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Surface Engineering for Molecular Electronics

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SUMMARY

Molecular electronics studies charge transport through molecules and the applications in electronic devices where molecules serve as the ultimate nanosized building blocks. Controllable charge transport properties and stable electrical junctions lie at the heart of molecular electronics because of their crucial impact on practical devices, and both of them concern engineering at the surface and interface, *e.g.*, anchoring functional molecules onto electrodes and forming densely packed monolayers resistive against electrostatic pressure. This thesis aims to unite the synthesis and characterization of functional (bio)organic semiconductive molecular self-assemblies and the fabrication of electronic devices comprising these ensembles for paradigm-shifting applications from a surface engineering perspective.

Chapter 1 provides a general survey on the state-of-the-art molecular electronics, particularly in large-area junctions comprising self-assembled monolayers. We start from a brief history of molecular electronics and an introduction of single-molecule and large-area junctions as two complementary approaches that help unveil the underlying physics of charge transport through molecules. Large-area junctions comprising molecular ensembles at their equilibrium state feature reliable device performance and self-assembled monolayers (SAMs) have been extensively studied due to their functionality and well-defined structure in contrast to other candidates, *e.g.*, Langmuir monolayers. Choosing the right binding chemistry for the formation of SAMs is only half of the production of an ideal large-area junction, the other half of the endeavour is the fabrication of a suitable top electrode that preserves the integrity of the monolayers. We further examine the approaches developed for producing device-like large-area junctions comprising SAMs and particularly focus on junctions using eutectic Ga-In (EGaIn) electrode because of its significant involvement in following chapters. At the end of this chapter, we discuss different charge transport mechanisms across molecular junctions and their identification based on charge transport properties.

In **Chapter 2**, we investigate the relationship between the mechanical deformation and the electrical properties of SAMs of a specific conjugated molecule, *i.e.*, oligothiophenes, in tunneling junctions using conductive probe atomic force microscopy (CP-AFM) or EGaIn top electrode. Shifts in conductivity and transition voltages under increasing force load measured on these SAMs are compared to SAMs of alkanethiolates. While these shifts usually correspond to an increasing tilt angle from the tip penetration on the SAMs of alkanethiolates, they are ascribed to distortions of the π system present in oligothiophenes because of a higher mechanical robustness - SAMs comprising oligothiophenes show about five times higher Young's modulus (a measure of stiffness of a solid material in elastic regime) than alkanethiolates. The mechanical robustness of oligothiophenes manifests an increased tolerance against high bias in large-area EGaIn junctions, suggesting that electrostatic pressure plays a significant role in the short circuit of molecular junctions at high bias. We relate our understanding of the relationship between the

mechanical deformation and the electrical properties of SAMs to molecular structure such that the mechanical properties of a SAM and how a tunneling junction responds to forces can be tailored synthetically to increase the robustness and stability of junctions and to develop devices that respond to mechanical inputs. We also demonstrate that it is possible to design molecules that maximize mechanical properties and breakdown voltages in large-area tunneling junctions comprising SAMs.

Chapter 3 describes a strategy for fabricating soft, stretchable biophotovoltaic devices that generate photocurrent from self-assembled, light-harvesting photosystem I (PSI) complexes on Au electrodes with a preferred orientation. In these devices, charges are collected by the direct injection of electrons into the Au electrode and the transport of holes through a redox couple to EGaIn electrodes that are confined to microfluidic pseudochannels by arrays of posts. The pseudochannels are defined in a single-step fabrication by exploiting the non-Newtonian rheology of EGaIn. We further extend this strategy to the fabrication of reticulated electrodes that are inherently stretchable and potentially allows devices to be stacked to compensate for the relatively low optical cross-section. A simple shadow evaporation technique is used to increase the surface area of Au electrodes by a factor of 10^6 and a power conversion efficiency of 10^2 compared to planar electrodes. The efficiency of these biophotovoltaic devices decrease over time, presumably as a result of the denaturation and/or detachment of PSI complexes from the Au electrodes. However, by circulating a solution of active PSI complexes, the devices self-regenerate by mass-action/self-assembly. These devices leverage simple fabrication techniques to produce complex function and prove that photovoltaic devices comprising PSI can retain the ability to regenerate, one of the most important functions of photosynthetic organisms.

