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DESIGN, FABRICATION AND TESTING OF A NOVEL ENERGY-HARVESTING THERMOELECTRIC POWER SUPPLY FOR WIRELESS SENSORS

Velimir Jovanovic, Saeid Ghamaty and John C. Bass
Hi-Z Technology, Inc., 7606 Miramar Rd. #7400,
San Diego, California 92126, USA, 858-695-6660,
FAX 858-695-8870, v.jovanovic@hi-z.com

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ABSTRACT

A prototype energy-harvesting thermoelectric generator (TEG) was designed and fabricated and it is being tested to provide power for wireless sensors used in the health monitoring (monitoring of temperatures, vibrations, strains, etc) of Navy shipboard machinery. TEGs are rugged, reliable, solid-state devices that convert heat directly into electricity without any moving parts. The TEGs designed in this project utilize the heat transfer between shipboard waste heat sources and ambient air to generate electricity. To satisfy the required small design volume of less than one cubic inch, Hi-Z Technology, Inc. (Hi-Z) is using its innovative Quantum Well (QW) thermoelectric technology that provides a factor of four increase in the conversion efficiency, and a large reduction in the design volume over the currently used bulk bismuth-telluride thermoelectics. QWs are nanostructured multi-layer thin films. These wireless sensors can be used to detect cracks, corrosion, impact damage, and temperature and vibration excursions as part of the Condition Based Maintenance (CBM) of the Navy ship machinery. The CBM of ship machinery can be significantly improved by automating the process with the use of self-powered wireless sensors. These power-harvesting TEGs can be used to replace batteries as electrical power sources and to eliminate tethered wires and cables, thus significantly reducing the installation and maintenance costs. The very first QW TEG module anywhere was just successfully tested (it produced electricity from heat). It remains to package this module with thermal insulation in the housing and heat sink, and to test this entire TEG device in a simulated thermal environment of a Navy gas turbine. Following this test, it is planned to attach this device to the surface of a gas turbine on a Navy ship and to test it in its actual environment, in conjunction with a wireless sensor. This power supply for wireless sensors can also be used in health monitoring of equipment in the nuclear and conventional power plants, process plants, and the monitoring of temperatures, vibrations and pressures of steam lines, etc. Hi-Z has chosen this small power supply as the first practical application of its emerging QW TEG technology. However, this technology can also be used on a much larger scale in, for example, recovering the waste heat from the exhaust of the truck and automobile engines, where the generated electricity can be used to eliminate the alternator and thus reduce the load on the engine, improve overall efficiency and reduce fuel consumption.

INTRODUCTION

There is a need to develop and commercialize generators for harvesting energy from interior shipboard environments to provide electrical power to the CBM sensor systems. Several exploratory research studies have been conducted showing the feasibility of extracting power from environmental sources such as tides, wind, sunlight, vibrations, shock, heat, and animal life to either replace or augment batteries as electrical power sources. The use and life cycle cost of integrating smart and/or wireless sensors in system health monitoring applications is severely limited by current battery life. A concept for harvesting energy from internal shipboard environments to provide low-level electrical power has been demonstrated recently in the Navy's Reduced Ship's crew by Virtual Presence (RSVP) Advanced Technology Demonstration (ADT). However, the RSVP demonstration components are not adequately scaled in size and electrical energy capacity to support the small one cubic inch volume targeted for integrated condition health monitoring sensor systems that are emerging into commercial markets.

Hi-Z has completed the Phase I and it is currently in the Phase II of a Small Business Innovative Research (SBIR) in which it is using its TEG modules that harvest energy from the interior shipboard thermal environment. These TEGs harvest power from the temperature difference (ΔT) between the hot equipment surfaces and the colder ambient air, and Hi-Z has already demonstrated the feasibility of this type of power harvesting to supply power for sensors in two applications using its currently-available bulk bismuth-telluride based TEGs. The latest of these applications was for a ΔT of only 5°C (in this case between the hotter ambient air and the colder ship's hull) and this TEG module (Ref. 1) was successfully installed on USS Monterey (CG 61). However, the footprint of this TEG would be too large for a small power harvesting system required in this SBIR. In order to satisfy the small design-volume target of one cubic inch, Hi-Z is using its emerging thin-film Quantum Well (QW) thermoelectric technology that will provide a factor of four increase in efficiency and a large reduction in the design volume over the bulk bismuth-telluride based TEGs. QWs are nanostructured multi-layer films. Hi-Z has been engaged in energy harvesting from its inception 16 years ago with the applications ranging from the recovery of waste energy from truck diesel engine exhaust to energy harvesting from wood burning stovetops. This study represents the logical extension of the Hi-Z existing power harvesting technology to a much smaller design volume by using the Hi-Z emerging QW TEG technology.

