Final Scientific/Technical Report

A Nuclear Microbattery for MEMS Devices

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Executive Summary

This project was designed to demonstrate the feasibility of producing on-board power for MEMS devices using radioisotopes. MEMS is a fast growing field, with hopes for producing a wide variety of revolutionary applications, including "labs on a chip," micromachined scanning tunneling microscopes, microscopic detectors for biological agents, microsystems for DNA identification, etc. Currently, these applications are limited by the lack of an on-board power source. Research is ongoing to study approaches such as fuel cells, fossil fuels, and chemical batteries, but all these concepts have limitations. For long-lived, high energy density applications, on-board radioisotope power offers the best choice.

We have succeeded in producing such devices using a variety of isotopes, incorporation methods, and device geometries. These experiments have demonstrated the feasibility of using radioisotope power and that there are a variety of options available for MEMS designers. As an example of an integrated, self-powered application, we have created an oscillating cantilever beam that is capable of consistent, periodic oscillations over very long time periods without the need for refueling. Ongoing work will demonstrate that this cantilever is capable of radio frequency transmission, allowing MEMS devices to communicate with one another wirelessly. Thus, this will be the first self-powered wireless transmitter available for use in MEMS devices, permitting such applications as sensors embedded in buildings for continuous monitoring of the building performance and integrity.

Final Technical Report

Introduction

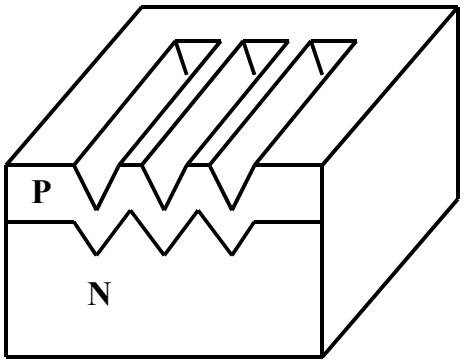
For the past 3 years we have been exploring the feasibility of producing on-board power for MEMS devices using radioisotopes. This report describes the achievements of this project, along with the publications and patents that have resulted from our work.

Phase I Achievements

The goals of Phase I were to 1) obtain radioactive materials and incorporate them into a MEMS device and 2) to incorporate several stable isotopes into a MEMS device and irradiate it in a fission reactor.

We obtained radioisotopes from commercial vendors in two forms, solid (thin films) and liquid (metal ions in an acid solution). The solid sources were 63-Ni and 210-Po. 63-Ni is a weak beta emitter with an average beta energy of 17.4 keV and a half-life of 100.2 years. 210-Po is an alpha emitter with an energy of 5304.3 keV and a half-life of 138.4 days. The liquid sources were all 63-Ni . Typical source strengths were on the order of a few millicuries. 63-Ni was chosen because the maximum beta energy emitted by this isotope provides a range of approximately 21 microns in silicon, while higher energy beta emitters can easily provide ranges of several millimeters. Hence, for small scale devices, low energy beta emitters are necessary in order to avoid losing a significant number of energetic particles. Damage of the silicon can also be a problem for higher energy beta emitters. The alpha particles from 210-Po have a range of approximately 26 microns in silicon, so they are suitable for MEMS, but radiation damage provides very short device lifetimes for the direct conversion devices we've focused on in this project.

