Understanding losses in halide perovskite thin films

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Summary

Semiconductors have been an integral element in our 21st century society. We find semiconductors at the heart of every electronic device such as microprocessor chip, transistor, as well as light-emitting diode (LED). Although, the seminal theory of semi-conductors was proposed by A.H. Wilson in 1931 after the birth of quantum mechanics, the main impetus of the fast development of semiconductors for devices, perhaps only came after several ground breaking experiments in transistors by W.B. Shockley, J. Bardeen, and W.H. Brattain who received the Nobel prize in 1956. Rapid progress in techniques to deposit and study semiconductor interfaces in the 1980s helped close the gap between our knowledge in solid-state physics semiconductor and light science, most recently exemplified by the LED. An energy-efficient LED can reduce electricity consumption by about 75%. High-efficiency LEDs are enabled by high quality GaN semiconductor films, firstly introduced by I. Akasaki, H. Amano, and S. Nakamura who received the Nobel prize in 2014. They introduced a growth technique to make uniform nucleation, non-selective growth, and good coalescence that leads to reduce defect density in GaN.

On the other hand, advances in thin-film semiconductor technology will also find applications in highly efficient and low-cost photovoltaics. Hybrid-halide perovskites have emerged over the unprecedented timeframe over the last 6 years as a promising class of materials for such applications. Most notably, their solar cells have achieved power conversion efficiencies above 20 % in the laboratory, even though many fundamental questions still remain unanswered. Therefore for halide perovskite thin-films to have an impact beyond the laboratory requires a systematic understanding and eliminating sources of losses.

In Chapter 1 we outline the methodology used in this thesis to improve our understanding, while pointing the way forward to eliminate the losses and ultimately design even better devices. Technically the development cycle involves controlled and clean experimental systems along with careful measurements and full optoelectronic modelling/theory to verify, and quantify the losses in halide perovskite thin-films. By quantifying and considering all of the losses, the ultimate goal is directed at designing a novel architecture device that potentially exceeds the performance and relaxes the limitations of traditional solar cell configurations.

In Chapter 2 we report experimental values of carrier diffusion lengths in halide perovskite thin films and describe how processing, composition, aging and surface passivation affect the results. Considering the many possibilities for all three ions in the halide perovskite structure, hundreds of distinct compositions have already been reported. Such compositional changes can alter the carrier diffusion length - a key parameter for solar cell performance. Given the large compositional and processing parameter space, a rapid and simple technique for directly measuring diffusion length is needed. Here we use a laser grating technique to screen the diffusion length in perovskite materials. First, in pure $CH_3NH_3PbI_3$ we observe the diffusion length is largely dependent on the controlled processing conditions. Next, we partially replace iodide (I) with bromide (Br) and show that surprisingly, the diffusion length increases after aging for 1 month in air. Finally, we use a 4-nm Al_2O_3 layer (atomic layer deposition) to passivate the surface of $CH_3NH_3PbBr_3$, leading to a remarkable increase in diffusion length from 201 nm to 532 nm. The correlation that we have established between materials processing and diffusion length offers guidance in how to improve materials for devices.

In Chapter 3 we describe the use of electron backscattering diffraction (EBSD) to properly determine the grain boundary locations in halide perovskite thin-films. Grain boundaries play a key role in the performance of thin-film optoelectronic devices and yet their effect in halide perovskite materials is still not understood. The biggest factor limiting progress is the inability to identify grain boundaries; the gold standard - EBSD - destroys halide perovskite thin films. Non-crystallographic techniques commonly misidentify grain boundaries, leading to conflicting literature reports about their influence. Here we solve this problem using a solid-state EBSD detector with 6,000 times higher sensitivity than the traditional phosphor screen and camera. We used the crystal misorientation data set from the EBSD to model the characteristics of grain boundary interface energy in $CH_3NH_3PbBr_3$ thin-films, and show that the halide perovskite grains do not exhibit twinning. In addition, we find a peculiar case, where the grain boundary very likely consists of amorphous halide perovskites.

In Chapter 4 we attempt to correlate the true grain size with photoluminescence lifetime, carrier diffusion length, and mobility in halide perovskites. We find that the grain boundaries are not benign as is often claimed, but have a recombination velocity of 1670 cm/s, comparable to that of crystalline silicon. However, as with silicon, amorphous perovskite can passivate crystalline boundaries, leading to brighter photoluminescence and longer carrier lifetime without reducing diffusion length. This variable grain boundary character explains the mysteriously long lifetime and record efficiency achieved in small grain halide perovskite thin films, while pointing the way forward to even better performance.