In **Chapter 1-3**, we show that the relatively simple and versatile chemistry of metal-thiolate bonds makes SAMs of thiolates the preferred option for engineering the surface properties of metals toward a range of application, yet fragility and a tendency to oxidize in air limit their long-term use. We switch gears in **Chapter 4** and introduce thiol-free self-assembled mono- and bilayers of glycol ethers, which bind to the surface of coinage metals through the spontaneous chemisorption of glycol ether-functionalized fullerenes. As-prepared assemblies are bilayers presenting fullerene cages at both substrate and ambient interfaces. Subsequent exposure to functionalized glycol ethers displaces the topmost layer of glycol ether-functionalized fullerenes, and the resulting assemblies expose functional groups to the ambient interface. These layers exhibit the properties of thiolate SAMs, yet they are stable to ambient conditions for several weeks, as shown by the performance of tunneling junctions formed from SAMs of alkyl-functionalized glycol ethers. Such unprecedented stability facilitates rapid prototyping, long-term studies of tunneling junctions and opens up the possibility of in place exchange *in operando*, for self-repair and functionality that reflects past exposure to specific chemical compounds. Glycol ether-functionalized spiropyran incorporated into mixed monolayers lead to reversible, light-driven conductance switching. We show that the self-assemblies of glycol ethers are drop-in replacements for SAMs of thiolates that retain all of their useful properties while avoiding the drawbacks of metal-thiolate bonds. Glycol ether SAMs can be formed from any molecule bearing a glycol ether tail, creating the opportunity to extract useful functionality from robust, static devices that, in part, fabricate themselves.

As a follow-up to **Chapter 4**, **Chapter 5** describes the reconfiguration of molecular

tunneling junctions during operation via the self-assembly of bilayers of glycol ethers. Here we use well-established functional groups to modulate the magnitude and direction of rectification in assembled tunneling junctions by exposing them to solutions containing different glycol ethers. Variable-temperature measurements confirm that rectification occurs by a bias-dependent tunneling-hopping mechanism and that glycol ethers, beside being an unusually efficient tunneling medium, behave identically to alkanes. We further fabricate memory bits from cross-bar junctions prepared by injecting EGaIn into microfluidic channels. The state of two 8-bit registers were set by trains of droplets such that we were able to perform logical AND operation on bit strings encoded into chemical packets that alter the composition of the cross-bar junctions through self-assembly to effect memristor-like properties. And because its electrical output is defined by its composition, the concepts demonstrated in this paper could be extended to any process capable of generating chemical signals and is not limited to stochastic computation. In general, this proof of concept work demonstrates the potential for fieldable devices based on molecular tunneling junctions comprising self-assembled monolayers and bilayers.

In **Chapter 6**, we investigate charge transport through non-covalent SAMs of the magnetic phthalocyaninato lanthanide-ligated polyoxovanadate cages on atomically smooth Au substrates. These SAMs exhibit varied conductance in large-area molecular junctions using EGaIn top electrodes at low bias but similar conductance at high bias, which corresponds to the molecular states coming into resonance with the electrode/substrate Fermi level at higher voltage. While the magnetism of these metal complexes are dominated by the spin-orbit effects of lanthanide cations, the molecular charge-transport characteristics are strongly influenced by electron transport through the fully-oxidized vanadium center. Our findings in this chapter pave the way for discovering novel materials that are responsive to multiple inputs in electronic devices.

The materials, systems and methods developed in this dissertation are the basis for myriad possibilities in future molecular electronics. The quantitative determination of the mechanical robustness of molecular ensembles which corresponds to specific intermolecular interactions serves as a useful reference for synthesizing practical electronic devices comprising molecules of rational design. Air-stable molecular self-assemblies that leverage reversible, non-covalent interactions enable convenient installation of functional molecules and open up new opportunities for next-generation memory and neuromorphic computing. We also demonstrate that the combination of micro-/nanofabrication techniques can be used to solve problems and introduce new features for applications of molecular electronics in other scenarios, *e.g.*, conversion of solar energy. As Richard Feynman once said, "there is plenty of room at the bottom", we have not yet discovered the whole realm called molecular electronics - numerous challenges lie ahead, so do opportunities.