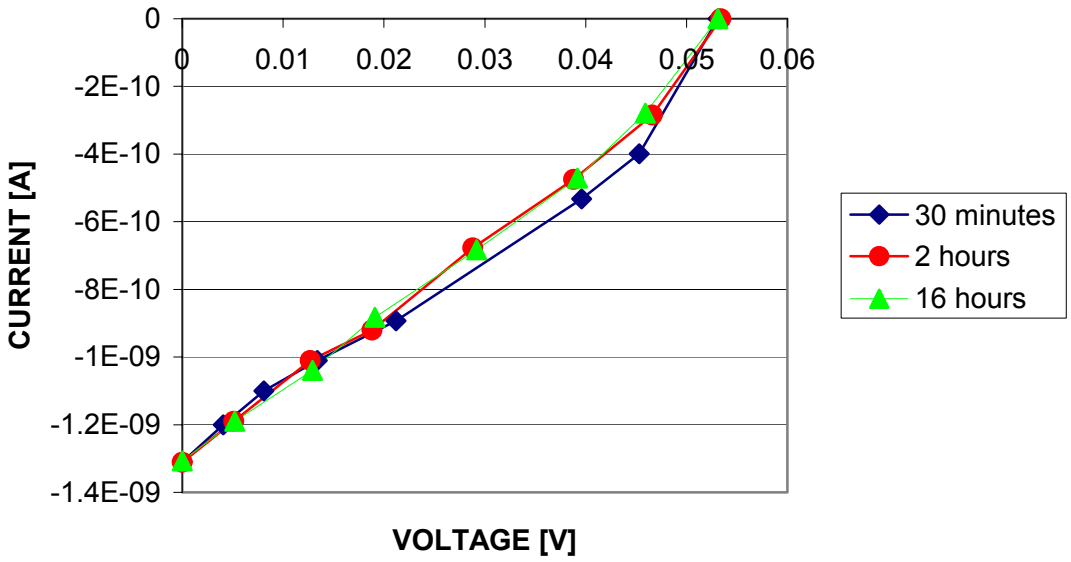
We demonstrated the feasibility of creating microbatteries for MEMS devices by producing the device shown below.



The device consists of a layer of p-type silicon on top of a layer of n-type silicon. Liquid source is introduced into the channels on the top of the device. As the source decays, a fraction of the beta particles travel through the junction between the p-type and n-type silicon layers. When ionization occurs in the vicinity of this junction, a potential is produced across the layers. One can then place contacts on each layer and use the device

as a power source. The output power depends on the source strength and the device efficiency.

To test this device, we placed 64 microcuries of 63-Ni (in liquid form) in the channels and measured the IV characteristic curve for the device. The measured curve is shown below.



Note that potentials are on the order of .05 volts and currents are a few nanoamps. The current is largely dependent on the source strength and the potential is largely dependent on the device design. The peak output power of this device (with a 64 microcurie source) is on the order of .069 nW, which corresponds to a device efficiency of approximately 1.0%.

The above curve demonstrates that there was no degradation in the device power over a 16 hour period. Previous studies have demonstrated significant degradation in about 1 hour when alpha emitters are used. This is a result of radiation damage, which is avoided here by the use of the low energy beta emitters.

In the device described above, the source was incorporated using a liquid poured into channels. We have also demonstrated the use of electroless plating of 63-Ni. This is done using an aqueous solution of nickel salt and hypophosphite. The nickel ion is provided by the use of water-soluble nickel salts such as nickel acetate, nickel chloride, or nickel sulphate. The hypophosphite radical can be obtained by the use of sodium hypophosphite, potassium hypophosphite, or ammonium hypophosphite.

Our recipe for electroless plating of nickel is given below

Nickel Chloride	15mg
Sodium hypophosphite	5mg
Sodium hydroxyacetate	25mg
Water	0.5mL
Ni-63 liquid source	9uL
pH	4.5 - 5

The radioactive Ni-63 is in a solution of HCl and it is used to maintain the pH of the solution in the required range. The above solution was placed in a vial and a gold-coated silicon piece of dimensions 3mm x 3mm was submerged in the solution. The vial was placed in a water bath, which was maintained at 80-90 degrees C. Plating of nickel on gold was observed in about 15 minutes.