In Chapter 5 we use our understanding of the losses to design a novel device architecture - nanoscale back-contact perovskite solar cell to improve tandem efficiency. Using coupled optical-electrical modelling, we optimize this architecture for a planar perovskite-silicon tandem, highlighting the roles of nanoscale contacts to reduce the required perovskite electronic quality such as minority carrier diffusion length. We discuss the advances of our design over the traditionally used two- (2-T) and four-

terminal tandem (4-T), and point the way towards further improvements enabled by our design such as surface texturing, surface passivation and photoluminescence outcoupling.

Samenvatting

Halfgeleiders zijn onmisbaar in onze 21e-eeuwse maatschappij. We kunnen halfgeleiders vinden in de kern van elk elektronisch apparaat, zoals de microprocessor chip, transistors en licht-emitterende diodes (LED). Hoewel de rudimentaire theorie van de halfgeleiders al was voorgesteld in 1931 door A.H. Wilson na de geboorte van de kwantummechanica, kwam de voornaamste impuls voor de snelle ontwikkeling van halfgeleiders voor apparaten kwam pas na verscheidene baanbrekende experimenten met transistors door W.B. Shockley, J. Bardeen, en W.H. Battain, die daarvoorde in 1956 de Nobelprijs hebben ontvangen. Razendsnelle technologische ontwikkelingen tussen 1980 en 1990 om halfgeleiders te deponeren en de grensvlakken te bestuderen hielpen om de kloof te dichten tussen onze kennis van vaste-stof halfgeleiderfysica en de wetenschap van het licht ("fotonica"). Een goed voorbeeld hiervan is de LED. Een energiezuinige LED kan het elektriciteitsverbruik met ongeveer 75 % verminderen. LEDs met een hoge efficiëntie zijn mogelijk door het gebruik van een dunne laag gallium nitride (GaN) van hoge kwaliteit. Deze zijn voor het eerst geïntroduceerd door I. Akasaki, H. Amano, en S. Nakamura, die daarvoor in 2014 de Nobelprijs in ontvangst namen. Deze wetenschappers introduceerden een kristalgroeitechniek waarmee uniforme nucleatie, non-selectieve groei en goede samensmelting mogelijk werden wat vervolgens leidde tot een vermindering in de defectendichtheid in GaN.

Anderzijds zal de vooruitgang in dunne-film halfgeleidertechnologie ook toepassingen vinden in fotovoltaïca met hoge efficiëntie en lage kosten. Hybride-halide perovskieten zijn een categorie materialen welke in een uitzonderlijk korte tijdspanne van 6 jaar een enorme opkomst hebben gemaakt voor dergelijke toepassingen. Hybride-halide perovskiet zonnecellen hebben een elektriciteitsopwekkingefficiëntie van 20 % bereikt in het laboratorium, ondanks dat vele fundamentele vragen nog steeds onbeantwoord zijn. Om dunne-film halide perovskite ook buiten het laboratorium een impact te laten hebben is het nodig om systematisch ons begrip te vergroten en oorzaken van energieverlies te elimineren.

In hoofdstuk 1 wordt de onderzoeksmethodologie van deze thesis geschetst. Hierin verbeteren wij onze kennis en wijzen wij de weg naar het elimineren van verliezen om uiteindelijk betere apparaten te ontwerpen. Vanuit een technisch oogpunt heeft het

ontwikkelingsproces gecontroleerde en schone experimentele systemen nodig, gecombineerd met zorgvuldige metingen en volledige optisch-elektronische modellering en bijbehorende theorie om de verliezen in halide-perovskiet dunne films te kunnen verifiÃ«ren en kwantificeren. Door alle verliezen te kwantificeren en doorgrondig te onderzoeken wordt het uiteindelijke doel gestuurd richting het ontwerpen van een apparaat met een nieuwe architectuur, die mogelijk de prestaties en beperkingen overtreft van traditionele zonnecelconfiguraties.