SAMENVATTING

In de moleculaire elektronica wordt ladings transport door moleculen en toepassingen in elektronische apparaten onderzocht, waar moleculen dienen als ultieme nano-formaat bouwstenen. In het hart van de moleculaire elektronica liggen, vanwege hun cruciale invloed op de praktische apparaten, controleerbare eigenschappen van het ladingstransport en de stabiele elektrische verbindingen liggen. Beide hebben betrekking op de techniek aan het oppervlak en op de interface, bijvoorbeeld door het verankeren van functionele moleculen op elektroden en het vormen van dicht opeengepakte monolagen die resistent zijn tegen elektrostatische druk. Deze dissertatie heeft als doel de synthese en karakterisering van functionele (bio)organische halfgeleidende moleculaire zelfassemblages en de fabricage van elektronische apparaten die bestaan uit deze ensembles voor paradigmaverschuivende toepassingen vanuit het perspectief van de oppervlaktetechniek te verenigen.

In **Hoofdstuk 1** wordt een algemeen overzicht gegeven van de meest geavanceerde moleculaire elektronica, met name verbindingen met grote oppervlaktes die bestaan uit zelfgeassembleerde monolagen komen aan bod. We gaan uit van een korte geschiedenis van moleculaire elektronica en introduceren enkel-molecuuls en grote-oppervlakte verbindingen als twee complementaire benaderingen die helpen de onderliggende fysica van moleculair ladingstransport te onthullen. Groot-vlakkige knooppunten bestaande uit moleculaire ensembles op hun evenwichtstoestand zijn voorzien van betrouwbare apparaatprestaties en zelfgeassembleerde monolagen (SAM's) zijn uitgebreid bestudeerd vanwege hun functionaliteit en goed gedefinieerde structuur in tegenstelling tot andere kandidaten, bijvoorbeeld Langmuir-monolagen. Het kiezen van de juiste bindende chemie voor de vorming van SAM's is slechts de helft van de productie van een ideale verbinding met een groot oppervlak, de andere helft van de inspanning is de fabricage van een geschikte top-elektrode die de integriteit van de monolagen behoudt. We onderzoeken de benaderingen die zijn ontwikkeld verder voor de productie van apparaat-achtige groot gebied kruispunten die bestaan uit SAM's en richten ons in het bijzonder op kruispunten met behulp van eutectische Ga-In (EGaIn) elektrodes vanwege de significante betrokkenheid bij de volgende hoofdstukken. Aan het einde van dit hoofdstuk bespreken we verschillende ladingstransportmechanismen van moleculaire knooppunten en hun identificatie op basis van ladingstransport-eigenschappen.

In **Hoofdstuk 2** onderzoeken we het verband tussen de mechanische vervorming en de elektrische eigenschappen van SAM's van een specifiek geconjugeerd molecuul, van het type oligothiofenen, in tunnelverbindingen met behulp van atoomkrachtmicroscopie, met een geleidende sonde (CP-AFM), of EGaIn-topelektrode. Verschuivingen in geleidbaarheid en overgangsspanningen onder toenemende krachtbelasting gemeten op deze SAM's worden vergeleken met SAM's van alkanethiolaten. Terwijl deze verschuivingen meestal overeenkomen met een toenemende kantelhoek van de tip penetratie op de SAM's van alkanethiolaten, worden ze toegeschreven aan vervormingen van het π -systeem, dat

aanwezig is in oligothiolen, vanwege een hogere mechanische robuustheid - SAM's bestaande uit oligothiolen tonen ongeveer vijf keer hogere Young's modulus (een maat voor de stijfheid van een vast materiaal in elastisch regime) dan alkanethiolaten. De mechanische robuustheid van oligothiolen vertoont een verhoogde tolerantie voor hoge bias in grote EGaIn-verbindingen, wat suggereert dat elektrostatische druk een significante rol speelt in de kortsluiting van moleculaire verbindingen bij hoge bias. We relateren ons begrip van de relatie tussen de mechanische vervorming en de elektrische eigenschappen van SAM's aan de moleculaire structuur, zodat de mechanische eigenschappen van een SAM, en hoe een tunneling junctie reageert op krachten, synthetisch kunnen worden aangepast om de robuustheid en stabiliteit van de juncties te verhogen en om apparaten te ontwikkelen die reageren op mechanische inputs. We tonen ook aan dat het mogelijk is om moleculen te ontwerpen die de mechanische eigenschappen en de afbraakspanningen in grote tunneling juncties met SAM's maximaliseren.

