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Ph.D. Thesis booklet

The complex physics of photoinduced charge carriers in novel materials

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Introduction

The semiconductor and solar cell industry is constantly on the lookout for new materials and methods that can lead to transistors and solar cells with higher efficiency, lower cost, and easier fabrication. The insatiable hunger of humanity for energy propels the research of new solar cell materials that can fulfill the demands of society. The semiconductor industry continuously requires devices in the fields of power electronics, thin film transistors, and transparent electronics that are more reliable, easier to produce, and cheaper than current devices.

Due to their cheap and easy fabrication and outstanding photovoltaic properties [1–3] metal halide perovskites are candidate materials for a wide range of applications. The optical properties of perovskite thin films and single crystals can be tuned by fine-tuning the halide ratio in mixed halide perovskites[4, 5]. These properties lead to their possible usage as light emitting[3, 5–7] and harvesting [1, 8–11] applications, gas sensors[12], photodetectors[13, 14], X-ray[15], gamma[16] and neutron[17] detectors. Solar cells based on metal halide perovskites currently surpass 26% efficiency[18] and the materials are proposed to be applicable in harsh environments such as outer space[19, 20].

Wide bandgap materials are in the focus of research due to their application in devices where conventional semiconductors are not ideal, such as for high-temperature conditions, transparent electronics, and power applications. While the metal oxide semiconductors such as indium gallium zinc oxide[21, 22] and gallium oxide[23, 24] are promising candidates for flat panel displays[25–27], flexible displays [28–30], power electronics[31], and sensory applications [32–39], they exhibit the persistent photoconductivity phenomena[40–48]. The presence of persistent photoconductivity complicates the proper comparison of samples manufactured with varying methods.

Objectives

While the growth of new materials and their study as a solar cell or transistor components can be done by fabricating a proof of concept device the result of the measurement of such a device only provides information about the usefulness of the material under given conditions. If the properties of the materials of interest are studied under different conditions one can uncover the physical processes that lead to the observed properties of the material. By conducting temperature-dependent studies of the charge carrier recombination dynamics the processes governing the recombination mechanism can be understood to a higher degree. If such measurements uncover a way to create samples with desired properties, the scientific and industrial community can focus research in a given direction, thus creating the solar cell and transistor materials that propel future research and development of the devices humanity will use. The development of devices based on wide bandgap semiconductors that exhibit persistent photoconductivity can be problematic since the material properties change significantly due to optical excitation with a long relaxation time. Measurement methods that allow the reliable comparison of wide bandgap materials are of utmost importance for the development of devices that incorporate them.

In my research, I investigated the temperature-dependent recombination dynamics of photoexcited charge carriers and photoconductivity in organic-inorganic hybrid metal halide perovskites and inorganic metal halide perovskites. For these measurements, I developed two instruments, a cavity-based and a coplanar waveguide-based measurement system. The cavity-based system is equipped with a high Q-factor cavity and automatic frequency control for a high-sensitivity measurement of the recombination dynamics, which allows quick cooling of the sample. The coplanar waveguide-based measurement system can accommodate samples of any geometry since the samples can be placed on the surface of the antenna. The frequency of the probing radiation can be set in a wide range in the case of the coplanar waveguide-based system. Both measurements are based on the change in the microwave signal reflected by the sample as a result of the change in surface impedance connected to charge carrier density. These measurements lead to the observation of charge carrier recombination dynamics as a function of temperature. I investigated the effect of phase transitions, quenching, and preparation methods in methylammonium lead halide perovskites to uncover the cause of the ultralong charge-carrier lifetime at cryogenic conditions and the connection with the emergence of domains in the material. I observed the power dependence together with a simulation of recombination dynamics in cesium lead bromide to investigate the recombination processes responsible for the observed ultralong recombination time.

