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SOLID-STATE CHEMISTRY OF TWO-DIMENSIONAL LEAD-FREE TIN HALIDE PEROVSKITES FOR STABLE OPTOELECTRONIC AND PHOTOVOLTAIC APPLICATIONS

by

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A dissertation submitted in partial fulfillment of
the requirements for the degree of

DOCTOR OF PHILOSOPHY

(CHEMISTRY)

at the

UNIVERSITY OF WISCONSIN-MADISON

2026

Date of final oral examination: July 6th, 2026

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CHAPTER 6

Atomic-Level Architecture – Materials Chemistry for People in a Hurry

In collaboration with the Wisconsin Institute for Science Literacy

6.1. Introduction

Picture the modern world just twenty years ago, circa 2006 CE. The world was a much quieter place. Smart phones did not yet exist. LEDs were uncommon, and most commercial lightbulbs were still incandescent or CFLs. Solar panels were niche, expensive, and less efficient. Computers were much larger than they are today, yet not nearly as powerful. These technologies that were uncommon or entirely nonexistent in my childhood have since become ubiquitous in modern society. The world has changed in unimaginable ways over the past twenty years due to these technologies, and who knows what new technologies will come in another twenty. We owe many of these exciting (and sometimes overwhelming) developments to the underlying *materials* – the chemically engineered substances, compounds, or crystals – that make these technologies possible. Our civilizations have always been tied to our materials, so much so that we have named our major historical eras after them, e.g. the “stone age”, the “bronze age”, the “iron age”, the “atomic age”, and now the “silicon age”.¹

We now live in an interesting time in history when new materials are developed every day. But have you ever wondered what gives different materials their unique properties? Or how different elements can be combined and rearranged to enable the different semiconductors, rechargeable batteries, and other technologies we enjoy today? These are the questions that shaped

my interest in *materials chemistry* and eventually evolved into the focus of my Ph.D. research. Synthesizing and discovering new materials, uncovering what exactly makes them good at specific applications, and understanding how to make them even better at what they do are the exciting challenges that form the basis of materials chemistry.

As new technologies develop and evolve, our world not only becomes enriched with new possibilities but also becomes more complicated. Especially today, with the rapid developments of artificial intelligence (which, by the way, are also based on advanced semiconductors), it can feel as though life is not as simple as it once was. Technology is moving faster than ever before, yet we, as the busy humans we are, only have so much capacity to keep up with the new developments made every day. In this final chapter of my dissertation, I aim to make a brief and digestible introduction to solid-state materials chemistry, from the basics of crystals and semiconductors to snapshots of ongoing research in the field, centered on my experience in designing emerging materials known as metal halide perovskites. This chapter is specifically dedicated to those who are curious to learn more about the underlying materials chemistry making many exciting recent technologies possible, but are stretched too thin to fully delve into the subject. With the writing below, I hope that those of us *in a hurry* may not only find a newfound appreciation for materials chemistry and new materials like perovskites, but also develop new curiosities on how and why the different materials in our lives behave the way they do.

6.2. Everything is Made of Something

“Everything is made of something” is a famous saying in the fields of materials chemistry and materials science. As obvious as it may be, there is a simple truth to it – that all matter we interact with has some distinct composition responsible for its properties. A major component of

current materials research is how different solids, whether crystals, plastics, glasses, ceramics, etc., could be designed or engineered at the atomic, nano, and micro scales to behave in desirable ways. Sometimes our research questions arise out of necessity, and other times, curiosity. For example, how could we design a new semiconductor that could emit bright and color-pure blue light? This invention of the blue LED based on gallium nitride (GaN) was recognized with the 2014 Nobel Prize in Physics. Or conversely, could there be a material capable of selectively capturing CO₂ from polluted air, or other materials that are capable of spontaneously capturing water from dry desert air? Metal organic frameworks (MOFs), which were recognized with the Nobel Prize in Chemistry just last year, could do just that. Materials chemistry offers unique and creative solutions to modern challenges and demands.

In my research as a *solid-state materials chemist*, my curiosities lie in how new crystalline materials can be synthesized and how their crystal structures could be designed at the atomic level to alter or enhance their fundamental behaviors. In my dissertation, I focus on an emerging class of semiconductors known as *metal halide perovskites* and how deliberate and systematic changes to their crystal structures could lead to enhanced capabilities for better solar cells, LEDs, and beyond. But before we delve into research on the new, let us first approach solid-state chemistry from its roots: What are crystals? And what is a semiconductor?