NOMENCLATURE

T	temperature
V	volts DC
Z	thermoelectric figure of merit (K^{-1})
Å	angstroms
in	inches
Δ	difference
α	Seebeck coefficient (°K/V)
κ	thermal conductivity
σ	electrical conductivity

Discussed in this paper are the energy-harvesting methods for the interior shipboard environment, a brief review of the Quantum Well thermoelectric technology, review of the power and voltage requirements for wireless sensors, review of the shipboard interior thermal environment data, and the analysis and design of a power-harvesting Quantum Well thermoelectric generator for wireless sensors.

Energy Harvesting Methods for Interior Shipboard Environment

Three energy-harvesting methods from the interior shipboard environment were investigated in the RSVP program (Ref. 2): (1) photovoltaics, (2) thermoelectrics, and (3) vibration. The Oak Ridge National Laboratory (ORNL) performed an ambient light survey aboard USS Supply (AOE 6) and concluded that there is not a sufficient light level in the measured compartments to supply all the power required by a sensor cluster. Thus, photovoltaics are not a realistic option, and thermoelectrics and vibration remain the only viable options (Ref. 1). While the thermoelectric and vibration energy-harvesting technologies each have their unique advantages and disadvantages, the Navy does not regard them as competing technologies but as complementary technologies. This paper covers just the thermoelectric energy-harvesting application.

Quantum Well Thermoelectric Generators

A summary of the Quantum Well thermoelectric technology is provided in this section. More detailed discussion is given in Ref. 3. Hi-Z is developing new QW thermoelectric materials that are expected to yield conversion efficiencies several times that of present day bulk materials. A comparison of Hi-Z's results versus others is shown in Figure 1 illustrating time history of the figure of merit, which is a measure of performance as defined in Section 3.2.6. For over 35 years, the figure of merit stayed close to the value of 1. However, recent breakthroughs have occurred in the figure of merit by using the QW alternatives to bulk material, with the Hi-Z's material reaching the remarkable ZT value of 4.1 in tests in 2002. This value corresponds to a conversion efficiency of 14%, which was measured in tests at Hi-Z in October 2002. This high efficiency has been reconfirmed in separate tests at Hi-Z completed in May 2003 as shown in Figure 2. It is this breakthrough that allows Hi-Z's QW TEGs to meet the goals of this SBIR. Based on the current experimental work, Hi-Z anticipates thermal to electric conversion efficiencies of 20-40% at a T_H of 250°C to 700°C and a T_C of 50 to 100°C.

