Manufacturing Science and Technology Group
Room 202B - Session MS+MI+RM-TuM

IoT Session: Challenges of Neuromorphic Computing and Memristor Manufacturing (8:00-10:00 am)/Federal Funding Opportunities (11:40 am-12:20 pm)

Moderators: Christopher L. Hinkle, University of Texas at Dallas, Sean Jones, National Science Foundation, Alain C. Diebold, SUNY College of Nanoscale Science and Engineering

8:00am **MS+MI+RM-TuM-1 ReRAM – Fabrication, Characterization, and Radiation Effects***, **David Hughart**, R Jacobs-Gedrim, K Knisely, N Martinez, C James, B Draper, E Bielejec, G Vizkelethy, S Agarwal,* Sandia National Laboratories*; H Barnaby,* Arizona State University*; M Marinella,* Sandia National Laboratories **INVITED**

Resistive switching properties in transition metal oxides and other thin films have been an active area of research for their use in nonvolatile memory systems as Resistive Random Access Memory (ReRAM). ReRAM is a candidate for storage class memory technologies, and studies have also revealed a high degree of intrinsic radiation hardness making digital ReRAM a candidate for radiation-hardened memory applications. Analog ReRAM has also generated interest from the neuromorphic computing community for use as a weight in neural network hardware accelerators.

One of the manufacturing challenges for the valence change memory (VCM) type of ReRAM has been the development of substoichiometric switching layer films. Physical vapor deposited (PVD) substoichiometric TaO_x films are an attractive option for a VCM switching layer because they are complementary-metal-oxide-silicon (CMOS) compatible and are deposited at low temperatures. However, control of the oxygen partial pressure to produce substoichiometric TaO_x films cannot be directly achieved through flow control because the oxygen consumption by the Ta target and chamber surfaces is nonlinear as the chamber transitions from metal to insulator conditions. The oxygen partial pressure can be controlled using a feedback system, though feedback-assisted deposition techniques are difficult to regulate, making them ill-suited to production. One alternative to a feedback system is to deposit a higher stoichiometry TaO_x film, deposited in a more stable flow-partial pressure chamber regime, and use annealing to drive Ta into the film to achieve the desired stoichiometry. Here, we compare switching layers fabricated using both techniques, and discuss the relative merits of each technique. The devices are manufactured in crossbar arrays to be testable by automatic probers, enabling the collection of large scale yield and performance data sets across process splits.

Manufacturing improvements enabled fabrication of analog ReRAM with characteristics suitable for neuromorphic computing applications. The performance of a TaO_x ReRAM based hardware accelerator at image classification accuracy after training was evaluated. The classification accuracy showed little degradation in initial radiation tests, suggesting analog ReRAM may be suitable for neuromorphic computing applications in radiation environments as well.

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8:40am **MS+MI+RM-TuM-3 Memristive Synapses – Tuning Memristors for Performance and CMOS Integration***, **Nathaniel Cady**,* SUNY Polytechnic Institute **INVITED**

Neuromorphic computing systems can achieve learning and adaptation in both software and hardware. The human brain achieves these functions via modulation of synaptic connections between neurons. Memristors, which can be implemented as Resistive Random Access Memory (ReRAM), are a novel form of non-volatile memory expected to replace a variety of current memory technologies and enable the design of new circuit architectures. Memristors are a prime candidate for so-called "synaptic devices" to be used in neuromorphic hardware implementations. A variety of challenges persist, however, for integrating memristors with CMOS, as well as for tuning device electrical performance. My research group has developed a fully CMOS-compatible integration strategy for ReRAM-based memristors on a 300 mm wafer platform, which can be implemented in both front-end-of-line (FEOL) and back-end-of-line (BEOL) configurations. With regard to memristor performance, we are focusing on strategies to reduce stochastic behavior during both binary and analog device switching. This is a key metric for neuromorphic applications, as variability in device conductance state directly influences the ultimate number of levels (weights) that can be implemented per synapse. Using a two pronged approach, we have developed device operational parameters to maximize analog performance, while also tuning the ReRAM materials stack and processing conditions to reduce stochasticity and optimize switching parameters (forming, set, and reset).

