RADIOISOTOPE MICROPOWER FOR SEMI-ACTIVE RFID

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Abstract: We demonstrate a microfabricated ^{63}Ni radioisotope-powered RFID transponder realized with a SAW (surface acoustic wave) device as the transmission frequency selector. The transponder is powered by a 1.5 milli-Ci ^{63}Ni source which has a half-life of 100 years. Even with a conversion efficiency of 0.06%, we have achieved a 5mW, 10-μs long, 100MHz carrier envelope, RF pulses which occur every 3-minutes, across a 50Ω load. The transponder can potentially work autonomously for decades, which can revolutionize long term reliable sensing and monitoring.

Keywords: Radioisotope, ^{63}Ni, Power generation, RFID

INTRODUCTION

A necessity of an autonomous sensor is a miniature power source with a long in-use and shelf lifetime. For sensor networks working in harsh, inaccessible environments, battery replacement can be hard or impossible, and expensive. While traditional power sources, such as chemical batteries, can only work up to several years without replacement, radioactive isotope power sources can work on time scale of the half-life which can be 100s of years. The emission of radioisotopes is mostly unaffected by the temperature. For example, ^{63}Ni power sources have a high energy density (~10^5kJ/m^3) and long half-life (100.2 years). ^{63}Ni emits β-particles with an average kinetic energy E_{avg}=17.3keV, and a penetration depth of less than 10μm in most solids. As a result, devices powered by ^{63}Ni thin-films can be deployed safely with millimeter or microscale shields.

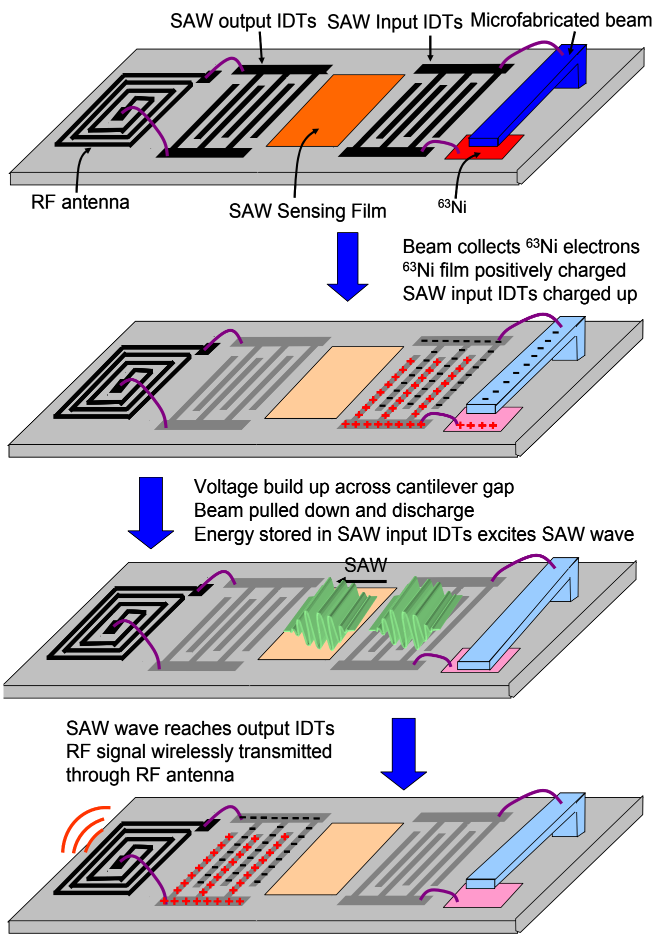

Figure 1. Schematic illustrating the radioisotope actuated reciprocation of gold cantilevers.

The power requirements for a typical low-power wireless sensor node are 1-10 nW for retaining the memory state, 0.1-1 mW for periodic sensing and processing, and 1-100 mW power for periodic wireless communication [1]. The power to retain memory states can be provided by betavoltaics as reported in [2] even with the low activity radioactive thin films presented here. However, the nanoWatt range power is insufficient for computation and transmission. MEMS radioisotope-powered piezoelectric power generators [3] can generate the output power needed for periodic sensing and processing using even small amounts of radioactivity. In this paper, we focus on radioactive RF power generation with an integrated SAW frequency selector that can be used as a CMOS compatible wireless beacon and for communications.