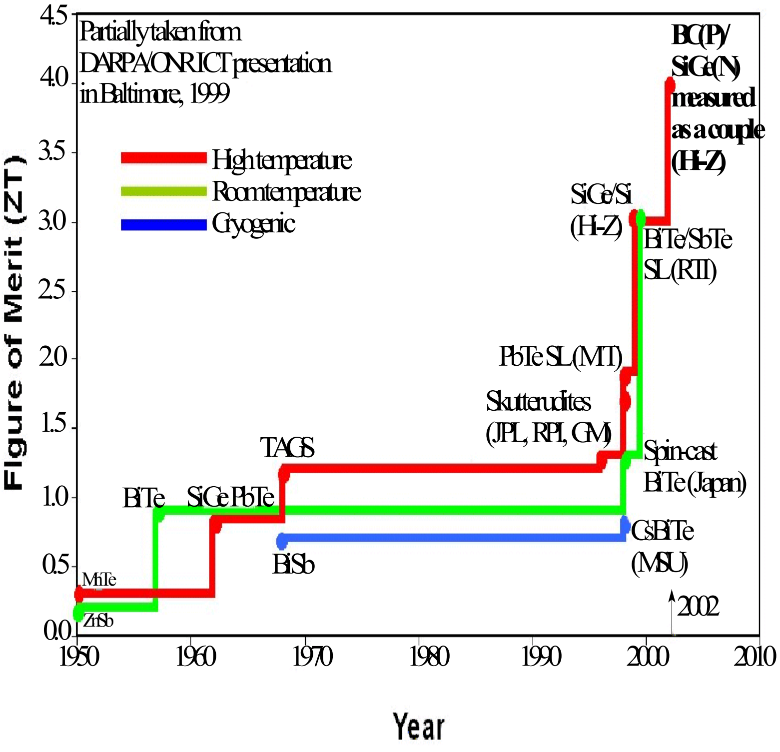


Fig. 1 History of Thermoelectric Figure of Merit, ZT, (partially taken from Ref. 4)

Thermoelectric materials are presently used for power generation in remote locations, for example in deep space probes. Usage in a wider range of applications is conditional upon improvement in the efficiency of energy conversion from heat into electricity and in the specific cost of power generation ($/W). The efficiency of thermoelectric energy conversion

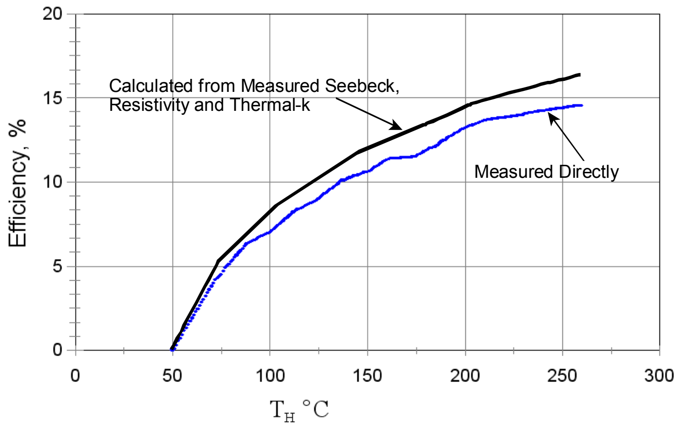


Fig. 2. Measured and Calculated Efficiency (P_{out}/P_{in}) of QW Couple Versus Hot-Side Temperature from Power Data Measured in Hi-Z Tests in May 2003

devices is strongly limited by the performance of the materials, which is normally measured in terms of a *Figure of Merit* Z. The thermodynamic efficiency, η, of a thermoelectric power generator is given by

$$\eta = \{ (T_h - T_c) / T_h \} * \{ (M - 1)/(M + T_c / T_h) \}, \qquad (1)$$

where M is defined by

$$M = \{ 1 + Z (T_c + T_h) / 2 \}^{1/2}, \qquad (2)$$

with T_h and T_c the temperature of the hot and cold junctions respectively. To achieve a high efficiency, the figure of merit Z must be high. For a specific material,

$$Z = \sigma\alpha^2 / (\kappa_L + \kappa_e), \qquad (3)$$

where σ is the electrical conductivity, α is the Seebeck coefficient, κ_L is the lattice or phonon contribution to the thermal conductivity and κ_e is the electron contribution to the thermal conductivity. Much of the effort to improve Z over the last 20-30 years has been focused on attempts to reduce the lattice thermal conductivity without affecting the electrical conductivity. Solid solution alloying, as in the case of silicon-germanium, has been effective in this respect; also the search for new materials with structures favorable for poor phonon propagation has led to several promising candidates such as the skutterudites (Ref. 5).

The breakthrough approach to increasing Z is to form compositionally modulated materials, mainly by QW confinement of carriers in the active layers in a multilayer film by the adjacent barrier layers. The core concept is to enclose each electrically active layer by a material that has a band offset sufficient to form a barrier for the charge carriers. The major improvement in Z is expected to follow from an increased Seebeck coefficient that results from an increase in the density of states. The electrical conductivity σ increases due to a large increase in the mobility of the carriers and the thermal conductivity κ is reduced due to strain between the QW and barrier layers which in turn inhibit phonon flow. QW effects become significant only when the thickness of the active layer is small, below about 200Å.