9:20am **MS+MI+RM-TuM-5 Analog In-Memory Computing for Deep Neural Network Acceleration***, **Hsinyu Tsai**, S Ambrogio, P Narayanan, R Shelby, G Burr,* IBM Almaden Research Center **INVITED**

Neuromorphic computing represents a wide range of brain-inspired algorithms that can achieve various artificial intelligence (AI) tasks, such as classification and language translation. By taking design cues from the human brain, such hardware systems could potentially offer an intriguing Non-Von Neumann (Non-VN) computing paradigm supporting fault-tolerant, massively parallel, and energy-efficient computation.

In this presentation, we will focus on hardware acceleration of large Fully Connected (FC) DNNs in phase change memory (PCM) devices [1]. PCM device conductance can be modulated between the fully crystalline, low conductance, state and the fully amorphous state by applying voltage pulses to gradually increase the crystalline volume. This characteristic is crucial for memory-based AI hardware acceleration because synaptic weights can then be encoded in an analog fashion and be updated gradually during training [2,3]. Vector matrix multiplication can then be done by applying voltage pulses at one end of a memory crossbar array and accumulating charge at the other end. By designing the analog memory unit cell with a pair of PCM devices as the more significant weights and another pair of memory devices as the less significant weights, we achieved classification accuracies equivalent to a full software implementation for the MNIST handwritten digit recognition dataset [4]. The improved accuracy is a result of larger dynamic range, more accurate closed loop tuning of the more significant weights, better linearity and variation mitigation of the less significant weight update. We will discuss what this new design means for analog memory device requirements and how this generalizes to other deep learning problems.

1. G. W. Burr et al., "Experimental demonstration and tolerancing of a large-scale neural network (165,000 synapses), using phase-change memory as the synaptic weight element," IEDM Tech. Digest, 29.5 (2014).

2. S. Sidler et al., "Large-scale neural networks implemented with non-volatile memory as the synaptic weight element: impact of conductance response," ESSDERC Proc., 440 (2016).

3. T. Gokmen et al., "Acceleration of Deep Neural Network Training with Resistive Cross-Point Devices: Design Considerations," Frontiers in Neuroscience, 10 (2016).

4. S. Ambrogio et al., "Equivalent-Accuracy Accelerated Neural Network Training using Analog Memory," Nature, to appear (2018).

11:00am **MS+MI+RM-TuM-10 Computation Immersed in Memory: Integrating 3D vertical RRAM in the N3XT Architecture***, **Weier Wan**, W Hwang, H Li, T Wu, Y Malviya,* Stanford University*; M Aly,* Nanyang Technological University, Singapore*; S Mitra, H Wong,* Stanford University **INVITED**

The rise of data-abundant computing, where massive amount of data is processed in applications such as machine learning, computer vision and natural language processing, demands highly energy-effcient computing systems. However, the limited connectivity between separated logic and memory chips in conventional 2D system results in majority of program execution time and energy spent at memory access.The Nano-Engineered Computing Systems Technology (N3XT) [1] approach overcomes these memory bottlenecks by monolithically integrating interleaving layers of memory and logic on the same chip, and leveraging nano-scale interlayer vias (ILVs) to provide ultra-dense connectivity between logic and memory.

The metal oxide resistive switching memory (RRAM) [2] offers non-volatility, good scalability, and monolithic 3D integration, making it a good candidate as on-chip high-capacity main memory and storage in the N3XT system. Our experimentally calibrated studies show that a N3XT system with RRAM as digital storage and CNFET as logic devices could achieve 2-3 orders of magnitude improvement in energy efficiency (product of execution time and energy) in a wide range of applications (e.g. PageRank, deep neural network inference) compared to a conventional 2D system. Such 3D nano-system has also been experimentally demonstrated with

RRAM, CNFET and CMOS monolithically integrated to perform in-situ ambient gas classification [3] and hyper-dimensional computing [4].

Besides offering substantial benefits for conventional digital systems, the monolithic integration of RRAM and logic devices also enables “in-memory computing”, where computation is performed in the memory itself without explicitly moving data between memory and logic. Various types of in-memory computing operations could be performed using RRAM arrays, including analog multiply-accumulate and bit-wise logical operations. We perform system modeling that models program scheduling, communication and routing, and memory array and its peripheral circuits design on various operations to study their benefits and bottlenecks from application level. In particular we analyze the in-memory vector-matrix multiplication for deep neural network inference and bit-wise operations in 3D vertical-RRAM for hyper-dimensional computing. We show that with algorithm-architecture co-design, RRAM-based in-memory computing could further improve energy and area efficiency compared to digital implementation in a 3D monolithically integrated system.

