3-D ICs as a Platform for IoT Devices

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Abstract— **3-D ICs are a natural platform for IoT devices. IoT devices exhibit a small footprint, integrate disparate technologies, and require long term sustainability (extremely low power or self powered). The 3-D structure exhibits opportunities essential for IoT devices, including heterogeneity, small form factor, and reduced power dissipation, making 3-D integration a favorable candidate for IoT devices. The challenges of IoT devices and related opportunities of 3-D integration are discussed in this paper. The 3-D structure is shown to enable hybrid energy harvesting and improved security capabilities to ensure trusted IoT systems. Physical and cyber security threats are both naturally reduced in 3-D ICs.**

I. INTRODUCTION

The Internet of Things (IoT) is a novel computing paradigm based on connecting physical devices to the global network. IoT devices should typically exhibit the following characteristics [1], [2]: (1) small physical dimensions, (2) communication (typically wireless) capability, (3) sensing/actuation modality, and (4) low energy consumption. In addition to these key characteristics, IoT devices operate in extreme environments, such as automotive engines, industrial facilities, building automation, home appliances, and corrosive surroundings such as within or on the human body. IoT devices withstand hostile environments such as increased and highly variable temperatures, liquid immersion, and significant vibration.

Three-dimensional (3-D) integrated circuits (ICs) are a platform for heterogeneous integration, exhibiting a small form factor [3]. These traits of 3-D ICs make the 3-D platform a natural match for IoT devices. The disparate technologies of IoT devices, including MEMS sensors and actuators, RF and wireless communication, energy harvesting circuitry, and computational logic, can be integrated as individual layers within the 3-D structure [4], [5]. Interface circuits should effectively communicate information from the IoT sensors to the relevant layer(s) within a 3-D IC, and from the on-chip controllers within a 3-D system to the IoT actuators.

The layers within the 3-D IC are connected by through substrate vias (TSVs). The TSVs are short vertical interconnections (typically 20 µm in length and 2 to 4 µm in diameter [3]) that carry a variety of signals (power, clock, and data) between different layers within a 3-D IC. The TSVs alleviate global signaling issues (less power dissipated by the interconnects) [3].

The rest of the paper is composed of the following sections. Common IoT circuits and substrate materials are reviewed in Section II. Challenges of IoT devices are described in Section III. Opportunities for integrating IoT circuits within a 3-D platform are discussed in Section IV. Some conclusions are offered in Section V.

II. COMMON IOT CIRCUITS AND SUBSTRATE TYPES

Each layer in a 3-D IC is individually fabricated using a process optimized for that application [3]. Different substrate materials are compatible with different circuits. The electrical, thermal, mechanical, and optical properties of each substrate material used in common ICs for IoT devices are listed in Table I.

Each of the substrate materials listed in Table I is beneficial for a certain type of circuit. Silicon (Si) is typically lower cost and technologically more mature than all of the other materials listed in Table I and is therefore used for mainstream, high complexity processor and memory applications. Polyethylene terephthalate (PET) is widely used in industry with low cost and high transparency [6]. PET is used as the substrate of p-i-n type solar cells and is compatible with the traditional deposition process of solar cells on glass substrates [6]. Thermoelectric generators (TEG) typically consist of multiple pairs of p-type and n-type bismuth telluride (Bi_2Te_3) thermoelectric structures, which produce electrical energy by employing the temperature gradient between the hot surface (human body) and the cold surface (ambient air) [7], [8]. Aluminum nitride (AlN) is commonly used for piezoelectric devices as this material can be processed by CMOS-compatible technologies at low temperature (200 to 400 °C). AlN also exhibits higher phase velocity and a moderately high piezoelectric coefficient than other piezoelectric materials (*e.g.*, GaN and ZnO). Piezoelectric sensors support harvesting kinetic energy from the ambient. This energy originates from vibrations and other physical movement. Piezoelectric sensors capture and transform these motions into electrical energy. The superior electron mobility and direct bandgap of gallium arsenide (GaAs) makes GaAs attractive for certain high performance digital and analog devices. Germanium (Ge) is also a favorable substrate material for photovoltaic and photodetector applications due to its high absorption coefficient. Military and space application that require high quality infrared detectors commonly use mercury cadmium telluride (HgCdTe) which

