

DEVELOPMENT OF A SURFACE MOUNT HYBRID AMBIENT LOW FREQUENCY, LOW INTENSITY VIBRATION ENERGY SCAVENGER

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Abstract: This paper describes new fabrication techniques employed to manufacture a surface mount piezoelectric energy scavenger device toward the development of a compact hybrid energy scavenger system that couples both piezoelectric and electrostatic energy conversion mechanisms. Based on an energy survey, the system is targeting maximum power generation using sinusoidal acceleration of 2.5m/s^2 at 120Hz in a fixed volume of $<0.25\text{cm}^3$. The primary goal of the system is to maximize energy density within the volume that is dominated by a large proof mass for low frequency resonant operation by using the mass as a variable capacitor (C_{VAR}) electrode for co-generation.

Keywords: energy scavenging, piezoelectric, electrostatic, hybrid, surface mount assembly

INTRODUCTION

While vibration scavengers have been widely reported, harmonic cantilever-based piezoelectric scavengers require either low spring constants that limit piezoelectric performance, or large proof masses to resonate at the low frequencies that are dominant in the environment. Furthermore, charge-based electrostatic scavengers require storage of a pre-charge and synchronization with the mechanical oscillation to operate properly [1]. Both scenarios result in lower power densities due to the volume occupied by non-transducing components and substantial power consumption by control electronics. To mitigate this, a system-based approach to couple both piezoelectric and electrostatic energy scavenging mechanisms simultaneously in a shared volume has been previously described at the proof-of-concept level and is shown in Figure 1. This design suffered from a substantial volume overhead due to a large mechanical clamping fixture as well as high power consumption from utilization of commercial-off-the-shelf (COTS) components, and poor electrode alignment [2,3].

This paper reviews modifications to the low cost piezoelectric transducers fabrication process and discusses the efforts to overcome the challenges in volumetric scaling and development of a self-aligned electrostatic assembly by employing novel, yet simple microfabrication techniques to produce a surface mount device (SMD) that provides hybrid energy scavenging. Furthermore, while the primary focus of this paper is on the scaling of the mechanical assembly and resulting performance impact, the system operation has been enhanced by focusing on integration of low-power COTS components. This enables efficient analog processing while preserving the peak detector synchronization scheme for low overhead synchronous electrostatic charge control over a wider range of self-generated DC voltages.

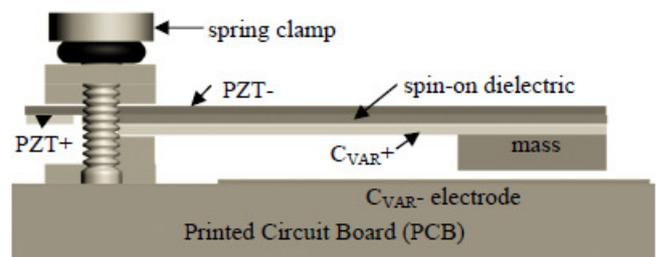


Figure 1. Diagram of initial hybrid scavenge prototype cross-section. The piezoelectric beam (PZT) forms the resonant beam that creates an AC voltage that provides a displacement feedback signal and a rectified DC rail for operating control and load circuits [2].

TRANSDUCER FABRICATION

The fabrication process for the surface mount transducer design, detailed in Figure 2, differs slightly from prior prototypes and begins with the evaporative deposition of a backside gold contact layer covering the surface of a commercial piezoelectric sheet that is temporarily bonded to a carrier wafer for handling purposes. The coated piezoelectric sheet is then debonded from the handle, inverted and remounted. Following this transfer process, a standard UV photolithography processes is used to create an isolation layer, comprised of thick negative resist, between the piezoelectric electrical contact and an electrostatic capacitive contact. Using a shadow mask, Ti/Au is then evaporated to metalize both the piezoelectric and electrostatic contact areas. Following this step, the wafer is cleaned and prepared for dicing with standard dicing tap and diced into transducer beams measuring $1.25\text{mm} \times 25.4\text{mm}$.

To complete the fabrication process, indium solder alloy paste (MP 150°C) is applied to the isolated gold contact on the beam and constantan wire is attached to the piezoelectric contact (denoted as PZT-) through low temperature reflow on a hotplate. At this point,

the beam is removed from the silicon carrier and cleaned. A lower temperature indium alloy is applied to attach another constantan wire to the backside piezoelectric contact (shown as PZT+ in Figure 3), thus creating a standalone transducer with accompanying wire connections. A tungsten proof mass is center-aligned and adhered to the transducer using cyanoacrylate. This constructed transducer is then clamped to the printed circuit board (PCB).

