

7th Annual Non-Volatile Memories Workshop 2016

March 6-8, 2016

Non-Volatile Computer Memory: Other Dimensions, Other Domains

By Tiffany Fox

QUALCOMM Institute

San Diego, Calif., March 31, 2016 — Some sources estimate that by 2025, the total amount of information generated and stored by the world's computing devices will be upwards of 3.7 zettabytes.

To conceptualize zettabytes, think of them this way: If the 11-ounce cup of coffee on your desk is the equivalent of one gigabyte, one zettabyte would have the same volume as the Great Wall of China. And in this case, we're talking 3.7 Great Walls of China.

Another way to look at it: The amount of data we're about to dump into cyberspace is the equivalent of Netflix streaming its entire catalog of movies simultaneously to almost 10 million users. That's a lot of bits. A global tsunami of bits. And the "Internet of Things" has barely gotten started.

Against this backdrop of intense digital desire and demand, computer engineers in both industry and academia find themselves on a seemingly never-ending quest to develop novel ways to store and retrieve all that data quickly, reliably, and on the cheap.

It's no surprise, then, that the 7th annual Non-Volatile Memories workshop at the University of California, San Diego elicited the interest of more than 185 researchers from around the world, representing both academia and industry. They were there to hear where things might be headed for non-volatile computer memory, or NVM, in a world where bigger, better, faster and stronger are not just the goal, but the expectation.

NVMs are crucial components of modern computing systems — components that make it possible to store increasingly large amounts of information in smaller spaces, at faster data transfer speeds and at lower cost to the consumer. NVM, in its most basic sense, is what makes it possible for you to turn off your computer (or unplug your flash drive, a form of NVM) and have it still 'remember' the last draft of the novel you've been working on. It's also relatively low-power, boasts fast random access speed and is known for being rugged since it doesn't require a spinning disk or other moving mechanical parts.



More than 185 researchers from around the world, representing both academia and industry, attended the 7th annual Non-Volatile Memories Workshop to hear where things might be headed for non-volatile computer memory. Photos by Alex Matthews and Joel Polizzi for the Qualcomm Institute. For more photos, [click here](#).

In This Issue

- NVMW 2016 (P.1-3)
- Passing of Professor Ami E. Berkowitz (P.1)
- Director's Letter (P.4)
- Graduating Students & Summer Internships (P. 4)
- Research Highlight (P. 5-6)
- New CMRR Researchers (P. 7)
- Honors & Awards (P. 8)
- Selected Papers (P.8)

But even if there were no disks spinning at NVMW this year, there were certainly heads spinning. The workshop featured a full three days of talks on advances that have not only made it possible to store data in three dimensions, but also inside an entirely new material: strands of DNA.

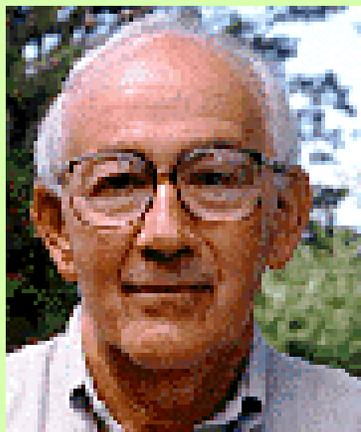
Another day, another dimension

Although NVMs have been a field of active research for decades, engineers always make room for improvement, which explains the conference-goers' excitement about rumors that a representative from Intel would provide an inside look at a groundbreaking method for storing data.

The rumor, it turns out, was true: In a talk called "Wicked Fast Storage and Beyond," Frank Hady, an Intel Fellow in Intel Corporation's Non-Volatile Memory Solutions Group, made a case for why Intel's 3D XPoint Technology -- which stores data in three dimensions in an entirely new way -- could transform the industry.

Article continued on page 2

Passing of CMRR's Professor Ami Berkowitz



CMRR would like to pay tribute to Professor Ami E. Berkowitz who passed away on March 31, 2016. Professor Berkowitz was well respected among all peers and students. His dedication to CMRR was astonishing as he spent hours at the office helping his students and encouraging them to make their dreams come true. Ami was greatly devoted to his career and UCSD as a whole. Even when his health began to decline he continued to work to uncover novel phenomena in nanoscale materials. In 1986, he came to UCSD as an Endowed Chair Professor in the Physics Department and CMRR to establish a materials group. In his lifetime, he published extensively in the scientific and patent literature. Over the years, he gave many invited talks and has been twice appointed a Distinguished Lecturer for the IEEE Magnetics Society. Professor Berkowitz will always be remembered for his wonderful contributions to the scientific world.



Frank Hady, an Intel Fellow and Chief Architect of 3D XPoint Storage.

3D XPoint (pronounced “3D crosspoint”) derives its name from its structure, which incorporates layers of memory stacked in a crosshatch pattern in three dimensions and makes it possible to pack an array of memory cells at a density 10 times that of conventional NAND memory, an industry standard in solid-state memory.

Notably, the memory element in 3D XPoint doesn’t include a transistor for switching electrical signals: instead, the memory cells are comprised of a material that changes the cell’s physical properties, giving it either a high or low electrical resistance, representing the 1s and 0s of binary code. No transistor means the memory can be made very dense -- specifically, 8 to 10 times greater than DRAM, a type of random-access memory that stores each bit of data in a separate cell.

Contrast 3D XPoint with NAND, which works by shifting electrons to either side of a “floating gate” to change from 1 to 0 and back. The problem with NAND memory is that to rewrite one cell, a computer has to rewrite an entire block of cells, which slows down the process. 3D Xpoint makes it possible to both read and write, on each individual cell, at the byte level.

