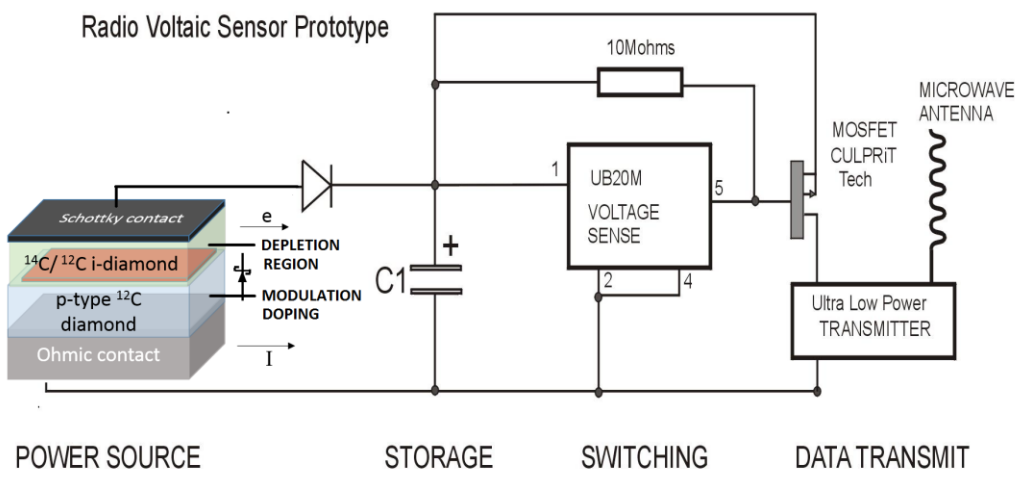

Early Technology Development

Executive Summary

OSIP Open Channel Early Technology Development

*Activities Evaluation Session 2020-03 –**Idea I-2020-01241***

Affiliation(s): University of Bristol

Activity summary:

A Radio Voltaic Power Supply (RVPS^{TM}) aims to provide electronics self-heating as well as continuous micropower for decades, supporting long duration missions and sensor applications.

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Implemented as ESA Initial Support for Innovation

Under this activity, a novel Diamond-based RVPS has been modelled, technology matured, and fabricated, incorporating the beta-emitting radioisotope carbon-14 within the device semiconductor lattice.

The fabrication method was custom-designed and developed in collaboration with UKAEA, and greatly improves the micro-battery efficiency while reducing fabrication costs over existing beta voltaic batteries. The fabricated RVPS's developed under this activity give internal activity levels of ca 3MBq/4nW, and further testing is ongoing to establish battery operation and performance.

1. Introduction

The overall goal of this project was to design and fabricate a non-chemical, long life battery that could supply microwatt levels of electrical power for use in space applications and to explore an initial application in an active Radio Identification (RFID) application for on-orbit spacecraft.

Prior research on diamond beta voltaic batteries have made use of an 'external' source of beta radiation that is physically separated from the voltaic diode and subject to significant losses and low, nanowatt power output. This project sought to demonstrate the fabrication of a synthetic diamond radio-voltaic battery structure that incorporates carbon-14 diamond layers at the atomic level as the beta electron source. This integrated concept is novel[1] and leads to significant source efficiency gains that increases battery efficiency and micro power output. The continuous energy output and temperature insensitive operation of the carbon-14 diamond beta battery make it feasible to power, for example, a microwave transmitter for RFID applications for tagging space craft and space payloads.

This report describes the fabrication and preliminary evaluation of a carbon-14 diamond battery.

2. Project Background

New battery technologies are required to deliver reliable energy at micropower levels for very long duration deployments in space. Such sources may be used to provide low-duty cycle whereby the electronics are not powered continuously. Radio Voltaic Power Supplies (RVPS) are solid state primary batteries with no temperature limited performance due to their chemical stability and microwatt beta decay heat.

In this study a novel diamond-based RVPS will be fabricated that incorporates carbon-14 as the active material which is atomically incorporated within the diamond diode structure so that beta radiation is efficiently converted into electrical power.

This study will focus on establishing design rules for spatially localizing active isotopic diamond into a monocrystalline Schottky diode structure to inform on the configuration of vertically stacked diode devices for the target power output. This novel battery concept prevents any release of radioactivity and can be packaged into a standard pill cell for easy integration. The technological goal is a device designed to maintain an output of 10μW for two hundred years.

Such power levels are compatible with, for example, the operation of a Micro Electrical Mechanical Systems (MEMS) sensor platform and periodic burst communication with a base station.

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[1] [1] European Patent Application No. 18728702.4 The University of Bristol - Radiation powered devices comprising diamond material.

As the energy requirements to operate low band width communication systems move into the micro-Watt levels of power consumption, the use of such energy sources to power identification beacons becomes possible. Asset tagging will become an important requirement for future space missions as the amount of hardware being taken into space increases year-on-year.

