figure 1-6.** PDMS surface modification with hydrophobins followed by covalent immobilization of chicken IgG and demonstration of immunogenicity using FITC-labeled anti-chicken IgG [74].22
- Figure 1-7.** Scheme of fabricating the protein G-immobilized hydrogel chip. (a) The PDMS surface modification with PEMs (PEI/PAAc) in microchannel by layer by layer (LBL) technique; (b) absorption of photoinitiator (PI) into the PEMs-modified PDMS microchannel; (c) protein G was covalently bonded to NHS-PEG-acrylate molecules for copolymerization with the AAm/bisAAm; (d) certain region in the PEMs-modified PDMS microchannel were exposed to UV light through the microscope objective for in situ synthesis of hydrogel

plugs in the PEM-modified PDMS microchannel; (e) patterned hydrogel plugs were formed within PDMS microchannels [112].....	29
Figure 1-8. Sectional AFM scan of a sine wave-like ripple pattern that present on the PDMS surface after ion implantation [131].....	31
Figure 1-9. Chemical patterning in PDMS microchannel. (a) Schematic of the microfluidic device. For patterned coating in microchannel, a polyelectrolyte sequence was flushed through inlet D and water was injected through inlet B simultaneously, while Inlet C was blocked and A was used as an outlet. (b and c) Bright field micrographs of the microfluidic device after patterned coating. (d and e) Corresponding fluorescence micrographs of the microfluidic device after patterned coating. Only the lower part of the microchannel was coated with fluorescent PEMs. No deposition occurred within the upper part. Scale bars denote (a) 2 mm, (b and d) 750 μm , (c and e) 150 μm [55].....	32
Figure 1-10. Schematic illustration of producing patterned PDMS using bond-detach lithography method. (a) PDMS patterned surface was formed <i>via</i> capturing a plasma oxidized film onto another plasma oxidized PDMS stamp corresponding to the stamp patterns [133]. (b) PDMS patterned surface was formed <i>via</i> capturing PDMS from a plasma oxidized PDMS stamp onto substrates (silicon, glass or PDMS) with/without plasma oxidization [128]...	34
Figure 1-11. Integrated elastomeric valves. (A) Scheme for fabrication of PDMS elastomeric valve. A patterned oxidized PDMS 1, achieved by bonding and detaching an entire oxidized PDMS 1 with a native PDMS 3, was bonded with PDMS 3/PDMS 2 to form elastomeric valve. (B) Elastomeric valve in a closed position with the membrane flat. Scale bar: 0.25 mm. (C) Elastomeric valve in an open position with the membrane deflected [130].	34
Figure 1-12. (Left) schematic of a COMOSS separation column made from PDMS and (right) scanning electron micrograph of the inlet section of the COMOSS [60].	47
Figure 1-13. Schematic of surface functionalization and the application of an immunoassay: (a) carboxy-terminated silane monolayer derived from the PDMS surface by three steps, including oxygen plasma pretreatment, silanization of 7-octenyltri(chloro)silane and permanganate-periodate oxidation; (b) biotin-PEG-functionalized surface silane monolayer after 1-ethyl-3(dimethylamino)-propylcarbodiimide- <i>N</i> -hydroxysuccinimide	

activation of the carboxy groups; (c) schematic view of on-chip immunoassay within surface-functionalized PDMS channel. Biotinylated anti-IgG was firstly immobilized on the biotin-PEG-functionalized PDMS surface via avidin–biotin linkage, and then used to capture IgG. Finally, AP-labeled anti-IgG was bonded to IgG for electrochemical detection [140].52

Figure 1-14. Conjugate capture schematics responding to temperatures. (a) Conjugate capture schematic (cold start). Conjugates were loaded at room temperature. When the temperature was raised above 36 °C, conjugates aggregated and moved onto the PNIPAAm-modified surface; (b) Conjugate enrichment schematic (Hot Start). When the microfluidic device was heated above 36 °C and conjugates were introduced into the microchannel under continuous flow, conjugates were sequentially captured onto the PNIPAAm surface as they aggregated and were concentrated. Hereafter, a cool wash was applied to release surfaces bound conjugates from the PNIPAAm surface into the solution, following a warm buffer for removing unbound conjugates in both cold start (a) and hot start (b) procedures. Conjugate solution with higher concentration than that in the original sample stream (enrichment) was obtained in hot start (b) procedure [95].55