This capability greatly impacts processing speed: 3D Xpoint has a data rate of 77K Input/Output Operations Per Second (IOPS) compared to NAND’s data rate of 11K IOPS. NAND is also a 2D technology, and one less dimension means that much less density, which can adversely affect overall device size.

Paul Siegel is a professor of Electrical Computing and Engineering at UC San Diego and past director of the Center for Memory and Recording Research (CMRR, formerly the Center for Magnetic Recording Research), a co-sponsor of the workshop. “3D storage eases the pressure to make the memory component smaller,” said Siegel. “You can pack the bits more efficiently, because now you have a cube to work with instead of just a flat plane.”

Hady, the chief architect of the technology, noted that the unique design of 3D XPoint also makes it tough to beat in terms of latency, or the time between IOPS. Acknowledging that latency has long been a thorn in the side of systems engineers, Hady cited an anonymous saying from the world of networking: “Bandwidth problems can be cured with money. Latency problems are harder because the speed of light is fixed. You can’t bribe God.”

But that doesn’t mean there aren’t ways to work around the limitations of the universe.

“3D XPoint has a 12x latency advantage and that’s why I’m calling it wicked fast,” he added. “Because of this low latency, performance shoots up very quickly, and you will see that kind of performance increase as you run your apps.

“Every three decades or so, we see a leap in latency that makes a huge impact on the system,” he continued. “The really neat thing is we’re about to make that three orders of magnitude jump again. The memory guys are now kind of where the networking guys have been -- for the first time in decades, there’s a reason to go tune the system.”

Referring to the technology as a “fertile systems research area,” Hady -- who was visibly excited throughout his presentation -- claimed it will pave the way for “rethinking applications for big improvements”

“If you are a systems grad student, you picked a good time,” he said. “You don’t always have these technological shifts to base your research on and you have one now.”

As for how “high-performance” 3D XPoint is, only time will tell. No 3D XPoint devices have been independently tested for bit-error rates, but a paper presented at NVMW by Jian Xu and Steven Swanson of the UC San Diego Department of Computer Science and Engineering concludes that there are a number of integration issues with “managing, accessing, and maintaining consistency for data stored in NVM.”

For one, existing file systems won’t be able to take advantage of 3D NVM technology until new software can be written and the system re-engineered. Xu and Swanson, who is co-director of the Non-Volatile Systems Lab (NVSL), a co-sponsor of the workshop, propose in their paper that 3D NVMs like 3D XPoint be used in conjunction with DRAM solid-state drives rather than as replacements for flash SSDs.

Hady seemed to agree that DRAM isn’t going anywhere. When an audience member asked if it would replace NAND flash, he replied “I think there’s a long life for both.” And as for cost, because 3D XPoint is proprietary, Hady couldn’t reveal much other than to say it will be “somewhere between DRAM and NAND.”

Taking Data’s Temperature

Intel isn’t the only company working at the forefront of 3D memory -- Toshiba is another major player in the global effort to cope with the world’s data tsunami.

In his NVMW keynote address entitled “Advances in 3D Memory: High Performance, High Density Capability for Hyperscale, Cloud Storage Applications, and Beyond,” Jeff Ohshima, a member of the Semiconductor and Storage Products executive team at Toshiba Corporation, discussed three new technologies in the works at Toshiba (which, along with Western Digital, Huawei, Samsung, Intel and several other corporations, is a corporate sponsor of the workshop).

The trio of technologies described in his talk are designed to “fit into a hierarchy of bits,” Ohshima explained -- a hierarchy made ever more complex by the sheer volume of data being generated by server farms, datacenters and smartphones.



Prof. Paul Siegel, professor of Electrical Computing and Engineering at UC San Diego.



Jeff Ohshima, member of the Semiconductor and Storage Products executive team at Toshiba Corporation.

Fortunately, not all of the data is being used all the time. Engineers refer to bits as being either “hot,” “warm” or “cold,” meaning hot bits (data in active use) are typically stored in a computer’s DRAM or MRAM (types of random-access memory) to allow for fast retrieval, while warm bits (less frequently accessed bits) are stored in a high-performance solid-state drive (SSD) and cool bits are stored in an archival SSD.

For so-called “warm data” Toshiba last year developed a form of NAND flash memory using a technology called Through Silicon Via (TSV), which achieves an input-output data rate of over 1 Gbps. That’s higher than any other NAND flash memory and also reduces power consumption by approximately 50 percent with low voltage supply.

Toshiba has also developed its own version of 3D NVM called BiCS Flash, so-called for the technology’s “bit column stackable” design. BiCS Flash was first introduced in 2007, but the newest generation device features the triple-level cell, or TLC, technology, which makes it possible to store three bits per cell.

As if solid-state drive development wasn’t fast and furious enough, Ohshima also pointed out Toshiba’s solution for storing cool data: Quadruple Level Cell or QLC, which is capable of storing four bits per cell. QLC and other technologies are expected to drastically increase SSD drive size in the near future, resulting in capacities of up to 128 terabytes by 2018.

But even with bigger, denser drives, Ohshima notes that all of the existing storage media represent only a third of what’s needed in the coming decade to store the aforementioned 3.7 zettabytes of data expected to saturate cyberspace. Imagine a warehouse stacked to the rafters with 250 billion DVDs (that’s billion with a ‘b’), add 2.7 identical warehouses and maybe you get some idea for why engineers are so excited about storing more bits per cell, and in an extra dimension.