The plating can be altered in the following aspects

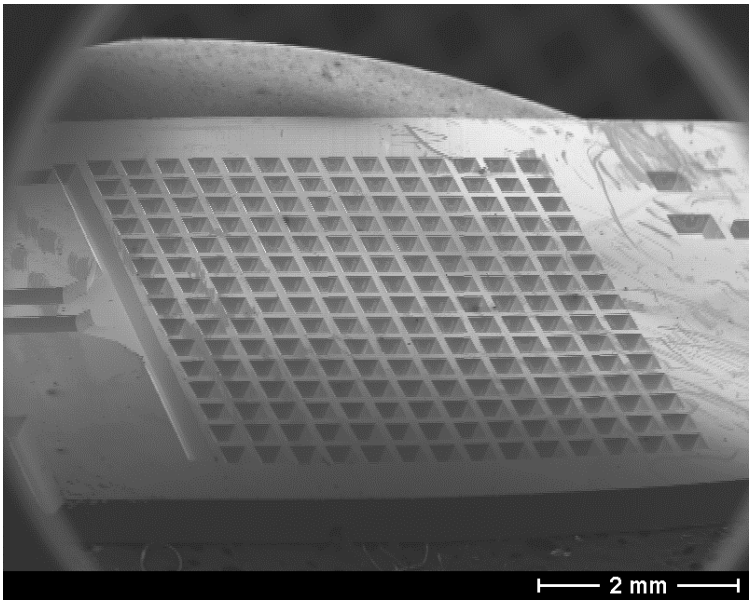
- The deposition rate can be varied by the temperature of the bath. The optimal temperature range is 80-90 C. A higher temperature would result in rapid evaporation of the water bath and commensurate reduction in the plating rate.
- The plating can be controlled by the pH, which can be varied by varying the amount of the liquid radioactive source. Hence the activity of the plated piece can be varied according to the power needs.
- The thickness of plating deposit in a given length of time depends on the relation of the area of the surface of the metal object being plated to the total volume of the plating bath composition.

Our final approach for incorporating source into our devices is irradiation of a stable isotope in our 1 MW UW TRIGA reactor. In our initial experiments we obtained a sample of glass beads (with radii on the order of 20 microns) containing 6-Li. When these beads are irradiated, the Li is converted to tritium, which is a weak beta emitter (5.7 keV average energy and 12.3 year half-life). We irradiated 0.25 grams of beads in an aluminum canister for approximately 37 minutes and obtained 2 mCi of tritium. The aluminum canister was filled with water to avoid overheating of the glass beads. Worst case estimates of the maximum temperature reached in the beads during the irradiation were on the order of 360 C, which is well below the melting temperature of the beads. These beads are easily handled, as they can be poured into channels or cavities in the device and thus are quite flexible.

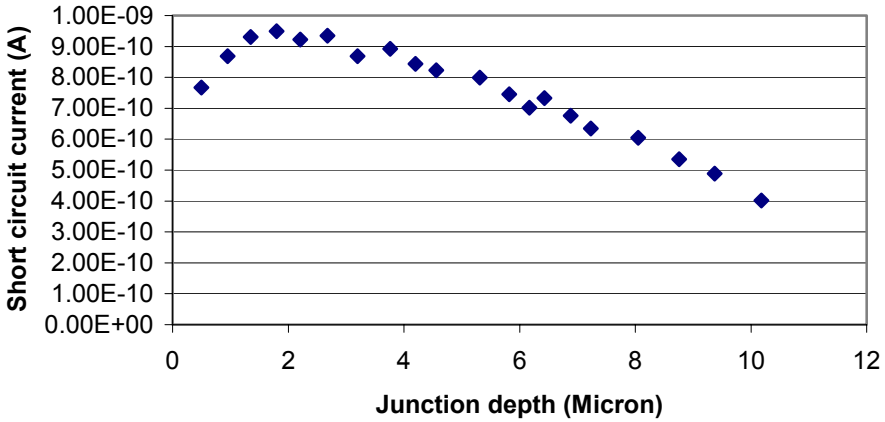
Phase II Achievements

The goal of Phase II was to utilize different device designs in order to assess the impact on device efficiency.

