CMRR REPORT

Center for Memory and Recording Research

Fall 2015 : Issue 44

In This Issue

CMRR Officially Changes Name!

The **Center for Magnetic Recording Research** has officially changed its name to the **Center for Memory and Recording Research**.

CMRR was established in 1983.The ongoing mission of the Center is the advancement of the state-of-the-art in information storage and memory technologies and systems, in partnership with the information technology industries and government agencies. To fulfill this mission, the Center engages in three interrelated activities: basic and applied research; education at the undergraduate, graduate, and postgraduate levels; and transfer of technology to the public and private sectors.

In all three areas, CMRR has been successful over the last three decades in contributing to the remarkable progress in digital data storage and memory technologies, one of the underpinnings of the modern information age. While initially founded to study data storage systems, CMRR's research has expanded to include significant research into non-volatile memory technologies and systems that are increasingly becoming an important component of modern computers. The change of name to Center for Memory and Recording Research is a natural move because of the expanded research thrust into memory technologies. This name retains the CMRR acronym that has become well known over the past 30 years but better reflects the current research activities. The inclusion of 'Memory' in the name will also be important for the future of CMRR's major research thrusts in fundamental memory properties of materials and devices and new computer paradigms.

LIA KICKOFF MEETING

CMRR has a successful collaboration with two French universities, the University of Paris Sud and University of Lorraine . This collaboration resulted in co-funded US-French projects such as co-organized workshops, regular faculty visits between laboratories, student exchanges, several high-profile publications, and discussions on establishing a joint degree. As a final outcome of this fruitful partnership, the Associated Laboratory on Nanoelectronics (LIA) was created. LIA held its kickoff meeting at CMRR on September 17 & 18, 2015.The kick-off meeting focused on the feasibility of Franco-American collaborations in the fields of scientific and technological research. The French Consul, Professors, Researchers, Directors, Deans, and Chancellors from all the participating institutions congregated to explore potential possibilities for projects, programs, research exchanges, shared teaching, and the development of the joint degree. The two-day summit was not only productive but also strengthened the professional and personal relationships between the LIA members.

Participants of the LIA Kickoff Meeting

7th Non-Volatile Memories Workshop

La Jolla, California USA

March 6-8, 2016

http://nvmw.ucsd.edu

The 7th Annual Non-Volatile Memories Workshop (NVMW 2016) provides a unique showcase for outstanding research on solid state, non-volatile memories. It features a "vertically integrated" program that includes presentations on devices, data encoding, systems architecture, and applications related to these exciting new data storage technologies. Last year's workshop (NVMW 2015) included 46 speakers from top universities, industrial research labs, and device manufacturers and attracted over 230 attendees. (The website for NVMW 2015 can be found at http://nvmw.ucsd.edu/2015.) NVMW 2016 will build on this success.

The organizing committee is soliciting presentations on any topic related to non-volatile, solid state memories, including:

- Advances in memory devices or memory cell design.
- Characterization of commercial or experimental memory devices.
- Error correction and data encoding schemes for non-volatile memories.
- Advances in non-volatile memory-based storage systems.
- Operating system and file system designs for non-volatile memories.
- Security and reliability of solid-state storage systems.
- Applications of non-volatile memories to scientific, "big data", and high-performance workloads.
- Implications of non-volatile memories for applications such as databases and NoSQL systems

The goal is to facilitate the exchange of the latest ideas, insights, and knowledge that can propel future progress. To that end, presentations may include new results or work that has already been published during the 18 months prior to the submission deadline. In lieu of printed proceedings, we will post the slides and extended abstracts of the presentations online. Presentation of new work at the workshop does not preclude future publication.

For more information on this event visit:

http://nvmw.ucsd.edu

Letter from the Director

Eric Fullerton
Director, CMRR

This newsletter comes at a time with many new activities as well as new and returning faces to CMRR where we are now officially the Center for Memory and Recording Research. The name change is meant to reflect the growth in the CMRR research into areas such as non-volatile memory that complements our strong history in magnetic recording research. The research on non-volatile memory will be highlighted at the 7th annual Non-Volatile Memories Workshop (NVMW 2016) that is organized by Steve Swanson and Paul Siegel. This workshop provides a unique showcase for outstanding research on solid state, non-volatile memories. It features a "vertically integrated" program that includes presentations on devices, data encoding, systems architecture, and applications related to these exciting new data storage technologies. This year's workshop (NVMW 2015) included 46 speakers from top universities, industrial research labs, and device manufacturers and attracted over 200 attendees. For more information visit http://nvmw.ucsd.edu/.