Hoofdstuk 3 beschrijft een strategie voor het fabriceren van zachte, rekbaar biofotovoltaïsche apparaten die fotostroom genereren uit zelf geassembleerde, lichtharvestende fotosysteem I (PSI) complexen op gouden elektroden met een voorkeursrichting. In deze apparaten worden ladingen verzameld door de directe injectie van elektronen in de gouden elektrode en het transport van gaten door een redox-paar naar EGaIn elektroden die zijn beperkt tot microfluidische pseudokanalen door middel van arrays van pilaren. De pseudochannels worden in één enkele stap gefabriceerd door gebruik te maken van de niet-Newtoniaanse reologie van EGaIn. We breiden deze strategie verder uit tot de fabricage van reticulair elektroden die inherent rekbaar zijn en die het mogelijk maken om apparaten te stapelen om de relatief lage optische doorsnede te compenseren. Een eenvoudige schaduwverdamptechniek wordt gebruikt om het oppervlakte van de gouden elektroden te vergroten met een factor van 10^6 en een vermogensconversie-efficiëntie van 10^2 in vergelijking met vlakke elektroden. Het rendement van deze biofotovoltaïsche apparaten neemt in de loop van de tijd af, vermoedelijk als gevolg van de denaturatie en/of onthechting van PSI-complexen van de gouden elektroden. Echter, door het circuleren van een oplossing van actieve PSI-complexen, regenereren de apparaten zichzelf door massa-actie / zelf-assemblage. Deze apparaten maken gebruik van eenvoudige fabricagetechnieken om complexe functies te produceren en te bewijzen dat fofovoltaïsche apparaten met PSI het vermogen kunnen behouden om te regenereren, een van de belangrijkste functies van fotosynthetische organismen.

In **Hoofdstuk 1-3** laten we zien dat de relatief eenvoudige en veelzijdige chemie van metaal-thiolaatbindingen SAM's van thiolaten tot de voorkeursoptie maakt voor de engineering van de oppervlakte-eigenschappen van metalen in een scala aan toepassingen, maar de kwetsbaarheid en de neiging om te oxideren in de lucht beperken hun gebruik op lange termijn. We schakelen in een hogere versnelling in **Hoofdstuk 4** en introduceren thiolvrije zelfgeassembleerde mono- en bilayers van glycolethers, die zich binden aan het oppervlak van muntmetalen door de spontane chemisorptie van glycol-ether gefunctionaliseerde fullerenen. Geprepareerde assemblies zijn bilayers die fullerenen-kooien op zowel substraat- als omgevingsinterfaces presenteren. Latere blootstelling aan gefunctionaliseerde glycolethers verdringt de bovenste laag van glycol-ether gefunctionaliseerde fullerenen, en de resulterende assemblies stellen functionele groepen bloot aan omgevingsraakvlakken. Deze lagen vertonen de eigenschappen van thiolaat

SAM's, maar zijn enkele weken stabiel aan de omgevingsomstandigheden, zoals blijkt uit de prestaties van tunnelverbindingen gevormd uit SAM's van alkyl-gefunctionaliseerde glycolethers. Dergelijke ongekende stabiliteit vergemakkelijkt snel prototyping, lange termijn studies van tunneling knooppunten en opent de mogelijkheid van in plaats uitwisseling *in operando* voor zelfherstellende functionaliteit die het blootstellingsverleden aan specifieke chemische verbindingen weerspiegelt. Glycol ether-gefunctionaliseerde spiropyran, opgenomen in gemengde monolagen, leidt tot een omkeerbare lichtgedreven geleidingsschakeling. We laten zien dat de zelfassemblages van glycolethers drop-in vervangers zijn voor SAM's van thiolaten die al hun nuttige eigenschappen behouden en tegelijkertijd de nadelen van metaal-thiolaatbindingen vermijden. Glycol ether SAM's kunnen worden gevormd uit elk molecuul met een glycol etherstaart, waardoor de mogelijkheid ontstaat om nuttige functionaliteit te halen uit robuuste, statische apparaten die, voor een deel, zichzelf fabriceren.