Theoretical models predict that values of ZT of 2 and above are possible in a variety of low-dimensional structures, but only the B_4C/B_9Cs and Si/SiGe have demonstrated performance above this level to date, *i.e.*, a ZT of ~4. It appears that Si/SiGe, Si/SiC and B_4C/B_9C QW layers can be economically and reliably sputtered on Si substrates. Si/SiGe QW layers have also been sputtered on Kapton substrates.

Hi-Z has measured the thermal conductivities of Si/SiGe quantum well films with the 3ω-method. Values obtained by this technique indicate a large decrease (factor of 3) in $\kappa_{in\text{-}plane}$ for the Si/SiGe quantum wells versus bulk material and is in agreement with theory. Hi-Z, under DOE funding, generated the first data that indicated that multi-layer films of alternating layers of Si and SiGe have a figure-of-merit that is more than an order of magnitude higher than bulk SiGe near room temperature and below. These films were grown by MBE at NRL and UCLA and by sputtering at LLNL and Hi-Z. All the thermoelectric property data were measured by Hi-Z. Hi-Z's recent progress in the development of high efficiency QW thermoelectics is given in References 6 and 7.

Review of Wireless Sensor Requirements

In order to determine the state-of-the-art wireless sensor/transmitter power and voltage requirements, Hi-Z conducted a review that included direct contact with the known Original Equipment Manufacturers (OEM) of the machinery health monitoring sensors/transmitters, university and research institutions, Internet searches, and relevant technical conferences, journals, and trade shows. In addition to the power and voltage requirements, the configuration, size and weight were also significant parameters in designing a small power harvesting system and demonstrating interface compatibility with the QW TEG module. The results of this review indicated a large variation in power and voltage requirements and also a variation in the wireless protocol used, Bluetooth, Wi-Fi (802.11b), ZigBee, and several proprietary technologies. These different technologies have different power requirements and different characteristics regarding interference, transmission distance, frequency including frequency hopping, etc. IEEE is working on a standard for wireless sensor technology, but it has not yet been approved. The power requirements for the wireless sensors found in this review ranged from 1 mW to 30 mW. The majority of the wireless sensors required a 3 V DC input, while some required an input voltage as high as 5.5 V. In order to obtain an estimate of the emerging wireless sensor requirements, the OEMs were asked what their power and voltage requirements may be in a six-year time frame. The responses varied from an order-of-magnitude reduction in power from the current levels to a more cautious factor-of-two reduction, while some manufacturers were unwilling to quantify future power reductions. Some US research organizations assume much lower power requirements. For example, Rabaey [8] of the UC Berkeley Wireless Research Center reports a goal for power of < 100 µW. Some US OEMs project the voltage requirements to go down to 1.2 V, while others think that they will remain at 3 V. Based on the above information, the power requirement for the emerging wireless sensors was conservatively estimated to be ≤ 1 mW, and the voltage requirement to be ≤ 3 V.

Review of Shipboard Thermal Environments for Energy Harvesting

In order to base the energy-harvesting TEG design on the actual shipboard thermal environment, a review was made of the available Navy data regarding the machinery surface temperatures and adjacent ambient air temperatures from which the ΔT across the TEG module can be calculated and this ΔT is one of the key parameters affecting the size of the module. Review of these temperature data indicated that there are many locations with good potential for energy harvesting. The thermal environment selected for the conceptual design corresponds to the compressor section of the gas turbine. In addition to its good potential for energy harvesting, this equipment surface was selected because of the availability of complete temperature data (both the equipment surface temperature and the adjacent ambient air temperature) so that no assumptions would be necessary in the design analysis. The surface temperatures at the compressor section range from 111.2°C, to 221.1°C, and 342.2°C. These surface temperatures, in conjunction with the maximum ambient air temperature of 71°C in this area, will provide adequate ΔTs for energy harvesting. It should be noted that the given maximum ambient air temperature is the maximum allowable value and that the actual temperature should be lower, and that using the maximum allowable value in the TEG sizing is conservative because it would underpredict the performance due to a lower than actual ΔT. Also, the outside diameter of the compressor section is 28 in., which will allow for easy installation of the TEG at this location.

Analysis and Design of QW TEG Energy Harvesting System

A thermal analysis of the TEG system was performed that included the sizing and material selection of the thermal insulation, sizing of the heat sink, determining whether or not extended surfaces (fins) are required based on the latest power and voltage requirements of the wireless sensors, duty cycles, etc.