[1] M.M.S. Aly et al., IEEE Computer, 2015. [2] H.-S P. Wong et al., Proc. IEEE, 2012. [3] M.M. Shulaker et al., Nature, 2017. [4] T. Wu et al., ISSCC, 2018.

11:40am **MS+MI+RM-TuM-12 Materials for the Second Quantum Revolution***, Tomasz Durakiewicz,* Los Alamos National Laboratory

Onset of the second quantum revolution is marked by proliferation of quantum technologies. Still mostly in the laboratory R&D phase, but likely to emerge soon as a growing sector of general consumer technology, quantum devices require constant supply of novel functional quantum materials. The current paradigm of meticulous long-term studies to understand fundamental properties in detail and be able to model them ab initio is unlikely to disappear; however, the rapid growth of technology may require modification of classical approach by accelerated discovery process aided by machine learning, data mining, and ability to model, synthesize and test novel materials quickly. In this presentation we will discuss opportunities and current developments in select classes of quantum materials, like low-dimensional materials, strongly correlated systems and topological insulators, and the role NSF plays in this rapidly growing area.

12:00pm **MS+MI+RM-TuM-13 SynBio(medicine): The Intersection Biomaterials and Living Systems***, David Rampulla,* National Institute of Health

The National Institute for Biomedical Imaging and Bioengineering (NIBIB) has long supported the development of biomaterials as platform technologies with broad biomedical application and has recently started a program in Synthetic Biology. This presentation will discuss the biomaterials portfolio at NIBIB with a specific focus on the use of synthetic biology approaches to engineer next generation materials for biomedicine. The talk will also highlight specific funding opportunities of interest and discuss some strategies for navigating the NIH application process.

Manufacturing Science and Technology Group
Room 103C - Session MS-TuB

Working with Government Labs and other User Facilities

Moderator: Bridget Rogers, Vanderbilt University

10:00am **MS-TuB-1 Joining the Research Community at the Cornell NanoScale Science and Technology Facility*, Michael Skvarla,*** Cornell University

The Cornell Nanoscale Science and Technology Facility (CNF) is one of network of open-access shared facilities partially subsidized by the US National Science Foundation to provide researchers with rapid, affordable, shared access to advanced nanofabrication tools and associated staff expertise. Projects can be accomplished either hands-on or remotely. Hundreds of engineers and scientists worldwide, from throughout academia, industry, and government, utilize CNF to make structures and systems from the nanometer scale to the centimeter scale. All users are welcome; no experience in nanofabrication is necessary and a central part of CNF's mission is to assist users from "non-traditional" fields seeking assistance to implement nanofabrication techniques for the first time. CNF's user program is designed to provide the most rapid possible access (as little as 2 weeks from first contact) with the lowest possible barriers to entry (users retain full control of their IP, with no entanglement by CNF or Cornell University). CNF offers unique capabilities in world-leading electron-beam lithography, advanced stepper photolithography, dedicated facilities for soft lithography, and direct-write tools for rapid prototype development, along with the flexibility to accommodate diverse projects through the ability to deposit, grow, and etch a wide variety of materials. CNF's technical staff is dedicated full-time to user support, providing one-on-one help with process development, tool training, and troubleshooting. They can offer expertise for a wide range of fabrication projects, including electronics, nanophotonics, magnetics, MEMS, thermal and energy systems, electrochemical devices, fluidics, and basic studies in physics, chemistry, and the life sciences (30% of CNF's users now come from the biology/bioengineering fields). This talk will explore the tools, services, and advice available to CNF users, and present examples of ongoing work with the hope of stimulating ideas and possibilities. CNF is a member of the National Nanotechnology Coordinated Infrastructure (NNCI) program, a new NSF-sponsored network of shared facilities. We invite you to explore the CNF and NNCI, and discuss ways we can help bring your research visions to fruition. The CNF technical staff meets every Wednesday afternoon for conference calls where we welcome questions about any topic related to nanofabrication and can provide detailed processing advice and cost estimates for potential new projects. Visit cnf.cornell.edu to contact us and get started.