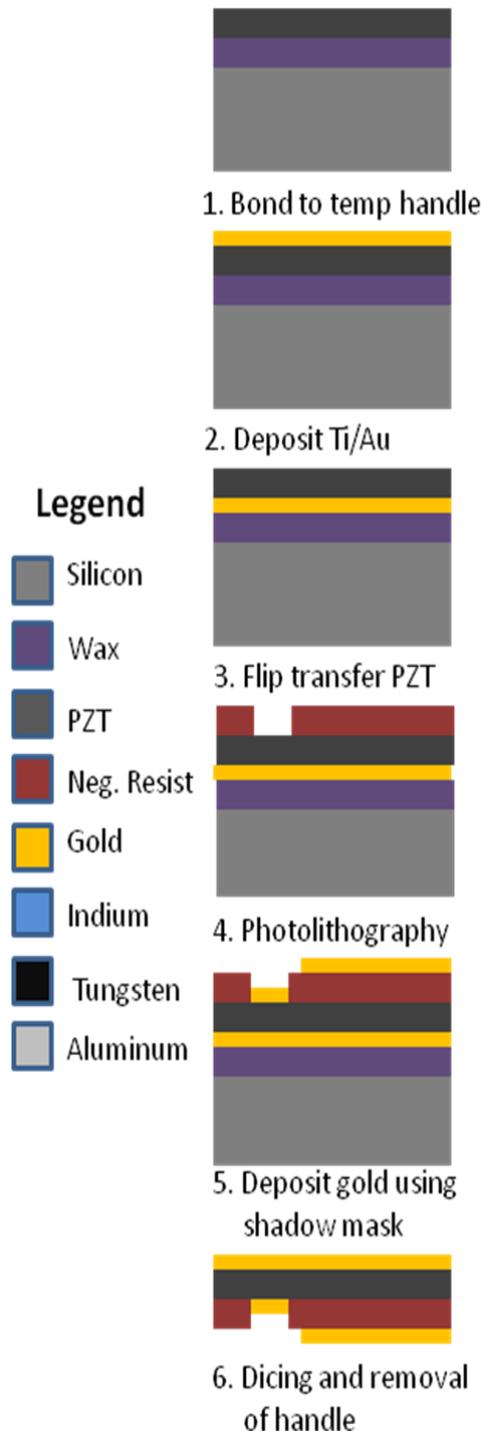


Figure 2. A modified simple, low cost transducer fabrication process flow that enables surface mount assembly using double-sided electrical contacts. The use of a temporary 150mm diameter handle wafer enable robust handling of the fragile piezoelectric sheets through all require process steps and tools.

MECHANICAL CLAMPING

On initial prototype designs, the utilization of a mechanical clamp on the piezoelectric beam induced a large volume overhead. This has been rectified via a re-design that exploits surface mount assembly technologies as illustrated in Figure 3. The piezoelectric transducer is attached using cyanoacrylate to a 2mm-on-a-side polished copper cube that is used as a riser to create vertical separation between the tungsten proof mass and the PCB surface as well as the electrical contact for the moving side of the electrostatic variable capacitor (marked as C_{VAR+}).

The utilization of cyanoacrylate in lieu of a rigid mechanical clamp substantially reduces the volume while inducing several unintended consequences in the performance of the surface mount device (SMD) transducer. The most notable negative impact is a reduction in peak and DC voltage levels, only producing 1.2-1.5V versus the 3.0-3.3V from the rigidly clamped design. This reduction is a result of a more elastic clamping regime that results in lower peak stress on the piezoelectric beam. Despite this, the lower Q-factor of the surface mount piezoelectric cantilever enables operation over a broad frequency range. One device demonstrated a bandwidth of 178Hz and is capable of surviving overdrive conditions, thereby making the surface mount device more suitable for field applications than previous designs that had bandwidths of less than 10Hz. While this provides an engineering tradeoff between voltage generation and bandwidth/reliability, the use of cyanoacrylate assembly inhibits replacing damaged beams or in-situ adjustment of beam length for modification of resonance or electrode alignment.

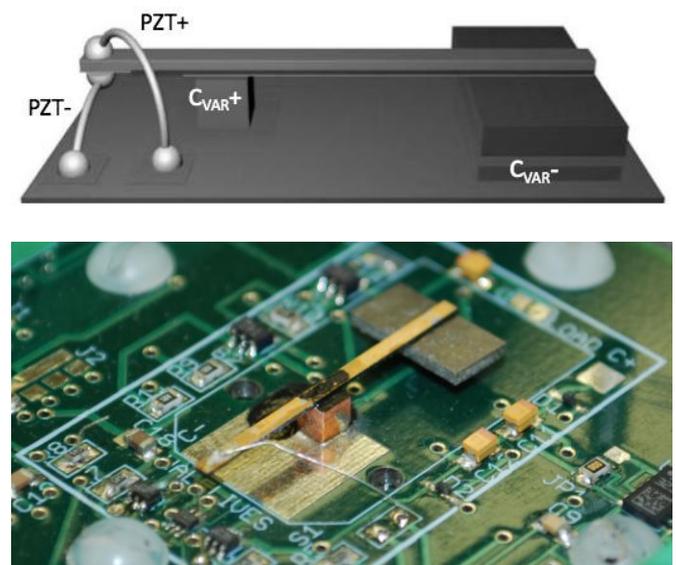


Figure 3. (top) Diagram and (bottom) photograph of a surface mount simple hybrid scavenger cross-section that enables substantial volume reduction (electrostatic counter electrode C_{VAR} . not shown).