The Si/SiGe film has good thermoelectric properties in the lower temperature range which is appropriate for this application and because it can be manufactured in both N and P type which should minimize the development problems with contacting, laying down the legs, and with annealing. Hi-Z has also successfully deposited N & P Si/SiGe QW on both silicon and Kapton substrates. The use of the Kapton substrate has advantages related to its lower thermal conductivity, which is desirable to minimize thermal bypass losses. Thus, for this application, the analysis and design efforts were primarily focused on the N & P Si/SiGe QW films deposited on a Kapton substrate.

An analysis was performed in order to assess the effect of QW film thickness on conversion efficiency for a QW thermoelectric module consisting of Si/SiGe P and N films deposited on a Kapton substrate. The purpose of the analysis was to determine the optimum film thickness that will result in the maximum conversion efficiency. This type of an analysis has been already performed for the test couple consisting of the B_4C/B_9C and Si/SiGe P and N films deposited on a Si substrate and the optimum thickness was 25 μm. Because Kapton has much lower thermal conductivity than Si, the bypass heat losses through the substrate will be significantly lower resulting in lower optimum film thickness. A parametric study was performed for three points on the compressor section of the gas turbine. The quantum well (QW) film thickness was varied from 0.2 μm to 30 μm. The Kapton thickness of 0.001 inch was used in the analysis.

The results of the analysis are presented in Figure 3, which shows the variation of the conversion efficiency for the Si/SiGe QW TEG module with the film thickness for the three points on the compressor section of the gas turbine. These results illustrate that the conversion efficiency is a very strong function of the temperature difference across the TEG module (as shown by the variation at the three GT points), that the efficiency reaches an asymptotic value with increasing film thickness, and that there is hardly any benefit in going beyond a certain film thickness. This optimum film thickness for the Si/SiGe films on 0.001-inch Kapton substrate is between 10 to 15 μm, depending on the location, i.e. the temperature difference. For B_4C/B_9C-Si/SiGe QW films on a 5 μm silicon substrate, the optimum film thickness is approximately twice as large because it takes a much thicker film to compensate for the larger bypass heat losses in the silicon substrate due to its much larger thermal conductivity. The results of this analysis have a direct impact on the design, manufacturing and cost.

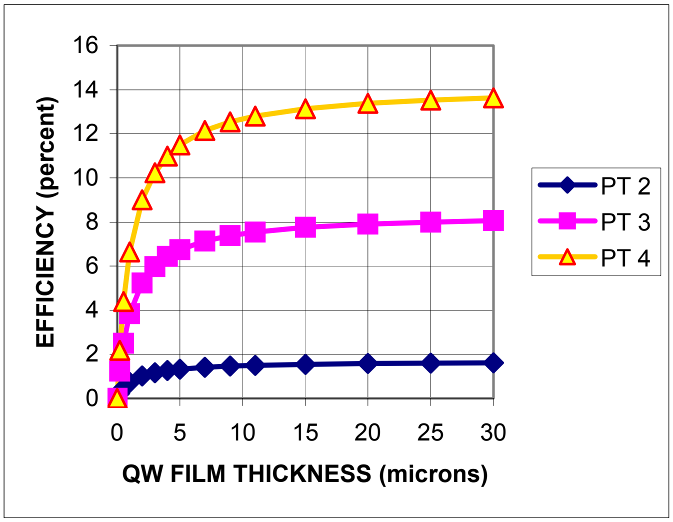


Fig. 3. Conversion Efficiency Variation with QW Film Thickness for Si/SiGe P & N QW TEG at Three Gas Turbine Points with Different Surface Temperatures

The QW TEG module sizing calculations were performed for the compressor section of the gas turbine using the temperature data provided by the Navy. Sizing calculations were performed for the locations with the highest surface temperature (342°C) and the lowest temperature (112°C). The modules were originally sized for an output electrical power of 1 mW, which is adequate to charge the capacitor that is included to provide the capacity to power the sensor for short durations when no ΔT is available, such as during the start up. Yet, the capacitor charging time can be substantially reduced by converting more of the available thermal potential in the shipboard environment into electrical power. Thus, in order to reduce the capacitor charging time, the TEG power output was increased to 10 mW.