“The emergence of these 3D technologies across the storage industry represents a significant inflection point in the trajectory of computer memory capabilities,” said Siegel, who works on modulation and error-correction coding techniques, or algorithms that modify the information before storing it in order to help prevent, detect and fix errors that might occur when the information is retrieved from the memory. “They are driving new paradigms in computing system architecture and sparking the invention of entirely new data encoding and management techniques.”

But what if bits and cells and disks and drives weren’t the only way to go about storing data? What if data could be stored in an entirely new way, a way that might change the world of computing as we know it?

The DNA Domain

When it comes down to it, DNA -- the same stuff that serves as a blueprint for all organic life -- is really not much different from binary code. Instead of using 1s and 0s to encode information as magnetic regions on a hard drive, DNA uses four nucleobases (known by the abbreviations T, G, A and C) to encode information onto strands comprising a double helix. To “sequence” DNA essentially means to decode it from those TGAC bases into binary code.

But that also means, of course, that binary code can be converted into nucleobases -- a new area of research that has major implications for data storage, and for human society.

DNA, first of all, is extremely dense: you can store one bit per base, and a base is only a few atoms large. It’s also extremely durable. While most archival computing systems need to be kept in subzero temperatures, DNA (as we know from paleontological digs) can still be read hundreds of thousands of years later, even after being dug up out of the Gobi Desert.

Imagine once again that coffee cup on your desk. DNA is so dense and so robust that singer Justin Bieber’s catalog could be stored more than 66 million times in about .03 ounces of that coffee, or the equivalent of a single gram of DNA. What’s more, Bieber’s music, when stored this way, wouldn’t be destroyed for hundreds of thousands of years (for better or worse).

“This is what makes DNA a form of super-archival data storage,” explained Ryan Gabrys, an electrical engineer at Spawar Systems Center in San Diego who gave a talk at NVMW on “Coding for DNA-Based Storage (the Bieber analogy came from his talk).” “Using (artificial) DNA, you could store 6.4 gigabytes of information within a human cell,” or the equivalent of about 100 hours of music. In one human cell.

“All the world’s data,” added Gabrys, “could be stored in an area the size of a car.”

Eitan Yaakobi, an assistant professor of computer science at the Technion – Israel Institute of Technology and an affiliate of CMRR, acknowledged that “DNA storage may sound like science fiction at this point.” But, he added, “I believe that in the near future we will see tremendous progress in this direction and literally the sky will be the limit. It will be a great opportunity to combine efforts from researchers from all different fields starting from biology to systems and coding.”

And yet, as Gabrys pointed out, “everything’s complicated with DNA.” The technologies available to sequence DNA are prone to substitution- and deletion-based errors (hence Gabrys’ work to develop error-correction codes) and the process to convert binary code into nucleobases requires proprietary and expensive technology. “For this to even be a consideration we’re talking six to seven years down the road,” he said. Which means just about the only thing that’s guaranteed in the wild world of data storage is that there will be a lot to talk about at the Non-Volatile Memories Workshop come six or seven years from now.



Ryan Gabrys, electrical engineer at Spawar Systems Center in San Diego.



Eric Fullerton

This is the second newsletter that comes out under the name Center for Memory and Recording Research. As you will see in the presentation and discussion, the new name reflects the growth in the CMRR research into areas such as non-volatile memory research that complements our strong history in magnetic recording research. The research on non-volatile memory is also highlighted by the 7th annual Non-Volatile Memories Workshop (NVMW) that was held on March 6-8, 2016 and was organized by Steve Swanson and Paul H. Siegel. This workshop provides a unique showcase for outstanding research on solid state, non-volatile memories and the planning for the next workshop has begun. We finalized the agreement to form the new partnership between CMRR and the University of Lorrain, University of Paris Sud and the Thales

Laboratory in France. This agreement forms a new International Associated Laboratories (LIA) which is a "laboratory without walls" focused on Nanoelectronics that is sponsored by the Centre National de la Recherche Scientifique (CNRS) in France. This will enhance the exchange of faculty, post-doc and students between labs and provide new opportunities for collaborative research.

We have new affiliated faculty at CMRR including Professors Ping Liu and Oscar Vazquez Mena from the NanoEngineering Department. Professor Liu works on materials and architectures for energy conversion and storage; solid-state actuation; nanomaterials synthesis and reaction mechanism in batteries; energy storage device architecture design. Prof. Vazquez Mena's research focus is on the integration of graphene and nanoscale materials into nanoscale devices for photovoltaics, biosensing, memories and two-dimensional hybrid metamaterials. We also welcome back Professor Eitan Yaakobi of the Computer Science Department at Technion who continues to be an active and valued member of CMRR.

I have to close on a sad note, both for me and the CMRR community. Professor Ami Berkowitz, one of the original four CMRR Endowed Chairs, passed away March 31 at the age of 89. Ami contributed to every aspect of CMRR and it wouldn't be the institution it is today without his leadership, creativity and support over the last 30 years. I first got to know Ami when I was graduate student working at CMRR. I co-authored my first paper with him in 1993 and the last one just last year. It was an honor to be know and work with Ami over the years.



For the first five years as a Director, I had a companion that joined me almost everyday and she spent most of the day sleeping under my desk. Everyone knew Marigold, she was a fixture in the Director's office. Unfortunately, she succumbed to cancer just after her 16th birthday. I definitely miss her.