Figure 1-15. Optical micrographs of A427 colon cancer cell immobilization in microfluidic devices based on (a) native PDMS (b) Arg-Gly-Asp modified PDMS [61].57

Figure 1-16. Schematic illustrations of double emulsification devices. (a) One-step breakup of droplet for double emulsion formation [92]; (b) two-step breakup of droplet for double emulsion formation [93].60

Figure 3-1. WCA vs. aging time for NP1 and MP1 (10:1). The samples were stored in air (filled symbols) and in MilliQ water (empty symbols). Diamond: NP1; triangle: 10 min MP1 (10:1); circle: 1 h MP1 (10:1); pentagram: 1 d MP1 (10:1).80

Figure 3-2. FTIR-ATR spectra of (a) NP1, (b) 10 min MP1 (10:1), (c) 1 h MP1 (10:1), and (d) 1 d MP1 (10:1).81

Figure 3-3. Zeta potential measurements of NP1 and 1 d MP1 (10:1) at pH 4 and pH 12. (n=3).82

Figure 3-4. FTIR-ATR spectra of (a) 1 d MP1 (10:1) before zeta potential analysis, (b) 1 d MP1 (10:1) after zeta potential analysis at pH 4, and (c) 1 d MP1 (10:1) after

zeta potential analysis at pH 12.	83
Figure 3-5. Stability of the carboxyl peak in FTIR-ATR spectra of 1 d MP1 (10:1) surfaces: of (a) immersion in MilliQ water for 3 h and 17 h at 50 °C; (b) immersion in PBS buffer (pH 7.2) for 3 h and 17 h at 50 °C; (c) immersion in PBS buffer (pH 7.2) for 3 h and 17 h at room temperature; (d) stored in a desiccator for 5.5 h and 19.5 h at room temperature.	84
Figure 3-6. WCA vs. aging time for 1 d MP1 (10:1) and 1 d MP1 (5:1). The samples were stored in air (filled symbols) and in MilliQ water (empty symbols). Pentagram: 1 d MP1 (10:1); circle: 1 d MP1 (5:1).	85
Figure 3-7. FTIR-ATR spectra of (a) 1 d MP1 (5:1) and (b) 1 d MP1 (10:1).....	86
Figure 3-8. Stability of the carboxyl peak in FTIR-ATR spectra of (a) 1 d MP1 (5:1) and (b) 1 d MP1 (10:1) after immersing in 1 mM KCl pH 4 or pH 12 for 1 d at room temperature.	87
Figure 3-9. Stability of the carboxyl peak in FTIR-ATR spectra of (a) 1 d MP1 (5:1) and (b) 1 d MP1 (10:1) after immersing in PBS buffer (pH 7.2) for 3 h and 17 h, at room temperature or 50 °C.....	88
Figure 3-10. Fluorescence microscopy images: (a) NP1 and 1 d MP1 (10:1) with Lucifer Yellow CH after cleaning with MilliQ water; (b) NP1 and 1 d MP1 (10:1) with Lucifer yellow CH after cleaning with MilliQ water and ethanol; (c) NP1 and 1 d MP1 (5:1) with Lucifer Yellow CH after cleaning with MilliQ water and ethanol. (Scale bar: 100 μm).....	90
Figure 4-1. WCA measured on the surfaces of (a) blank gold slide; (b) MPA modified gold slide; (c) NP2 and (d) MP2.	96
Figure 4-2. FTIR-ATR spectra of (a) NP2 and (b) MP2.....	97
Figure 4-3. High resolution XPS C 1s spectra of (a) NP2 and (b) MP2.....	98
Figure 4-4. Streaming zeta potential measurements for NP2 and MP2 at pH 4, 6, 8, 10 and 12; (n=3).	99
Figure 4-5. Stability of the carboxyl peak in FTIR-ATR spectra of MP2 immersing in: (a) MilliQ water, (b) PBS (pH 4.8) and (c) PBS (pH 7.4) for 3 h and 17 h at room temperature and/or 50 °C.	100
Figure 4-6. Fluorescence images of (a) NP2 and (b) MP2 with Lucifer Yellow CH labeling.	101
Figure 4-7. Fluorescence microscopy images of (a) Oligo 1/NP2 and (b) Oligo 1/MP2 after DNA hybridization with Oligo2. (c) shows the line intensity profile,	