I investigated samples that present persistent photoconductivity. Persistent photoconductivity is present in wide bandgap materials and may lead to the problematic comparison of samples due to the long-lasting change caused by optical excitation. I developed a measurement sequence that allows for the comparison of the charge carrier density, charge carrier mobility, and resistivity of samples despite the change in these parameters as a result of optical excitation before the measurement without the need for a prolonged relaxation process between the contacting of the sample and the measurement. With the developed method I studied Indium Gallium Zinc Oxide thin films created with various oxygen concentrations during deposition, thicknesses, and passivation, and compared the result to the tendencies found in the literature regarding these manufacturing changes.

New scientific results

1. I developed a cavity-based microwave photoconductivity decay measurement setup capable of measurements in the $4-300$ K temperature range. With the assembled instrument, I investigated the temperature-dependent recombination dynamics of photoexcited charge carriers in methylammonium lead halide perovskites. I carried out the temperature-dependent measurements in a range where structural phase transitions were previously reported in the materials. I conducted multiple measurements during which I found substantial changes in charge-carrier recombination dynamics and photo response at the orthorhombic to tetragonal phase transition while the tetragonal to cubic phase transition shows no such change. The changes could be identified due to the structural transformation. I presented ultralong charge-carrier recombination times in the orthorhombic phase for all three perovskites with the longest being over 68 μs in the $MAPbBr_3$ single crystal.[T1]

2. I observed the effect of charge-carrier scattering on grain boundaries in $CH_3NH_3PbBr_3$ perovskite crystals with varying morphology and quenching state. To do this, I observed the difference in temperature-dependent charge-carrier dynamics of a slowly cooled and quickly cooled sample allowed by the realized measurement system, thus creating quenched and normal phases in the same sample. To further investigate this effect I compared the temperature-dependent charge carrier dynamics of three $CH_3NH_3PbBr_3$ crystals created with different sample preparation methods leading to differences in the sample morphology. The observations demonstrate that grain boundaries caused by either morphology or quenching lead to a decrease in charge-carrier lifetime due to the increase in carrier scattering events and the possible increase in recombination centers.[T1]

3. I developed a temperature-dependent microwave photoconductivity decay measurement system based on a coplanar waveguide capable of fast detection with high sensitivity. The measurement system is developed to be able to measure the fast and slow recombination processes during a single measurement covering a time domain range of 3 orders of magnitude. I investigated the temperature-dependent recombination dynamics of photoexcited charge carriers in cesium lead bromide single crystals with the developed measurement system. I carried out photoconduc-

tivity decay measurements in a wide temperature range and observed recombination times over 1 ms at cryogenic conditions. [T2] [T3]

4. I investigated the power dependence of the charge-carrier recombination dynamics and made simulations of charge-carrier recombination processes to prove the effect of charge-carrier trapping and the microwave reflection of the measurement system to rule out heating effects. I presented results that suggest that the long charge-carrier recombination time is caused by the trapping of one kind of charge carrier in shallow traps leading to ultralong recombination times. A simulation was developed to recreate the measured charge carrier recombination dynamics in a system with a shallow and deep-level trap in the bandgap. [T2]

5. I developed a measurement sequence for the characterization and comparison of thin films that possess the persistent photoconductance phenomena. With the measurement sequence, I compared the change of charge carrier density, mobility, and sheet resistance during and after excitation with the help of a sample series consisting of five samples. The samples provided a pool of manufacturing changes that allowed for the observation of effects related to sample thickness, oxygen concentration during fabrication, and the passivation of the sample surface. With the help of this measurement, I reliably reproduced the tendencies reported in the literature and showed a method that can compare samples with properties that vary substantially between measurements without the proper precautions. I conducted these measurements with the help of the PDL-1000 system made by Semilab. During my PhD studies, I contributed to the development of the hardware and software of the PDL-1000 system. [T4]

List of Publications

[T1] A. Bojtor, S. Kollarics, B. G. Márkus, A. Sienkiewicz, M. Kollár, L. Forró, and F. Simon, “Ultralong Charge Carrier Recombination Time in Methylammonium Lead Halide Perovskites,” *ACS Photonics*, vol. 9, no. 10, pp. 3341–3350, 2022.