PhD Students Near Completion

Summer Internships



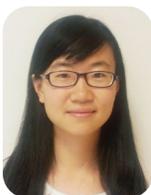
Youyi Fu
Prof. Frank Talke



Benjamin Suen
Prof. Frank Talke



Veeresh Taranalli
Prof. Paul H. Siegel



Bing Fan
Prof. Paul H. Siegel



Richard Choi
Prof. Eric Fullerton



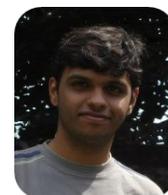
Sohini Manna
Prof. Eric Fullerton



Sidi Fu
Prof. Vitaliy Lomakin



Robert Tolley
Intern at Seagate



Anay Pandit
Intern at Cymer



Bing Fan
Intern at SanDisk



Richard Choi
Intern at Bosch



Tan D. Trinh
Intern at WD



Pengfei Huang
Intern at CNEX Labs

Elucidating the Phase Transformation of $\text{Li}_4\text{Ti}_5\text{O}_{12}$ Lithiation at the Nanoscale

Michael G. Verde^{1*}, Loïc Baggetto², Nina Balke³, Gabriel M. Veith², Joon Kyo Seo⁴, Ziyang Wang¹, Ying Shirley Meng^{1*}

¹Department of NanoEngineering, University of California San Diego, La Jolla, CA 92093, USA

³The Center for Nanophase Materials Sciences, Oak Ridge National Lab, Oak Ridge, TN 37831, USA

²Materials Science and Technology Division, Oak Ridge National Lab, Oak Ridge, TN 37831, USA

⁴Materials Science & Engineering Program, University of California San Diego, La Jolla, CA 92093, USA

Due to the demand for high energy density batteries for mobile electronics and electric vehicles, the quest for high capacity, low voltage anode materials – especially involving Si – has been heavily pursued in recent years. In this respect, $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO) is viewed as an inferior lithium ion battery anode. It exhibits relatively low capacity and high voltage compared to the most commercially available Li-ion anode, graphite (175 vs 372 $\text{mAh}\cdot\text{g}^{-1}$ and 1.55 vs ~ 0.1 V Li/Li^+). Nevertheless, the same undesirable properties that contribute to low energy densities provide attractive advantages as well. For example, the high redox potential of LTO lies safely within the electrolyte stability window.¹ This enables cycling without the formation of deleterious passivation layers, which are a problem for the long-term stability of conventional graphite anode and the popular alternatives such as silicon.² The two-phase reaction, which leads to moderate capacity, is also highly facile. It proceeds between two members ($\text{Li}_4\text{Ti}_5\text{O}_{12}$ and $\text{Li}_7\text{Ti}_5\text{O}_{12}$) that possess the same crystallographic space group, Fdm. Even upon intercalation of 3 Li^+ per formula unit, there is only a 0.2% volume change of the spinel lattice, resulting in its description as a *zero-strain* material.³ The stability, robustness, and safety of LTO have in fact led to its successful commercialization.

While the ionic conductivity of LTO is comparable to other Li-ion anodes, a major shortcoming is its inherently low electronic conductivity.⁴ $\text{Li}_4\text{Ti}_5\text{O}_{12}$ is considered to be an insulator, with experimentally reported band gaps typically between 3.0 and 4.0 eV. In order to circumvent this problem for use as an electrode, several strategies have been implemented. Coatings, such as carbon, have been applied to improve the electronic conductivity.⁵ Doping with a host of cations has also been performed to decrease the band gap and improve performance.⁶ Alternatively, LTO nanostructures have been synthesized to shorten Li^+ diffusion lengths and increase surface areas.⁷ By applying these treatments, extremely high reversible rates of up to 100C (full charge or discharge in almost 30 seconds) have been reported.⁸ Understanding exactly how the phase transformation between $\text{Li}_4\text{Ti}_5\text{O}_{12}$ and $\text{Li}_7\text{Ti}_5\text{O}_{12}$ proceeds and what factors promote it, however, is still relatively ill-defined. Because the lattice parameters of both structures are near identical, few diffraction techniques are able to physically differentiate them.

This work exploits the most significant property difference between the two phases – their difference in electronic conductivity – in order to more fully explain the insulator-metal transition occurring within the system. Using conductive atomic force microscopy (c-AFM) we directly visualize the formation and distribution of each phase at the nanoscale, for the first time (Figure 1). We present comprehensive current and topography maps of LTO, at various states of charge, to demonstrate where the transition between these two phases occurs, and what features promote it. These results are combined with chemistry-resolved surface measurements using X-ray photoelectron spectroscopy (XPS), at the same states of charge, to explain changes in surface morphology and composition. The unique application of the SPM methods presented here is a valuable key for the future optimization of this material, its composite electrode, and others like it.

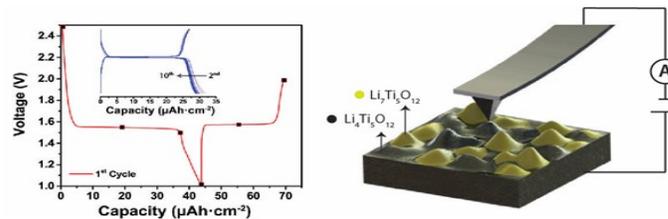


Figure 1. First cycle electrochemical profile of thin-film $\text{Li}_4\text{Ti}_5\text{O}_{12}$ anode vs Li/Li^+ , with squares indicating points where samples were characterized, and first 10 cycles – inset (left). An illustration of the c-AFM capability to detect the presence of each phase due to their unique conductivities (right).