In Hoofdstuk 2 rapporteren wij experimentele waarden van energiedragerdiffusielengtes in halide perovskiee dunne films en beschrijven we hoe de verwerking, samenstelling, veroudering en oppervlaktepassivering invloed heeft op de resultaten. Omdat er veel verschillende samenstellingsmogelijkheden zijn voor de drie ionen in de halogenide perovskietstructuur zijn er al honderden verschillende samenstellingen gerapporteerd. Dergelijke wijzigingen in de samenstelling kunnen de energiedragerdiffusielengte veranderen - dit is een kernparameter voor zonnecelprestaties. Aangezien er vele mogelijkheden zijn voor de samenstelling en de verwerking is een snelle en eenvoudige techniek voor het direct meten van de diffusielengte nodig. Wij hebben gebruik gemaakt van een laser-traliewerk techniek om de diffusielengtes van perovskieten door te lichten. Ten eerste, in zuiver $CH_3NH_3PbI_3$ observeren we dat de diffusielengte grotendeels afhankelijk is van de vervaardigingsomstandigheden. Vervolgens vervangen we gedeeltelijk de jodide (I) ionen met bromide (Br). Verrassend genoeg observeren wij dat de diffusielengte toeneemt na blootstelling aan de lucht gedurende één maand. Ten slotte deponeren wij een 4-nm Al_2O_3-laag (door middel van atomaire laag depositie; ALD) op het oppervlak van $CH_3NH_3PbBr_3$ om deze te passiveren. Dit zorgde voor een opmerkelijke toename in diffusielengte van 201 nm naar 532 nm. De correlatie die we hebben vastgesteld tussen materiaalvervaardiging en diffusielengte biedt richtlijnen voor toepassing in apparaten.

In hoofdstuk 3 beschrijven we het gebruik van elektron-terugverstrooiingdiffractie (EBSD) om de korrelgrenslocaties in halide perovskite dunne films nauwkeurig te bepalen. Korrelgrenzen hebben een grote invloed op de prestaties van dunne film opto-elektronische apparaten en toch wordt hun effect in halide perovskieematerialen nog steeds niet begrepen. De grootste voortuitgangsbeperkende factor is het onvermogen om korrelgrenzen te identificeren; de gouden standaard - EBSD - vernietigt halogeen perovskiet dunne films. Niet-kristallografische technieken lijden onder het vaak misidentificeren van korrelgrenzen, wat leidt tot tegenstrijdige experimentele data in de literatuur over de invloed van deze korrelgrenzen. Dit probleem lossen wij op met behulp van een vaste-stoft EBSD-detector met een 6000 maal hogere gevoeligheid dan een traditioneel fosforscherm met een camera. Wij maken gebruik van de kristalmisoriëntatiedataset van de EBSD om de kenmerken van de korrelgrens grensvlak-energie in $CH_3NH_3PbBr_3$ dunne films te modelleren. Deze gegevens laten zien dat halogenide perovskiet korrels geen tweelingeffecten vertonen. Verder vonden wij een bijzondere situatie waarbij de korrelgrens van dit geval zeer waarschijnlijk bestaat uit amorfe halogenide perovskieten.

In Hoofdstuk 4 proberen we de ware korrelgrootte te correleren met fotoluminescentielevensduur, de energiedragerdiffusielengte en -mobiliteit in halogenide perovskieten.

Verder ontdekken we dat de korrelgrenzen niet onschuldig zijn zoals vaak wordt beweerd. Deze korrelgrenzen hebben namelijk een recombinatie snelheid van 1670 cm/s. Dit is vergelijkbaar met de recombinatiesnelheid van kristallijn silicium. Echter kan amorf perovskiet, net als silicium, kristallijne grenzen passiveren, wat leidt tot helderdere fotoluminescentie en een langere levensduur van de ladingsdragers zonder de diffusielengte te verminderen. Dit variabele karakter van de korrelgrenzen verklaart de verrassend lange levensduur en recordefficiëntie welke bereikt wordt in klein-korrelige halide perovskiet dunne films. Verder wijst het ook de weg voorwaarts naar nog betere prestaties.

In hoofdstuk 5 gebruiken we ons begrip van de verliezen om een apparaat met een nieuwe architectuur te ontwerpen: perovskietzonnecellen met een nanoschaal contact aan de achterkant om zo de tandemefficiëntie te verbeteren. Met behulp van gekoppelde optisch-elektrische modellering, optimaliseren we deze architectuur voor een vlakke perovskiet-silicium tandem. Hierbij leggen we de nadruk op de rol van de nanoschaal contacten om de vereiste elektronische kwaliteit van perovskiet te verminderen, zoals de diffusielengte van minderheidsenergiedragers. Ook wordt de vooruitgang van ons ontwerp ten opzichte van de traditioneel gebruikte twee- (2-T) en vier-contacten (4-T) tandem zonnecellen besproken en wijzen we de weg naar verdere verbeteringen die mogelijk zijn met ons ontwerp zoals oppervlaktetextureren, oppervlaktepassivering en fotoluminescentieuitkoppelingsefficiëntie.

