The Science of Electronics in Extreme Electromagnetic Environments II – Circuit Effects

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***Abstract*—This abstract covers Part-II of a two-part presentation series on the scientific advancements made in the AFOSR/AFRL Center of Excellence (CoE) for Electronics in Extreme Electromagnetic Environments, spanning the time-period 2015-present. In specific, this presentation focuses on the development and experimental validation of statistical and deterministic physics-based predictive models describing the functional state of electronic devices (semiconductor, electro-optic and quantum), and the amalgamation of these devices to circuits and subcomponents, when subjected to extreme electromagnetic interference (EEMI). This presentation follows a companion presentation [1] which discusses the development and experimental validation of statistical and deterministic physics-based models describing coupling paradigms for EEMI in complicated enclosures which houses these sensitive electronic devices, circuits and subcomponents. Taken together, the two presentations advance the state-of-the-art in fundamental physics-based modeling of current and future electronic technologies in extreme electromagnetic environments.**

I. INTRODUCTION

The susceptibility and vulnerability of complex digital electronic systems to extreme electromagnetic interference (EEMI) from unintentional and intentional sources is a growing concern with the Electromagnetic Compatibility (EMC) test community. In many cases, rigorous EMI/EMC testing of such complex digital electronic systems to EEMI stimulus with varying spectral content, temporal properties (EEMI pulse width, EEMI pulse repetition frequency) and incident power densities can prove to be prohibitive in terms of costs, personnel and testing resources required. Thus, predictive models for EEMI susceptibility and vulnerability of complex digital electronic systems that are based on the fundamental physics describing the interaction of EEMI waveform parameters with electronic devices, components and subsystems, is vital towards developing appropriate scaling-laws for EMC compliance margins as well as for setting the paradigm for designing future electronic systems which are resistant to EEMI.

Taking the contextual example of a generic Personal Computer (PC), as a complex digital electronic system subjected to EEMI, Figure 1 highlights the scope of our research endeavor under the AFOSR/AFRL CoE. A companion paper focused on the right portion of Figure 1 and this paper focuses on the left.

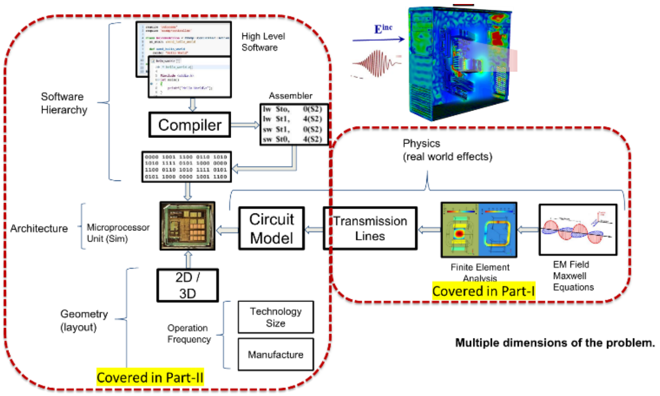

Figure 1: Scope of the AFOSR/AFRL CoE Research

In Section II, we present an overview of our technical contributions in the different topical areas delineated in Figure 1.

II. OVERVIEW OF TECHNICAL CONTRIBUTIONS

A. Nonlinear EEMI Effects on Semiconductors, Electro-Optic Photonic Materials, Quantum-Dots and Plasmonic nanostructures

In this research topical area, we have developed analytical models for elemental NMOS, PMOS, ESD devices, elemental logic circuits and shift registers for varying device sizes (180 nm down to 65 nm). We have developed and validated scaling laws for device failure as a function of EEMI signal amplitude and frequency. In addition, we are developing predictive models for RF injection in data transmission digital systems. Our model predicts and characterizes the impact of EEMI on the quality of data transmission using eye-diagram parameters. We have found that the impact of EEMI injection on eye height depends primarily on the level of injected noise and its frequency, whereas the width of the eye depends not only on the level of injected noise and its frequency, but it also depends heavily on the bit rate of the data transmission. We also developed a model for bit-error-rate (BER) as a function of the eye-diagram parameters.