10:20am **MS-TuB-2 Opportunities at DOE Nanoscale Science Research Centers*, Arthur Baddorf,*** Oak Ridge National Laboratory

DOE Nanoscale Science Research Centers (NSRCs) were established for use by the international science community to advance scientific and technical knowledge in nanoscale science. The mission of the NSRCs is twofold: to enable the external scientific community to carry out high-impact nanoscience projects through an open, peer-reviewed user program, and to conduct in-house research to discover, understand, and exploit functional nanomaterials. To fulfill this mission, the NSRCs house the most advanced facilities for nanoscience research and employ world-class scientists who are experts in nanoscience and enjoy working with external users. Access to these centers is through a simple, peer-reviewed proposal process and is free-of-charge if the user intends to publish the research results in open literature.

As an example, the Center for Nanophase Materials Sciences (CNMS) at Oak Ridge National Laboratory (ORNL) provides access to expertise and equipment for a broad range of nanoscience research, including nanomaterials synthesis, nanofabrication, imaging/characterization, and theory/modeling/simulation. CNMS also acts as gateway for the nanoscience community to benefit from ORNL's neutron sources and computational resources. In addition to a broad assortment of nanomaterials characterization tools, the CNMS has specific expertise in the following capabilities:

• Nanofabrication

• Bio-Inspired Nanomaterials

• Inorganic and Hybrid Nanomaterials Synthesis

• Macromolecular Nanomaterials Synthesis

• Chemical Imaging

• Electron and Atom Probe Microscopy

• Scanning Probe Microscopy

• Nanomaterials Theory

This talk will provide a broad overview of opportunities at NSRCs and how to take advantage of their capabilities and expertise through user programs. More information can be found at https://nsrcportal.sandia.gov/

Manufacturing Science and Technology Group
Room 202B - Session MS+MN-TuA

IoT Session: Challenges of Sensor Manufacturing for the IoT

Moderator: Robert Lad, University of Maine

2:20pm **MS+MN-TuA-1 Manufacturing Strategies for Flexible Hybrid Electronics*, Scott Miller,*** NextFlex **INVITED**

Flexible Hybrid Electronics (FHE) combines technologies and manufacturing capabilities from the worlds of printing and additive manufacturing; flexible, bendable, stretchable, and 3D substrates; and conventional silicon integrated circuits to bring novel form and function to high-performing electronic devices. The US manufacturing ecosystem for FHE is rapidly growing and applications of FHE devices are being advanced in areas as diverse, and yet overlapping, as human health and performance monitoring, antennas and wireless communications, soft robotics, structural health management, and IoT. A single device build can require solving substrate challenges, printing functional conductors, resistors, and dielectrics, placing discrete passives, attaching bare-die integrated circuits using conductive adhesives, integrating a power supply, and encapsulating the entire device. As a Manufacturing Institute, NextFlex works with its members on technologies that have passed the applied research stage to advance their readiness for manufacturing and position them for product development. This talk will explore challenges and opportunities in FHE, including translating designs to manufacturing, material and device characterization, availability of material and process data, and scaling processes to high-rate manufacturing. Approaches to address these challenges will be discussed and example projects related to IoT will be presented.

3:00pm **MS+MN-TuA-3 Enabling Smart and Connected Living through High Volume Roll to Roll Manufacturing*, Enid Kivuti,*** Sheldahl Flexible Technologies **INVITED**

Enabling Smart and Connected Living through High Volume Roll to Roll Manufacturing

The presentation will provide an overview of automated, continuous processing technologies available in the manufacture of Flexible Printed Electronics for the Internet of Things applications. Beginning with material choice, and concluding with proposed useable devices, we will explore Additive, Subtractive and Hybrid technologies and the governing design rules. We will review recent industry developments that enable finished products to improve user experience. Finally, we will provide examples of scalable IOT applications that meld the use of existing capital assets with the rapidly evolving industry options to deliver improved performance at a lower total cost of ownership.