An illustration of the prototype design of the energy-harvesting QW TEG is shown in Figure 4. It includes the QW TEG module, the heat sink, the thermal insulation and the housing. These components are shown in Figure 5.

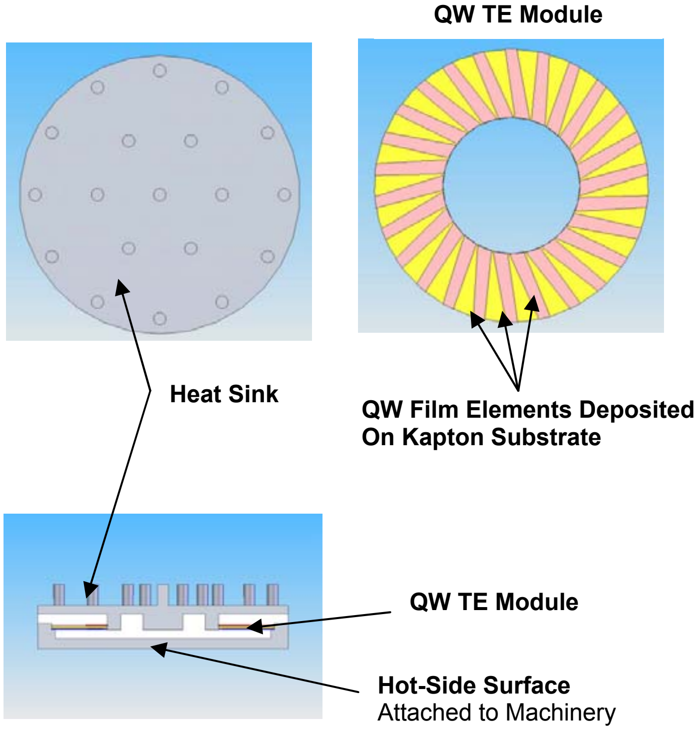


Fig. 4. Prototype Design of Energy-Harvesting QW TEG System

The results of the module sizing calculations indicated that each design was feasible regarding the maximum heat flux and manufacturing considerations. An example of a module design is shown in Figures 4 and 5. This design is for the GT compressor location with the 342°C surface temperature and this module will produce 10 mW of electrical power at the open circuit voltage of 6 V. The module is in the form of a flat disk. It contains 26 semi-radial QW film legs with the N type Si/SiGe film deposited on one side of the substrate and P type Si/SiGe film on the other. These legs will be made by depositing the film through a mask. The legs will be made of multiple 100Å thick layers. Electric connections can be made by either depositing metal on the inner and outer edges of the disk or by a plated through hole at each end of each leg. Some applications require a much larger number of legs, which are typically narrower than shown in Figure 4, and for such cases it may be preferable to use two or three sub-modules for the ease of manufacturing and making of electrical connections. The sub-modules will be stacked.

The main heat flow through this generator system is in the bottom and up the side, radially inward through the QW TEG module, up the center post to the heat sink above the module and into the pin fins where it is dissipated to the ambient air. A nylon screw is used between the bottom hot surface and the heat sink in order to minimize the bypass heat losses. A thin support tube, made of Vespel, or similar thermally insulating material, is used to separate the heat sink from the hot surface at the outer boundary in order to minimize the thermal bypass losses and to contain the internal thermal insulation. Aerogel is the material of choice for the thermal insulation although the closed-cell foam insulation could also be used. Additional thermal insulation will be provided to the QW TE module by hot pressing 1-mil bondable Kapton on both flat side of the module where QW legs were deposited. This will also provide electrical insulation to the QW legs.