[T2] A. Bojtor, D. Krisztián, F. Korsós, S. Kollarics, G. Paráda, T. Pinel, M. Kollár, E. Horváth, X. Mettan, H. Shiozawa, B. G. Márkus, L. Forró, and F. Simon, “Millisecond-Scale Charge-Carrier Recombination Dynamics in the $CsPbBr_3$ Perovskite,” *Advanced Energy and Sustainability Research*, p. 2400043, 2024.

[T3] A. Bojtor *et al.*, “Time-resolved Photoconductivity Decay Measurements with Broad-band Radiofrequency Detection and Excitation Energy,” *In preparation*, 2024.

[T4] A. Bojtor, G. Paráda, P. Tüttő, H. Korka, K. Szőke, and F. Korsós, “Investigation of Persistent Photoconductance and Related Electron Mobility in Thin IGZO Layers With the PDL Hall Technique,” *Materials Today: Proceedings*, vol. 93, pp. 9–15, 2023, international Conferences & Exhibition on Nanotechnologies, Organic Electronics & Nanomedicine – Nanotexnology (NANOTEX 2022).

Other publications not included as thesis points

1. S. Kollarics, A. Bojtor, K. Koltai, B. G. Márkus, K. Holczer, J. Volk, G. Klujber, M. Szieberth, and F. Simon *Optical–Microwave Pump–Probe Studies of Electronic Properties in Novel Materials* Phys. Status Solidi B, vol. 257, no. 12, p. 2000298, 2020.

2. S. Kollarics, F. Simon, A. Bojtor, K. Koltai, G. Klujber, M. Szieberth, B. Márkus, D. Beke, K. Kamarás, A. Gali, D. Amirari, R. Berry, S. Boucher, D. Gavryushkin, G. Jeschke, J. Cleveland, S. Takahashi, P. Szirmai, L. Forró, E. Emmanouilidou, R. Singh, and K. Holczer *Ultrahigh nitrogen-vacancy center concentration in diamond* Carbon, vol. 188, pp. 393–400, 2022

3. G. Paráda, F. Korsós, A. Bojtor, J.-W. G. Bos, E. Don, J. W. Bowers, M. Togay *Exploiting bi-modulated magnetic field and drive current modulation to achieve high-sensitivity Hall measurements on thermoelectric samples* MRS Advances 7, 608–613 (2022)

4. B. Gyüre-Garami, B. Blum, O. Sági, A. Bojtor, S. Kollarics, G. Csősz, B. G. Márkus, J. Volk, F. Simon *Ultrafast sensing of photoconductivity decay using microwave resonators* J. Appl. Phys. 126, 235702 (2019)

5. J. Palotás, M. Negyedi, S. Kollarics, A. Bojtor, P. Rohringer, T. Pichler, F. Simon *Incidence of Quantum Confinement on Dark Triplet Excitons in Carbon Nanotubes* ACS Nano 14 (9), 11254-11261 (2020)

6. S. Kollarics, J. Palotás, A. Bojtor, B. G. Márkus, P. Rohringer, T. Pichler, F. Simon *Improved Laser Based Photoluminescence on Single-Walled Carbon Nanotubes* Phys. Status Solidi B 256, 1900235 (2019)

References

[1] J.-P. Correa-Baena, M. Saliba, T. Buonassisi, M. Graetzel, A. Abate, W. Tress, and A. Hagfeldt, “Promises and challenges of perovskite solar cells,” *Science*, vol. 358, no. 6364, pp. 739–744, 2017.

[2] J. Huang, Y. Yuan, Y. Shao, and Y. Yan, “Understanding the physical properties of hybrid perovskites for photovoltaic applications,” *Nat. Rev. Mater.*, vol. 2, p. 17042, 2017.

[3] K. Lin, J. Xing, L. N. Quan, F. P. G. de Arquer, X. Gong, J. Lu, L. Xie, W. Zhao, D. Zhang, C. Yan, W. Li, X. Liu, Y. Lu, J. Kirman, E. H. Sargent, Q. Xiong, and Z. Wei, “Perovskite light-emitting diodes with external quantum efficiency exceeding 20 per cent,” *Nature*, vol. 562, no. 7726, pp. 245+, 2018.

