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Heterogeneous integration of autonomous systems in package for wireless sensor networks

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Abstract

The concept of Energy Harvester in Package (EHiP) is focused on the vertical heterogeneous integration of a MEMS die, dedicated to scavenge energy, with another auxiliary chip which includes the control and power management circuitry, sensors and RF capabilities. Based on this concept, we have developed and characterized several approaches for piezoelectric and electrostatic transductions to extract energy from the harmonic motion generated by a permanent magnet attached to the EHiP and placed in the surroundings of a cable of the power grid, i.e. an alternate electromagnetic field, in addition to the ambient mechanical vibrations.

Keywords: Energy harvesting; Energy scavenging; EHiP; Energy Harvester-in-Package; CMOS Integration; CMOS-MEMS;

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1. Introduction

In the near future, hundreds of wireless sensor nodes spread all around our ambient and even our body will be continuously receiving and sending information, measuring data and working together to make more complex calculations. The main difficulty to make this vision real is the way of powering all these tiny devices. The charge or replacement of batteries is not feasible when we have a large number of nodes or they are body implanted. The notion of energy scavenging has received a huge attention during the last years because of the need of finding an autonomous way of supplying this type of ultralow-power integrated systems. There are three common methods to convert the mechanical energy into electricity: electromagnetic, piezoelectric and electrostatic. In this work, only the two last transduction types have been utilized.

2. Energy Harvesting in Package

The concept of Energy Harvester in Package (EHiP) [1-2] becomes an excellent platform to build vibration energy scavenging systems. It is focused on the vertical heterogeneous integration of a MEMS die, which plays the double role of inertial mass and transduction unit, with another auxiliary chip which includes the control and power management circuitry, sensors and RF capabilities (Fig 1). It has two main advantages, the increase of the power density, compared with the traditional approach, and the resonance tunability by adaptation of the movable die mass. In addition, it allows reaching lower frequency values because of the mass increase, enabling the matching between

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the device resonance frequency and the acceleration peaks of the most common vibration sources available in industrial and residential ambients.

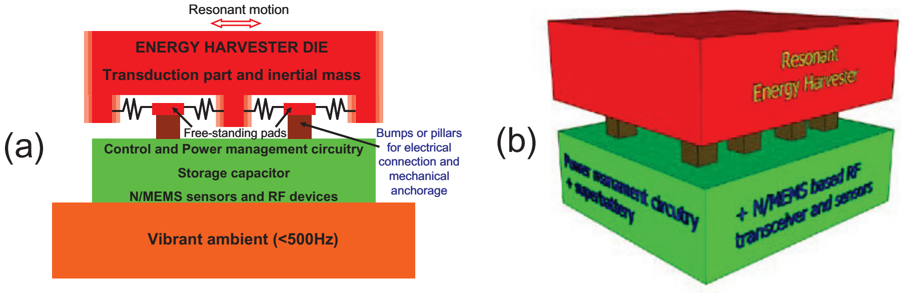


Fig. 1. Diagram of Energy Harvester-in-Package (EHiP) concept (a) and 3D model (b).

Based on this concept, we have developed and characterized several approaches depending on the transduction, piezoelectric and electrostatic, and the vibration source. Regarding the last point, we have used the vibration generated when attaching a permanent magnet to our EHiP that is placed in the surroundings of a power grid cable, i.e. an alternate electromagnetic field [1], in addition to the ambient mechanical vibrations.

2. Electrostatic transduction

The first device based on the same ideas involved in the EHIP concept was fabricated in a standard CMOS technology [2], demonstrating the feasibility of integrating large MEMS structures in a commercial technology (Fig 2a). In order to overcome the issues found with the previous CMOS device, the dedicated MEMS die shown in Fig 2b has been fabricated with MEMSOI technology [3]. A pseudo flip-chip technique has been performed to achieve the first heterogeneous integration of an EHiP-concept based device. The MEMS die, which is fully dedicated to harvest energy, is placed on top of another chip to be powered. In order to perform a preliminary characterization, a test PCB with raised pads connected through two metallic tracks was used to get an electrical output of the total capacitance of the structure.