What are crystals? When you think of an example of a crystal, chances are that quartz or amethyst are the first ones that come to mind. Let's look at how glass, quartz, and amethyst compare to one another. Each is comprised primarily of the elements silicon and oxygen, and each has the same general chemical formula, SiO₂. However, not all of these materials are crystalline. The precise nature of what atoms are present and how they are arranged (see Figure 6.1) dictates their very different appearances and properties. Glass has an *amorphous* structure, where the

silicon and oxygen atoms do not have a pre-defined arrangement. In contrast, quartz and amethyst have specific arrangements of their silicon and oxygen atoms, thus making them *crystals*.

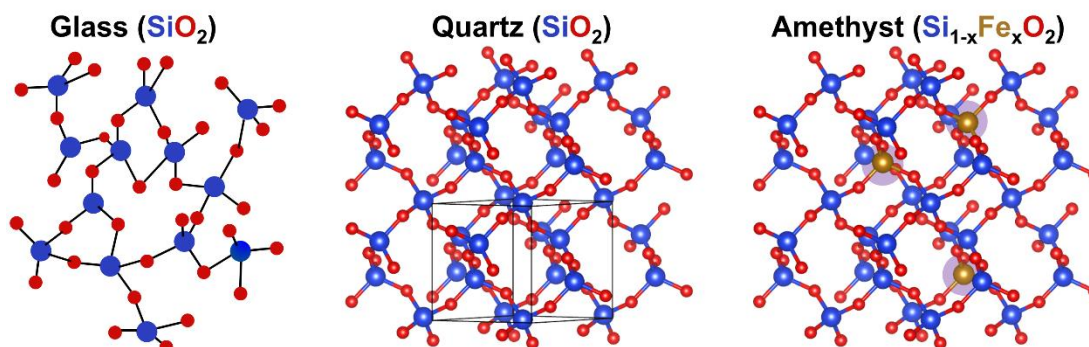


Figure 6.1. Amorphous structure of glass featuring random and disorganized orientations of the silicon (blue) and oxygen (red) atoms. In contrast, the crystal structures of quartz and amethyst are highly ordered, and the atomic positions are well-defined and predictable. The box in the quartz structure shows one unit cell showing its smallest repeating structural unit that can repeat itself in all three dimensions.

Crystals are solid-state materials that have ordered and well-defined arrangements of specific atoms. A crystal of table salt will exhibit the exact same sodium (Na) and chlorine (Cl) atoms in the same exact arrangement, regardless of where it came from. Different crystalline materials can be made up of different elements, exhibit different arrangements, or both. But fundamentally, all crystals can be described by their *unit cell*, the smallest structural unit of specifically arranged atoms that can be repeated on itself in all three dimensions. The unit cell sizes vary between materials, but they are generally on the order of Angstroms (Å) in each dimension (one Å is 10^{-10} m, or one ten-billionth of a meter). Thus, the unit cell repeats itself millions of times over to give us the large crystals that we observe with our naked eyes.

Notably, quartz and amethyst exhibit the exact same crystal structure, yet differ only in the presence of Fe^{3+} (iron(III)) impurities. It is these impurities, or *defects*, that give amethyst its distinct and well-adored purple hue. As it turns out, having pure and highly crystalline materials is very appealing for many applications, however the defects in crystals can give materials further “character” and further tunability of their optical or electronic behaviors. These considerations play a major role in the applications of semiconductors, which leads us to our next subject...

What is a semiconductor? As a second exercise, let’s compare the crystal structures of diamond, silicon, and gallium nitride (Figure 6.2, top). You may notice that diamond and silicon exhibit the exact same arrangement of atoms in their crystal structure, and differ only in their carbon-based versus silicon-based composition, while gallium nitride exhibits a slightly more complex crystal structure with a two-atom basis. What then, is responsible for their differences in properties, especially between diamond and silicon?

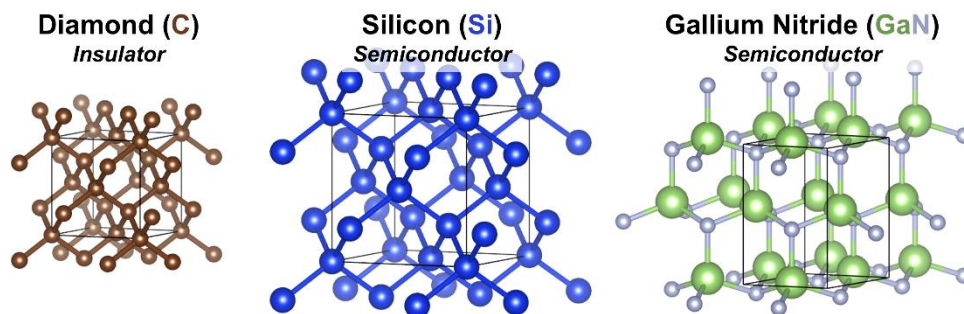


Figure 6.2. Crystal structures of diamond, silicon, and gallium nitride. The brown, blue, green, and gray atoms represent C, Si, Ga, and N, respectively. The specific elements and their bonding arrangements with the crystal structure dictate their overall properties.