The completed under this activity is the first instance of an RVPS being manufactured with C-14 embedded in the diamond structure. This approach incorporates carbon-14 diamond as a physical layer within the diode fabrication process. This greatly simplifies the battery manufacturing process as it eliminates the need to produce a separate radioisotope source module that would need to be integrated with the voltaic diode to produce a battery.

3. Methodology

Two approaches for making a diamond battery structure were evaluated at the start of this activity:

- The first involved the transmutation (by neutron irradiation) of a nitrogen doped carbon-13 diamond layer, incorporated within a diode structure, into carbon-14.
- The second approach employed Chemical Vapour Deposition (CVD) to form a carbon-14 diamond layer directly within a diode structure.

Carbon-14 by transmutation

The first methodology to be evaluated involved the neutron irradiation of carbon-13 rich diamond as a means to incorporate a carbon-14 layer into a fully functional Schottky diamond diode structure. In support of this activity the use of a modified CVD process was adopted and developed to allow carbon-13 diamond to be synthesized from a series of charges of carbon feedstock into a sub-atmosphere hydrogen gas-plasma environment. Compared to conventional continuous flow CVD systems, this so-called static flow CVD process requires only a fraction of the amount of expensive carbon-13 methane gas but produces diamond films of comparable quality. To implement the static flow growth process, a plasma-assisted CVD system was designed and commissioned for isotopic diamond synthesis.

Modelling of the transmutation (by neutron irradiation) of carbon-13 diamond with and without impurity dopants such as nitrogen was performed using NEA 1880 code, to generate predictions of the yield of carbon-14 produced within selective, carbon-13-rich layers of a Schottky diamond diode. These values were subsequently used to estimate the irradiation times required to obtain useful micropower output. These results revealed that whilst this approach would work, the neutron irradiation times would be too long as to make the method cost prohibitive. Therefore, this approach was not pursued further.

Carbon-14 by direct chemical vapour deposition

The second method to be evaluated involved the direct incorporation of carbon-14 into a diamond diode structure. To synthesize radioactive diamond by this method a non-conventional chemical vapour deposition method was developed - a reduced volume static flow CVD growth system (Mini PDR) based upon the pulsed DC plasma CVD system. This custom-designed deposition system was constructed and installed in the active handling facility at UKAEA (Culham).

For the growth of radioactive diamond, a limited supply of carbon-14 methane with a total activity of 185 MBq was acquired from Amersham International in the form of five glass vials. For each carbon-14 growth experiment, charges of carbon-14 were introduced into a hydrogen gas-plasma energized in a ca. 800cc CVD chamber by pulsed DC plasma supply. This led to deposition of a carbon-14 diamond layer onto boron-doped diamond film supported on either a diamond or non-diamond substrate. Once this carbon source had become depleted in the gas phase, as observed by optical emission spectroscopy, charges of carbon-12 methane were introduced into the gas-plasma mix to consolidate and encapsulate the carbon-14 diamond layer.

Analysis revealed that carbon-14 diamond was successfully produced and incorporated into a diamond diode structure. The diamond structures produced were subsequently shipped to the University of Bristol for material analysis and electrical testing to evaluate battery operation.

4. Key Findings

The key findings from this activity include:

- Successful production of micro-power diamond beta batteries using direct C-14 CVD, and contain C-14 directly into a diamond diode structure - the first of a kind
- Viable sources of the Carbon-14 radioisotope feedstock have been identified
- Successful fabrication method by modified CVD method
- Beta source efficiency gains of greater than 80%
- Cost reduction in active diamond fabrication of the RVPS by 50%
- Estimation of source incorporation efficiency and battery efficiency of carbon-14 batteries with an activity of 3MBq

5. Conclusion

During this ESA Discovery project a collaboration between the University of Bristol and UKAEA was established that facilitated access to the Material Research Facility at Culham and the installation therein of a diamond growth CVD system designed and built by the University of Bristol for the safe synthesis of carbon-14 diamonds using a novel synthesis method termed Static Flow CVD.

Carbon-14 diamond was successfully synthesized from carbon-14 methane and hydrogen gas and selectively incorporated into a carbon-12 diamond semiconductor diode structure, estimated efficiency of the battery is 25% compared with 10% for diamond beta voltaic battery with an ‘external’ beta source.

6. Future Work

Follow-up work would initially focus on integrating a carbon-14 diamond battery with an active RFID tag, to demonstrate its application for space missions. The follow-on activity envisioned would ideally include several industrial collaborators including UKAEA, and some form of participation from URENCO, and Jacobs Space.

Specific scope items would include:

- Improved fabrication and increased power output of C-14 batteries and cost savings on the complete fabrications
- Investigation of various sources of commercial C-14 feedstock (including from Magnox reactors) and their use in synthesizing carbon-14 battery structures. This is hoped to identify and establish a continuous, sustainable supply chain for future fabrications.
- Continue the development of space applications including the radio-voltaic active RF ID tag and remote sensing in harsh environments
- Raise diamond RFID technology from current TRL 3 to TRL 5.