We began this phase by switching to a new device geometry. Instead of channels, this approach incorporates a "waffle" geometry, allowing a more modular design approach and increased surface area between the source and device. The geometry is pictured below.



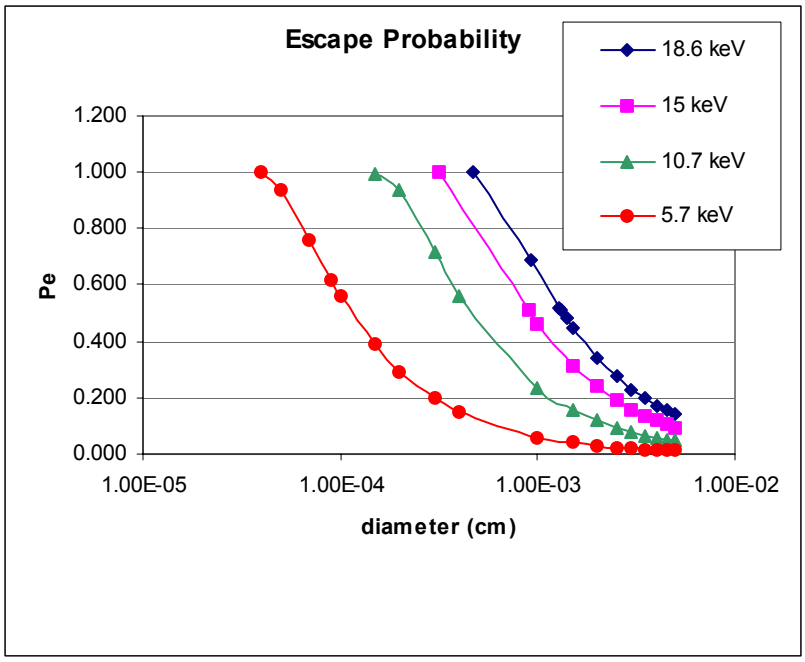
A second optimization was related to the device design. Our goal was to select the optimum PN junction depth. If the junction is too deep, beta particles will not reach it, while if it is too shallow, the device performance will be poor. Hence, we measured the device power for a number of junction depths using a solid 63-Ni source. The results are shown below.



As can be seen, the optimum junction depth is approximately 2-3 microns. This result is specific to 63-Ni, as other isotopes will have different particle ranges and thus will optimize differently.

A third optimization involved the devices using a liquid source. In most cases, a fraction of the energetic betas produced within a liquid source will be absorbed in the liquid and will not contribute to the device power. To measure this effect, we placed liquid source in one of our devices and measured the power. We then let the liquid evaporate, depositing a layer of 63-Ni on the surface. The power was then measured again and an increase of 25% was found. Hence, approximately 25% efficiency loss was created by self-absorption in the liquid in the initial experiment (assuming no nickel ions evaporated with the liquid).

A similar phenomenon is created by the glass beads in the tritium source. As the range of the average energy beta emitted by tritium is approximately 3 microns in glass, one would expect low efficiency from any beads with radii significantly greater than this value. We estimated the escape probability of betas from glass spheres and the results are shown below.



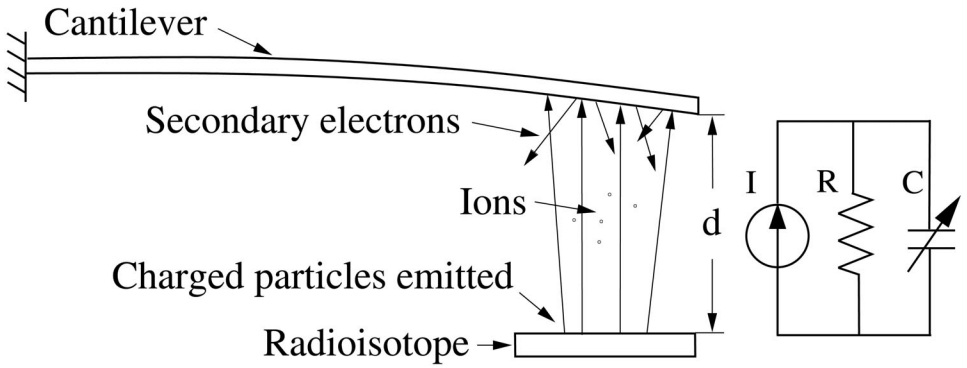
This curve shows that the sphere diameter must be on the order of 1 micron to allow an appreciable number of the average energy betas from tritium to escape.