LTO Electrochemistry

In order to determine how LTO's fundamental mechanism proceeds, we made use of thin-films that possessed only the electrochemically active material. LTO was grown on Pt-coated (ca. 225 nm) Al_2O_3 disks using RF magnetron sputtering and exhibit a thickness around 800 nm. The Pt layer was incorporated to ensure good electrical contact for use in batteries as well as for c-AFM analysis. Figure 1 highlights the material's first electrochemical cycle and demonstrates very good reversibility over the first 10 cycles. The flat redox potential at 1.55 V vs Li/Li^+ is clearly indicative of the two-phase reaction between $\text{Li}_4\text{Ti}_5\text{O}_{12}$ and $\text{Li}_7\text{Ti}_5\text{O}_{12}$, as has been previously reported.⁹ In order to explore the unique changes occurring in this system during the first cycle, we analyze the thin-films at the points indicated along the voltage profile in Figure 1: 1) pristine LTO; 2) LTO discharged to 50% of the initial discharge capacity; 3) LTO immediately following the voltage plateau, discharged to 1.5 V; 4) LTO fully discharged to 1.0 V; 5) LTO charged to 50% of the 1st charge capacity; 6) LTO fully charged to 2.0 V.

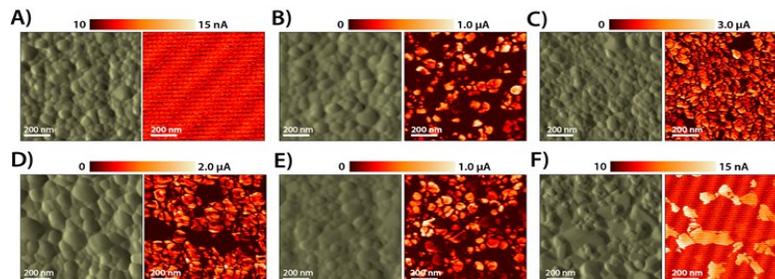


Figure 2. AFM deflection (left) and current (right) images of LTO thin-films cycled to various states of charge, corresponding to (A) pristine, (B) discharged 50%, (C) discharged to 1.5V, (D) discharged to 1.0V, (E) charged 50%, and (F) charged to 2.0V. Note the difference in units between scale bars.

LTO Conductivity

While the morphology did not change upon initial discharge, due to negligible volume expansion upon lithiation, the electronic conductivity measured using c-AFM significantly increased. Figure 2 depicts the current response of all samples when a potential of 0.4 V was applied between the c-AFM tip and substrate. While no current is observed in the pristine material, it is measured within an array of individual grains upon discharging to 50% capacity. Figure 2b suggests that the transition of $\text{Li}_4\text{Ti}_5\text{O}_{12}$ to $\text{Li}_7\text{Ti}_5\text{O}_{12}$ proceeds via a limited number of narrow percolation channels that connect current collector and electrolyte. Figure 2c demonstrates that immediately following the total lithiation, or completion of the two-phase reaction, nearly all grains in the LTO film are electronically conductive.

In order to summarize and compare the wide range of measured currents (from nA to μA), the $\log(\text{current})$ values of all samples are shown in Figure 3. Current histograms of the measured c-AFM images are depicted in Figure 3a. On the left is the low current region, with the single peak corresponding to noise at the instrument's detection limit. On the right is the high current region, resulting from current measured because of changes among each sample. As the LTO sample is discharged, its measured current increases, which results in the low current peak decreasing and the high current peak increasing, until it reaches its maximum when discharged to 1.5 V. Further discharge to 1.0 V reduces the current and the area fraction of regions showing current, with a strong increase in surface roughness (Figures 3b & 3c). Upon charge, the average current and surface roughness decrease again. While the average current of samples discharged and charged to 50% were fairly similar, their RMS surface roughnesses were not. The difference in morphology is likely related to the first cycle partial irreversibility, where surface reconstruction occurred below 1.5 V of the initial discharge.

Research Highlight

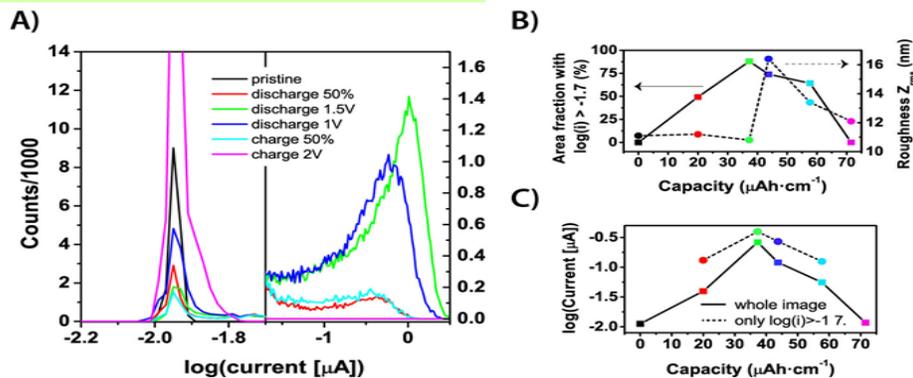


Figure 3. [LEFT] (A) Histograms of c-AFM images for all samples divided in two regimes. (B) Area fraction of regions where current is measured (left axis), as well as surface roughness (right axis), as a function of the first cycle capacity. Note that discharge to 1.5 V and 1.0 V corresponds to $37\mu\text{A}\cdot\text{cm}^{-2}$ and $44\mu\text{A}\cdot\text{cm}^{-2}$, respectively. Larger capacities correspond to the first charge. (C) Average current measured in the whole images of Figure 2 and average current measured in areas exhibiting current above a certain threshold.