PRINCIPLE OF OPERATION

Our group has previously demonstrated macro-size prototype radioisotope-powered RF pulse generators housed inside large vacuum chambers [4-6]. Radioisotope energy emitted in electrons from ^{63}Ni thin films is used to electrostatically charge a cantilever, which generates an arc when electrostatic force induced motion moves the cantilever very close

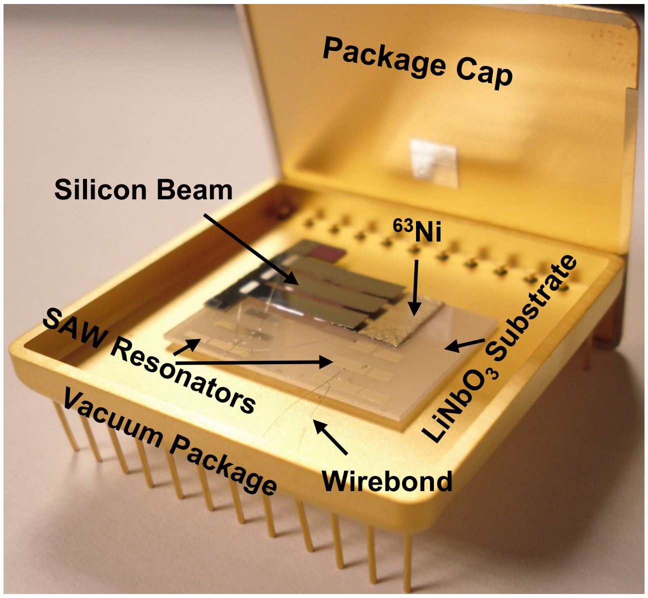

Figure 2: Photo of the microfabricated integrated RFID device inside a 1 inch^2 vacuum package

to the ^{63}Ni source. The frequencies of the generated RF pulses are determined by the equivalent LC circuit of the RF cavity surrounding the arc impulse [5]. The RF pulse power is determined by the cavity Q which is typically low (8~10). To increase the signal power while having better frequency control, a microfabricated SAW resonator is integrated with a microfabricated discharge system (Figure 1.) The SAW resonator is connected such that the high impedance port of the SAW device is in parallel with the charge collection cantilever. The emitted charge is shared across the SAW port and the nonlinear capacitor, resulting in direct strain in the SAW device. A SAW pulse is generated as a result of strain release and induced displacement currents due to sudden charge release. The SAW resonator energy collected over 3-5 minutes is released in nanoseconds, which excites the SAW wave on the time scale of microseconds. This results in a collected-to-released power amplification of 10^8. Hence, even a very small amount of radioisotope can be used to generate useful high power pulses.

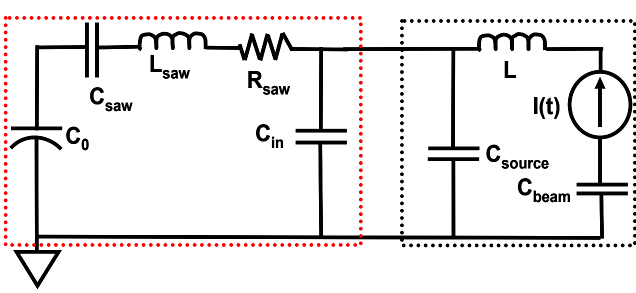

Figure 3: Schematic illustrating operation principle of the RF transmitter integrated with SAW resonator