The *electronic structure* of a material reflects the possible electronic energy states that arise due to how the different atoms interact with one another. In diamond, the electrons are shared

between neighboring carbon atoms to form tight covalent bonds, which leaves no free electrons to move throughout the material. Therefore, diamond is an electronic *insulator*. In contrast, the electrons in pure metals are not so strongly bound to their atoms, making them *conductors* that can readily transport electricity. Both Si and GaN are *semiconductors*, meaning they both possess unfilled electronic energy levels that are in the accessible range to interact with light and electricity in interesting and meaningful ways. The specialty of semiconductors is their electronic states put them in an intermediate regime between insulators and conductors, where they can conduct electricity but only under the right conditions.

This unique ability of semiconductors to selectively store and pass charge only under applied conditions is precisely what has enabled their success as versatile materials: *Solar cells* can harvest energy from light when their electrons are excited from their low energy states to their high energy states. *Light-emitting diodes* (LEDs), emit light when electricity is passed through the semiconductor and the electrons relax from the high energy states to the low energy states (in some sense, the opposite of a solar cell). *Transistors* in our phones and computers can store information as “0” or “1” depending on whether electricity is allowed to flow through the semiconductor.

A defining trait of semiconductors is their *bandgap*, the energy difference between their high and low energy states. The bandgap dictates the manner in which different semiconductors can interact with light and electricity. Silicon, for instance, has a bandgap of 1.1 eV (electron-volts), which allows it to readily interact with most visible light wavelengths emitted by the sun – perfect for energy harvesting applications as solar cells. On the other hand, GaN has a bandgap of 3.4 eV, which limits its interactions to high-energy (i.e. blue and UV) light only. As such, GaN would make a mediocre solar cell, but it is an excellent blue-light emitter for LED applications.

Different materials are good at different things, and very few materials are a “jack of all trades”. With these examples above, I hope that it is now evident how distinct arrangements and combinations of different elements within a crystal provide very diverse and distinct materials that each have their own unique properties and appearances. Now, you can imagine, with a periodic table of 118 elements (though many are radioactive and non-existent in natural settings) and further permutations of different carbon-based molecules that could also be incorporated into crystal structures, there is a nearly endless supply of new materials waiting to be discovered, researched, and understood. As a materials chemist, the elements are our paints, our synthetic and analytical techniques are our brushes, and the world is our canvas. This is why I really enjoy my research as a materials chemist: beyond serving as a means to address modern challenges, materials chemistry is also an inherently creative and artistic field with a seemingly endless playground of new toys to explore, design, and contemplate.

6.3. Metal Halide Perovskites as New “Stovetop” Semiconductors

At multiple times every year, the National Laboratory of the Rockies (formerly, the National Renewable Energy Laboratory) releases an updated solar cell efficiency chart highlighting the record efficiencies of different semiconductor materials.² If we focus primarily on the superstar solar materials boasting over 27.0% solar power conversion efficiency, two materials stand out. Silicon, which has been researched and developed for over 50 years, and *metal halide perovskites* (colloquially, just “perovskites”), which have only recently emerged as high-performance semiconductors yet have rapidly caught up to silicon-level efficiency (Figure 6.3, left). While “beating” silicon can be a feat of its own, a major appeal of perovskites is their additional and unusual benefits that are not observed in most semiconductor materials.

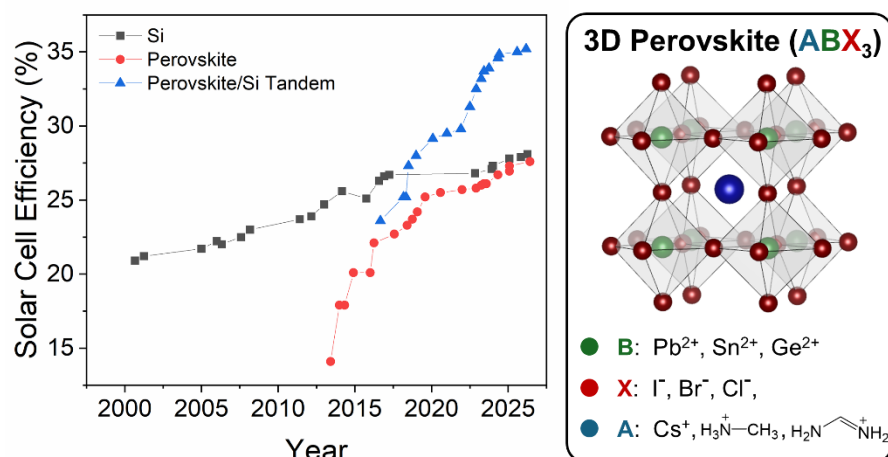


Figure 6.3. Record solar cell power conversion efficiencies for silicon, perovskite, and perovskite/Si tandem solar cells since the year 2000 (left). The crystal structure of a three-dimensional (3D) metal halide perovskite is shown, with its common ABX₃ components (right).