We received a number of new visitors at CMRR including Osamu Torii from Toshiba who will spend more than a year at CMRR and Eitan Yaakobi from Tel Aviv University who spent the summer at CMRR. We have 3 new visiting graduate students; 4 new grad students and 1 new post doc. Welcome to all of you. We also welcome back 9 graduate students who participated in summer internships with a range of companies including Western Digital, Intel, HGST, CNEX, VMWare and Facebook. Their summer research covered much of the current research at CMRR .This strong interaction of our students with our industrial partners is a clear part of the CMRR mission to train students for the information technologies industries. I hope we continue to keep this strong participation of our students with our corporate sponsors in the coming years.

Finally, there's a new partnership between CMRR and the University of Lorrain, University of Paris Sud and the Thales Laboratory in France. We have recently formed 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-docs and students between labs and provide new opportunities for funding and collaborative research.

Research Highlight

Continued on P. 3

Near Contact Thermal Flying height Control in Hard Disk Drives

By Liane M. Matthes, Bernhard E. Knigge, Raymond A. de Callafon, & Frank E. Talke

The flying height in hard-disk drives needs to be reduced below 2 nm to allow storage densities beyond 1 Tb/in [1]. Thermal flying height control (TFC) sliders have been introduced to control the spacing between the read and write element and the disk (magnetic spacing) [2]. TFC sliders feature embedded thin-film resistive heater elements in the slider trailing edge (see Fig. 1). Providing electric power (heater actuation) heats up the nearby material which expands due to the heat, causing a thermal deformation at the location of the read and write element. Typically, TFC sliders are being used in a quasi-static fashion by supplying the heater with a constant level of heater power to compensate for static spacing variations. The level of heater power is adjusted according to changes in environment and disk operation (i.e., reading vs writing). There are, however, several factors that cause the flying height to change more dynamically around the circumference of the disk. These dynamic flying height changes result from disk waviness, disk distortions due to clamping, and slider vibrations induced by turbulence or even external shocks [3]. A dynamically controlled TFC slider can be used to optimally tune magnetic spacing while avoiding slider-disk contacts.

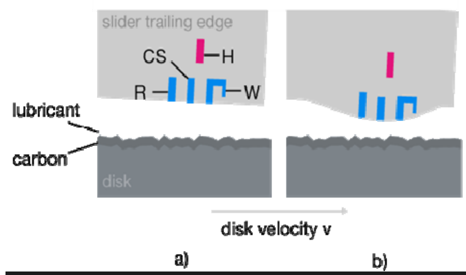

Fig. 1. Schematic depiction of the operation of a thermal flying height control (TFC) slider. Head-disk interface showing the trailing edge of a TFC slider and the disk in a) its default state, and b) under heater actuation. The schematic depiction shows the resistive heater element (H), the contact sensor (TCS), the read element (R), and the write coil (W).

In recent years, thermal contact sensors (TCS), or touchdown sensors (TDS), have been implemented in TFC sliders, allowing detection of head-disk contacts and mapping of disk topography or disk defects [8], [9]. Thermal contact sensors are temperature sensitive resistive elements and located between the read and write element as indicated in Fig. 1.

In this study, we propose a method for minimizing flying height variations of TFC sliders. The method utilizes the embedded thermal contact sensor to estimate the flying height error, and model the dynamics of the TFC slider. First, we identify the static and dynamic behavior of the thermal contact sensor as a function of heater power. Based on the static and dynamic behavior of the system, the optimal power input profile to the heater is calculated using a convex optimization technique similar to Boettcher et al. [6]. The proposed approach is verified experimentally on a spin-stand tester and used to illustrate how flying height variations can be reduced dynamically.