Table 1: Representation and values of R, L, C components in Fig. 3 circuit model

Component	Representation	Value
C_{beam}	Beam ground capacitance	8.3pF
C_{source}	Source ground capacitance	8.3pF
I(t)	Air gap current	-
L	Discharge system inductance	72nH
C_{in}	Input SAW IDT capacitance	2.2pF
C_0	output SAW IDT capacitance	2.2pF
L_{saw}	SAW equivalent inductance	758μH
C_{saw}	SAW equivalent capacitance	0.337fF
R_{saw}	SAW equivalent resistance	84Ω

The propagating SAW wave generates charges on the output interdigitated transducers (IDTs), which can be coupled to a microfabricated antenna. The SAW resonator has a well-defined and designable resonance frequency, which determines the RFID's output frequency. Since SAW devices are pervasive in communication and sensor systems, this new design of the transponder might lead to widespread acceptance of integrated electron-emitting radioisotope power sources for reliable transduction.

FABRICATION AND EXPERIMENTS

Single crystal cantilevers, 30μm thick, with lengths of 4mm to 8mm were micromachined using a two-step deep reactive ion etch (DRIE) process on a SOI wafer, and assembled alongside a 1.5 millicurie ^{63}Ni source plate that is housed inside a 1-cm × 1-cm x 0.5-cm vacuum package (Figure 2). The SAW resonators are fabricated with aluminum (500nm thick) lift-off process on 128^o Y-cut lithium niobate wafers. SAW resonator devices of various frequencies are fabricated with 35 pairs of interdigitated transducers

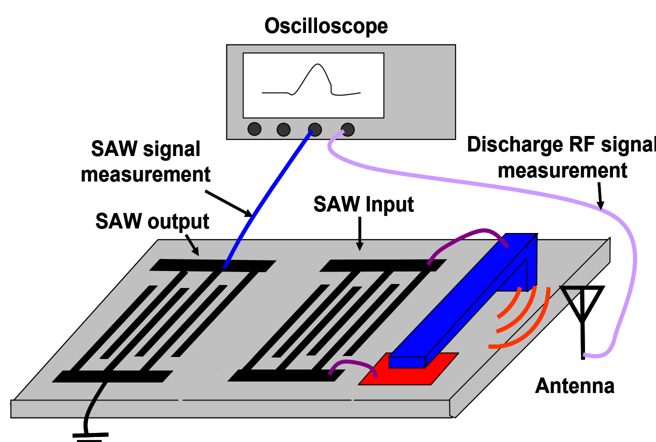

Figure 4: Schematic illustrating the measurement set for the RF signals from SAW and discharge system

at both input and output ports. The equivalent circuit of the system consists of SAW equivalent inductance on the pulser side and receiver side (Figure 3) with the components listed in Table 1. The circuit in the right dotted box represents the discharge cantilever, while the equivalent circuit of the SAW resonator is in the left box. The vacuum package is pumped down to 10^{-5} Torr and sealed by melting a solder layer on the edge of the package.

With a 100MHz SAW resonator connected to the ^{63}Ni discharge system, the SAW RF output signal is measured on a 50Ω oscilloscope load, while the RF output from the discharge system is measured wirelessly with an antenna (Figure 4). With a beam length of 5mm, the RF signal from the discharge system has a frequency of 1.31GHz with a low quality factor of ~40. The SAW RF signal with a maximum output power of 5mW and duration of 10µs is achieved. With a quality factor of over 400, the RFID signal can be detected from hundreds of feet away with the same SAW tuned receiver. The RF signal at the cantilever is also measured for the same discharge event, and a signal delay of 750ns is detected for the SAW signal (Figure 5), which is due to the 3mm gap between its input and output IDTs. The conversion efficiency of the system η can be defined as the energy in the *detected SAW wave* divided by the *collected* radioactive energy,

$$\eta = \frac{E_{SAW}}{E_{rad}} = \frac{\frac{1}{2}Q\frac{V^2}{R}\frac{1}{f}}{T_{rec}E_eA} \qquad (1)$$