First, the multicomponent perovskite crystal structure readily allows different elements to be swapped out and adapted to alter the material properties. The perovskite structure is defined as a network of metal and halide (ex. iodide, bromide, chloride) ions that form a small “cage” for a small cation to reside (see Figure 6.3, right). Similar to how table salt, NaCl, is composed of positively charged Na⁺ and negatively charged Cl⁻ ions that have lost electrons (i.e. cations) or gained electrons (i.e. anions), metal halide perovskites are also ionic. The “oxidation state” of each element reflects how many electrons it has gained or lost compared to its neutral state.

Within the ABX₃ perovskite structure, and “A” is a smaller positively charged +1 cation, such as cesium, methylammonium, or formamidinium, “B” represents a metal in the +2 oxidation state, “X” is a halide anion (like chloride, bromide, or iodide) in the -1 state (see Figure 6.3, right). The ease of tunability of halide perovskites in “mixing and matching” different structural components to obtain desirable bandgaps and other behaviors allows them to be readily adapted

for versatile applications: solar cells, LEDs, transistors, and even quantum materials. A recent triumph for perovskites is their international commercialization in *tandem solar cells*, which consist of two different semiconductors that can respectively absorb wavelengths (or colors) of light that its partner semiconductor misses.

Another major benefit of metal halide perovskites is that their ionic crystal structures make them *solution processable*, allowing perovskite crystals to be easily grown under mild conditions. This contrasts greatly from silicon, which requires carefully-controlled crystallization at 1500 °C to form large, perfectly crystalline silicon ingots with minimal defects. The conditions to grow a halide perovskite crystal are in fact so mild that, in principle, you could do it on a stovetop; though I would strongly discourage this, as you will find shortly. The various components of the perovskite structure, for example, Pb^{2+} , I, and formamidinium (FA), are also earth-abundant and cost-effective. These qualities – structural tunability, versatility, solution-processability, and cost efficiency – make it very apparent why metal halide perovskites have rapidly emerged as a highly competitive semiconductor.

Among the possible 3D perovskite compositions, lead (Pb) halide perovskites such as $(\text{FA})\text{PbI}_3$ have quickly risen to the forefront of research and development into various technologies, raising some toxicity concerns. For eventual applications, this requires robust and resilient devices with casings and encapsulants that could limit or entirely prevent leaching of Pb into the environment. While our electronic devices already have various toxic metals, such as cadmium (Cd) or arsenic (As), this does beg the question: Could we produce equally high-performing perovskites using non-toxic metals aside from Pb? This is a hot topic in the field of halide perovskites, and has been the focus of my Ph.D. research.

6.4. Tin Halide Perovskites – Designing Materials That Don’t Want to Exist

High-performance alternatives to lead halide perovskites are indeed possible, but introduce new challenges of their own. If we think about what other +2 metals could substitute for lead to form a viable perovskite network, the immediate neighbors above lead on the periodic table, tin (Sn) and germanium (Ge), come to mind. Conversely, it is possible to substitute a +2 metal for a 1-to-1 mixture of a +1 metal and a +3 metal in “double-perovskites”, and thus mixed silver (Ag)/bismuth (Bi) perovskites also provide an option. Few other +2 metals could also form perovskite networks, such as copper (Cu) or manganese (Mn), but these no longer behave as semiconductors and are instead more interesting as magnetic materials. So, this leaves three major options to consider for semiconducting perovskites that could compete with lead perovskites.

Among these options, tin halide perovskites offer the most promise towards replacing lead. Compared to lead perovskites that exhibit a smallest possible bandgap of ~ 1.5 eV, tin perovskites offer even narrower bandgaps of 1.3 – 1.4 eV that are closer to those of silicon and are ideal for solar applications.³ Moreover, the optical properties of tin perovskites are less mediated by defects, unlike lead perovskites.⁴ With these advantages, you would expect that tin perovskites should already outperform lead perovskites as solar cell materials, yet they have not: the best performing tin perovskites solar cells have only recently surpassed 17% efficiency, compared to over 27% in lead perovskites. This is because, unlike Pb^{2+} which is fairly stable in the +2 oxidation state, Sn^{2+} is more likely to interact with oxygen and subsequently oxidize (i.e. lose more electrons) and convert into Sn^{4+} over time. With this air sensitivity, tin perovskites not only degrade into various byproducts such as tin oxide (SnO_2) over time, but their semiconducting behavior is also lost. As you can imagine, this is not great for a solar cell or any other device. But luckily, materials chemistry offers us creative solutions.