marked as dotted lines, of Oligo 1/NP2 (from left to right) and (d) the Oligo 1/MP2 (from top to bottom) after DNA hybridization with Oligo 2. The samples were placed on a glass slide for microscopy imaging.....	102
Figure 5-1. FTIR-ATR spectra of AAc plasma modified PDMS with different operational pressures ((a) 0.1 mbar, (b) 0.2 mbar, (c) 0.3 mbar, and (d) 0.4 mbar,) and fixed 5 min treatment time on an Ar pretreated surface (0.7 mbar, 0.5 min).....	107
Figure 5-2. FTIR-ATR spectra of AAc plasma modified PDMS with different treatment times ((a) 0.5 min, (b) 1 min, (c) 2 min, (d) 3 min, (e) 4 min, (f) 5 min and (g) 10 min) and fixed 0.2 mbar operational pressure on an Ar pretreated surface (0.7 mbar, 0.5 min).....	107
Figure 5-3. WCA versus aging time for PDMS samples in air. Diamond: NP3; triangle: Ar plasma treated NP3; circle: Ar and then AAc plasma treated NP3; pentagram: MP3 in air.....	109
Figure 5-4. FTIR-ATR spectra of (a) NP3 and (b) MP3.....	110
Figure 5-5. High resolution XPS C 1s spectra of (a) Soxhlet-extracted NP3 and (b) MP3.....	111
Figure 5-6. Stability of the carboxyl peak in FTIR-ATR spectra of MP3 immersing in: (a) MilliQ water, (b) PBS (pH 4.8), (c) PBS (pH 7.4) and (d) HEPES buffer (pH 7.4) for 0.5 h, 3 h and 17 h at room temperature and/or 50 °C.....	113
Figure 5-7. AFM images ($4 \times 4 \mu\text{m}^2$) of (a) Soxhlet-extracted NP3 and (b) MP3. The Z scale is 70 nm.....	114
Figure 5-8. Fluorescence images of (a) NP3 and (b) MP3 with Lucifer Yellow CH labeling, and (c) the line intensity profile of images (a) NP3 and (b) MP3 (from left to right). The samples are placed on a glass slide for microscopy imaging.	115
Figure 5-9. Fluorescence images of (a) Oligo 1/Soxhlet-extracted NP3 and (b) Oligo 1/MP3 after DNA hybridization with Oligo 2. (c) shows the line intensity profile of Oligo 1/Soxhlet-extracted NP3 and (b) Oligo 1/MP3 after DNA hybridization with Oligo 2 (from left to right). The samples were placed on a glass slide for microscopy imaging.	117
Figure 6-1. Fluorescence emission spectra upon excitation at 360 nm recorded for solutions of aptamer/cocaine/Hoechst 33342 after different incubation protocols: (a) A solution containing aptamer (100 nM) and cocaine (100 nM) in Tris buffer (pH 8.4) was then maintained at room temperature for 20 min;	

(b) A solution containing aptamer (100 nM) and cocaine (100 nM) in Tris buffer (pH 8.4) was heated at 80 °C for 10 min, and then cooled in fridge to 4 °C for 10 min; (c) A solution containing aptamer (100 nM) and cocaine (100 nM) in Tris buffer (pH 8.4) was heated at 80 °C for 10 min, and then cooled to room temperature for 10 min. Hoechst 33342 (100 nM) was then added into the above three aptamer/cocaine solutions and incubated for 30 min.124

Figure 6-2. Fluorescence emission spectra recorded from different solutions (aptamer, cocaine, Hoechst, aptamer/cocaine, aptamer/Hoechst 33342, cocaine/Hoechst 33342, aptamer/cocaine/Hoechst 33342) using the same temperature protocol as in Figure 1 (c) (heating at 80 °C for 10 min, then cooling to room temperature over 10 min).....125

Figure 6-3. MBET response using a 510-550 nm bandpass filter for the aptamer-based sensor to cocaine at varying concentrations on NP2 and MP2 surfaces after functionalization with aptamer and incubation with cocaine and Hoechst 33342. The insert shows a plot of fluorescence intensity for the aptamer-based sensor against the cocaine concentrations.127

