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A DEDICATED SYNCHROTRON BEAMLINE SUITE FOR ENHANCED VALIDATION OF INTEGRATED CIRCUITS

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INTRODUCTION

In the August 2019 issue of *EDFA* magazine, I and my team members outlined the present state of the art in large area delayering of integrated circuits (ICs), with forward looking prospects for improvements in terms of both hardware and software.[1] As a follow up, this guest column describes the economic and technical benefits of developing a dedicated intergovernmental synchrotron-based tool suite for advanced, high throughput characterization and deprocessing of ICs. This initiative will leverage more than $1 billion in infrastructure investment in one of the world's newest and brightest synchrotron facilities: National Synchrotron Light Source II (NSLS-II) at Brookhaven National Laboratory in Upton, New York. The facility would combine unique synchrotron capabilities with experienced and established technical staff in a manner that cannot be matched by most government or private labs around the world. In the mission to ensure hardware security and combat counterfeit fraud, this initiative will establish a foundation upon which state-of-the-art hardware security may be maintained and advanced without the threat of rapid obsolescence due to the pace of advancing IC technology.

Synchrotrons are, in brief, facilities that provide a source of extremely high brightness, tunable electromagnetic radiation from hard x-ray energies down to infrared radiation for the purpose of materials characterization, materials processing, and fundamental studies. Both the source brightness and the tunability of the source are critical and unique properties of a synchrotron. My first experience with synchrotron-based analytical tools was in 1997 when I was a member of the x-ray photoelectron spectroscopy (XPS) staff at Charles Evans & Associates, now Evans Analytical Group. I was assigned the task of evaluating the use of the micro-XPS endstation at the Advanced Light Source at Lawrence Berkeley National Laboratory as a commercial business. At that time, the lack of automation and poor throughput of the endstations, combined with the programmatic downtime of the synchrotron facilities, made that venture untenable.

Today the situation is far different in a modern third generation synchrotron. A modern beamline experimental endstation may integrate a very high degree of automation with a very stable bright light source to provide orders of magnitude higher efficiency, resolution, and sensitivity than can be achieved with laboratory equipment. However, there still remain barriers to timely access to these powerful facilities, even for other government agencies. Equally important, there is a lack of specialized experimental endstations designed to interrogate large area IC devices. In the next few paragraphs, those challenges will be addressed and the outline of a dedicated facility will be proposed.

CHALLENGES

Timely access is critical for this initiative and is one reason why a dedicated facility with intergovernmental agency access is vital. Traditionally, academics may apply for beamline time through user proposals, which typically have a six-month lead time and a duration of one week for specific experiments. For industry, the preferred option is to engage a partner beamline in a Cooperative Research and Development Agreement (CRADA). At NSLS-II, the National Institute of Standards and Technology (NIST) Synchrotron Science Group operates a suite of three partner beamlines at NSLS-II with a dedicated staff of 10 highly experienced scientists.[2] A CRADA allows industry partners to engage with the NIST staff with timely access to focused problems, which falls squarely within the NIST mission statement to enhance industrial competitiveness. Those interested in further information may reach out to Ron Jones, the lead for synchrotron strategic partnerships.[3]

The NIST beamline suite at NSLS-II is by far the most complex suite of integrated beamlines at the nation's newest synchrotron facility, combining a broad range of energies with nine independent experimental endstations. As such, the NIST beamline suite acts as a successful model for a proposed suite of dedicated beamlines for IC validation, which would combine hard x-ray beamline for tomography with a soft x-ray beamline(s) for hyperspectral large area rapid full-field chemical delayer imaging of full die. I believe a comprehensive solution to IC deprocessing combines high resolution spectroscopic electron-based imaging from backside thinned die of the first several layers with x-ray tomography of the upper layers. Ptychography[4] is beneficial, but not necessarily required, in such an approach. In the previous article,[1] we discussed the "imaging problem" limiting the rate at which high resolution images of IC structures may be acquired. The Large Area Rapid Imaging Analytical Tool (LARIAT) is a "non-scanned" full field hyperspectral chemical imaging system developed through NIST, which is one example of the type of synchrotron-based technology that can be transformative in IC deprocessing.[5] The LARIAT can acquire hyperspectral chemical images over a 20 x 20 mm area in just three seconds (limited currently by camera readout). This is several orders of magnitude faster than the most rapid scanning electron imaging systems. Moreover, due to the tunable monochromatic nature of the source, the x-ray energy is tuned to the species of interest (i.e., silicon, phosphorous, nitrogen, boron, copper, tungsten) to optimize x-ray absorption. Maximizing the x-ray absorption in turn maximizes the secondary electron yield used for energy filtered electron imaging.

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PROPOSAL

Synchrotron-induced electron imaging overcomes laboratory-based electron imaging for rapid IC deprocessing in several important ways: 1) Full field illumination

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eliminates scan speed limits; 2) the tunable x-ray energy maximizes secondary electron yield for chemical imaging; and 3) the high brightness sources optimize chemical sensitivity and throughput relative to laboratory sources. The LARIAT technology roadmap is to achieve <10 nm lateral resolution within the next two years. These large area chemical imaging systems will be paired with x-ray tomography endstations designed to accommodate IC device geometries, as opposed to the typical smaller area geometries in science experiments. Sample handling for ICs is a primary engineering specification for the tomography experimental endstation, which must be considered from the onset to perform the IC deprocessing task. Experimental endstations such as the LARIAT may also evolve continuously to keep pace with technology with relatively minor additional investment. In my opinion, NIST also has a role to play in helping to define and validate the methods and criteria that are being explored to accomplish the measurement objectives. This couples with the need to establish a roadmap document for measurement methods associated with hardware security metrics for detection and validation.

Mechanisms already exist to embed the dedicated beamline suite within a secure facility inside the NSLS-II within Brookhaven National Laboratory. Synchrotron tools would be complemented by a suite of lab-based tools for sample preparation and smaller scale deprocessing and laboratory spaces already exist immediately adjacent to where new beamlines will be placed. This highlights the fact that NSLS-II is not yet fully populated and has both the capacity and infrastructure to add new custom beamlines, another unique and timely opportunity. As a historical benchmark, the NIST beamline suite cost roughly $50 million dollars to build and requires approximately $1 million annually to maintain. Developing optimal endstations with associated specifications for ICs represents a separate cost. The NIST synchrotron staff is an excellent resource to provide onsite technical support and guidance during the design, construction, and operations phase of such a facility. Considering the program expenditures by DARPA[6] and IARPA[7,8] to address this critical mission, this dedicated facility proposal has a strong economic basis. Technically, it would also leverage the most advanced science and infrastructure the United States has to offer, while providing a foundation to develop unmatched capabilities and methods for verification, validation, and root of trust for ICs. These tools also have the potential to benefit the commercial electronics sector for both design and failure analysis. This approach makes economic sense, leverages the highest levels of our nation's science infrastructure, and allows for cooperative synergy among various intergovernmental agencies and international allies.

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Edward L. Principe obtained a Ph.D. in engineering science from The Pennsylvania State University and M.S. and B.S. degrees in mechanical engineering from the University of Central Florida. He is founder and president of Synchrotron Research Inc., a designer and manufacturer of imaging NEXAFS tools. Principe has authored two textbook chapters on FIB-Auger and FIB-based 3D nanotomographic reconstruction and co-authored the EDFAS Best Paper in 2013 and EDFAS Outstanding Paper in 2017. He holds two patents in FIB-based 3D reconstruction and is focused on the development of computational guided microscopy.