Ringkasan

Semikonduktor sudah menjadi kesatuan utuh dalam kehidupan manusia abad-21. Kita menemukan semikonduktor dalam setiap komponen alat elektronik seperti mikroprosesor, transistor, termasuk didalamnya lampu LED. Dasar teori lahirnya semikonduktor pertama kali diajukan oleh A.H. Wilson pada tahun 1931 setelah lahirnya mekanika kuantum, meski dari itu penerapan semikonduktor itu sendiri baru berkembang pesat setelah beberapa eksperimen terobosan pada transistor yang dilakukan oleh W.B. Shockley, J. Bardeen, dan W.H. Brattain (penerima hadiah Nobel 1956). Perkembangan pesat berikutnya terjadi ditahun 1980an dimana pengetahuan tentang cara memproses, dan pengkarakterisasian semiconductor telah membantu kita dalam menjembatani dua bidang penting yaitu dasar fisika struktur dan ilmu cahaya. Contoh paling penting yaitu lahirnya lampu LED yang mampu mengurangi konsumsi listrik sebesar 75 %. Faktor keberhasilan utamanya terletak pada penggunaan GaN semikonduktor material berkualitas tinggi, yang pertama kali di pelopori oleh I. Akasaki, H. Amano, dan S. Nakamura (penerima hadiah Nobel 2014). Dimana mereka berhasil memperkenalkan cara membuat lapisan tipis GaN dengan proses pembibitan atom secara merata, tidak terlokalisasi, dan membentuk kesatuan kristal yang mampu mengurai jumlah cacat material.

Pada sisi lain, kemajuan dalam teknologi lapisan tipis semikonduktor sudah terbukti untuk menghasilkan sel surya yang sangat efisien namun murah. Hibrida-halogen perovskait adalah jenis mineral baru, yang dalam waktu singkat 6 tahun sudah membuktikan diri memenuhi kriteria diatas. Terbukti dengan efisiensi sel surya yang dihasilkan sudah diatas 20 % di skala laboratorium, meskipun banyak dasar-dasar sains yang belum diketahui mengapa material ini begitu efisien. Maka dari itu agar Hibrida-halogen perovskait ini bisa berdampak lebih luas dibutuhkan pemahaman sains mendasar yang sistematis, serta cara untuk mengurai jumlah cacat material yang dimilikinya.

Pada Bab 1 kami menjelaskan metodelogi yang digunakan di disertasi ini untuk memahami sains mendasar tersebut. Sekaligus memberikan saran penting bagaimana mengurai jumlah cacat material, yang pada akhirnya kami mengajukan terobosan desain baru untuk merancang solar cell yang lebih efisien. Secara teknis ini mencakup pembangunan ide bagaimana membuat sistem penelitian yang bersih, terpercaya dan teliti, yang kemudian menggabungkannya dengan teknik permodelan serta teori yang

utuh dengan tujuan untuk memverifikasi, mengidentifikasi, dan menghitung sumber sumber cacat dari hibrida-halogen perovskait. Dengan semua cara ini, kita pada akhirnya akan bisa membuat teknologi sel surya baru yang melebihi, dan mengurai keterbatasan dari teknologi yang ada sekarang.

Pada Bab 2 kami melaporkan hasil pengukuran seberapa jauh muatan listrik bisa mengalir di hibrida-halogen perovskait ini, dan menjelasakan bagaimana teknik pemrosesan, komposisi, penuaan, dan pelapisan permukaan mempengaruhi persepsi kita akan hasil penelitian. Walaupun hanya memiliki tiga jenis ion dalam struktur materialnya, namun kombinasi dari ketiganya mampu mengasilkan ratusan jenis kombinasi struktur yang berbeda-beda. Semua kombinasi ini akan mempengaruhi hasil pengukuran tersebut, terutama panjang muatan listrik yang mampu mengalir karena ini merupakan komponen penting untuk aplikasi sel surya. Kita mengajukan teknik pengukuran yang mampu mengukur parameter panjang muatan listrik ini dengan cara cepat dan tepat. Teknik ini menggunakan cahaya laser untuk membuat pola interferensi permukaan. Pertama, kita menemukan bahwa pada jenis material perovskait murni pun, $CH_3NH_3PbI_3$, pengukuran panjang muatan listrik bisa berbeda beda tergantung bagaimana kita membuatnya. Kemudian kita secara bertahap mengganti iodida (I) dengan bromida (Br) dan hasilnya panjang muatan listrik bisa bertambah setelah didiamkan selama 1 bulan di udara. Akhirnya, kami menggunakan lapisan tipis Al_2O_3 sebesar 4-nm (pembuatan dengan cara atom per atom) untuk mengisolasi permukaan, dan hasilnya panjang muatan listrik pertambah dari 201 nm menuju 532 nm. Korelasi penting ini akan menjadi panduan penting bagimana meningkatkan kualitas material untuk aplikasi yang dibutuhkan.