Figure 7-1. FTIR-ATR spectra of (a) MP3 and (b) MP3 after 10 sec O₂ plasma (0.2 mbar).....131

Figure 7-2. Linear relationship between the measured current value and the applied voltage in native PDMS-based microchannel (measurement performed in 10 mM pH 8.2 PBS buffer).....132

Figure 7-3. EOF values of native PDMS, MP2 and MP3-based microfluidic device. (n=3).....133

Figure 7-4. Fluorescence images of (a) native PDMS, (b) MP2 and (c) MP3-based microchannels, and (d) the line intensity profile of images (a) native PDMS, (b) MP2 and (c) MP3-based microchannels (from left to right).....134

LIST OF SCHEMES

Scheme 2-1. Schematic illustration of the procedure for preparing native PDMS 1 (NP1) and modified PDMS 1 (MP1).....	64
Scheme 2-2. Schematic illustration of the procedure for preparing modified PDMS 2 (MP2).....	66
Scheme 2-3. Schematic illustration of (a) plasma system and (b) the procedure for preparing modified PDMS 3 (MP3).	67
Scheme 2-4. Schematic illustration of the static sessile drop for the measurement of WCA.....	68
Scheme 2-5. Schematic illustration of the procedure for preparing SU-8 master. 1) Rinse with acetone IPA, then dried with nitrogen gas, and finally dehydrated at 200 °C for 20 min. 2) Spin-coat 50 µm thick SU-8 2050 photoresist. 3) Pre-bake at 65 °C for 3 min and 95 °C for 9 min. 4) Exposure to UV light at an intensity of 215 mJ/cm for 22 sec through the glass mask. 5) Post-bake at 65 °C for 2 min and 95 °C for 7 min. 6) Develop in PEMA for 7 min, then rinse with PGMEA and IPA, and finally dried under a stream of nitrogen. (Dimensions: main channel = 2 cm length, side channel = 0.5 cm length. Both channels are 250 µm wide and 50 µm in deep).	73
Scheme 2-6. Schematic illustration of the procedure for fabrication of (a) native PDMS-based, (b) MP2-based and (c) MP3-based microfluidic devices. 1) Pour PDMS in Petri dish and cure at 80 °C for 20 min for (a) native PDMS-based microfluidic devices or 1 h for (c) MP3-based microfluidic devices. 2) Peel flat PDMS slides off Petri dish. 3) Pour PDMS over SU-8 master and cure at 80 °C for 20 min for (a) native PDMS-based microfluidic devices or 1 h for (c) MP3-based microfluidic devices. 4) Peel microchannel featured PDMS slides off the master. 5) Bring two PDMS slides together and keep for 2 h at 80 °C. 6) Soxhlet-extract native PDMS with hexane and then treat the surfaces with 2-step plasma (Ar and AAc). 7) Treat the surfaces with O ₂ plasma for 10 sec, then clean with ethanol and finally apply another 10 sec O ₂ plasma for bonding the devices.	74
Scheme 2-7. Schematic illustration of the procedure for EOF measurements.....	76

Scheme 3-1. Immobilization of Lucifer Yellow CH dipotassium salt dye on carboxyl functionalized PDMS surface.	89
Scheme 4-1. Process of PDMS surface modification by UDA and DNA hybridization on MP2 surface.	94
Scheme 6-1. Schematic illustration of MBET aptamer sensors for cocaine detection on MP2 surface.	121
Scheme 6-2. Schematic illustration of fluorescence resonance energy transfer MBET aptamer sensors for cocaine detection in solution.	123
Scheme 7-1. Hydrosilylation reaction between PDMS curing agent and UDA.	130

LIST OF TABLES

Table 1-1. Comparison of different PDMS surface modification methods (and submethods)	4
Table 1-2. Comparison of separation conditions for different biomolecule groups in microchannels featuring surface-modified PDMS.	37
Table 2-1. Details of the surface characterization methods used on each modified PDMS surface.....	68
Table 4-1. Chemical compositions of the surfaces of NP2 and MP2 within the depth of information of XPS.	97
Table 5-1. Chemical compositions of the the surfaces of NP3 and MP3 within the depth of information of XPS.	111
Table 5-2. Fluorescent microscopy results of DNA hybridization on two different surfaces using different Oligo combinations.....	117