How do we go about designing a material that would prefer to oxidize and would rather not exist under ambient conditions? We have done it before: Iron (Fe) reacts with oxygen and forms rust (Fe_2O_3) over time, but the introduction of other elements into its crystal structure (i.e. **alloying**), such as carbon, to form steel makes the material stronger and more resilient to oxygen. With tin perovskites, instead of substituting elements into the perovskite structure to better protect the air-sensitive Sn^{2+} centers (which would alter the semiconducting properties like bandgap), reducing the **dimensionality** of the 3D perovskite network into layered 2D structures using large hydrocarbon molecules is arguably one of the best avenues (Figure 6.4, top). The large organic molecules, called **spacer cations**, template the perovskite network into individual layers (hence 2D) and provide perovskites with some degree of **hydrophobicity**, or water-repelling character.

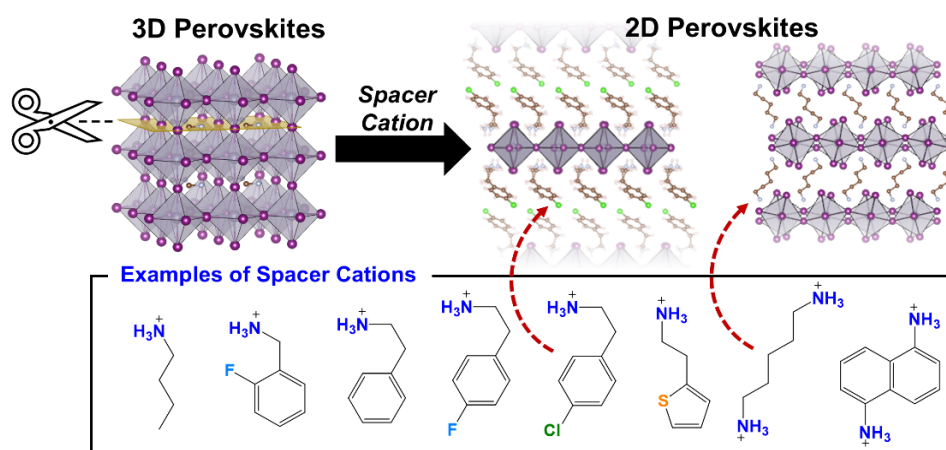


Figure 6.4. Schematic of the dimensional reduction of 3D perovskites into layered 2D perovskites by introducing large organic “spacer cation” molecules (top). 2D tin perovskites have the general formulae $(\text{LA})_2\text{SnI}_4$ or $(\text{LA})\text{SnI}_4$, where LA represents the large spacer cation. Spacer cations with various shapes, sizes, and functionalities can form 2D perovskites, but all spacer cations always have one or two positively charged nitrogen (N) atoms that interact and balance out the negatively charged perovskite network (bottom).

A wide variety of spacer cations can successfully template the perovskite network and form viable 2D structures, but the way in which they interact, protect, or potentially distort the 2D perovskite layers are entirely dependent on the molecular structure of the spacer cation (Figure 6.4, bottom). How do these different molecules impact the crystal lattice of tin perovskites? And how can we find the best spacer cations to protect tin perovskites and minimize distortion simultaneously? These multifaceted questions have driven multiple research projects of mine over the past five years, two of which I have distilled into their essentials for materials design, below.

As a baseline, the most commonly researched 2D perovskites are those based on the phenethylammonium (PEA) spacer cation, which enables minimal distortion, enhanced air stability, and enhanced light-emitting and light-harvesting capabilities. However, even (PEA)₂SnI₄ tin perovskites degrade over just a few weeks in air, meaning new spacer cations need to be considered. When I first entered the field in 2021, few studies had uncovered spacer cations that limit oxidation to a greater extent than PEA, and worse yet, the general features of the spacer cations that could lead to high air stability in tin perovskites were not well understood. Could very long spacer cations better shield tin perovskites from oxygen, or perhaps wider ones could behave better? This lack of understanding provided an open window to explore new tin perovskites and develop insights for how to best design them for high air stability.