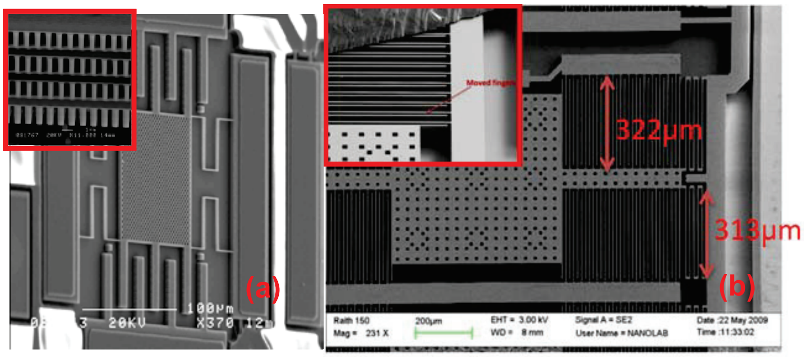
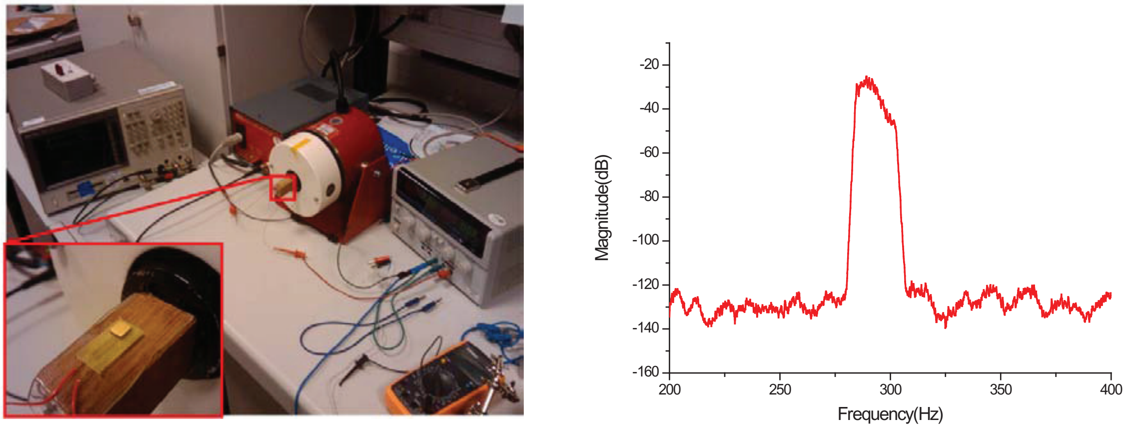


Fig. 2. SEM images of free-standing pads, suspensions and comb drivers of the chip integrated in (a) a standard CMOS technology (Inset: cross section of compound layer) and (b) fabricated with SOI-MEMS technology. (Inset: detail of finger displacement.).

The resonant frequency measurement has been carried out with a low-frequency network analyzer. A power amplifier was used to supply the commercial shaker where the assembled system was mounted (Fig 3a). An AHDL model of this device has been developed and several power management circuit architectures have been investigated. A maximum ideal power of 20 μW can be achieved with an initial voltage of 10 V (Fig 3b).

The measurement setup was formed by a network analyzer in order to measure the capacitive current resulting from a frequency sweep around the resonance value. The device has been excited with the shaker V20 SignalForce from G&W powered by the power amplifier PA100E SignalForce from G&W (Fig 3a). The measured resonance peak is centred at a frequency of 289 Hz with a quality factor of around 30 for a DC voltage of 6 V.



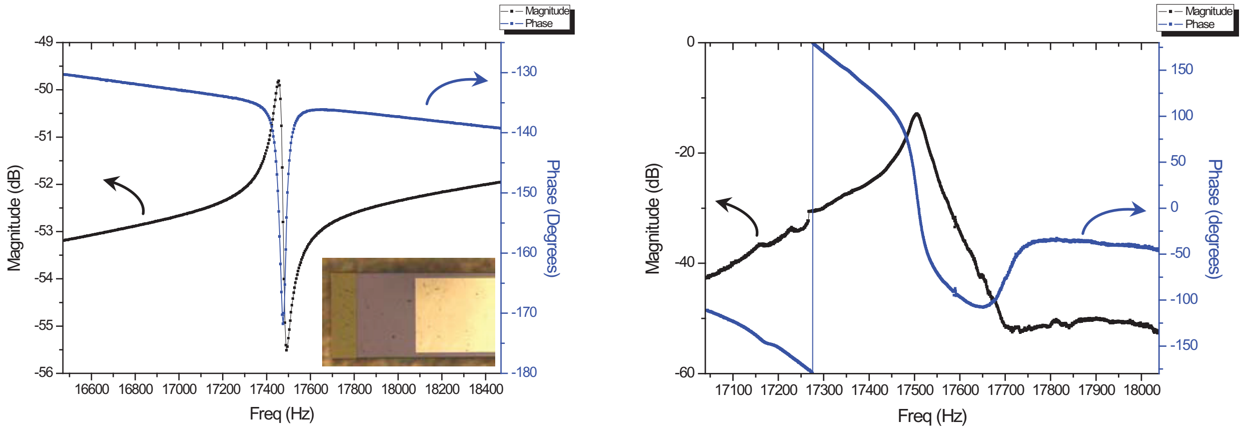
(a) **(b)**

Fig. 3. Measurement setup used to characterize the device (a) and resonance peak (278 Hz) of the assembled EHiP excited by the shaker (b).