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TABLE I

COMMON CIRCUITS AND COMPATIBLE SUBSTRATE TYPES

Applications	**Substrate materials**	**Electrical resistivity $\Omega \cdot$ cm**	**Thermal conductivity W/(m°K)**	**Refractive index**	**Young's modulus GPa**	**Thermal expansion coefficient at 300°K 10^{-6}/°K**	**Wavelength range nm**
Processor/ memory	Silicon (Si)	1 to 10	138	3.42 to 3.48	130 to 185	2.6	400 to 1,060
Solar cells	Polyethylene Terephthalate (PET)	$1 \cdot 10^{16}$	0.2	1.58 to 1.64	2 to 2.7	3.9	400 to 1,600
Thermoelectric	Bismuth Telluride (Bi_2Te_3)	$0.6 \cdot 10^{-3}$	1.2	9.2	50 to 55	1.3	400 to 2,500
Piezoelectric	Aluminum Nitride (AlN)	$1 \cdot 10^{14}$	140 to 180	1.9 to 2.2	308	5.27	1,000 to 1,500
RF/analog	Gallium Arsenide (GaAs)	$4 \cdot 10^{7}$	40	3.93	85.9	6.86	650 to 870
Photonics	Germanium (Ge)	$1 \cdot 10^{-3}$	45	4.01 to 4.05	102.7	5.8	600 to 1,600
Space/ detectors	Mercury Cadmium Telluride (HgCdTe)	2	0.2	4	42 to 48	4.7	2,000 to 5,400

has a tunable bandgap ranging from 0.1 eV to 1 eV [9]. This property of HgCdTe supports detection of long wavelengths of light. Each of these technologies can support a variety of IoT applications while comfortably fitting into a single 3-D system.

III. CHALLENGES OF IOT DEVICES

IoT devices are intended for a multitude of applications including smart cities and grids, health care, factories, wearable devices, and many other systems. The challenges of IoT ICs are posed by the unique environments and requirements of IoT. These challenges are reviewed in the following subsections.

A. Environmental effects

In common commercial ICs, the heat generated by integrated circuits is moved from the IC into the ambient, lowering the on-chip temperature. The increased ambient temperature in cars and factories, important IoT applications, can significantly affect the performance of IoT devices. IoT devices used in high ambient temperature applications require unique thermal solutions including expensive technologies such as liquid cooling.

Another important environmental effect is the electric and magnetic fields that exist in both indoor and outdoor settings. Smart power grids include IoT devices for monitoring and intelligent diversion of current to loads [10]. Significant magnetic fields are generated by the large currents propagating within the power grid that affect the IoT devices. Magnetic coupling can lead to loss of data in memory cells and performance degradation in processors [11], [12]. This challenge, however, can become an opportunity if the electromagnetic waves available in the ambient are harvested to power the IoT devices, as described in Subsection III-B.

Additional environmental challenges include mechanical and chemical effects. IoT devices may be submerged in liquids (*e.g.*, inside a human body or within a water delivery system). Contact with liquids may lead to an electrical short circuit destroying the IoT device. If the package is water proof, corrosion may slowly degrade the structure of the device, affecting long term reliability. Mechanical stress can also ruin the device due to fractures in the substrate and detachment of mechanical (*i.e.*, MEMS) parts and I/O bonding wires.

The reliability of IoT devices is a key challenge since replacing these devices can be cumbersome and costly. In certain cases, for example, IoT devices implanted within the human body, replacement of faulty components may require difficult procedures. In other cases, such as space applications, replacement of IoT devices may be impractical.

B. Powering IoT devices

Many IoT devices are intended to be self powered. Some low cost and easily accessible devices can be replaced when the battery becomes depleted; however, other devices are dependent on alternative forms of energy to prolong the lifetime of the device.

Four basic forms of energy exist in the ambient [13], (1) thermal, (2) electromagnetic (EM), (3) solar, and (4) kinetic. The most common energy harvesting circuits target solar and electromagnetic energy. It has been experimentally shown that the ambient exhibits EM power densities of 0.1 to 1 μW/cm^2 [14], [15]. The available solar power density in the ambient is on the order of mW when illuminated using the standard global solar irradiance spectrum [16]. Although the available solar power density is significantly larger than the EM power density, the conversion efficiency of solar to electric power is around 10% [17]. The magnitude of the harvested thermal (using TEG) and kinetic (using piezoelectric device) power is, respectively, 0.52 mW and 8.4 mW [13].

IV. 3-D ICS AS A PLATFORM FOR IOT DEVICES

An example of a 3-D structure for IoT devices is depicted in Figure 1. Four types of energy harvesting, communications, processing, memory, and actuator devices, are integrated within a single 3-D structure. Opportunities for IoT devices enabled by 3-D ICs are described in the following subsections.

