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# Heterogeneous 3-D ICs as a Platform for Hybrid Energy Harvesting in IoT Systems

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***Abstract*— Three-dimensional integrated circuits are a natural platform for IoT systems. IoT systems exhibit a small footprint, integrate disparate technologies, and require long term sustainability (extremely low power or self-powered). A hybrid energy harvesting system within a three-dimensional integrated circuit is proposed in this paper. The harvesting system exploits different types of energy available from the ambient (electromagnetic, solar, thermal, and kinetic). Integration of the hybrid harvesting system onto a three-dimensional platform ensures that each type of harvested energy can be individually collected. Both static and dynamic evaluations of a hybrid energy harvesting system are provided. For an example IoT system, the static power requirements are approximately 85% of the power delivered to the load. In the dynamic evaluation, a range of activity factors characterizing the load and different storage capacitors are considered. The power requirements of a typical IoT system are shown to be satisfied by a hybrid energy harvesting system within a 3-D platform.**

***Index Terms*— 3-D IC, internet of things, hybrid energy harvesting, heterogeneous integration.**

## I. Introduction

The Internet of Things (IoT) is a novel computing paradigm based on connecting physical devices to the global network. IoT devices typically exhibit the following characteristics [1]: (1) small physical dimensions, (2) communications (typically wireless) capability, (3) sensing/actuation modality, and (4) low energy consumption. In addition to these key characteristics, IoT devices often operate in extreme environments, such as automotive engines, smart homes, industrial facilities, home appliances, and corrosive surroundings such as within or on the human body. IoT devices need to 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, and exhibit a small form factor [2]. These traits of 3-D ICs make 3-D integration a natural platform for IoT devices [3]. 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 a 3-D structure. Interface circuits efficiently communicate 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 a 3-D IC are connected by through substrate vias (TSVs) [4]. The TSVs are short vertical interconnections (typically 20 μm in length and 2 to 4 μm in diameter [2]) that carry a variety of signals (power, clock, and data) between different layers within a 3-D IC.

IoT devices are typically intended to be self-powered [5], [6]. 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 lifetime. Four basic forms of energy exist in the ambient [7], (1) electromagnetic (EM), (2) solar, (3) thermal, 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$^2$ [8]. The available solar power density in the ambient is on the order of mW when illuminated using the standard global solar irradiance spectrum [9]. The magnitude of the harvested thermal power, using a thermoelectric generator (TEG), and kinetic power, using a piezoelectric device is, respectively, 0.52 mW and 8.4 mW [7]. The different types of energy in the ambient and the range of harvested power are summarized in Table I.

Hybrid energy harvesting circuits have recently been developed for solar and EM energy [10]. The 3-D platform, however, can integrate available energy harvesting methods within a single structure. In addition to harvesting multiple sources of energy (solar, EM, thermal, and kinetic, see Figure 1), the power efficiency of delivering harvested power to the load in 3-D ICs is higher than in conventional two-dimensional (2-D) ICs. Each energy harvesting circuit benefits from different substrate materials. For example, efficient solar cells have been demonstrated on a PET substrate [11], while thermoelectric circuits are commercially available using a $Bi_2Te_3$ substrate [12]. Several energy harvesting and management techniques for powering IoT devices, applicable to any

TABLE I

Typical harvested power for different energy types available from the ambient [7]–[9]

| Energy type | Harvested power |
|---|---|
| EM | 0.1 to 1 μWatt |
| Solar | 1 to 10 mWatt |
| Thermal | 0.52 mWatt |
| Kinetic | 8.4 mWatt |

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