ELECTRODE ALIGNMENT

In order to achieve substantial energy gain from the electrostatic component in the hybrid energy scavenger, a notable change in capacitance is required. While interdigitated structures would naturally provide capacitance enhancement, the most significant change in capacitance occurs with sub-micron electrode gaps. For simplicity of initial fabrication and testing, a smooth tungsten block was used as the proof mass/electrostatic electrode. While this initially appears to be a trivial design choice, the weight of the proof mass causes the tip of the transducer to pitch downward and thus was not parallel to the PCB electrode surface. As a result, an alignment between the two electrodes is required to increase parallelism for maximum capacitance.

For laboratory testing, the alignment problem in initial prototypes was addressed by providing fine-pitch micrometers that enabled pitch and height adjustment of the variable capacitor electrode, shown in Figure 4(b). While the design was sufficient to demonstrate rudimentary hybrid vibration scavenging, with 2nW additional power from the electrostatic device, the tripod platform induced additional problems including mass loading that introduced higher order vibration modes on the test PCB.

Currently in development is a self-aligning approach to mitigate the electrode alignment issue. One possible solution is to measure the displacement of the proof mass electrode at rest. This can be followed by thin film deposition of a temporary bonding material used to hold the two capacitor plates together during the mechanical alignment process.

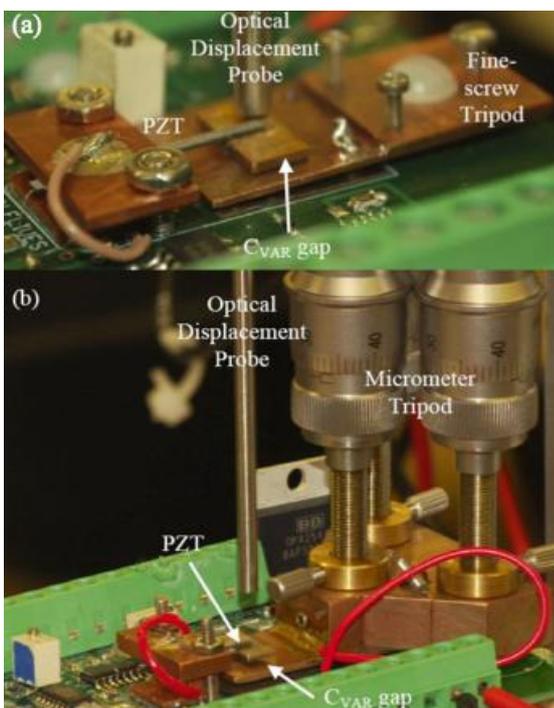


Figure 4(a) Photograph of original prototype using coarse screws for alignment. (b) Fine-pitch micrometer used for electrostatic counter electrode alignment for laboratory testing purposes.

Once the plates are bonded, shims and cyanoacrylate are used to position and affix the base electrode to the measured displacement. The temporary bonding material can then be dissolved to release the moving electrode. One substantial challenge is using temporary bonding materials that are soluble in solutions that will not degrade the cyanoacrylate that comprises the rigid mechanical assemblies.

CIRCUIT MODIFICATIONS

In addition to the miniaturization of the mechanical design, the system operation has been enhanced by focusing on low-power circuit designs that enable efficient analog processing while preserving the peak detector synchronization despite the lower voltage levels from the SMD transducer.

A major aim of the modification of the hybrid energy scavenging system was a reduction in power overhead that would facilitate a positive net power output. In this case, the harvesting piezoelectric system would produce greater power output than the control electronics consume in contrast to the first prototype that consumed substantial power for the operational amplifiers (Texas Instruments OPA4347UA-ND) as well as the edge-triggered monostable multivibrators (Texas Instruments SN74LV123ADR) used in the peak detector circuit as voltage comparators and triggering elements.

In the case of both the operational amplifiers and the multivibrators, these commercial-off-the-shelf (COTS) parts consume power several orders of magnitude beyond that produced by the energy harvesting system's reported 145 μ W. Specifically, the operational amplifiers consumed 102 mW per channel, while the multivibrators consumed approximately 30 mW per channel. In order to become feasible as a mass-producible energy harvester, power consumption levels of these circuit elements would need to be reduced considerably.