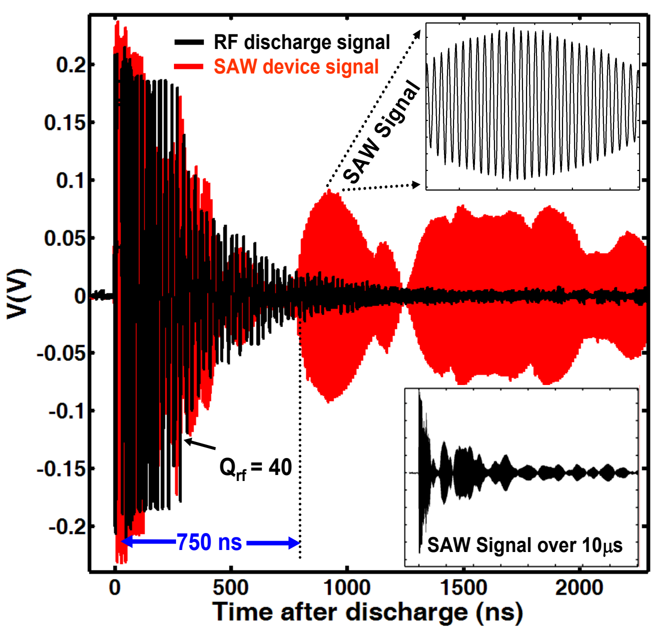

Figure 5: RF discharge signal measured at the discharge cantilever compared to the signal from the SAW devices show a 750ns SAW delay

where E_{SAW} and E_{rad} are the SAW output energy and radioisotope input energy respectively. Q and V are the quality factor and voltage of the output SAW signal respectively, R is the load resistance (50Ω) , T_{rec} (180s) is the reciprocation period of the discharge system, and E_e and A are the average electron energy (17 keV) and activity of the radioactive source (1.5 mCi/cm^2). The prototype device reported here has a conversion efficiency of 0.06%.

CONVERSION EFFICIENCY

To improve the conversion efficiency of the integrated RFID system, we analyze the energy transformation process in the cantilever discharge cycle. Assuming the leakage across the vacuum gap is zero, when the radioisotope emitted-electrons cross the vacuum-gap to reach the collector, the radioisotope kinetic energy is converted to electromechanical energy and thermal energy. The thermal energy is due to electron kinetic energy dissipated in the cantilever, while the electromechanical energy is stored in the cantilever, across the air gap, across the input port of the SAW resonator, and across other capacitances in the system.

To reduce the percentage of radioactive energy converted into thermal energy within a discharge cycle, we can increase the average voltage across the vacuum gap by increasing the gap. Therefore, more of the radioisotope kinetic energy will be converted into electrostatic energy by overcoming the impeding electric field rather than generating heat. Since only the electromechanical energy stored across the input port of the SAW device contributes to the output RF signal, as show in Fig. 3, we can increase these capacitances while reducing other capacitances in the equivalent circuit. Other studies in the electrical domain, such as impedance matching and parasitics reduction will also be performed to increase the overall conversion efficiency.

CONCLUSIONS

In this paper, we demonstrate a microfabricated ^{63}Ni radioisotope-powered RFID transponder realized with a SAW device as the transmission frequency selector. We have achieved 5mW, 10-µs long, 100MHz carrier envelope pulses every 3 minutes, across a 50Ω load, using a 1.5 milli-Ci ^{63}Ni source. Because the frequency is determined by a SAW device, narrowband detection with an identical SAW device enables the possibility for a long distance RF-link. With MEMS microfabrication and vacuum packaging, we achieve an integrated system in less than 1cc volume. Since the half life of ^{63}Ni is 100 years, the integrated transponder can work autonomously for decades, which can revolutionize long term reliable sensing and monitoring. Such devices can be buried deep inside structural constructs such as steel and concrete, where changing batteries, and harvesting vibrational or EM energy is not reliable. The SAW transducer frequency can be further modulated by integrated or attached mass-sensors or a RFID code. One can integrate sensing films or coded floating IDT fingers between the excitation and receiving IDT pairs [7]. For future research, SAW sensors will be fabricated and integrated into the system to realize a complete miniature self-powered wireless sensor node.

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