III. STATIC CHARACTERIZATION OF THERMAL CONTACT SENSORS

A. Mean and standard deviation trends

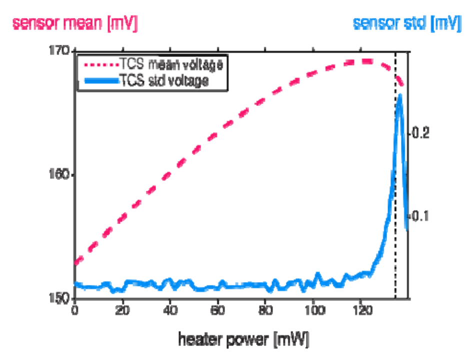

Fig. 4. TCS voltage output versus heater input power. Head-disk contact is detected at 134.5 mW according to the sensor standard deviation (std) as indicated by the vertical dashed line.

To illustrate the sensitivity of the TCS, we show the sensor voltage as a function of heater power in Fig. 4 at a radial position of 27 mm on the disk. We observe from Fig. 4 that the standard deviation of the sensor voltage (solid curve) is nearly constant for heater powers up to 130 mW. For heater powers larger than 130 mW, a sudden increase in the sensor standard deviation is observed. The onset of slider-disk contact occurs at 134.5 mW (vertical dashed line). The dashed curve in Fig. 4 represents the mean of the sensor voltage. The sensor mean voltage increases initially, reaches a local maximum at 122.5 mW, and decreases thereafter.

Fig. 4 illustrates that the mean sensor voltage creates a measurable signal and becomes ’active’ in close proximity with the disk – the exact operating condition where the flying height should be for minimal magnetic spacing and largest read-back signals. However, spacing variations need to be reduced as much as possible to avoid intermittent contact at these spacing levels. The resistance and hence voltage output of the sensor are temperature dependent. The voltage output of the sensor, V_{TCS}, may therefore be expressed as a function of

$$V_{TCS} = f(I_{TCS}, P_{heater}, q) \qquad (1)$$

in which I_{TCS} denotes the bias current for driving the sensor, P_{heater} is the electrical power applied to the heater for adjusting the head-disk spacing, and q refers to the heat flux in the neighborhood of the sensor which is a function of the head-disk spacing.

Research Highlight

Continued on P. 4

B. Compensation for heater power

To use the sensor as an estimate for changes in flying height, it is desirable to eliminate the effect of heater power *Pheater* from equation (1). To do this, we apply a third order polynomial curve fit to the sensor mean voltage over a specified curve fit range and subtract the curve fit from the sensor mean voltage. The curve fit *yfit* is described by

$$y_{fit} = a_0 + a_1 P_{heater} + a_2 P_{heater}^2 + a_3 P_{heater}^3 ,$$

$$P_{heater} \in [0, k \cdot TDP]\ mW \qquad (2)$$

in which a_0, a_1, a_2, a_3 are the coefficient of the third order polynomial curve fit and k denotes the curve fit range expressed as a percentage of the touch-down power TDP (i.e. the onset of slider-disk contact indicated by the vertical dashed line in Fig. 4 [Previous Page]) .

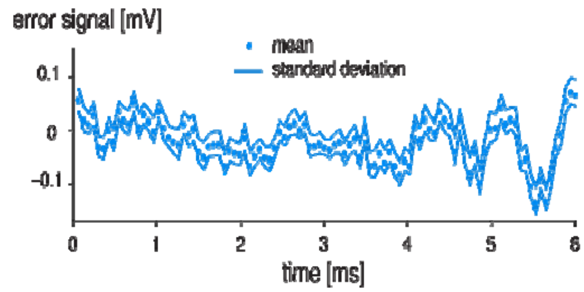

Fig. 10. Error signal versus time for one disk revolution (average of 20 consecutive disk revolutions).

IV. DYNAMIC MODELING

In order to compute the optimal feedforward heater profile via convex optimization, a dynamic model of the thermal actuator is needed. The step-based realization algorithm [6] allows the estimation of a linear time invariant discrete time model of the thermal actuator from experimentally obtained step-response data. The step response data is created via a step-wise excitation signal applied to the TFC and measuring the TCS signal around the operating condition of P_0.

To obtain a measure of the flying height error over one disk revolution, the following procedure was used: First, the average sensor voltage V_{TCS} of 20 disk revolutions was acquired. Thereafter, the curve fit y_{mean} of the mean voltage was subtracted from the instantaneous sensor voltage V_{TCS} via linear interpolation. The resulting curve was then compared to the control curve set-point *rcc*, yielding error signal ε

$$\varepsilon = r_{cc} - (V_{TCS} - y_{fit}) \ (3)$$

The error signal ε of 20 disk revolutions at 16.67 kHz is shown in Fig. 10. The dots represent the average of 20 continuous disk revolutions and the solid lines indicate the corresponding standard deviation. It can be seen that the error signal varies repetitively with every disk revolution.