Inquiries into replacements for the operational amplifiers led to the implementation of the National Semiconductor LMV7291 single 1.8V low power comparator with rail-to-rail input. The overarching advantages of this element were three-fold. Most notably, the National Semiconductor comparator consumes a mere 16.2 μ W per channel, an improvement of four orders of magnitude that places the power consumption of this portion of the charge control circuit within a feasible range. Additionally, while the previous operational amplifiers required a supply rail voltage of approximately 3V, the new circuit elements operate using a single voltage rail of 1.8V and is demonstrated to work at rail voltages as low as 1.2-1.4V, as shown in Figure 5, thereby enabling the SMD transducer to function properly despite the drop in output voltage due to the elastic clamping of the cyanoacrylate.

Finally, to address size reduction, the LMV7291 offers a much smaller physical footprint compared to

the OPA4347UA. While the operational amplifiers have surface area dimensions of 8.75mm x 6.2mm, the new comparator elements have a footprint of only 2mm x 2.4mm, an area savings of 91%. It is apparent from these advantages that the LMV7291 is a viable alternative to the operational amplifiers used in previous versions of the energy scavenger that relies on COTS parts.

While improvements to the comparator elements used in the peak detector circuit were successfully implemented into the design of the charge control circuit, attempts to make similar improvements for the monostable retriggerable multivibrator units were not successful. All COTS monostable retriggerable multivibrators consume at minimum several tens of milliwatts. This level of power consumption remains beyond the feasible scope of an energy scavenger that currently produces power in the microwatt regime. As an alternative to the high power COTS multivibrator circuit, the functionality can be instituted through either the use of low power discrete circuit elements, or of an even greater advantage, through development of a low power Application Specific Integrated Circuit (ASIC) that embodies the full functionality of the control system. In both cases, the advantages of pursuing a low power monostable retriggerable multivibrator would almost certainly outweigh any disadvantages either in footprint or cost for a mass produced system, but has not yet been implemented in this work. As a developmental mid-step, the legacy multivibrator is utilized and powered by an external source with the purely diagnostic circuit components. The entire control circuit is proven to operate at the lower voltage levels from the SMD transducer.

DISCUSSION

The current embodiment of the hybrid energy scavenger seeks to improve the system performance by enhancing the power density of the entire system. As a multifaceted approach several key areas have been targeted to make evolutionary progression toward a mass producible system. Volume reduction by eliminating the bulky mechanical clamp and alignment mechanisms was a natural choice in volume minimization. This design change only slightly complicated the transducer fabrication while providing greater than 50-percent reduction in total transducer assembly volume. However, the unintended consequence of using elastic, cyanoacrylate clamping mechanism was lower voltage output. While this seems to be a negative result, the useable bandwidth of the transducer improved by more than an order of magnitude. Furthermore, the exploration of SMD packaging techniques has provided opportunities for developing a self-aligned set of electrostatic electrodes and is an active area of investigation. Finally, replacement of the operational amplifiers with low power comparators places the bulk of the control system within the sustained power of the hybrid

transducer with the sole exception of the monostable multivibrator. This improvement is substantial and pushes this revision closer to the goal of demonstrating a self-sufficient hybrid piezoelectric-electrostatic energy scavenger system. It is now clear that the ultimate improvement in control circuit efficiency and volume minimization will require development of an ASIC.

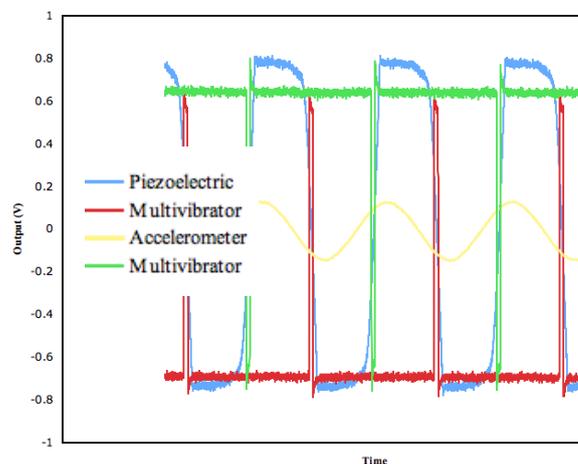


Figure 5. Demonstration of low-voltage, low-power peak detector operation that tracks capacitance peaks to provide synchrony for electrostatic scavenger; enabling hybrid energy scavenging by providing essential pre-charge and synchrony for charge-constrained electrostatic sub-component.

CONCLUSIONS

For the first time, a hybrid energy scavenger system providing wide bandwidth piezoelectric and electrostatic energy conversion within the volume of a SMD transduction platform is reported. Circuit modifications enable a decrease in power consumption bringing the device closer to self-sustainability. Improvements in electrode alignment are outlined but have not yet been implemented.

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