Phase III Achievements

The goal of Phase III was integrate one or more of the optimized concepts into a practical MEMS device.

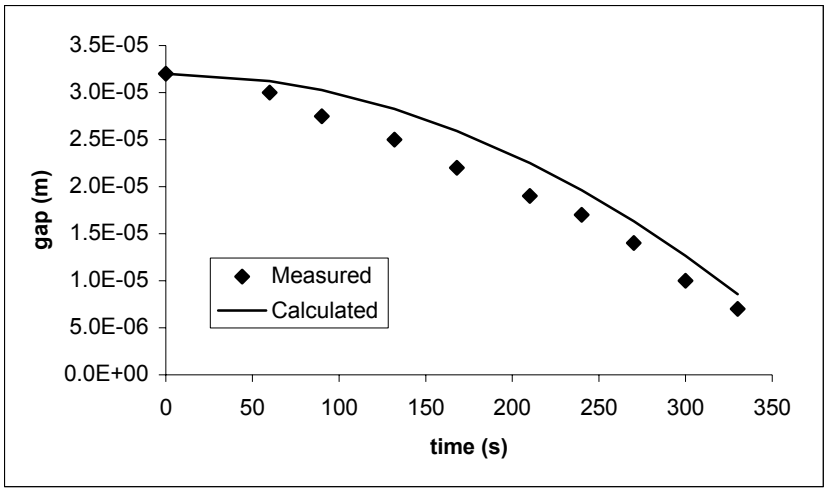
Our primary device is a self-oscillating cantilever beam (recently awarded a patent). The central idea behind this device is to collect the charged particles emitted from the radioisotope by a cantilever. By charge conservation, the radioisotope will have opposite charges left. Thus an electrostatic force will be generated between the cantilever and the radioisotope. With appropriate distance between the cantilever and the nuclear source and provided the cantilever is flexible enough, the electrostatic force will attract the cantilever toward the source. With a suitable initial distance the cantilever will eventually reach the sourcee and the charges will be neutralized via charge transfer. As the electrostatic force is nulled, the cantilever will retract back to its original position and begin to collect charges again for the next cycle. Based on this idea, a prototype cantilever device has been made and an analytical model developed. This device should be capable of high temperature operation, as its operation does not rely on the diode behavior used in the batteries described above.

A prototype device has been made to verify the idea and the model. A schematic of this device is shown below.

