

Perovskite semiconductors for next generation optoelectronic applications

Cite as: APL Mater. 7, 080401 (2019); doi: 10.1063/1.5119744

Submitted: 12 July 2019 • Accepted: 12 July 2019 •

Published Online: 5 August 2019



View Online



Export Citation



CrossMark

Felix Deschler,¹  Dieter Neher,²  and Lukas Schmidt-Mende³ 

AFFILIATIONS

¹Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom and Technische Universität München, Fakultät für Physik, Walter Schottky Institut, 85748 Garching bei München, Germany

²Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany

³Department of Physics, University of Konstanz, 75457 Konstanz, Germany

Note: This paper is part of the special topic on Perovskite Semiconductors for Next Generation Optoelectronic Applications.

<https://doi.org/10.1063/1.5119744>

INTRODUCTION

Since 2012, when two groups reported for the first time power conversion efficiencies exceeding numbers with only one digit for metal-halide perovskite solar cells, the field has progressed rapidly. Tremendous efforts have brought a lot of advancement in the field of perovskite semiconductors and their applications in optoelectronic devices. Record efficiencies of over 24% have been reported for solar cells, but we have seen also strong developments in perovskite-based optoelectronic devices such as LEDs and photodetectors. We have now a much better understanding about this fascinating semiconductor material. Nevertheless, there are still numerous aspects to be addressed, and despite the progress in the field, we find new questions arising after answering others. This special issue on perovskite semiconductors is devoted to the next generation of optoelectronic applications. We want to summarize some important aspects concerning interface engineering, device lifetime, novel applications, and physical understanding of the processes in perovskite semiconductor applications. In this article, we will only pick selected examples to demonstrate not only the progress of the field but also the open questions and interesting research questions ahead of us.

INTERFACE ENGINEERING

The device performance of perovskite solar cells is mainly limited by nonradiative recombination processes, either in the perovskite material itself¹ or at the perovskite/transport layer interface.² Therefore, we have seen many recipes for the preparation of perovskite films, improving the film quality and also many interfacial engineering to avoid recombination at the perovskite interfaces.³ Droseros *et al.* demonstrated in a series of different hole transporting

materials (HTMs) that interfacial traps are formed. Interestingly, the energy level of the different HTMs was not decisive for hole injection, leading to the assumption that the injection occurs from hot states as it is very fast and happens in the time range of thermalization. Spectroscopic measurements also revealed that interfacial electron trapping is on a much longer time scale than hole transfer, which explains the high efficiency despite the interfacial trap formation.⁴

Another example is given by Shibayama *et al.*, where they showed that in inverted perovskite solar cells the device characteristics are strongly influenced by a bathocuproine (BCP) buffer layer between the perovskite and the metal top metal electrode. This buffer layer changed the n-type perovskite/metal contact from a Schottky-type contact into an ohmic contact.⁵ Interfacial modifications strongly influence the charge transport across interfaces and also the hysteretic behaviour observed in many current-voltage scans of perovskite solar cells. Horn *et al.* reported about a 2-dimensional interface layer of phenylethylmmonium (PEA) fomamidinium tin iodide, PEA_{0.08}FA_{0.92}SnI₃, which seems to suppress ion migration at the interface.⁶

STABILITY AND DEGRADATION

One major issue of perovskite solar cells is their stability. Exposed to moisture, air, and illumination, we observe a rapid chemical degradation of metal-halide perovskites.⁷ Kakekhani *et al.* used first-principles density functional theory calculations to simulate the catalyzing effect of water incorporated into the methylammonium lead-iodide perovskite. The water is leading to a phase transformation and degradation of the perovskite film.⁸ Experimentally

Gan *et al.*⁹ demonstrated with FTIR spectra the (only partially reversible) hydration of the mixed halide perovskites.

Ion migration in the perovskite films is another factor limiting the device performance, leading often to interfacial reactions. Highly polycrystalline films with a number of defects are supposed to support ion migration due to a number of mobile ions present. This migration and the accumulation of ions at the interfaces are responsible for the characteristic slow response of many perovskite solar cells.¹⁰ Light induces an even stronger ion migration as ions are driven by the optical field. Zhong *et al.* observed in photoluminescence microscopy measurements *in situ* the ion localization leading to PL quenching on light-soaking.¹¹

At the metal/perovskite interface chemical reduction of oxidation reactions might also take place, influencing the energy levels at the interface. Kerner *et al.* investigated the MAPbI₃/Au interface in more detail concerning electrochemical reactions. There are indications that I₂, HI, and methylamine at the interface catalyze degradation. For example, in the presence of methylamine, the formation of Pb₀ is accelerated.¹²

Lim *et al.* demonstrated an interesting method to encapsulate lead-bromide perovskites in a nanoporous GaN film conserving the photoluminescence of the film for long term. They observed a blueshift of the perovskites emission when incorporated into smaller pores indicating that the GaN scaffold is influencing the perovskite crystal growth within the pores.¹³