Pada Bab 3 kami menjelaskan penggunaan teknik elektron backsketering difraksi (EBSD) untuk mengidentifikasi dengen benar keberadaan dan lokasi dari kristal batas dari lapisan tipis hibrida halida perovskite. Pengetahuan akan kristal batas ini menjadi begitu penting mengingat perannya di hibrida halida perovskite sangatlah ambigu. Faktor penghalang utamanya yaitu ketidakjelasan akan konsensus yang digunakan dalam menentukan lokasi kristal batas ini. Konsensus standard seperti EBSD tidak mampu membantu karena biasanya langsung menghancurkan material ini ketika diterapkan. Kami menyelesaikan masalah ini dengan menggunakan detektor padat jenis baru yang memiliki sensitifitas 6000 kali detektor EBSD yang ada sekarang seperti kamera, dan jendela klasik phosporus. Kami menggunakan informasi dari misorientasi kristal untuk memodelkan dan mengkarakterisasi jenis kristal batas tersebut, dan kemudian total rugi-rugi energi yang ada di kristal batas tersebut. Kami menemukan kristal batas di $CH_3NH_3PbBr_3$ tidak memiliki kristal kembar seperti material pada umumnya, namun kristal batasnya memiliki karakteristik yang sangat tidak jelas sekaligus penting.

Pada Bab 4 kami mencoba untuk mencari hubungan antara ukuran kristal yang asli dari informasi EBSD dengan waktu hidup emisi cahaya, panjang, dan mobilitas dari muatan listrik yang dihasilkannya. Kami berkesimpulan bahwa kristal batas di hibrida-halida perovskait tidaklah bermanfaat, sebagaimana diklaim sebelumnya, namun memiliki kecepatan rugi rugi sebesar 1670 cm/s, yang hampir setara dengan rugi-rugi di tradisional material seperti silikon. Namun, sebagaimana silikon keberadaan

kristal batas yang sangat tidak jelas ini mampu mengisolasi material, dan menghasilkan emisi cahaya yang lebih lama, dan mobilitas muatan listrik yang lebih jauh. Hasil dari penelitian ini menjawab semua misteri yang pernah ada sejauh ini tentang emisi cahaya yang begitu lama yang kaitannya dengan sel surya berefisiensi tinggi dari material ini, walaupun ukuran kristalnya begitu kecil. Penelitian ini memberi panduan jelas bagaimana membuat material ini lebih baik lagi.

Pada Bab 5 kami menggunakan pengetahuan yang telah kami dapat sejauh ini untuk mendesain jenis arsitektur baru untuk sel surya. Arsitektur ini kami namakan sel surya dengan semua colokan dibelakan bersekala nano. Kami menggabungkan teori optik dan elektronik untukm memodelkan, dan mengoptimalkan arsitektur ini pada jenis sel surya perovskait-silikon berpermukaan datar, dengan menekankan pada peran colokan belakang berskala nano. Peran colokan nano ini adalah untuk mengurangi kriteria pengggunaan material murni. Terlebih desain kami mampu menghilangkan halangan yang ada pada desain yang ada sekarang (2-colokan atau 4-colokan). Faktor penting yang membuat desain ini menarik adalah permukaan atasnya yang kosong bisa dimanfaatkan untuk desain permukaan struktur penangkap cahaya, strategi pengisolasian permukaan, dan pelepasan emisi cahaya keluar permukaan.

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I personally would dedicate this thesis to my late grandpa(s) who (to me) were truly great scholars and inspired me to be the one. Next to them, also my grandma(s) who keep reminding me of being genuine. Ayu, thank you for your patience and love. On top of everything, the spirit in this thesis always belongs to my Bapak, Ibu, and Indra.

Scientific portfolio

This thesis is based on the following publications:

1. *The expanding world of hybrid perovskites: materials properties and emerging applications*. S. Brittman, G.W.P. Adhyaksa, and E.C. Garnett. MRS Communications **5**, 7-26 (2015). (**Chapter 1**)

2. *Carrier diffusion lengths in hybrid perovskites: processing, composition, aging, and surface passivation*. G.W.P. Adhyaksa, L.W. Veldhuizen, Y. Kuang, S. Brittman, R.E.I. Schropp, and E.C. Garnett. Chemistry of Materials **28**, 5259-5263 (2016). (**Chapter 2**)

3. *Understanding detrimental and beneficial grain boundary effects in halide perovskites*. G.W.P. Adhyaksa, S. Brittman, H. Abolins, A. Lof, X. Li, J.D. Keelor, Y. Luo, T. Duevski, S.R. Ellis, D.P. Fenning, and E.C. Garnett. under review (2018). (**Chapter 3 and 4**)

4. *Nanoscale back contact perovskite solar cell design for improved tandem efficiency*. G.W.P. Adhyaksa, E. Johlin, and E.C. Garnett. Nano letters **17**, 5206-5212 (2017). (**Chapter 5**)

Patent applications:

1. *Multi-junction back contacts solar cell*. E.C. Garnett, G.W.P. Adhyaksa, and L.J. Geerligs. EU Patent Application P6062079NL (2017).