3. Piezoelectric transduction

The AlN-based technology developed for the integration of FBAR resonators has been used to manufacture several piezoelectric energy scavenging devices [4], including a design based on the EHiP concept. A variety of cantilever-based devices have been fabricated to demonstrate the capability of recovering energy from low-frequency ambient vibrations and acoustic waves.

We have performed two different frequency response measurements. The first one uses the output port of a network analyzer to directly actuate the cantilever beam, because of the reverse piezoelectric effect over the AlN thin-film, and measuring the generated current with the input port. On the other hand, a speaker and a piezoelectric actuator, i.e. an audio buzzer, working over the substrate were used to shake the device through sonic waves. The resonance frequencies of these devices go from hundreds of Hz to tens of kHz, depending on the presence of a proof mass and its size. Two resonance peaks of the same cantilever beam without a proof mass were measured by the two different methods. It can be noticed a double resonance in Fig 4a due to the measurement procedure and the parasitic capacitance of the piezoelectric thin-film. From Fig 4b a resonant frequency of 17.5 kHz and a quality factor of 550 can be calculated.

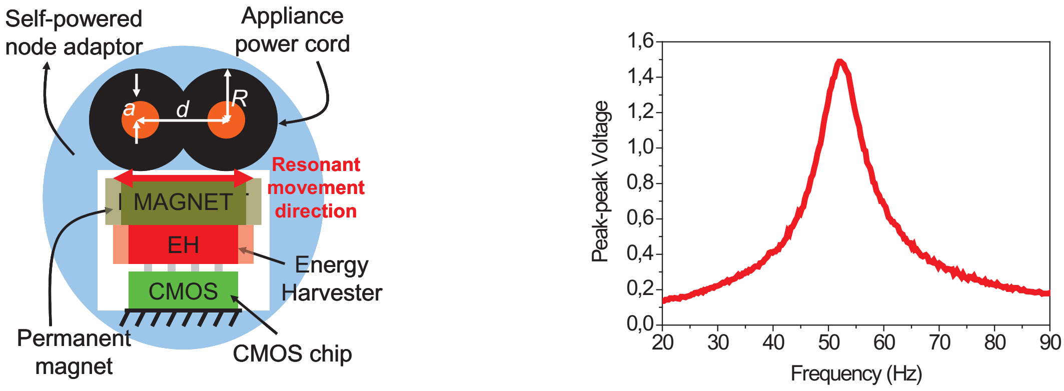


(a) **(b)**

Fig. 4. Resonance peak (17.5 kHz) of the piezoelectric cantilever measured with a Network Analyzer at 0 dBm with direct piezoelectric excitation (a) and externally actuated by using a piezoelectric buzzer (b). Inset: Optical image of characterized piezoelectric beam.

4. A different application: magnetically induced resonance due to a current-carrying power cable

Eventually, an ambient vibration with a constant-amplitude, frequency-stable and continuous-time can be unavailable. In contrast, the grid power is normally available in a domestic or industrial ambient and it is always generating parasitic magnetic energy which could be used to supply numerous self-powered devices. Aligned to the EHIP concept, a permanent magnet can be added on top of the MEMS die in order to reduce the final resonant frequency and provide a magnetically induced vibration (Fig 5a). A cm-scale prototype has been fabricated and characterized as a proof of concept (Fig 5b). The extracted power when the cable is carrying a current of 21.82 A is 336 nW for a load resistance of 1 MΩ [5].



(a) (b)

Fig. 5. Diagram of a magnetically-actuated Energy Harvester in Package (EHiP) attached to an appliance power cord [1] (a), and frequency response of the EHiP proof-of-concept prototype measured with an oscilloscope (R_{in} = 1 MΩ) (b).

5. Conclusions

It has been demonstrated that the use of the ideas involve in the concept of EHiP can achieve an improvement in the throughput of a vibration energy converter, regardless of the transduction type. Several methods to convert the mechanical energy to electricity have been investigated for several MEMS technologies. The use of a heterogeneous integration is presented as a key aspect in the proliferation of this type of devices and towards the development of real autonomous wireless sensors networks.

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