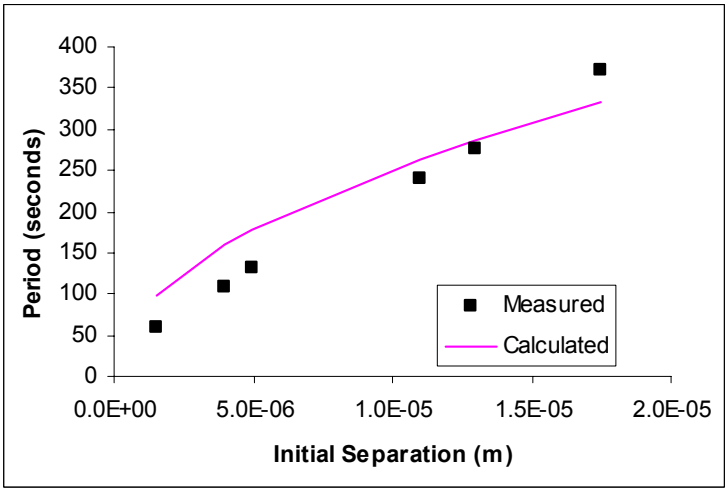


A 1 mCi, solid 63-Ni source, in the form of a 4 mm square thin film, is used as the power source. The cantilever is made of copper with dimensions 5 cm x 5 mm x 60 μm. The cantilever is clamped between two Teflon pieces for electrical insulation. The source is clamped by two glass slides, which are mounted on a Teflon base. The Teflon base is in turn mounted on a linear motion stage used to control the initial distance between the source and the cantilever. The setup is placed inside a vacuum chamber with a glass top. A microscope connected to a CCD camera outside the chamber is used to monitor the gap between the source and the cantilever.

A typical measurement for the gap as a function of time is shown below.



The initial gap can be seen to be about 32 microns and the time to contact, though not shown here, can be estimated to be approximately 6 minutes. This period can be adjusted by varying the initial gap, beam stiffness, or source strength. Some parametric measurements of the period as a function of initial gap are shown below.



In this case, the period is shown to vary from 1 to 6 minutes by varying the initial gap, and further variation is possible. Research is under way to demonstrate the use of this device as an RF transmitter for carrying out wireless communication between MEMS devices.

Conclusions

We have demonstrated the feasibility of creating radioisotope power sources for MEMS devices and built a working application that provides a self-oscillating cantilever beam for the life of the source. Future work will further develop this oscillator to provide wireless transmitters for MEMS devices. This will be the first RF transmitter powered from on-board power supplies.

Publications Created Under This Project

1. H. Li, A. Lal, J. Blanchard, and D. Henderson, "Self-reciprocating Radioisotope-powered Cantilever," accepted by J. Appl. Phys.
2. J. Blanchard, H. Li, and A. Lal, Modeling of a Self-Oscillating Cantilever, to be presented, SEM Annual Conference, Milwaukee, June, 2002.
3. J.P. Blanchard, D.L. Henderson, A. Lal, H. Li, H. Guo, R. Yao, and S. Santanam, Radioisotope Power For MEMS Devices, to be presented, ANS National Meeting, Hollywood, FL, June, 2002.
4. J. Blanchard, A. Lal, R. M. Bilbao Y León, D. Henderson, Radioisotope Power Sources For Mems Devices, Proc. ANS National Conference, Milwaukee, June 2001.
5. H. Li, A. Lal, J. Blanchard and D. Henderson, A Self-Reciprocating Radioisotope Powered Cantilever, Proc. 11th International Conference on Solid-State Sensors and Actuators, Munich, June 2001.
6. Lal, R. M. Bilbao Y León, H. Guo, H. Li, S. Santanam, R. Yao, J. Blanchard, D. Henderson, A Nuclear Microbattery For MEMS Devices, Proc. 9th International Conference on Nuclear Engineering, Nice, April, 2001.

Popular Press Citations

1. The Economist (March 16-22, 2002; page 30 of the Technology Quarterly insert)
2. New York Times (CIRCUITS, January 10, 2002, page 7)
3. Sunday Times (London, July 11, 1999)
4. Los Angeles Times (Aug 30, 1999, page 4, Home Section)
5. Wired News (http://www.wired.com/news/technology/0,1282,20508,00.html)
6. Nuclear Energy Institute (March 2001, page 6)
7. ASME NED Newsletter (Fall 2001, page 4)
8. New Scientist (vol. 172 issue 2318, November 24, 2001, page 30)
9. Nature Publishing Group - Materials Update (http://www.nature.com/materials/) - July 25, 2002 (http://www.nature.com/cgi-taf/gateway.taf?g=3&file=/materials/nanozone/news/articles/m020725-6.html)

Patents

1. Direct Charge Radioisotope Activation and Power Generation, US Patent Application SN 09/832,342 (allowed).
2. Nuclear Microbattery, US Patent Disclosure, 1999.

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Department of Energy.