[4] F. Zhang, H. Zhong, C. Chen, X.-g. Wu, X. Hu, H. Huang, J. Han, B. Zou, and Y. Dong, “Brightly Luminescent and Color-Tunable Colloidal $CH_3NH_3PbX_3$ (X = Br, I, Cl) Quantum Dots: Potential Alternatives for Display Technology,” *ACS Nano*, vol. 9, no. 4, pp. 4533–4542, 2015.

[5] L. Protesescu, S. Yakunin, M. I. Bodnarchuk, F. Krieg, R. Caputo, C. H. Hendon, R. X. Yang, A. Walsh, and M. V. Kovalenko, “Nanocrystals of Cesium Lead Halide Perovskites ($CsPbX_3$, X = Cl, Br, and I): Novel Optoelectronic Materials Showing Bright Emission with Wide Color Gamut,” *Nano Lett.*, vol. 15, no. 6, pp. 3692–3696, 2015.

[6] Y. Fu, H. Zhu, C. C. Stoumpos, Q. Ding, J. Wang, M. G. Kanatzidis, X. Zhu, and S. Jin, “Broad Wavelength Tunable Robust Lasing from Single-Crystal Nanowires of Cesium Lead Halide Perovskites ($CsPbX_3$, X = Cl, Br, I),” *ACS Nano*, vol. 10, no. 8, pp. 7963–7972, 2016.

[7] S. W. Eaton, M. Lai, N. A. Gibson, A. B. Wong, L. Dou, J. Ma, L.-W. Wang, S. R. Leone, and P. Yang, “Lasing in robust cesium lead halide perovskite nanowires,” *Proc. Natl. Acad. Sci.*, vol. 113, no. 8, pp. 1993–1998, 2016.

[8] N.-G. Park and K. Zhu, “Scalable fabrication and coating methods for perovskite solar cells and solar modules,” *Nat. Rev. Mater.*, vol. 5, pp. 333–350, 2020.

[9] F. Fu, T. Feurer, T. Weiss, S. Pisoni, E. Avancini, C. Andres, S. Buecheler, and A. Tiwari, “High-efficiency inverted semi-transparent planar perovskite solar cells in substrate configuration,” *Nat. Energy*, vol. 2, p. 16190, 2016.

[10] Y. Haruta, T. Ikenoue, M. Miyake, and T. Hirato, “One-Step Coating of Full-Coverage $CsPbBr_3$ Thin Films via Mist Deposition for All-Inorganic Perovskite Solar Cells,” *ACS Appl. Energy Mater.*, vol. 3, no. 12, pp. 11 523–11 528, 2020.

[11] K. P. Bhandari and R. J. Ellingson, “An Overview of Hybrid Organic–Inorganic Metal Halide Perovskite Solar Cells,” in *A Comprehensive Guide to Solar Energy*

Systems, T. M. Letcher and V. M. Fthenakis, Eds. Academic Press, 2018, pp. 233 – 254.

[12] K. Mantulnikovs, A. Glushkova, P. Matus, L. Ćirić, M. Kollár, L. Forró, E. Horváth, and A. Sienkiewicz, "Morphology and Photoluminescence of $CH_3NH_3PbI_3$ Deposits on Nonplanar, Strongly Curved Substrates," *ACS Photonics*, vol. 5, no. 4, pp. 1476–1485, 2018.

[13] J. Shamsi, P. Rastogi, V. Caligiuri, A. L. Abdelhady, D. Spirito, L. Manna, and R. Krahne, "Bright-Emitting Perovskite Films by Large-Scale Synthesis and Photoinduced Solid-State Transformation of $CsPbBr_3$ Nanoplatelets," *ACS Nano*, vol. 11, no. 10, pp. 10 206–10 213, 2017.