A. Energy harvesting

Hybrid energy harvesting circuits have recently been developed for solar and EM energy [18]. The 3-D platform, however, supports integrating the available energy harvesting techniques within a single structure. In addition to

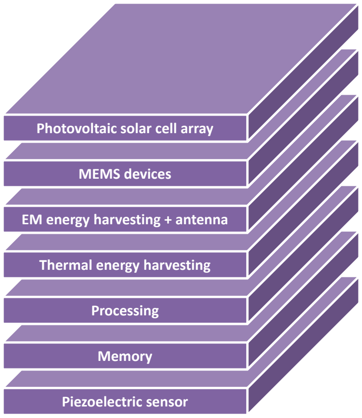

Fig. 1. Example of 3-D structure for IoT devices.

harvesting multiple sources of energy (solar, EM, thermal, and kinetic, see Figure 1), the power efficiency of delivering the harvested power to the load in 3-D ICs is higher than in conventional two-dimensional ICs. Each energy harvesting circuit benefits from different substrate materials. For example, efficient solar cells have been demonstrated on a PET substrate [6], while thermoelectric circuits are commercially available using a Bi_2Te_3 substrate [7]. The 3-D platform supports the integration of these heterogeneous substrates within a single, small platform.

Transmission devices typically consume significant power to transmit data. The power overhead originates in initializing the transmitter. To lower this power overhead, memory arrays are sometimes included in IoT devices. The data is stored in memory and transmitted at a later time when a sufficient amount of data has been accumulated. Advanced memory technologies can also be seamlessly integrated within 3-D ICs, exploiting ferromagnetic substrate materials and the short distance to the computational layer, as illustrated in Figure 1.

B. Thermal opportunity

Thermal mitigation is a key issue in 3-D ICs. Applied to IoT devices, however, this issue becomes an opportunity. TEG devices, typically unsuitable for mainstream processor/memory applications, can exploit the additional heat within the 3-D system to generate current. As shown in [19], [20], the horizontal thermal paths in 3-D ICs are significantly more thermally conductive than the vertical paths. This attribute benefits the thermoelectric effect since larger lateral temperature gradients increase the generated current.

C. TSVs - more than interconnects

TSVs are a seminal component of 3-D ICs. The TSVs carry signals between the different layers within a 3-D system. Alternatively, TSVs can be used for special circuit structures within a 3-D IC [21]. One important example, an antenna, is useful for IoT devices.

TSVs can also be used as a decoupling capacitor. A pair of TSVs exhibit a coupling capacitance that can be exploited to temporarily store charge. To enhance the capacitive storage, TSV bundles can be used consisting of an array of TSVs. A TSV-based decoupling capacitor bundle is depicted in Figure 2. The total decoupling capacitance is the sum of the parallel capacitances. A three by three TSV bundle exhibits a coupling capacitance of approximately 1.5 fF [22].

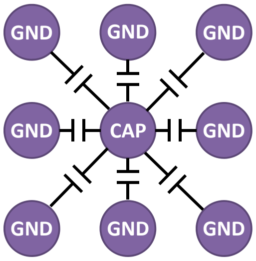

Fig. 2. Decoupling capacitance within a three by three TSV bundle.

D. Security for IoT devices

Security is another important topic in IoT. The 3-D structure provides a platform to mitigate both physical and cyber attacks. An example of a secure 3-D IC for IoT devices is illustrated in Figure 3. Separate fabrication of layers increases security by providing only partial design information to each manufacturer (assuming the layers are fabricated by different contractors). Trusted foundries may be used for certain portions of the 3-D IC (the trusted layers). This approach prevents supply chain attacks such as IP piracy, overbuilding, and hardware trojans [23]. In IP piracy, the attacker can reverse engineer to obtain the original netlist of the circuit, thereby extracting the circuit functionality. Overbuilding is used to obtain illegal copies of a fabricated design by exploiting existing processing steps. Insertion of hardware trojans can alter circuit functionality (by changing logic gates or connectivity), or decrease reliability (by affecting the fabrication process). To mitigate supply chain attacks on untrusted layers, design-for-security (DFS) circuits can be integrated within the trusted layers, providing an additional layer of security [23].