In order to establish what molecular features of spacer cations could best protect tin perovskites from air degradation, comparisons of different 2D tin perovskites with various spacer cations are required. To do this, I synthesized 2D tin perovskites by heating up precursor salts of Sn²⁺ and the different spacer cations in acidic water-based solutions and cooling them down back to room temperature to produce crystalline 2D perovskite (in some sense, the process is very similar to how “rock candy” is made by cooling supersaturated solutions of sugar). By allowing

the different 2D tin perovskites to age in air over time and comparing their relative rates of degradation, I found that several different spacer cation features could enable greater stability than PEA. In some cases, “decorating” the spacer cations with additional atoms (such as F or Cl) led to improved air stability. In other cases, using larger molecules led to improved stability. Meanwhile, shorter and “flimsy” spacer cations were already known to produce even poorer air stability in 2D tin perovskites. Each of these cases share a common theme: the density, or tightness, of the spacer cation packing strongly controls the rate of air degradation (Figure 6.5, left).⁵ This finding was very intuitive – better coverage and denser packing by the spacer cations produce stronger barriers that can inhibit the attack of O₂ and H₂O on the air sensitive perovskite network.

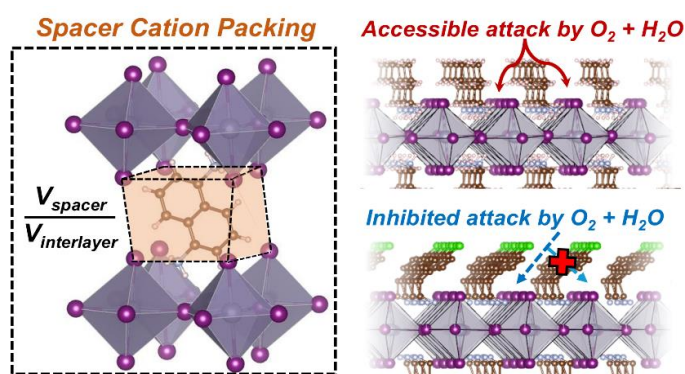


Figure 6.5. Schematic of tight spacer cation packing and its relation to limiting oxygen and water induced degradation of air sensitive 2D tin perovskites.

An unintended side effect of this design strategy for high air stability was that, in many cases, the use of these protective spacer cations also harmed the light-harvesting and light-emitting capabilities due to distortion of the tin perovskite network. This is not great for potential solar cell applications. On one hand, we have high-performance semiconductors that degrade quickly, and on the other, we have highly air stable semiconductors but with poor performance. Therefore, the next obvious step was to try to design tin perovskites that could simultaneously enable excellent

air stability and light-harvesting capabilities. But this was much easier said than done, as now a singular spacer cation needs to serve two roles at once.

Sometimes we need to ask ourselves, “Why reinvent the wheel?” If the PEA spacer cation is already quite effective at enabling excellent light-harvesting capabilities in tin perovskites, then how about making slight modifications to the PEA structure to further enhance its protective capability? To investigate this, I synthesized new 2D tin perovskites using functionalized PEA spacer cations with different halogen atoms (such as fluorine, chlorine, etc.) decorated onto the molecule, which thankfully, due to the wonders of well-established organic chemistry, were commercially available compounds. To our surprise, different halogen atoms decorating the spacer cations produced incredible differences towards the resultant air stability of tin perovskites. With this very simple modification, I found that a new 2D tin perovskite, $(4\text{ClPEA})_2\text{SnI}_4$, maintained its excellent properties for several months in air, compared to the previous “champion” $(\text{PEA})_2\text{SnI}_4$ that degraded within one week (see snapshot in Figure 6.6, left). In relating this excellent stability back to the crystal structures of $(\text{PEA})_2\text{SnI}_4$ and different $(4\text{XPEA})_2\text{SnI}_4$ (where $\text{X} = \text{F}, \text{Cl}, \text{Br}$), chlorine indeed enabled the tightest packing and strongest repulsion of O_2 and H_2O . For me, this was a breakthrough moment in working with these exciting lead-free materials, which have been generally assumed to be too air sensitive to serve as a viable semiconductor.