[14] J. Ding, S. Du, Z. Zuo, Y. Zhao, H. Cui, and X. Zhan, "High Detectivity and Rapid Response in Perovskite $CsPbBr_3$ Single-Crystal Photodetector," *J. Phys. Chem. C*, vol. 121, no. 9, pp. 4917–4923, 2017.

[15] L. Clinckemalie, D. Valli, M. B. J. Roeffaers, J. Hofkens, B. Pradhan, and E. Debroye, "Challenges and Opportunities for $CsPbBr_3$ Perovskites in Low- and High-Energy Radiation Detection," *ACS Energy Lett.*, vol. 6, no. 4, pp. 1290–1314, 2021.

[16] S. Yakunin, D. N. Dirin, Y. Shynkarenko, V. Morad, I. Cherniukh, O. Nazarenko, D. Kreil, T. Nauser, and M. V. Kovalenko, "Detection of gamma photons using solution-grown single crystals of hybrid lead halide perovskites," *Nat. Photon.*, vol. 10, no. 9, pp. 585–589, Sep 2016. [Online]. Available: https://doi.org/10.1038/nphoton.2016.139

[17] P. Andričević, G. Náfrádi, M. Kollár, B. Náfrádi, S. Lilley, C. Kinane, P. Frajtag, A. Sienkiewicz, A. Pautz, E. Horváth, and L. Forró, "Hybrid halide perovskite neutron detectors," *Sci. Rep.*, vol. 11, no. 1, p. 17159, Aug 2021. [Online]. Available: https://doi.org/10.1038/s41598-021-95586-3

[18] A. Singha, A. Paul, S. Koul, V. Sharma, S. Mallick, K. R. Balasubramaniam, and D. Kabra, "Stable and Efficient Large-Area 4T Si/perovskite Tandem Photovoltaics with Sputtered Transparent Contact," *Sol. RRL*, vol. 7, no. 12, p. 2300117, 2023. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/solr.202300117

[19] A. W. Y. Ho-Baillie, H. G. J. Sullivan, T. A. Bannerman, H. P. Talathi, J. Bing, S. Tang, A. Xu, D. Bhattacharyya, I. H. Cairns, and D. R. McKenzie, "Deployment Opportunities for Space Photovoltaics and the Prospects for Perovskite Solar Cells," *Adv. Mater. Technol.*, vol. 7, no. 3, p. 2101059, 2022.

[20] D. Pérez-del Rey, C. Dreessen, A. M. Igual-Muñoz, L. van den Hengel, M. C. Gélvez-Rueda, T. J. Savenije, F. C. Grozema, C. Zimmermann, and H. J. Bolink, "Perovskite Solar Cells: Stable under Space Conditions," *Sol. RRL*, vol. 4, no. 12, p. 2000447, 2020.

[21] K. Nomura, H. Ohta, K. Ueda, T. Kamiya, M. Hirano, and H. Hosono, "Thin-film transistor fabricated in single-crystalline transparent oxide semiconductor," *Science*, vol. 300, no. 5623, pp. 1269–1272, 2003.

[22] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors," *Nature*, vol. 432, no. 7016, pp. 488–492, 2004.

[23] R. Roy, V. G. Hill, and E. F. Osborn, "Polymorphism of Ga_2O_3 and the System Ga_2O_3—H_2O," *J. Am. Chem. Soc.*, vol. 74, no. 3, pp. 719–722, 1952. [Online]. Available: https://doi.org/10.1021/ja01123a039

[24] M. Higashiwaki and S. Fujita, *Gallium Oxide: Materials Properties, Crystal Growth, and Devices*. Springer Nature, 2020, vol. 293.

[25] H.-H. Hsieh, H.-H. Lu, H.-C. Ting, C.-S. Chuang, C.-Y. Chen, and Y. Lin, "Development of IGZO TFTs and their applications to next-generation flat-panel displays," *J. Inf. Disp.*, vol. 11, no. 4, pp. 160–164, 2010.