Key Words:

Thin Film Vacuum Deposition

Printed Electronics

Hybrid Technology

Sensors

Medical

Automotive

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4:20pm **MS+MN-TuA-7 New Generation Chemical and Biological Sensors: From New Ideas to Manufacturable Products in the era of Internet of Things and Industrial Internet*, Radislav Potyrailo,*** General Electric Global Research Center **INVITED**

Modern monitoring requirements of gases and liquids for demanding applications such as medical diagnostics, environmental surveillance, biopharmaceutical process control, industrial safety, and homeland security push the limits of existing detection concepts where we may reach their fundamental performance limits. Thus, without violating the laws of physics, chemistry, and electronics, we need to develop new practical detection concepts and instruments. We are developing new generation of handheld, wireless, and wearable sensors that bridge the gap between the existing and required sensing capabilities. This talk will stimulate your scientific and engineering senses by posing several fundamental and practical questions on principles of chem/bio sensing and by demonstrating on how we address these questions in the developments of sensors with previously unavailable capabilities with examples of strategies of bringing new ideas from their initial lab tests, to field validation, and to final products.

5:00pm **MS+MN-TuA-9 The Unique Challenges Implantable Sensor Manufacture*, Kimberly Chaffin,*** *S Terry,* Medtronic plc **INVITED**

Sensors onboard today's implantable medical devices monitor the critically ill and trigger the delivery of life sustaining and saving therapies. As medicine moves from retrospective treatment to predict and prevent, a transition enabled, in part, by the Internet of Things (IoT), sensors will no longer only be operational in the critically ill, but in all of us. In the future, sensors will have the sole purpose of measuring physiological signs and providing patient centric feedback to prevent future events. Setting aside the psychological challenges of receiving a long-term implant for prevention, this transition to prevent and predict is making the medical device industry rethink sensor manufacture, where the device-biological interface is one of several critical factors. The current design paradigm of isolating implantable device circuitry from the biological environment in hermetic titanium cans, largely limiting the signal to electrical feedthroughs, must shift to allow for new sensor modalities. Chemical sensors must detect biomarkers unhindered by the immune response that accompanies every implant. Optical sensors must 'see' into the body. Pressure sensors must employ sensitive diaphragms where the internal device pressure must remain constant and the fibrotic capsule formation associated with the immune response must not dampen sensitivity. In this talk, we will review the critical manufacturing technologies being developed for implantable sensors that predict and prevent.

Manufacturing Science and Technology Group
Room Hall B - Session MS-TuP

Topics in Manufacturing Science and Technology Poster Session

MS-TuP-1 Formation of High Entropy Film for Cutting Tool by Magnetron Sputtering, ***Ki Buem Kim,*** Sejong University, Republic of Korea*; T Choi,* Sejong university, Korea, Republic of Korea*; H Lee,* Korea Institute of Industrial Technology, Republic of Korea*; J Lee,* Kongju National University, Republic of Korea*; Y Kim,* Sejong University, Republic of Korea*; Y Park, K Kim, S Jeong,* YG-1 Co. LTD, Republic of Korea

Hard coating application is effective way of cutting tool for hard-to-machine materials such as Inconel, Ti and composite materials focused on high-tech industries which are widely employed in aerospace, automobile and the medical device industry also Information Technology. In cutting tool for hard-to-machine materials, high hardness is one of necessary condition along with high temperature stability and wear resistance. In recent years, high-entropy alloys (HEAs) which consist of five or more principal elements having an equi-atomic percentage were reported by Yeh. The main features of novel HEAs reveal thermodynamically stable, high strength, corrosion resistance and wear resistance by four characteristic features called high entropy, sluggish diffusion, several-lattice distortion and cocktail effect. It can be possible to significantly extend the field of application such as cutting tool for difficult-to-machine materials in extreme conditions. Base on this understanding, surface coatings using HEAs more recently have been developed with considerable interest due to their useful properties such as high hardness and phase transformation stability of high temperature.

In present study, the nanocomposite coating layers with high hardness on WC substrate are investigated using high entropy alloy target made a powder metallurgy. Among the many surface coating methods, reactive magnetron sputtering is considered to be a proper process because of homogeneity of microstructure, improvement of productivity and simplicity of independent control for several critical deposition parameters. The N2 is applied to reactive gas to make nitride system with transition metals which is much harder than only alloy systems. The acceleration voltage from 100W to 300W is controlled by direct current power with various deposition times. The coating layers are systemically investigated by structural identification (XRD), evaluation of microstructure (FE-SEM, TEM) and mechanical properties (Nano-indenter).