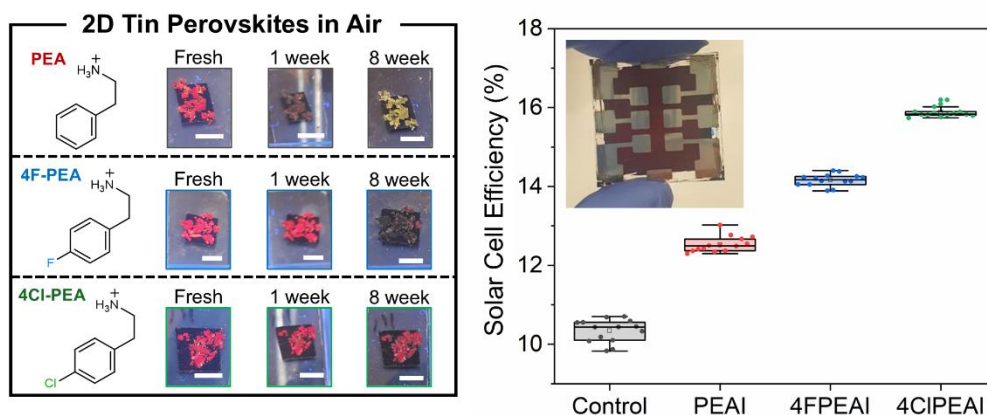


Figure 6.6. Experiment exposing crystals of 2D tin perovskites with different spacer cations (PEA, 4FPEA, 4CIPEA) to air over time (left; white scale bars are 0.5 cm). Degradation of the $(\text{PEA})_2\text{SnI}_4$ crystals is evident after only 1 week, as shown with the color change, but 4FPEA and 4CIPEA enable even greater stability. By incorporating these effective spacer cations into 2D/3D tin perovskite solar cells with ~ 1.4 eV bandgaps, dramatic improvements to efficiency and stability are observed (right). The inset shows an example of a laboratory-scale tin perovskite solar cell.

Driven by the superior air stability enabled by 4CIPEA, I pursued the fabrication of mixed 2D/3D tin perovskite solar cells in collaboration with experts at the National Laboratory of the Rockies. In measuring the efficiency and stability of mixed 2D/3D tin perovskite solar cells with the different spacer cations using a solar simulator (see Figure 6.6, right), we found that 4CIPEA not only enabled record air stability, but it also dramatically enhanced the perovskite layer crystallinity and power conversion efficiency compared to the other spacer cations. With this exciting demonstration,⁶ I am hopeful my work with my colleagues marks a major turning point in perovskite photovoltaics, where lead-free compositions will continue to become more stable, efficient, and eventually rival lead-based perovskite solar cells. But the beauty of materials chemistry is that the design insights uncovered in my works are transferrable, not only towards alternative applications of stable tin perovskites (i.e. quantum devices), but also potentially towards different classes of materials entirely.

6.5. Outlook to the Future of Materials Chemistry

Here I have shown just a few examples of what is possible with solid-state materials chemistry – in how crystal structures could inform material properties, and how systematic crystal

structure design could lead to enhanced performance in targeted applications. All materials we interact with have undergone similar chemical and crystal structure optimizations to reach their full potential, and all future materials we will ever interact with will undergo the same. Perovskite semiconductors are just one class of emerging solid-state materials that will continue to be deployed in society as we improve their materials design, and countless other materials will follow suit for diverse applications. Let's briefly consider some of these other possibilities.

Rechargeable batteries, for instance, rely on the free movement of active ions in and out of their parent lattices. In lithium battery materials, such as lithium cobalt oxide (LiCoO_2 , or just "LCO"), lithium ions are free to leave and re-enter the crystal lattice upon charging and discharging the battery. Could we design better materials that could potentially exhibit greater porosity to store lithium and thus enable greater charge capacities using less space?⁷ Conversely, could we design alternative battery materials that could store charge using other ions that are cheaper and more abundant than Li^+ , such as Na^+ or Mg^{2+} ?⁸ Each of these developments could allow batteries in electronics (and electric vehicles) to last much longer or be produced for much cheaper.

Other emerging materials like metal-organic frameworks (MOFs) are capable of capturing and storing CO_2 from air. But so far there are few materials that could also "activate" CO_2 and convert it into value-added chemicals. In fact, metallic copper is one of the best materials that could "force" CO_2 to react, but with poor product selectivity: a range of different carbon compounds can form, including carbon monoxide. Could we find even better materials that could form different carbon products with greater selectivity? Through such developments, CO_2 capture would not only be appealing for decarbonization of the atmosphere, but would also be greatly bolstered by the simultaneous production of value-added chemicals.⁹

The prospect of finding room-temperature and ambient-pressure superconductors (not to be confused with semiconductors) that can transfer electricity with zero resistance is also very tantalizing. Such superconductors would not only revolutionize modern electronics, but also exhibit unique phenomena, like magnetic levitation, that could be leveraged for new means of transportation. Over the decades, we have found many materials that could superconduct at liquid nitrogen temperatures ($-196\text{ }^{\circ}\text{C}$, or $-321\text{ }^{\circ}\text{F}$),^{10,11} but none that could maintain superconductivity in ambient conditions. The discovery of a room-temperature superconductor would change the world in unimaginable ways, just as the semiconductor has over the past decades.

There is still much to explore and many discoveries of new materials yet to be had. I very much look forward to exploring these new material playgrounds, and I hope that my readers also will too, either vicariously by keeping up to date with new scientific developments, or if I am especially successful, perhaps directly, in jumping into the unknown with me.