2. *Method for fabricating an efficient bio-photovoltaic*. J.K. Kang, G.W.P. Adhyaksa, D.K. Lee, I.W. Ock. US Patent 9293265 B1 (2016).

Other publications by the author:

1. *Anisotropic carrier diffusion across different grain orientations in lead-iodide perovskites*. S. Jariwala, D.W. deQuilettes, G.W.P. Adhyaksa, J.T. Wang, H.J. Snaith, E.C. Garnett, and D.S. Ginger. in prep (2018).

2. *Transparent quasi-interdigitated electrodes for back-contact solar cells*. G. DeLuca, A.N. Jumabekov, G.W.P. Adhyaksa, A.N. Simonov, J. Lu, B. Tan, E.C. Garnett, U. Bach, E. Reichmanis, and A.S.R. Chesman. submitted (2018).

3. *Converting rationally designed mineral architectures into semiconductors*. T. Holtus, L. Helmbrecht, H.C. Hendrikse, I. Baglai, S. Meuret, G.W.P. Adhyaksa, E.C. Garnett, and W.L. Noorduin. Nature Chemistry, accepted (2018).

4. *General considerations for improving photovoltage in metal-insulator-semiconductor photoanodes*. I.A. Digdaya, B.J. Trzesniewski, G.W.P. Adhyaksa, E.C. Garnett, and W.A. Smith. J.Phys. Chem. C. **9**, 17-36 (2018).

5. *Interfacial engineering of metal-insulator-semiconductor junctions for efficient and stable photoelectrochemical water oxidation*. I.A. Digdaya, G.W.P. Adhyaksa, B.J. Trzesniewski, E.C. Garnett, and W.A. Smith. Nature Communication. **8**, 15968 (2017).

6. *Benchmarking photoactive thin-film materials using a laser-induced steady-state photocarrier grating*. L.W. Veldhuizen, G.W.P. Adhyaksa, M. Theelen, E.C. Garnett, R.E.I. Schropp. Progress in Photovoltaics: Research and Application. **25**, 605-613 (2017).

7. *Engineering the kinetics and interfacial energetics of Ni/Ni-Mo catalyzed amorphous silicon carbide photocathodes in alkaline media*. I.A. Digdaya, P.P. Rodriguez, M. Ma, G.W.P. Adhyaksa, E.C. Garnett, A.H.M. Smets, W.A. Smith. J. Mater. Chem. A **4**, 6842-6852 (2016).

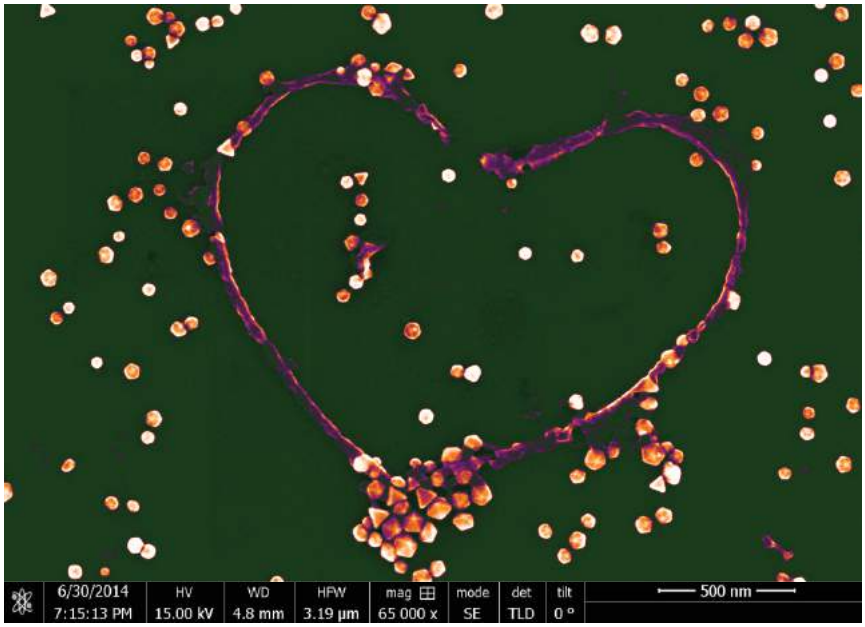
8. *A light harvesting antenna using natural extract graminoids coupled with plasmonic metal nanoparticles for bio-photovoltaic cells*. G.W.P. Adhyaksa, E.C. Prima, D.K. Lee, I. Ock, S. Yatman, B. Yuliarto, J.K. Kang. Advanced Energy Materials **4**, 18 (2014).