MS-TuP-2 Plasma Diagnostics Technique using Floating Harmonic Method for Pulsed Plasma Monitoring, ***Yusin Kim,*** Samsung Electronics, Republic of Korea*; C Chung,* Hanyang University, Republic of Korea*; J Kim,* Samsung Electronics, Republic of Korea

Pulsed plasma is widely used in semiconductor manufacturing. For stable production the plasma monitoring is necessary. To measure plasma parameters such as plasma density and electron temperature in pulsed plasma, a method in high time resolution of up to 100 msec was proposed in this study. The basic principle for the measurement of the plasma parameters is to use the measured plasma current which contains fundamental current and its harmonic currents [1]. To obtain data with high time resolution, the measured currents were divided into small pieces of data in a unit time and each data were grouped and calculated. Then plasma parameters in each group were obtained. Finally, the method can measure plasma parameters in the range of msec and the measured results were compared to conventional single Langmuir probe method.

[1] M. H. Lee, S. H. Jang, and C. W. Chung, J. Appl. Phys. 101, 033305 (2007)

MS-TuP-3 Trace Level Detection of Gas Impurities Using Atmospheric Pressure Ionization Mass Spectrometry, ***Gregory Thier,*** Extrel CMS

Analysis of trace amounts of impurities in gases is crucial for applications such as Environmental Monitoring, Catalysis, Semiconductor Production, and others. Atmospheric Pressure Ionization Mass Spectrometry (APIMS) provides a technique for detecting and monitoring very low level impurities in these gases. Atmospheric pressure ionization is a chemical ionization method used in a variety of spectrometry and chromatography analyses. APIMS uses gas-phase ion-molecule collisions at atmospheric pressure for ionization and detection of trace components and impurities. Using an Extrel® VeraSpec™ Trace API Mass Spec, detection limits of less than 5 parts per trillion (ppt) have been observed. By optimizing energy of ion-molecule collisions, these low detection limits have been observed in samples with complex mixtures. This method is used for research applications of gas characterization, but has also been applied to real-time monitoring of gases.

MS-TuP-4 Novel Safe Approach to Process Gas Delivery, ***Richard Elzer,*** Entegris*; K Olander,* Retired co-founder of ATMI Corp

The history of high pressure toxic gases is riddled with safety events, actual injuries and deaths as well as near misses, some reported and many not report. In some cases, the risk profile of these gases has driven organizations to adopt low % gas mixtures that may impact process results.

Technology has been developed to store and deliver pure undiluted (neat) gases in a manner that drastically reduces the risk, with multiple technologies implemented. In one implementation, gas is stored in a gas cylinder and delivered subatmospherically.

In another implementation, gases are stored at high pressure but delivered from the gas cylinder subatmopherically. Both neat gases as well as specialty gas mixtures may be delivered from this gas package.

In a third implementation for processes requiring delivery pressures above atmospheric pressure, gases are stored at high pressure but delivered from the gas cylinder at 100psi. Again, both neat gases as well as specialty gas mixtures may be delivered from this gas package.

We will present the technologies and provide insights

improved process results

Removal of excess impurities

More deliver grams of target gas per cylinder

Insurers and Regulatory Bodies' view and preference for the safe package

Unique classifications by the US DOT

Cylinder sizes and configurations available for various applications

MS-TuP-5 Advanced Characterization to Support Development of Next Generation Phosphors, ***Vincent Smentkowski****, R Davis, J Murphy, A Setlur, M Butts, J Lu,* General Electric Global Research Center*; W Beers,* Current by GE

Over the past decade significant improvements have been made in phosphor technology resulting in improved brightness, color gamut, lifetime and reliability in order to meet market demands for next generation LED Lighting and display technologies. Over 20 billion $K_2SiF_6:Mn^{4+}$ containing LEDs have been sold into the display industry in less than 4 years under GE RadiantRED™ Technology.

Achieving these demands require the development of accurate, and reproducible methods to characterize and monitor the microstructure, surface, subsurface, and bulk chemistry of the phosphor powders (including dopants such as Mn^{4+}). In this poster we will highlight a sub set of the novel analytical techniques we developed with an emphasis on the analysis of dopants and their three dimensional distribution in the phosphor powders. The criticality of sample handling and preparation for accurate analysis will be addressed.

Author Index

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