6.6. Afterword and Acknowledgements

This chapter was supported by the Wisconsin Initiative for Science Literacy, and was inspired by works by Dr. Neil deGrasse Tyson and the late Dr. Carl Sagan. Science is for everyone, and everyone can be a scientist. It is important for us to stay curious and informed, and it is especially important for scientists to communicate new developments in digestible ways for all to appreciate. My first thanks go to the reader, to whom I have dedicated this writing. Public knowledge and support for science are major driving forces for new innovations. By staying curious and dedicated to our science, the truths that mother nature offers us await our discovery. I also thank Elizabeth Reynolds and Dr. Ilia Guzei for their editorial revisions, and to Cayce Osborne and Prof. Bassam Shakhashiri for their support towards the dissemination of this work.

6.7. References

1. Padavic-Callaghan, K. *Nobel prizewinner Omar Yaghi says his invention will change the world*. NewScientist. <https://www.newscientist.com/article/2511141-nobel-prizewinner-omar-yaghi-says-his-invention-will-change-the-world/> (accessed 2026-05-31).
2. National Laboratory of the Rockies. *Best Research-Cell Efficiency Chart*. <https://www.nlr.gov/pv/cell-efficiency> (accessed 2026-06-25).
3. Shockley, W.; Queisser, H. J. Detailed Balance Limit of Efficiency of p-n Junction Solar Cells. *J. Appl. Phys.* **1961**, 32 (3), 510–519. <https://doi.org/10.1063/1.1736034>.
4. Mihalyi-Koch, W.; Folpini, G.; Roy, C. R.; Kaiser, W.; Wu, C.-S.; Sanders, K. M.; Guzei, I. A.; Wright, J. C.; De Angelis, F.; Cortecchia, D.; Petrozza, A.; Jin, S. Tuning Structure and Excitonic Properties of 2D Ruddlesden–Popper Germanium, Tin, and Lead Iodide Perovskites via Interplay between Cations. *J. Am. Chem. Soc.* **2023**. <https://doi.org/10.1021/jacs.3c09793>.
5. Triggs, C. T.; Ross, R. D.; Mihalyi-Koch, W.; Clewett, C. F. M.; Sanders, K. M.; Guzei, I. A.; Jin, S. Spacer Cation Design Motifs for Enhanced Air Stability in Lead-Free 2D Tin Halide Perovskites. *ACS Energy Lett.* **2024**, 1835–1843. <https://doi.org/10.1021/acsenergylett.4c00615>.
6. Triggs, C. T.; Chen, L.; Xie, J.; Weadock, N. J.; Zhang, Z.; Ye, J. Y.; Kerner, R. A.; Taddei, M.; Yang, F.; Addison, B.; Wang, X.; Liu, T.; Harvey, S. P.; Toney, M. F.; Beard, M. C.; Yan, Y.; Zhu, K.; Jin, S. Spacer Cation Chlorination Enables Stable 2D/3D Tin Iodide Perovskite Photovoltaics. *Manuscript in second revision in Nature Mater.*
7. Manthiram, A. A Reflection on Lithium-Ion Battery Cathode Chemistry. *Nat. Commun.* **2020**, 11, 1550. <https://doi.org/10.1038/s41467-020-15355-0>.
8. Yabuuchi, N.; Kubota, K.; Dahbi, M.; Komaba, S. Research Development on Sodium-Ion Batteries. *Chem. Rev.* **2014**, 114 (23), 11636–11682. <https://doi.org/10.1021/cr500192f>.
9. Nitopi, S.; Bertheussen, E.; Scott, S. B.; Liu, X.; Engstfeld, A. K.; Horch, S.; Seger, B.; Stephens, I. E. L.; Chan, K.; Hahn, C.; Nørskov, J. K.; Jaramillo, T. F.; Chorkendorff, I. Progress and Perspectives of Electrochemical CO₂ Reduction on Copper in Aqueous Electrolyte. *Chem. Rev.* **2019**, 119 (12), 7610–7672. <https://doi.org/10.1021/acs.chemrev.8b00705>.
10. Bednorz, J. G.; Müller, K. A. Condensed Possible High T_c Superconductivity in the Ba-La-Cu-O System. *Z. Phys. B. Condens. Mat.* **1986**, 64, 189–193. <https://doi.org/10.1007/BF01303701>.
11. Sun, H.; Huo, M.; Hu, X.; Li, J.; Liu, Z.; Han, Y.; Tang, L.; Mao, Z.; Yang, P.; Wang, B.; Cheng, J.; Yao, D. X.; Zhang, G. M.; Wang, M. Signatures of Superconductivity near 80 K in a Nickelate under High Pressure. *Nature* **2023**, 621 (7979), 493–498. <https://doi.org/10.1038/s41586-023-06408-7>.