[26] J.-h. Lee, D.-h. Kim, D.-j. Yang, S.-y. Hong, K.-s. Yoon, P.-s. Hong, C.-o. Jeong, H.-S. Park, S. Y. Kim, S. K. Lim *et al.*, "42.2: World's largest (15-inch) XGA AMLCD panel using IGZO oxide TFT," in *SID Symposium Digest of Technical Papers*, vol. 39, no. 1. Wiley Online Library, 2008, pp. 625–628.

[27] H.-N. Lee, J. Kyung, S. K. Kang, D. Y. Kim, M.-C. Sung, S.-J. Kim, C. N. Kim, H. G. Kim, and S.-t. Kim, "68.2: 3.5 inch QCIF+ AM-OLED panel based on oxide TFT backplane," in *SID Symposium Digest of Technical Papers*, vol. 38, no. 1. Wiley Online Library, 2007, pp. 1826–1829.

[28] K. Miura, T. Ueda, S. Nakano, N. Saito, Y. Hara, K. Sugi, T. Sakano, H. Yamaguchi, I. Amemiya, K. Akimoto *et al.*, "4.1: Low-Temperature-Processed IGZO TFTs for Flexible AMOLED with Integrated Gate Driver Circuits," in *SID Symposium Digest of Technical Papers*, vol. 42, no. 1. Wiley Online Library, 2011, pp. 21–24.

[29] S. Nakano, N. Saito, K. Miura, T. Sakano, T. Ueda, K. Sugi, H. Yamaguchi, I. Amemiya, M. Hiramatsu, and A. Ishida, "Highly reliable a-IGZO TFTs on a plastic substrate for flexible AMOLED displays," *J. Soc. Inf. Disp.*, vol. 20, no. 9, pp. 493–498, 2012.

[30] J.-S. Park, T.-W. Kim, D. Stryakhilev, J.-S. Lee, S.-G. An, Y.-S. Pyo, D.-B. Lee, Y. G. Mo, D.-U. Jin, and H. K. Chung, "Flexible full color organic light-emitting diode display on polyimide plastic substrate driven by amorphous indium gallium zinc oxide thin-film transistors," *Appl. Phys. Lett.*, vol. 95, no. 1, 2009.

[31] M. Higashiwaki, A. Kuramata, H. Murakami, and Y. Kumagai, "State-of-the-art technologies of gallium oxide power devices," *J. Phys. D: Appl. Phys.*, vol. 50, no. 33, p. 333002, 2017.

[32] Z. Liu, T. Yamazaki, Y. Shen, T. Kikuta, N. Nakatani, and Y. Li, “O_2 and CO sensing of Ga_2O_3 multiple nanowire gas sensors,” *Sens. Actuators, B*, vol. 129, no. 2, pp. 666–670, 2008.

[33] J. Zhu, Z. Xu, S. Ha, D. Li, K. Zhang, H. Zhang, and J. Feng, “Gallium oxide for gas sensor applications: A comprehensive review,” *Materials*, vol. 15, no. 20, p. 7339, 2022.

[34] X. Chen, F. Ren, S. Gu, and J. Ye, “Review of gallium-oxide-based solar-blind ultraviolet photodetectors,” *Photonics Res.*, vol. 7, no. 4, pp. 381–415, 2019.

[35] N. Kumar, J. Kumar, and S. Panda, “Low temperature annealed amorphous indium gallium zinc oxide (a-IGZO) as a pH sensitive layer for applications in field effect based sensors,” *AIP Adv.*, vol. 5, no. 6, 2015.

[36] H. Tang, Y. Li, R. Sokolovskij, L. Sacco, H. Zheng, H. Ye, H. Yu, X. Fan, H. Tian, T.-L. Ren *et al.*, “Ultra-high sensitive NO_2 gas sensor based on tunable polarity transport in CVD-WS_2/IGZO pN heterojunction,” *ACS Appl. Mater. Interfaces*, vol. 11, no. 43, pp. 40 850–40 859, 2019.

[37] Y.-H. Tai, H.-L. Chiu, and L.-S. Chou, “Active matrix touch sensor detecting time-constant change implemented by dual-gate IGZO TFTs,” *Solid-State Electron.*, vol. 72, pp. 67–72, 2012.