NOVEL APPLICATIONS

Whereas the research currently mostly focuses on solar cells, using this exciting semiconductor in other applications, such as light emitting diodes (LEDs) and detectors are coming up more and more. The issue of recombination and interfacial engineering is also very important for perovskite light emitting diodes (LEDs). Liu *et al.* demonstrated on an inverted LED device architecture with NiO as the hole transport layer that the photoluminescence yield can be strongly improved by more than twice when an additional organic poly(9-vinylcarbazole) (PVK) layer is added between NiO and the perovskite film.¹⁴ Tomanová *et al.*¹⁵ reported the use of cesium-lead-bromide (CsPbBr₃) colloidal nanoplatelets that emit in the blue. They used these particles embedded in a polystyrene matrix as scintillators for detection of ionizing radiation. Important for such an application is the fast decay time. The authors observed a decay time in the subnanosecond regime. Certainly other applications are also of interest. One example of an interesting application is given by Bruzzi *et al.* that shows the proof-of-principle that inorganic perovskites can be used as clinical radiotherapy dosimeters.¹⁶

UNDERSTANDING THE MATERIALS PROPERTIES

Very successfully different cations have been incorporated into the perovskite, leading to new properties, allowing to engineer the bandgap, or improving the device performance and stability. Next to mixed cation perovskites including Cs, other atoms, such as rubidium, have also been demonstrated to improve the solar cell performance and stability.¹⁷ However, the reason for this improvement after cation compositional engineering is still under debate.

Sutanto *et al.* mixed Cs into FA_(1-x)Cs_xPbBr₃ perovskite incorporating a Cs content of up to 30% leading still to uniform polycrystalline films. The open circuit voltage of solar cells with this composition showed an extremely high open circuit voltage of 1.4 V.¹⁸

Ruf *et al.* investigated the exciton binding energy of mixed halides including Cs and their temperature dependence, where the phase transition is suppressed.¹⁹ The variety of mixtures including doping opens up an exciting research space, which is currently just in its infancy. Adjokats *et al.* showed the effect of strontium doping in formamidinium tin iodide (FASnI₃) perovskites, which is affecting to a large extent the structural morphology. Only after doping concentrations of >15%, the Sr is incorporated into the perovskite bulk, below it forms just a heterogeneous phase dominantly at the film surface.²⁰

An interesting approach to modify the perovskite through the variation of the alkyl chain length in the layered perovskite based on (C_nH_{2n+1}NH₃)₂PbI₄ with n varying from 4 to 18 has been demonstrated by Sichert *et al.* The orthorhombic crystal structure was in all samples found, but the octahedral tilt angle varied depending on the organic chain length, leading to a blueshift in optical transitions with increasing ligand length.²¹

Often, theoretical approaches are used to understand the observed properties of the perovskites in more detail. Bannow *et al.*, for example, used density functional theory to calculate the optical properties²² and Beck *et al.* binding properties and lattice constants.²³ As already discovered in 2014 by Juarez-Perez *et al.*,²⁴ perovskites show an extremely large frequency dependence of the dielectric constant, which is even increasing upon light illumination. Wilson *et al.* investigated the dielectric constant as well as the ferroic properties from a theoretical perspective.²⁵ By separating the dielectric constant in a frequency dependent and static component, the frequency dependency can be explained by the orientational polarization due to rotating dipoles.

CONCLUSIONS

In summary, this special issue provides an opportunity for the readers to get a glimpse on the ongoing research in terms of the next generation of perovskite optoelectronic applications and some important research aspects toward a better understanding, but also a better device performance and lifetime for applications. While the research in the field is progressing fast, it is important to look back the last few years, since the field started off and summarize the most important findings, but also look ahead to the next questions leading to the future research, maybe with the next breakthroughs just in front of us.

REFERENCES

- ¹A. Dubey *et al.*, "A strategic review on processing routes towards highly efficient perovskite solar cells," *J. Mater. Chem. A* **6**, 2406–2431 (2018).
- ²M. Stollerfoht *et al.*, "Visualization and suppression of interfacial recombination for high-efficiency large-area pin perovskite solar cells," *Nat. Energy* **3**, 847 (2018).
- ³A. Fakharuddin, L. Schmidt-Mende, G. Garcia-Belmonte, R. Jose, and I. Mora-Sero, "Interfaces in perovskite solar cells," *Adv. Energy Mater.* **7**, 1700623 (2017).
- ⁴N. Droseros, B. Dänekamp, D. Tsokkou, P. P. Boix, and N. Banerji, "Charge injection and trapping at perovskite interfaces with organic hole transporting materials of different ionization energies," *APL Mater.* **7**, 041115 (2019).