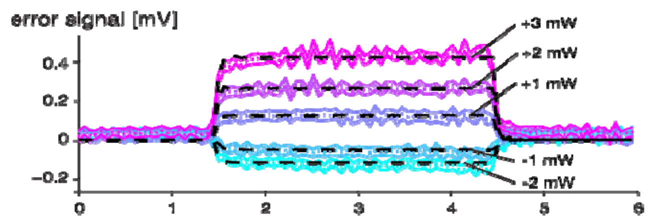

Fig. 11. Comparison between measured and dynamic simulated error signal resulting from rectangular pulses in heater power (average of 20 consecutive disk revolutions).

We now estimate the dynamics between heater power and error signal using the following procedure: First, the average error signal of 20 disk revolutions, denoted ε0, is acquired while supplying the heater with the desired DC operating power *P0* = 130.5 mW. Next, the experiment is repeated while modulating the heater input with rectangular pulses, yielding ε*. We then subtract ε_0 from ε* to obtain the change in error signal due to applying a step in heater power.

Fig. 11 shows the error signal vs time for various steps in heater power. Using the realization algorithm in [6], a second order discrete time model was identified for each set of step response data. The simulated system response is indicated by black dashed lines in Fig. 11. We observe that the identified second order systems are in good agreement with the measured step response data. Moreover, the dynamics of the model characterized by the time constants of the identified systems appear to be on the same order.

V. COMPUTING THE OPTIMAL HEATER INPUT PROFILE

The flying height error can be eliminated by actuating the heater element in a way so that the induced flying height changes match the inverse of the flying height error. As Boettcher et al. [6] pointed out, this problem can be stated as a convex optimization problem where the flying height modulation is minimized in a 2-norm sense. The optimization algorithm will be discussed in the full paper, whereas experimental results are presented below.

The average error signal of 20 disk revolutions in Fig. 10 shows significant high-frequency variations in flying height. As the bandwidth of the thermal actuator is limited (see Fig. 12), accounting for these high frequency variations in the error signal would result in large high frequency control inputs to the thermal actuator which is undesirable. A non-causal lowpass filter is therefore applied to limit the bandwidth of the error signal to 5 kHz as shown in Fig. 13.

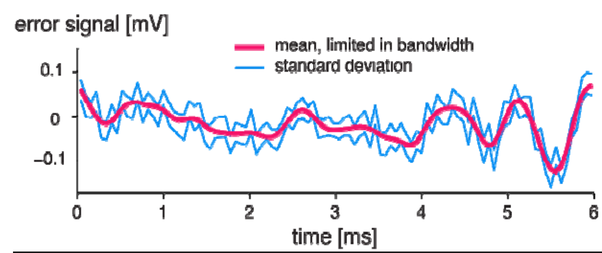

Fig. 13. A non-causal filter was applied to the average error signal of 20 disk revolutions to limit the bandwidth of the signal to 5 kHz in order to avoid large high frequency control signals.

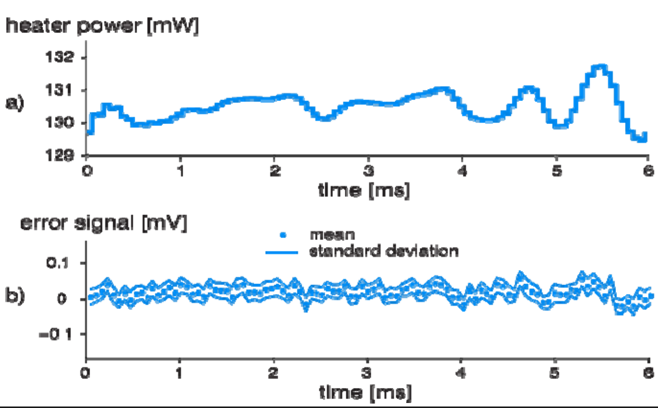

Fig. 14. a) Heater power versus time, and b) error signal versus time while applying the optimal feedforward profile to the heater (average of 20 consecutive disk revolutions).