9. *Coupled near-and far-field scattering in silver nanoparticles for high-efficiency, stable, and thin plasmonic dye sensitized solar cells*. G.W.P. Adhyaksa, S.W. Baek, G.I. Lee, D.K. Lee, J-Y. Lee, J.K. Kang. ChemSusChem. **7**, 9 (2014).

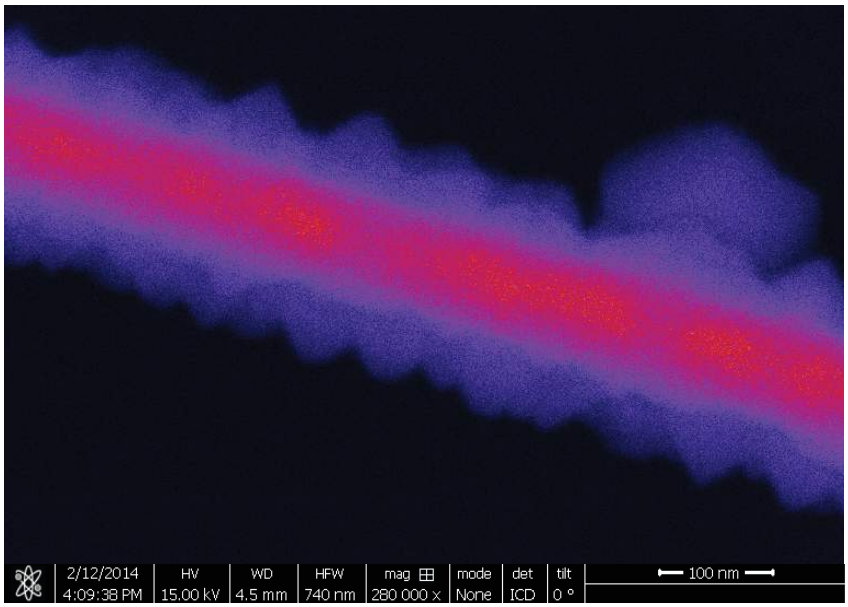
10. *Broadband energy transfer to sensitizing dyes by mobile quantum dot mediators in solar cells*. G.W.P. Adhyaksa, G.I. Lee, S.W. Baek, J-Y. Lee, J.K. Kang. Scientifc Reports **3**, 2711 (2013).

Image galery:

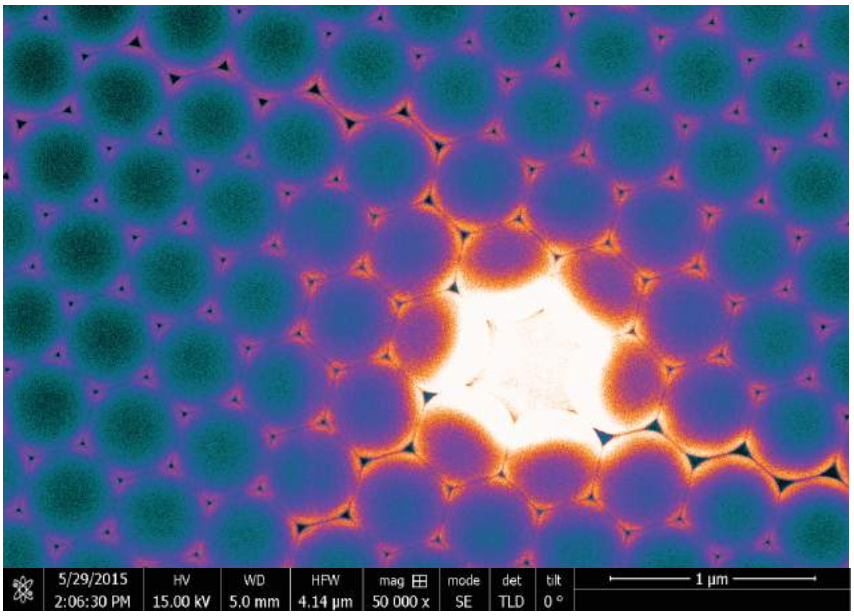
1. self-assembly "*Perovskite heart template*" with plasmonic nanoparticles (2014)*.