- ⁵N. Shibayama, H. Kanda, T. W. Kim, H. Segawa, and S. Ito, "Design of BCP buffer layer for inverted perovskite solar cells using ideal factor," *APL Mater.* **7**, 031117 (2019).
- ⁶J. Horn, M. Scholz, K. Oum, T. Lenzer, and D. Schlettwein, "Influence of phenylethylammonium iodide as additive in the formamidinium tin iodide perovskite on interfacial characteristics and charge carrier dynamics," *APL Mater.* **7**, 031112 (2019).
- ⁷C. C. Boyd, R. Checharoen, T. Leijtens, and M. D. McGehee, "Understanding degradation mechanisms and improving stability of perovskite photovoltaics," *Chem. Rev.* **119**, 3418–3451 (2019).
- ⁸A. Kakekhani, R. N. Katti, and A. M. Rappe, "Water in hybrid perovskites: Bulk MAPbI₃ degradation via super-hydrous state," *APL Mater.* **7**, 041112 (2019).
- ⁹Z. Gan, Z. Yu, M. Meng, W. Xia, and X. Zhang, "Hydration of mixed halide perovskites investigated by Fourier transform infrared spectroscopy," *APL Mater.* **7**, 031107 (2019).
- ¹⁰J.-W. Lee, S.-G. Kim, J.-M. Yang, Y. Yang, and N.-G. Park, "Verification and mitigation of ion migration in perovskite solar cells," *APL Mater.* **7**, 041111 (2019).
- ¹¹Y. Zhong, C. A. M. Luna, R. Hildner, C. Li, and S. Huettnner, "In situ investigation of light soaking in organolead halide perovskite films," *APL Mater.* **7**, 041114 (2019).
- ¹²R. A. Kerner *et al.*, "Reactions at noble metal contacts with methylammonium lead triiodide perovskites: Role of underpotential deposition and electrochemistry," *APL Mater.* **7**, 041103 (2019).
- ¹³K. T. P. Lim *et al.*, "Encapsulation of methylammonium lead bromide perovskite in nanoporous GaN," *APL Mater.* **7**, 021107 (2019).
- ¹⁴Y. Liu, T. Wu, Y. Liu, T. Song, and B. Sun, "Suppression of non-radiative recombination toward high efficiency perovskite light-emitting diodes," *APL Mater.* **7**, 021102 (2019).
- ¹⁵K. Tomanová *et al.*, "On the structure, synthesis, and characterization of ultrafast blue-emitting CsPbBr₃ nanoplatelets," *APL Mater.* **7**, 011104 (2019).
- ¹⁶M. Bruzzi, C. Talamonti, N. Calisi, S. Caporali, and A. Vinattieri, "First proof-of-principle of inorganic perovskites clinical radiotherapy dosimeters," *APL Mater.* **7**, 051101 (2019).
- ¹⁷M. Saliba *et al.*, "Incorporation of rubidium cations into perovskite solar cells improves photovoltaic performance," *Science* **354**, 206–209 (2016).
- ¹⁸A. A. Sutanto *et al.*, "Pushing the limit of Cs incorporation into FAPbBr₃ perovskite to enhance solar cells performances," *APL Mater.* **7**, 041110 (2019).
- ¹⁹F. Ruf *et al.*, "Temperature-dependent studies of exciton binding energy and phase-transition suppression in (Cs,FA,MA)Pb(I,Br)₃ perovskites," *APL Mater.* **7**, 031113 (2019).
- ²⁰S. Adjokatse, S. Kahmann, H. Duim, and M. A. Loi, "Effects of strontium doping on the morphological, structural, and photophysical properties of FASnI₃ perovskite thin films," *APL Mater.* **7**, 031116 (2019).
- ²¹J. A. Sichert, A. Hemmerling, C. Cardenas-Daw, A. S. Urban, and J. Feldmann, "Tuning the optical bandgap in layered hybrid perovskites through variation of alkyl chain length," *APL Mater.* **7**, 041116 (2019).
- ²²L. C. Bannow, J. Hader, J. V. Moloney, and S. W. Koch, "Microscopic calculation of the optical properties and intrinsic losses in the methylammonium lead iodide perovskite system," *APL Mater.* **7**, 011107 (2019).
- ²³H. Beck, C. Gehrman, and D. A. Egger, "Structure and binding in halide perovskites: Analysis of static and dynamic effects from dispersion-corrected density functional theory," *APL Mater.* **7**, 021108 (2019).
- ²⁴E. J. Juarez-Perez *et al.*, "Photoinduced giant dielectric constant in lead halide perovskite solar cells," *J. Phys. Chem. Lett.* **5**, 2390–2394 (2014).
- ²⁵J. N. Wilson, J. M. Frost, S. K. Wallace, and A. Walsh, "Dielectric and ferroic properties of metal halide perovskites," *APL Mater.* **7**, 010901 (2019).