The optimal feedforward heater input profile for minimizing flying height variations was computed using the CVX software package [12], [13]. The operating DC power was chosen to be 4 mW below the onset of slider-disk contact, i.e. P_0 = 130.5 mW. After completing the optimization procedure, the calculated power profile was applied to the heater element and the corresponding error signal of 20 disk revolutions was measured. Fig. 14 shows a) the heater power versus time, and b) the error signal versus time over the duration of one disk revolution. The dots in Fig. 14 b) represent the mean of the error signal of 20 continuous disk revolutions, and the solid lines represent the standard deviation of the error signal.

Our feedforward compensation targets the repeatable variations in flying height up to frequencies of 5 kHz. In fact, the error signal shown in Fig. 14 b) shows significantly less variations compared to the uncontrolled case shown in Fig. 10. In particular, the difference between the maximum and the minimum value is reduced from $2.1 \cdot 10^{-4}$ V to $1 \cdot 10^{-4}$ V and the standard deviation of the mean error signal is reduced from $4.1 \cdot 10^{-5}$ V to $1.8 \cdot 10^{-5}$ V. These results demonstrate that the proposed method is a promising technique for reducing variations in flying height in close proximity utilizing the embedded thermal contact sensor.

Research Highlight

VI. CONCLUSIONS

The optimization approach was verified experimentally, showing that the proposed approach reduces the difference between the maximum and the minimum value of the TFC measurements by a factor of two, indication a twofold reduction of flying height variations. Future work will involve independent measurements of the sub-nanometer flying height variations to verify the validity of using the TCS and control of the TFC for sub-nanometer flying height control.

VII. ACKNOWLEDGEMENTS

We would like to thank Dr. Uwe Boettcher for his help and comments.

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NEW CMRR MEMBERS

Mahsa Sina

Postdoc

Akihiro Orita

Visiting Scholar

Nirit Kantor

Visiting Grad Student

Luuk Rutten

Visiting Grad Student

Han Nguyen

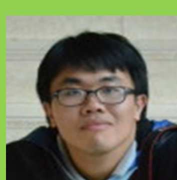
Grad Student

Chloe Yoon

Grad Student

Michael Verde

Grad Student



Yi Liu

Grad Student

MIPE Conference Winners

CMRR’s Youyi Fu and Young W. Seo were the winners of the best paper award at the 2015 MIPE Conference which took place on June 14-17, 2015 in Kobe, Japan. The title of one of the award-winning papers is "Thermal response of a thermal asperity sensor to disk asperities" written by Youyi Fu, Chuanwei Zhang, and Frank E. Talke. In this study, the researchers used the finite element method to study the transient thermo-elastic-plastic contact between a thermal asperity sensor, and a thermal asperity. The goal of this study was to improve the sensitivity of the thermal asperity sensor in hard disk drives. The title of the second award-winning paper is "Experimental and Numerical Investigation of Hydrocarbon Transfer Mechanism at the Head-Disk Interface" written by Young W. Seo, and Frank Talke. This paper is about investigating the effect of hydrocarbon contamination through experiments and using molecular dynamics simulation. Experiments and simulations complement each other in drawing the big picture of what may be happening at the head-disk interface in the existence of hydrocarbon oil molecules.

Youyi Fu

Young W. Seo

Roopali Kukreja Receives Melvin P. Klein Scientific Development Award

Roopali Kukreja, a postdoc at the Center for Memory & Recording Research, is the recipient of the Melvin P. Klein scientific development award 2015. The Melvin P. Klein Scientific Development Award honors pioneers at the forefront of accomplishments in NMR, EPR, and X-Ray absorption spectroscopy who are dedicated to the pursuit of the structure of the Mn complex characterized by the interplay of these methods. The award is intended to recognize outstanding research accomplishments by new investigators and also to promote dissemination of research results based on work performed at Stanford Synchrotron Radiation Lightsource (SSRL).
Roopali’s winning work: “Direct measurement of spin accumulation in the Cu across Co/Cu interface” will be presented at the SSRL/LCLS Annual meeting at the SLAC National Accelerator Laboratory on October 7-10, 2015,
Our heartfelt congratulations to Roopali!