Als vervolg op **Hoofdstuk 4** beschrijft **Hoofdstuk 5** de herconfiguratie van moleculaire tunneling juncties in werking via de zelfassemblage van glycolethers. Hier gebruiken we gevestigde functionele groepen om de grootte en de richting van de rectificatie in geassembleerde tunneling juncties te moduleren door ze bloot te stellen aan oplossingen die verschillende glycolethers bevatten. Variabele temperatuurmetingen bevestigen dat de rectificatie gebeurt door een bias-afhankelijke tunneling-hopping mechanisme en dat glycolethers, naast het feit dat ze een ongewoon efficiënt tunnelmedium zijn, zich identiek gedragen als alkanen. Verder fabriceren we geheugenbits van dwarsverbindingen die worden voorbereid door EGaIn in microvloeistofkanalen te injecteren. De toestand van twee 8-bits registers werden ingesteld door treinen van druppels, zodat we in staat waren om logische EN bewerkingen uit te voeren op bitreeksen gecodeerd in chemische pakketten die de samenstelling van de dwarsbalk kruispunten wijzigen door middel van zelf-assemblage om memristor-achtige eigenschappen te bewerkstelligen. En omdat de elektrische output wordt bepaald door de samenstelling, kunnen de concepten die in dit document worden gedemonstreerd worden uitgebreid tot elk proces dat chemische signalen kan genereren en is het niet beperkt tot stochastische berekeningen. In het algemeen toont dit werk aan conceptbewijs het potentieel voor fieldable praktisch uitvoerbare apparaten op basis van moleculaire tunneling knooppunten bestaande uit zelf-geassembleerde monolagen en bilayers.

In **Hoofdstuk 6** onderzoeken we het ladingstransport door middel van niet-covalente SAM's van de magnetische phthanlocyaninato lanthanide-gelieerde polyoxovannaat-kooien op atomisch-gladde-goud substraten. Deze SAM's vertonen gevarieerde geleiding in groot-gebied moleculaire knooppunten met behulp van EGaIn topelektroden bij lage bias, maar soortgelijke geleiding bij hoge bias, die overeenkomt met de moleculaire staten, komen in resonantie met het elektrode-substraat Fermi niveau bij een hogere spanning. Terwijl het magnetisme van deze metaalcomplexen wordt gedomineerd door spin-orbit effecten van lanthanide kationen, worden de moleculaire laad-transportkarakteristieken sterk beïnvloed door elektrontransport door het volledig geoxideerde vanadiumcentrum. Onze bevindingen in dit hoofdstuk maken de weg vrij voor het ontdekken van nieuwe materialen die reageren op meerdere inputs in elektronische apparaten.

De in dit proefschrift ontwikkelde materialen, systemen en methoden vormen de basis voor talloze mogelijkheden in de toekomstige moleculaire elektronica. De kwantitatieve

bepaling van de mechanische robuustheid van moleculaire ensembles die overeenkomt met specifieke intermoleculaire interacties dient als een nuttige referentie voor het synthetiseren van praktische elektronische apparaten die bestaan uit moleculen met een rationeel ontwerp. Luchtstabiele moleculaire zelfassemblages die gebruik maken van omkeerbare, niet-covalente interacties maken een gemakkelijke installatie van functionele moleculen mogelijk en openen nieuwe mogelijkheden voor de volgende generatie geheugenmodules en neuromorfe computers. We tonen ook aan dat de combinatie van micro-/nanofabricagetechnieken kan worden gebruikt om problemen op te lossen en nieuwe functies te introduceren voor toepassingen van moleculaire elektronica in andere scenario's, bijvoorbeeld de omzetting van zonne-energie. Zoals Richard Feynman ooit zei, "er is genoeg ruimte aan de onderkant", hebben we nog niet het hele rijk genaamd moleculaire elektronica ontdekt - er liggen tal van uitdagingen in het verschiet, en ook kansen.

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Andreas, thank you for being my mentor during my Topmaster Nanoscience program and later my PhD co-supervisor. The Photosystem I project would not have been possible without you and I have so much joy being part of it. Kees, you've always reminded me the importance of fundamentals and I could never learn enough about organic chemistry and organic electronics from you. The marriage between organic electronics and fullerene chemistry gave birth to exciting results and numerous papers (and I believe there are more to come) which would not have been possible without your participation. Best wishes on your retirement and a brand new adventure!

I would like to express my deep gratitude to Prof. George Palasantzas, Prof. Nathalie Katsonis and Prof. Michael Dickey for being on my assessment committee, their precious time and useful suggestions on improving this dissertation.

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Viktor, you are the best colleague one can ever have! You never stop surprising me with your extensive understanding of alchemy long hidden in the old tomes of Russian journals, ineffable dark humor in Slavic disguise and encyclopedic knowledge of some nameless Pacific islands, even to this day. It is such a pity that we only got to collaborate more at the late stage of our PhDs, but those projects that we came up with would not even be there without your wisdom. Thank you for being my friend and my colleague, I wish you all the best!