LTO Surface Chemistry

To further understand the LTO phase transition and the evolution of surface chemistry during the first cycle, we performed XPS on thin-films cycled to the same states of charge described previously. Figure 4 shows high-resolution scans of the C1s, O1s, and Ti2p regions. The single peak centered at 458.0 eV corresponds very well to the $2p_{3/2}$ peak of Ti^{4+} in LTO, as well as in TiO_2 .¹⁰ Upon discharge, a second peak at 455.9 eV forms, which corresponds to Ti^{3+} measured in Ti_2O_3 . This peak reaches a maximum relative to the Ti^{4+} peak, in the LTO sample discharged to 1.0 V and correlates to the formation of Ti^{3+} due to reduction of Ti^{4+} upon lithiation. This peak completely disappears upon charge and completely disappears at 2.0 V, indicating that the surface reaction is fully reversible.

The peak in the O1s spectra at 529.7 eV corresponds to O^{2-} in the LTO lattice. Upon discharge, a peak at 531.5 eV grows relative to it, and reaches a maximum at 1.0 V. This higher binding energy peak results from the contributions of several solid electrolyte interface (SEI) species, including CO_3^{2-} , $-\text{CO}_2^-$ and $\text{Li}_x\text{PO}_x\text{F}_z$, all of which originate from the decomposition of electrolyte.¹¹ The formation of decomposition products, Li_2CO_3 and/or LiCO_3R , are also shown to significantly occur in the sample discharged to 1.0 V, as suggested by the signal in the C1s peak near 289.5 eV.¹² The fact that we observe these species is significant because LTO is excessively championed to form no passivation or SEI layers, due to its high redox potential. This is clearly not the case. A passivation layer may form upon initial discharge (below 1.5 V) to create a relatively stable SEI; since subsequent cycles show markedly improved capacity retention, this reduction of electrolyte would not appear to occur continuously.

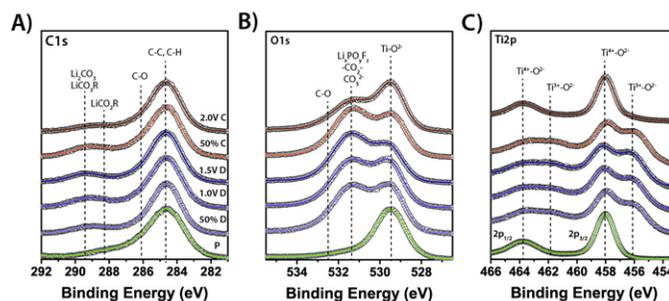


Figure 4. Normalized high-resolution C1s (A), O1s (B), and Ti2p (C) XPS spectra of the LTO thin-films discharged (blue) and then charged (red). From bottom to top is pristine (P), discharged 50% (50% D), discharged to 1.5V (1.5V D), discharged to 1.0V (1.0V D), charged 50% (50% C), and charged to 2.0V (2.0V C).

The combination of c-AFM and XPS described provides a more detailed understanding of the LTO lithiation/delithiation process. These insights may be used to optimize other materials with insulator to metal transitions behaviors. More detail regarding these results can be found in the following publication: Verde, M. G. et al. *ACS Nano* **2016**, *10* (4), 4312-4321.

This work has been a collaborative effort between UCSD and Oak Ridge National Lab and was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Award Number DE-FG02-10ER46672 (DE-SC0002357).

REFERENCES

- Goodenough, J. B.; Kim, Y. Challenges for Rechargeable Li Batteries. *Chem. Mater.* **2009**, *22* (3), 587-603.
- Oumellal, Y.; Delpuech, N.; Mazouzi, D.; Dupre, N.; Gaubicher, J.; Moreau, P.; Soudan, P.; Lestriez, B.; Guyomard, D. The failure mechanism of nano-sized Si-based negative electrodes for lithium ion batteries. *J. Mater. Chem.* **2011**, *21* (17), 6201-6208.
- Ohzuku, T.; Ueda, A.; Yamamoto, N. Zero-Strain Insertion Material of $\text{Li}[\text{Li}_{1/3}\text{Ti}_{5/3}]\text{O}_4$ for Rechargeable Lithium Cells. *J. Electrochem. Soc.* **1995**, *142* (5), 1431-1435.
- Takami, N.; Hoshina, K.; Inagaki, H. Lithium Diffusion in $\text{Li}_4/3\text{Ti}_5/3\text{O}_4$ Particles during Insertion and Extraction. *J. Electrochem. Soc.* **2011**, *158* (6), A725-A730.
- Luo, H.; Shen, L.; Rui, K.; Li, H.; Zhang, X. Carbon coated $\text{Li}_4\text{Ti}_5\text{O}_{12}$ nanorods as superior anode material for high rate lithium ion batteries. *J. Alloys Compd.* **2013**, *572* (0), 37-42.
- Zhang, Q.; Verde, M. G.; Seo, J. K.; Li, X.; Meng, Y. S. Structural and electrochemical properties of Gd-doped $\text{Li}_4\text{Ti}_5\text{O}_{12}$ as anode material with improved rate capability for lithium-ion batteries. *J. Power Sources* **2015**, *280* (0), 355-362.
- Chen, S.; Xin, Y.; Zhou, Y.; Ma, Y.; Zhou, H.; Qi, L. Self-supported $\text{Li}_4\text{Ti}_5\text{O}_{12}$ nanosheet arrays for lithium ion batteries with excellent rate capability and ultralong cycle life. *Energy Environ. Sci.* **2013**.
- Liu, J.; Song, K.; van Aken, P. A.; Maier, J.; Yu, Y. Self-Supported $\text{Li}_4\text{Ti}_5\text{O}_{12}$ -C Nanotube Arrays as High-Rate and Long-Life Anode Materials for Flexible Li-Ion Batteries. *Nano Lett.* **2014**, *14* (5), 2597-2603.
- Li, D.; Zhou, H. Two-phase transition of Li-intercalation compounds in Li-ion batteries. *Materials Today* **2014**, *17* (9), 451-463.
- Cai, R.; Jiang, S.; Yu, X.; Zhao, B.; Wang, H.; Shao, Z. A novel method to enhance rate performance of an Al-doped $\text{Li}_4\text{Ti}_5\text{O}_{12}$ electrode by post-synthesis treatment in liquid formaldehyde at room temperature. *J. Mater. Chem.* **2012**, *22* (16), 8013-8021.
- Baggetto, L.; Dudney, N. J.; Veith, G. M. Surface chemistry of metal oxide coated lithium manganese nickel oxide thin film cathodes studied by XPS. *Electrochim. Acta* **2013**, *90*, 135-147.
- Appapillai, A. T.; Mansour, A. N.; Cho, J.; Shao-Horn, Y. Microstructure of LiCoO_2 with and without "AlPO₄" Nanoparticle Coating: Combined STEM and XPS Studies. *Chem. Mater.* **2007**, *19* (23), 5748-5757.