Selected Papers

Professor Eric E. Fullerton

RD Tolley, T Liu, T Hauet, M Hehn, G Lengaigne, **EE Fullerton**, and S Mangin, “Control and Generation of Domain Walls Near Magnetic Compensation in Ferromagnetic CoTb via Applied Thermal Gradient,” *Magnetic Conference (INTERMAG), 2015 IEEE*, May 11, 2015.

Hao Shen, Dylan Lu, Bryan VanSaders, Jimmy J Kan, Hongxing Xu, **Eric E Fullerton**, and Zhaowei Liu, ”Anomalously Weak Scattering in Metal-Semiconductor Multilayer Hyperbolic Metamaterials,” *Physical Review X*, Vol.5, Issue 2, P. 021021, May 29, 2015.

Federico Pressacco, Vojtěch Uhlíř, Matteo Gatti, Azzedine Bendounan, **Eric E Fullerton**, and Fausto Sirotti, “Stable Room-Temperature Ferromangetic Phase at the FeRh (100) Surface,” *arXiv preprint: 1508.01777*, June 3, 2015.

R Tolley, T Liu, Y Xu, S Le Gall, M Gottwald, T Hauet, M Hehn, F Montaigne, **EE Fullerton**, and S Mangin, “Generation and Manipulation of Domain Walls Using a Thermal Gradient in a Ferromagnetic TbCo Wire,” *Applied Physics Letters*, Vol. 106, Issue 24, P. 242403, June 15, 2015.

Professor Paul H. Siegel

B. Peleato, R. Agarwal, J. M. Cioffi, M. Qin, and **P. H. Siegel**, “Adaptive Read Thresholds for NAND Flash,” *IEEE Trans. Commun.*, vol. 63, no. 9, pp. 3069-3081, September 2015.

Sarit Buzaglo, **Paul H. Siegel**, and Eitan Yaakobi, "Coding Schemes for Inter-Cell Interference in Flash Memory," *Proc. IEEE International Symposium on Information Theory (ISIT)*, Hong Kong, June 13-20, 2015, pp. 1736-1740.

Pengfei Huang, Eitan Yaakobi, Hironori Uchikawa, and **Paul H. Siegel**, “Linear Locally Repairable Codes with Availability,” *Proc. IEEE International Symposium on Information Theory (ISIT), Hong Kong,* June 13-20, 2015, pp. 1871-1875.

Paul H. Siegel, "Row-by-Row Coding for Mitigation of Bitline Inter-cell Interference in MLC Flash Memories," *Workshop on Coding for Emerging Memories and Storage Technologies, Technion, Haifa, Israel*, May 3, 2015.

Paul H. Siegel, "Constrained Codes for Multilevel Flash Memories," IEEE Information Theory Society Padovani Lecture, delivered at the 2015 North American School of Information Theory, La Jolla, CA, August 11-13, 2015.

Professor Frank E. Talke

L. Li, H. Zheng, and **F. E. Talke**, “Investigation of Nanoscale Heat Transfer in Thermal Flying Height Control Sliders Considering Near-field Radiation,” *Tribology Letters*, Vol.59, pgs.12, May 4, 2015.

L. Li, B. Suen, and **F. E. Talke**,“Investigation of Temperature Dependence of Raman Shift of Diamond-Like Carbon Coatings Used in Heat Assisted Magnetic Recording,” *IEEE Magnetics,* pg.1, June 1, 2015.

W. Song, L. Li, A. Ovcharenko, C. Zhang, and **F. E. Talke**, “Effect of Asperity Size during Contact between a Thermal Flying Height Control Slider and a Disk Asperity,” IEEE Magnetics, 2015.

W. Song, L. Li, A. Ovcharenko, and **F. E. Talke**, “A Comparison of Plowing and Flattening Behavior during Thermo-mechanical Contact between Rigid Sphere and Elastic-plastic Sphere,” *Tribology International*, 2015.

UC San Diego

Welcome Osamu Torri

Osamu Torri is a Visiting Scholar at CMRR. He is working in conjunction with Professor Paul Siegel and his group members to research endurance/ICI-mitigation codes for flash memories. Torii is a Senior Specialist at Toshiba Corp., Center for Semiconductor Research & Development. Before coming to UCSD Osamu was researching, developing, and evaluating error correcting codes for NAND flash memory controllers implemented in eMMC, UFS, enterprise and consumer SSD, etc.

Acknowledgements:
Agapi Tshamjyan
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