We are also investigating the vulnerability of electronics to EEMI at the small circuit, device (transistor) and sub-device levels. These vulnerabilities can lead to both soft errors and hard failures. The soft error is due to bit flips and system latch-ups that can be corrected by re-booting. The hard failure is a permanent damage to the individual devices (transistors), which are mainly Metal-Oxide Semiconductor Field Effect Transistors

(MOSFETs); the EEMI-related hard failures can degrade or even destroy the operability of the circuit. For soft errors, we study the internal mechanisms within a MOSFET that can be activated by transient high-level EEMI disruptions, including impact ionization and the snapback phenomenon. For hard failures, we are focusing on MOSFET gate oxide damage and rupture, due to high voltages and thermal effects. We have developed and continue to refine analytic models to compute the stochastic drain-source current through a single MOSFET as a consequence of (possibly) simultaneously stochastic gate-source and drain-source voltages, and to compute the probability of its functional failure as a consequence of such stochastic gate and drain voltages.

Our research group has also been working on integration of photonics and efficient light sources for robust optical interconnects that are insensitive to EEMI interference by exploring two approaches. The first is based hybrid integration of III-V semiconductors with Si, which combines the most promising material for light emission with the most scalable optical platform. We have successfully integrated quantum dots with a silicon photonic on-chip filter based on a ring resonator. The filter is compact and requires only 10 um footprint, making ideally suited for compact and scalable integration. We showed that the filter could efficiently route light with narrow bandwidth, and further improvements could fast switchable filters that are suitable for high efficiency wavelength and time-division multiplexing. In the second approach, we worked with another promising material platform, thin-film lithium niobate (LN). This emerging material combines the high electro-optic coefficient of lithium niobate with the efficient optical emission of rare-earth (RE) ions, which serve as the core technology for fiber amplifiers, the primary workhorses of the internet. This combination enables compact on-chip light emitters that can serve as sources for optical interconnects and transmit data at high bandwidths. In 2019, for the first time, we demonstrated integration of RE ions with thin-film LN. We showed that implanting RE ions in to thin-film LN does not degrade their properties, making them suitable for on-chip light emission.

We have also focused on pushing the boundaries for the development and fabrication of quantum dots at specific wavelengths (1100-1300 nm) using epitaxial processes including features such as distributed drag reflectors.

B. *Mathematical Frameworks for Modeling EEMI Effects on Digital Logic Circuits*

Recognizing that while the interaction of the EEMI with electronic devices occurs at the physical level, as demonstrated through our research delineated in Section II.A, the manifestation of this effect typically occurs at the functional level – in terms of observable software glitches and software lockups. For tractability, our research group has also been developing stochastic mathematical frameworks describing the erroneous behavior of software processes when the underlying hardware CMOS logic devices are stressed due to EEMI.

Inspired by the field of fluid-dynamics, we have combined the Navier-Stokes and Hamilton-Jacobi equations for evaluating the effects of EEMI for the empirically observed cascading of software failures on a complicated computing system exposed to EEMI. We have experimentally demonstrated the validity of this mathematical framework utilizing a simplified circuit comprising a series D-flipflops.

We have also advanced our understanding of the impact of EEMI pulses on the software execution of instructions on an elementary microcontroller. We demonstrated a relationship between the onset and width of the incident EEMI pulse with respect to the natural clock-cycle timing of the microcontroller and developed a probabilistic model using conditional probabilities to show the probability that a software script, comprising a series of different instruction cycles, will successfully execute/be affected due to EEMI injection. Building up on these research accomplishments, we have demonstrated the impact of machine pipelining architectures and augmented our probabilistic model to include pipelined architectures, which is more relevant to microcontroller architectures today. In addition, we showed a correlation in the susceptibility response of different types of instructions that belong to specific class of instruction cycles (memory, ALU, data operations) and its impact on creating reproducible and predictable outcomes in register contents.

III. CONCLUSIONS

Through this CoE, our research group has taken a forward-looking approach towards not just understanding and modeling the physics-based susceptibility mechanisms in existing semiconductor devices and circuits, but also studying EEMI induced upset and failure modes in electronic technologies which are slated to becoming mainstream in the next decade. Further details on our research contributions, publications and presentations can be found in [2].

ACKNOWLEDGEMENT

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REFERENCES

[1] The Science of Electronics in Extreme Electromagnetic Environments I- Coupling, E. Schamiloglu et.al., NRSM Presentation Talk, 2021.

[2] See http://ece-research.unm.edu/AFOSR-COE/index.html for an extended publication list