IoT devices may also become targets of cyber attacks. Fault injection attacks apply forms of energy radiation (EM, solar, etc.) to inject an incorrect state on a node within a circuit, thereby influencing the system output to reveal a secret key to encode the transmitted data. Power attacks consist of observing the power consumed by a system (assuming that increased power consumption is correlated with specific logical operations) and either directly or statistically deduce the key. The heterogeneous nature of 3-D ICs provides an inherit defense against fault injection attacks. The sensitive layers can be embedded in the middle of the structure (far from the ambient). This location prevents external radiation to reach and affect the internal nodes of a circuit. Specifically in IoT devices where energy harvesting circuits are heavily utilized, the attacking radiation can be harvested to power the device. The heterogeneous nature of 3-D ICs also assists in preventing power attacks. Many disparate devices are integrated

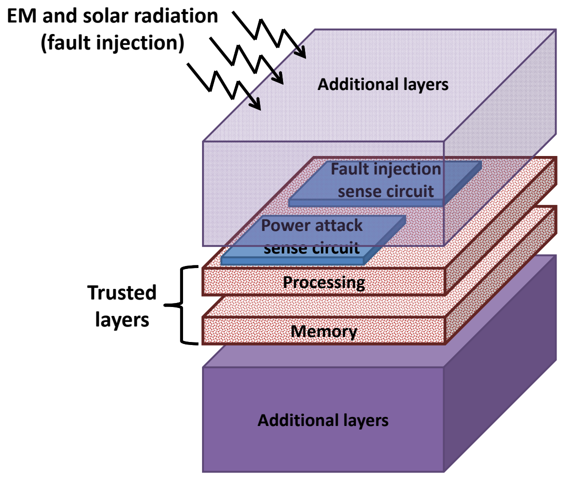

Fig. 3. Example of a secure 3-D structure for IoT devices.

within a single system creating an *electronic storm* within the 3-D structure, making the system difficult to correlate between logical computations and power consumption [23].

V. CONCLUSIONS

3-D ICs are a natural platform for IoT devices. Multiple challenges however block the path for IoT becoming a mainstream technology. The 3-D structure provides opportunities to enhance the internal power and external communication of IoT devices. 3-D ICs provide a platform for heterogeneous integration of the disparate technologies required for IoT systems, including different substrate materials and unique processing of individual layers.

Hybrid power harvesting of all four energy forms available in the ambient is supported by the 3-D structure, leading to self sustainable miniature, intelligent systems. The 3-D platform also provides a small form factor necessary for small footprint IoT devices.

TSVs can facilitate different on-chip circuits and devices. TSV-based antennas can enhance data transmission. Decoupling capacitors formed within the TSV bundles provide on-chip local charge storage.

3-D ICs also provide a platform for increased security to be integrated within the structure. Trusted layers can be fabricated by trusted providers, concealing sensitive circuits and including DFS circuitry. The 3-D structure also provides a natural defense against cyber attacks.

REFERENCES

[1] D. Blaauw, D. Sylvester, P. Dutta, Y. Lee, I. Lee, S. Bang, Y. Kim, G. Kim, P. Pannuto, Y. S. Kuo, D. Yoon, W. Jung, Z. Foo, Y. P. Chen, S. Oh, S. Jeong, and M. Choi, “IoT Design Space Challenges: Circuits and Systems,” *Proceedings of the IEEE Symposium on VLSI Technology*, pp. 1 – 2, June 2014.

[2] T. Wan, E. Salman, and M. Stanacevic, “A New Circuit Design Framework for IoT Devices: Charge-Recycling with Wireless Power Harvesting,” *Proceedings of the IEEE International Symposium on Circuits and Systems*, pp. 2046 – 2049, May 2016.

[3] V. F. Pavlidis and E. G. Friedman, *Three-Dimensional Integrated Circuit Design*, Morgan Kaufmann, 2009.

[4] S. Carreon-Bautista, L. Huang, and E. Sanchez-Sinencio, “An Autonomous Energy Harvesting Power Management Unit With Digital Regulation for IoT Applications,” *IEEE Journal of Solid-State Circuits*, Vol. 51, No. 6, pp. 1457 – 1474, June 2016.

[5] A. Klinefelter, N. E. Roberts, Y. Shakhsheer, P. Gonzalez, A. Shrivastava, A. Roy, K. Craig, M. Faisal, J. Boley, S. Oh, Y. Zhang, D. Akella, D. D. Wentzloff, and B. H. Calhoun, “21.3 A 6.45 μW Self-Powered IoT SoC with Integrated Energy-Harvesting Power Management and ULP Asymmetric Radios,” *Proceedings of the IEEE International Solid-State Circuits Conference*, pp. 1 – 3, February 2015.

[6] J. Ni, J. Zhang, J. Xue, X. Wang, L. Cao, C. Wu, S. Xiong, X. Geng, and Y. Zhao, “Effect of Pretreatment on PET Films and its Application for Flexible Amorphous Silicon Solar Cells,” *Proceedings of the IEEE Photovoltaic Specialists Conference*, pp. 293 – 296, June 2009.