Sylvia, Jane, Henry, Mihaela, Jingjin, Giuseppe, Meike, Sebastian, Kirill, Andrew, Marco, Ricarda, Jenny, Nutifafa, Musty, Maria, Shuyan, Azadeh, Jan Anton, Thijs, Marten, Remco,

Oleg, Oreste, Selim, Mark, Jerry, David and Chris, thank you all for your collaborations and helpful discussions. Special thanks to Dr. Harry Jonkman for your fascinating XPS training and teaching me an important lesson, never collaborate with self-claimed XPS expert who overexploits spectra for desired conclusion.

I would like to thank the Topmaster 2013-2015 cohort for their support and friendship over the past 7 years. Hendrik and Wytse, I miss all the fun we had together and thank you so much for being my paranymphs. Let's have coffee together again and I will make sure I have that "A Thousand Things About Topmaster" ready.

And finally, I would like to thank my parents for encouraging me to step out of my comfort zone and to explore the unknown. Although we are far away from each other at the moment, I know you always have my back. Love you both.

Ellen Goodman once put it, "there's a trick to the 'graceful exit.' It begins with the vision to recognize when a job, a life stage, or a relationship is over — and let it go. It means leaving what's over without denying its validity or its past importance to our lives. It involves a sense of future, a belief that every exit line is an entry, that we are moving up, rather than out." I would not have visioned the end of this splendid five-year journey until I wrote the first line of this dissertation, and now I am ready to move on - Xinkai out.

CURRICULUM VITÆ

1990.12.30 Born in Shaoguan, People's Republic of China.

EDUCATION

- 2015.10-
2020.09 PhD in Chemistry

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Thesis: Surface Engineering for Molecular Electronics
Supervisor: Prof. dr. Ryan C. Chiechi & Prof. dr. Andreas Her-
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2015.08 MSc in Nanoscience

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Short project: Reconstructing the 3D Structure of Bulk Heterojunc-
tion Solar Cells from Ultrathin Sections
Supervisor: Prof. dr. L. Jan Anton Koster & Prof. dr. Ryan C. Chiechi
Thesis: Symmetry Breaking in Self-assembled G-quartets
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- 2009.08-
2013.06 BSc in Polymer Chemistry

University of Science and Technology of China
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CONFERENCES VISITS

2017.06	Contributed talk @ ICMAT 2017 Conference
2018.08	Contributed talk @ CECAM-Psi-k Biomolelectron Conference
2019.05	Invited talk @ Vlieland 2019 Conference
2020.08	Invited talk @ IRIS Catalysis Virtual Summit 2020
2020.11	Contributed talk @ MRS Fall 2020
2014.12	Poster @ CHAINS 2014
2015.06	Poster @ Vlieland 2015
2016.12	Poster @ CHAINS 2016
2017.05	Poster @ Vlieland 2017
2017.11	Poster @ Molecular Machine Nobel Prize Conference
2017.12	Poster @ CHAINS 2017
2018.12	Poster @ CHAINS 2018
2019.06	Poster @ NextGen IV: PV Materials Conference
2019.07	Poster @ Nanolithography of Biointerfaces Faraday Discussions
2020.07	Poster @ RSC Porous Materials Group Poster Conference

SERVICES

2017.05	Art Design for Vlieland 2017 Conference
2019.05	Art Design for Vlieland 2019 Conference
2019.06	Volunteer & Art Design for NextGen IV: PV Materials Conference

TEACHING & SUPERVISION

2015.12- 2020.09	Lab Manager @ Chiechi Group
2016.03- 2016.06	Supervisor of master project "Soft Biophotovoltaic Devices"
2016.09- 2018.11	Teaching Assistant for Organic Synthesis II
2017.03- 2017.06	Supervisor of bachelor project "High-surface ZnO Electrode"
2017.09- 2018.06	Supervisor of master project "Cofabricated EGaIn Microelectrodes"
2018.09- 2019.06	Supervisor of master project "Transferable Electrode for M.E."
2019.09- 2020.06	Supervisor of PhD project "Fullerene-Photosystem I PV Devices"

LIST OF PUBLICATIONS

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2. Y. Zhang, **X. Qiu (equal contribution)**, P. Gordiichuk, S. Soni, T.L. Krijger, A. Herrmann & R.C. Chiechi *Mechanically and electrically robust self-assembled monolayers for large-area tunneling junctions*, The Journal of Physical Chemistry C **121**(27), 14920-14928 (2017).
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