Former CMRR
faculty member
Sungho Jin receives
the Acta Materialia
Hollomon Materials
& Society Gold
Medal



At the TMS Annual Meeting which took place on February 14-18, 2016 in Nashville, Tennessee, CMRR's Professor Sungho Jin was awarded one of the highest honors, the Acta Materialia Hollomon Materials & Society Gold Medal. The Acta Materialia Gold Medal was established by Acta Materialia Inc. in 1973 as an international award to recognize leadership in materials research. This award is presented in the memory of J. Herbert Hollomon, principal instigator of the journal *Acta Metallurgica*. Congratulations Professor Sungho Jin!

CMRR's Professor Frank E. Talke— Invited to become part of the *EU Academy of Science*



CMRR extends its profound congratulations to Professor Frank E. Talke on becoming a member of the EU Academy of Sciences. The EU Academy of Sciences is an international scientific organization and is among the most prestigious organization in Europe. It is composed of the world's leading scientists, scholars and business people aiming to promote excellence in science and technology. Professor Talke's hard work and dedication to the field of science and technology has made him a member in the EU Academy of Sciences (EUAS).

Shannon Graduate Fellowship Winner 2015

We would like to congratulate Veeresh Taranalli on winning the Shannon Graduate Fellowship. The purpose of the Shannon fellowship is to honor an outstanding graduate student at UCSD whose research is in the field of information theory. Veeresh's research interests are decoding of polar codes via linear programming and belief propagation; and characterization, mitigation and modeling of errors in multi-level cell (MLC) flash memories. Once again, congratulations Veeresh Taranalli on your outstanding work!



Congratulations to Phuong Truong on Winning the Gordon Fellowship



Phuong Truong is an undergraduate student working under the supervision of Professor Frank E. Talke. Ms. Truong's hard work and academic achievement has resulted in being the honorary award winner of the Gordon Fellowship. The Gordon Center presents annual Engineering Leadership Awards to recognize outstanding students and academic leaders. The purpose of the program is to reward and recognize successful leaders and to promote positive role models for Jacobs School of Engineering students. In recognition of Phuong's great achievement as a leader, her advisor, Professor Frank E. Talke nominated her for the award and she was chosen through a competitive selection process.

Selected Papers

Professor Eric E. Fullerton

Tingting Fan, Patrick Grychtol, Ronny Knut, Carlos Hernández-García, Daniel D. Hickstein, Dimitry Zusin, Christian Gentry, Franklin J. Dollar, Christopher Mancuso, Craig Hogle, Ofer Kfir, Dominik Legut, Karel Carva, Jennifer L. Ellis, Kevin Dorney, Cong Chen, Oleg Shpyrko, **Eric E. Fullerton**, Oren Cohen, Peter Oppeneer, Dejan Milosevic, Andreas Becker, Agnieszka Jaron-Becker, Tenio Popmintchev, Margaret Murnane, and Henry C. Kapteyn, "Bright Soft X-ray High Harmonic Generation with Circular Polarization for X-ray Magnetic Circular Dichroism", *Compact EUV & X-Rays Light Sources Conference*, Optical Society of America, March 20, 2016.

JC T Lee, J Chess, SA Montoya, XW Shi, N Tamura, SK Mishra, DH Parks, P Fischer, B McMorrin, SK Sinha, **EE Fullerton**, SD Keivan, and S Roy, "Synthesizing Skyrmion Molecules in Fe-Gd Thin Films", *Bulletin of the American Physical Society*, March 17, 2016.

T Fan, R Knut, C Hernandez Garcia, D Hickstein, D Zusin, C Gentry, F Dollar, C Mancuso, C Hogle, J Ellis, K Dorney, D Legut, K Carva, P Oppeneer, O Shpyrko, **EE Fullerton**, O Kfir, O Cohen, D Milosevic, A Becker, A Jaron Becker, T Popmintchev, M Murnane, H Kapteyn, and P Grychtol, "Tabletop Soft X-Ray Magnetic Circular Dichroism Measurements Using Circularly Polarized High Harmonic Sources", *Bulletin of American Physical Society*, March 16, 2016.

MacCallum Robertson, Christopher Agostino, Mi-Young Im, Sergio Montoya, **Eric E. Fullerton**, and Peter Fischer, "Polarization Dependent Soft X-Ray Spectro-Microscopy of Local Spin Structures", *APS Physics*, March 15, 2016.