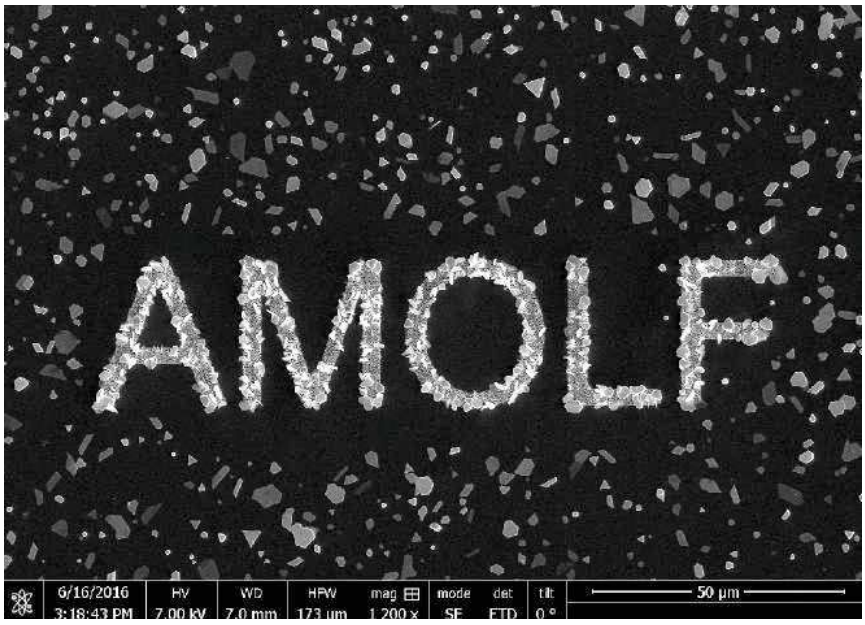
2. Plasmonic-perovskite core-shell nanowire (2014)*.



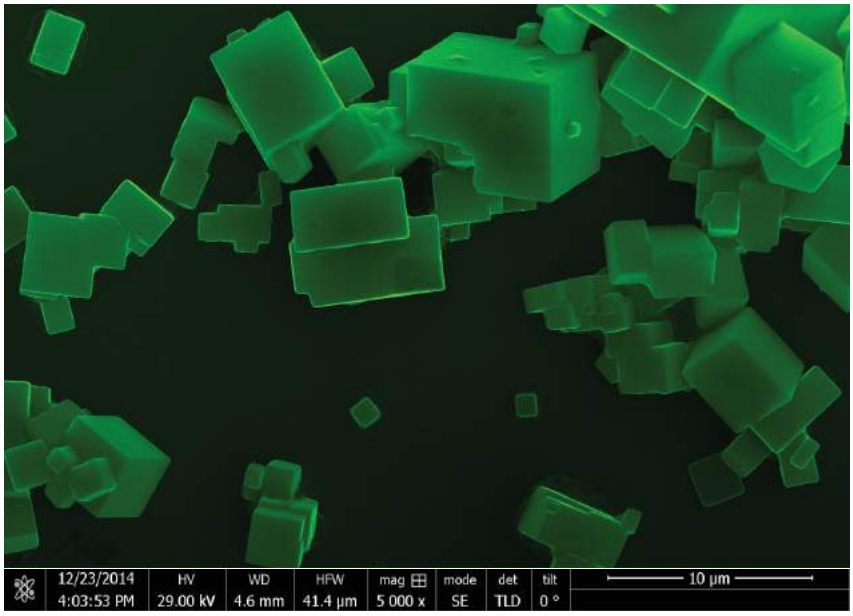
3. Vacancy defect inducing triple-plane boundaries in a hexagonal close packed structure (2015)*.



4. Selective area growth of perovskite crystals on "AMOLF" gold marker (2016).



5. Cubic perovskites (2014)*.



*false color image

About the author

Gede Adhyaksa was born in the island of Bali, Indonesia, on August 1, 1986. He studied Engineering Physics at Institut Teknologi Bandung in West Java, and graduated *Cum laude* (2008). Before starting his PhD at AMOLF (2014), during his master programs, he studied Engineering Physics at Technical University of Munich, Germany (2010), and Materials Science at Korea Advanced Institute of Science and Technology, Republic of Korea (2013). His research experience at AMOLF is presented in this book.

Besides research, he enjoys playing football, piano, traveling to unknown territories, and crafting aquatic plants at home.