[7] Micropelt, “Thermogenerators,” 2016. [Online]. Available: http://www.micropelt.com/thermogenerator.php.

[8] C. Lu, S. P. Park, V. Raghunathan, and K. Roy, “Efficient Power Conversion for Ultra Low Voltage Micro Scale Energy Transducers,” *Proceedings of the IEEE Design, Automation, and Test Conference in Europe*, pp. 1602 – 1607, March 2010.

[9] A. L. Betz and R. T. Boreiko, “Space Applications for HgCdTe at FIR Wavelengths between 50 and 150 um,” *Proceedings of the SPIE Materials for Infrared Detectors*, pp. 1 – 9, November 2001.

[10] A. Kheaksong, A. Prayote, and W. Lee, “Performance Evaluation of Smart Grid Communications Via Network Simulation Version 3,” *Proceedings of the IEEE International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, pp. 1 – 5, June 2016.

[11] E. A. Gutierrez-D. and P. Garcia-R., “RF Magnetic Emission and Electrical Coupling in Silicon Integrated Circuits,” *Proceedings of the IEEE International Caribbean Conference on Devices, Circuits and Systems*, pp. 1 – 5, April 2008.

[12] S. Tanaka, P. Fan, J. Ma, H. Aoki, M. Yamaguchi, M. Nagata, and S. Muroga, “Analysis of On-Chip Digital Noise Coupling Path for Wireless Communication IC Test Chip,” *Proceedings of the IEEE International Caribbean Conference on Devices, Circuits and Systems*, pp. 216 – 221, November 2015.

[13] A. Georgiadis, “Energy Harvesting for Autonomous Wireless Sensors and RFID’s,” *Proceedings of the IEEE General Assembly and Scientific Symposium*, pp. 1 – 5, August 2014.

[14] Y. Kawahara, K. Tsukada, and T. Asami, “Feasibility and Potential Application of Power Scavenging from Environmental RF Signals,” *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, pp. 1 – 4, June 2009.

[15] H. J. Visser, A. C. F. Reniers, and J. A. C. Theeuwes, “Ambient RF Energy Scavenging: GSM and WLAN Power Density Measurements,” *Proceedings of the IEEE European Microwave Conference*, pp. 721 – 724, October 2008.

[16] D. G. Collins, W. G. Blattner, M. B. Wells, and H. G. Horak, “Backward Monte Carlo Calculations of Polarization Characteristics of the Radiation Emerging from Spherical Shell Atmospheres,” *Applied Optics*, Vol. 11, No. 11, pp. 2684 – 2696, November 1972.

[17] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, “Solar Cell Efficiency Tables (Version 38),” *Progress in Photovoltaics: Research and Applications*, Vol. 19, No. 5, pp. 565 – 572, August 2011.

[18] I. J. Hwang, D. Kwon, D. J. Lee, J. W. Yu, and W. S. Lee, “EM/light Hybrid Energy Harvesting with Directional Dipole Antenna for IoT Sensor,” *Proceedings of the IEEE Antennas and Propagation Society International Symposium (USNC/URSI National Radio Science Meeting)*, pp. 1292 – 1293, July 2015.

[19] B. Vaisband, I. Savidis, and E. G. Friedman, “Thermal Conduction Path Analysis in 3-D ICs,” *Proceedings of the IEEE Symposium on Circuits and Systems*, pp. 594 – 597, June 2014.

[20] I. Savidis, B. Vaisband, and E. G. Friedman, “Experimental Analysis of Thermal Coupling in 3-D Integrated Circuits,” *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, Vol. 23, No. 10, pp. 2077 – 2089, October 2015.

[21] K. Salah and Y. Ismail, “New TSV-Based Applications: Resonant Inductive Coupling, Variable Inductor, Power Amplifier, Bandpass Filter, and Antenna,” *Proceedings of the IEEE International New Circuits and Systems Conference*, pp. 1 – 4, June 2015.

[22] B. Vaisband and E. Friedman, “Hexagonal TSV Bundle Topology for 3-D ICs,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, 2016, in press.

[23] Y. Xie, C. Bao, C. Serafy, T. Lu, A. Srivastava, and M. Tehranipoor, “Security and Vulnerability Implications of 3D ICs,” *IEEE Transactions on Multi-Scale Computing Systems*, Vol. 2, No. 2, pp. 108 – 122, April 2016.