MS El Hadri, P Pirro, C-H Lambert, N Bergard, S Petit-Watelot, M Hehn, G Malinowski, F Montaigne, Y Quessab, R Medapalli, **EE Fullerton**, and S Mangin, "Electrical Characterization of All-Optical Helicity-Dependent Switching in Ferromagnetic Hall Crosses", *Applied Physics Letters*, Vol. 108 – P. 92405, February 29, 2016.

AH Reid, X Shen, P Maldonado, T Chase, E Jal, P grantzka, K carva, RK Li, J Li, L Wu, T Vecchione, T Liu, Z Chen, DJ Higley, N Hartmann, R Coffee, J Wu, GL Dakowski, W Schlotter, H Ohldag, YK Takahashi, V Mehta, O Hellwig, A Fry, Y Zhu, J Cao, **EE Fullerton**, J Stohr, PM Oppeneer, XJ Wang, and HA Durr, "Ultrafast Spin-Lattice Coupling in Laser -Excited FePt Nanoparticles", *arXiv preprint arXiv: 1602.04519*, February 14, 2016.

Professor Paul H. Siegel

A.R. Iyengar, **P.H. Siegel**, and J.K.Wolf. "On the Capacity of Channels With Timing Synchronization Errors," *IEEE Transactions on Information Theory*, Vol. 62, no. 2, pp. 793 -810, February 2016.

Bing Fan, Hemant K. Thapar, and **Paul H. Siegel**, "Multihead Multitrack Detection with ITI Estimation in Next Generation Magnetic Recording Systems", *IEEE Transactions and Communications*, submitted February 17, 2016.

Veeresh Taranalli, Hironori Uchikawa, and **Paul H. Siegel**, "Channel Models for Multi-Level Cell Flash Memories Based on Empirical Error Analysis", *IEEE Transactions and Communications*, submitted February 24, 2016.

E. Yaakobi, J. Bruck, and **P.H. Siegel**, "Construction and Decoding of Cyclic Codes Over b-Symbol Read Channels", *IEEE Transactions on Information Theory*, vol. 62, no.4, pp. 1541-1551, April 2016.

Professor Frank E. Talke

Wenping Song, Longqiu Li, Andrey Ovcharenko, and **Frank E. Talke**, "Thermo-Mechanical Contact Between a Rigid Sphere and an Elastic-Plastic Sphere", *Tribology International*, Vol. 95 – P. 132-138, March 2016.

Young Woo Seo, Andrey Ovcharenko, and **Frank E. Talke**, "Simulation of Hydrocarbon Oil Contamination at the Head – Disk Interface Using Molecular Dynamics", *Tribology Letters*, Vol. 61, March 2016.

Youyi Fu, Vlado A. Lubarda, and **Frank E. Talke**, "The Effect of Diamond – Like Carbon Overcoat on the Tribological Performance of the Dimple/Gimbal Interface in Hard Disk Drives", *ASME*, August 2015.

WELCOME NEW CMRR RESEARCHERS

Associate Professor Ping Liu's Group:



Ping Liu

Prior to joining the Jacobs School of Engineering, Professor Ping Liu was a Program Director at the Advanced Research Projects Agency – Energy (ARPA -E) since 2012 where he initiated and managed research programs in energy storage for electric vehicles and thermal management technologies to improve building energy efficiency. He also served as the manager of the Energy Technology Department at HRL Laboratories and had a stint as a research staff member with the National Renewable Energy Laboratory. He received his Ph.D. in Chemistry from Fudan University in China in 1995. He was a Distinguished Inventor in multiple years at HRL and won an R&D 100 award in 2009 for a battery technology developed at NREL.

Ping Liu has published over 70 peer-reviewed papers and has been issued 36 US patents in the broad areas of batteries, fuel cells, sensors and actuators.

POSTDOC



Byoung Sun

VISITING SCHOLAR



Qian He



Chris Coaty



Xing Xing

UNDERGRADUATE STUDENTS



Albert Chan



Qizhang Yan



Benjamin Lam



Jason Huang



Sean Kim

Associate Professor Oscar Vazquez Mena's Group:



Oscar Vazquez Mena

Dr. Oscar Vazquez Mena received his Ph.D. from the Swiss Federal Institute of Technology of Lausanne (EPFL) in Switzerland. He did his postdoctoral research stages at the University of California, Berkely in the Department of Physics from 2011 to 2014, and at the Institute of Photonic Sciences in Barcelona in 2015 with a Marie Skłodowska—Curie fellowship. He obtained his B.S. in Physics Engineering from the Monterrey Institute of Technology in Mexico in 2000 and his M.S. degree from Chalmers University of Technology in Sweden. He defended his MS thesis at Delft University of Technology, Netherlands. At UC Berkeley, he founded the Indigenous Pipeline program in order to increase access to UC Berkeley of children from indigenous communities in the Bay Area.

GRADUATE STUDENTS



Malcolm Lockett



Xiaochen Li



Yang Huang



Wenjun Chen



Yiying Wang

RESEARCH VOLUNTEER



Jenna Lawrence

NEW MEMBERS JOINING VARIOUS GROUPS



Anay Pandit
Graduate Student
Prof. Frank Talke



Caleb Logan
Research Volunteer
Prof. Eric Fullerton



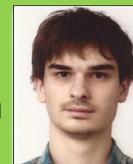
Wei Wu
Graduate Student
Prof. Paul H. Siegel



Vikas Sakaray
Graduate Student
Prof. Paul H. Siegel



Zac Blair
Graduate Student
Prof. Paul H. Siegel



Philippe Scheid
Visiting Graduate Student
Prof. Vitaliy Lomakin



Jie Zhao
Graduate Student
Prof. Zhaowei Liu



Li Zhang
Visiting Scholar
Prof. Zhaowei Liu