[38] D. J. Yang, G. C. Whitfield, N. G. Cho, P.-S. Cho, I.-D. Kim, H. M. Saltsburg, and H. L. Tuller, “Amorphous $InGaZnO_4$ films: Gas sensor response and stability,” *Sens. Actuators, B*, vol. 171, pp. 1166–1171, 2012.

[39] H. Jeong, C. S. Kong, S. W. Chang, K. S. Park, S. G. Lee, Y. M. Ha, and J. Jang, “Temperature sensor made of amorphous indium–gallium–zinc oxide TFTs,” *IEEE Electron Device Lett.*, vol. 34, no. 12, pp. 1569–1571, 2013.

[40] M. Lee, K.-T. Kim, M. Lee, S. K. Park, and Y.-H. Kim, “A study on the persistent photoconductance and transient photo-response characteristics of photochemically activated and thermally annealed indium-gallium-zinc-oxide thin-film transistors,” *Thin Solid Films*, vol. 660, pp. 749–753, 2018.

[41] S. Jeon, S.-E. Ahn, I. Song, C. J. Kim, U.-I. Chung, E. Lee, I. Yoo, A. Nathan, S. Lee, K. Ghaffarzadeh *et al.*, “Gated three-terminal device architecture to eliminate persistent photoconductivity in oxide semiconductor photosensor arrays,” *Nat. Mater.*, vol. 11, no. 4, pp. 301–305, 2012.

[42] W.-J. Lee, B. Ryu, and K.-J. Chang, “Electronic structure of oxygen vacancy in crystalline $InGaO_3(ZnO)_m$,” *Phys. B*, vol. 404, no. 23-24, pp. 4794–4796, 2009.

[43] S. Cui, Z. Mei, Y. Zhang, H. Liang, and X. Du, “Room-Temperature Fabricated Amorphous Ga_2O_3 High-Response-Speed Solar-Blind Photodetector on Rigid and Flexible Substrates,” *Adv. Opt. Mater.*, vol. 5, no. 19, p. 1700454, 2017. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/adom.201700454

[44] H. Liang, S. Cui, R. Su, P. Guan, Y. He, L. Yang, L. Chen, Y. Zhang, Z. Mei, and X. Du, "Flexible X-ray Detectors Based on Amorphous Ga_2O_3 Thin Films," *ACS Photonics*, vol. 6, no. 2, pp. 351–359, 2019. [Online]. Available: https://doi.org/10.1021/acsphotonics.8b00769

[45] H. Zhou, L. Cong, J. Ma, B. Li, M. Chen, H. Xu, and Y. Liu, "High gain broadband photoconductor based on amorphous Ga_2O_3 and suppression of persistent photoconductivity," *J. Mater. Chem. C*, vol. 7, pp. 13 149–13 155, 2019. [Online]. Available: http://dx.doi.org/10.1039/C9TC05159G

[46] R. Zhu, H. Liang, S. Hu, Y. Wang, and Z. Mei, "Amorphous-Ga_2O_3 Optoelectronic Synapses with Ultra-low Energy Consumption," *Adv. Electron. Mater.*, vol. 8, no. 1, p. 2100741, 2022. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/aelm.202100741

[47] S.-L. Gao, L.-P. Qiu, J. Zhang, W.-P. Han, S. Ramakrishna, and Y.-Z. Long, "Persistent Photoconductivity of Metal Oxide Semiconductors," *ACS Appl. Electron. Mater.*, vol. 6, no. 3, pp. 1542–1561, 2024. [Online]. Available: https://doi.org/10.1021/acsaelm.3c01549

[48] J. T. Jang, D. Ko, S. Choi, H. Kang, J.-Y. Kim, H. R. Yu, G. Ahn, H. Jung, J. Rhee, H. Lee *et al.*, "Effects of structure and oxygen flow rate on the photo-response of amorphous IGZO-based photodetector devices," *Solid-State Electron.*, vol. 140, pp. 115–121, 2018.