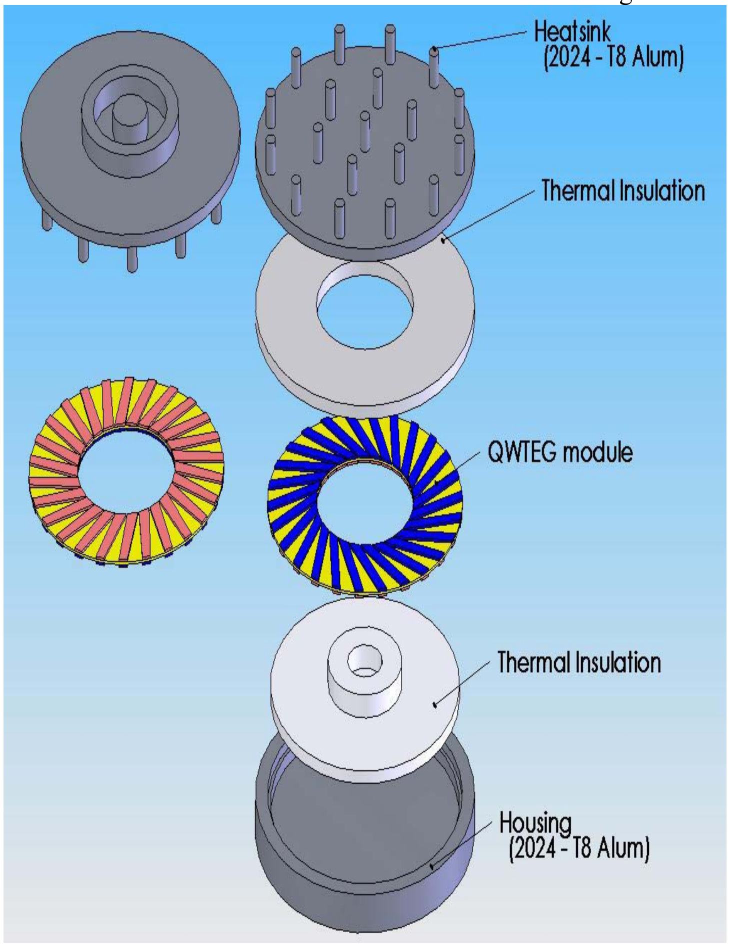


Fig. 5. Components of the QW TEG System

The control electronics board and the transmitter module are stacked above the pin fins. The transmitter module has a built-in temperature sensor and it is 1 inch in diameter and 0.25

inch high and it weighs 3 grams. It comes with 18 connector pins, which provide for convenient connection to the control electronics board. The height of the control electronics board is less than 0.2 inch and the board can be bonded to the pin fins with epoxy. The number of pin fins required to dissipate the heat depends on the application. For some applications no fins are required because for these applications the heat to be rejected is so low that natural convection from a one-inch disk is sufficient to dissipate the heat. For other applications considered in this study, the required number of pin fins ranged from 19 to 120 for pins with a 0.05-inch diameter. The fins can be made of aluminum and pin fins of this type are available from several manufacturers. For the applications requiring no fins, the power harvesting system can be packaged in a different configuration, so that the total volume would be substantially reduced. Although copper has higher thermal conductivity, aluminum was selected as the material for the housing and heat sink primarily for cost reasons and because the detailed thermal analysis indicated good performance with aluminum. The entire system can be attached to the compressor section of the gas turbine by either a clamp or a thermally conductive epoxy. If the clamp method is used, a thermally conductive pad or grease will be required between assembly and the compressor surface in order to minimize the contact thermal resistance and the temperature drop between the two surfaces.

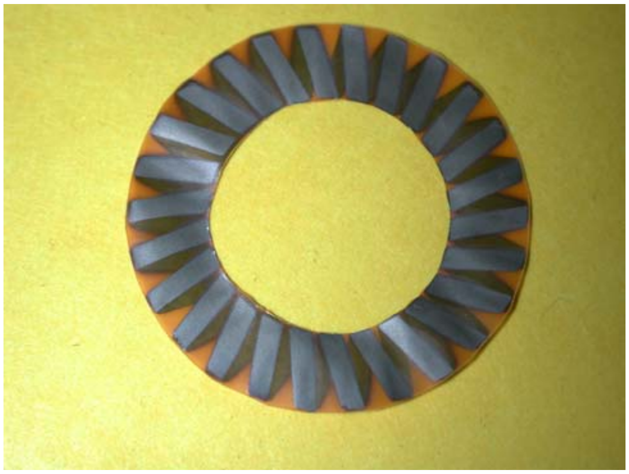
Manufacturing of the QW Module

During this effort several new manufacturing techniques had to be devised and tested regarding the QW film deposition for this configuration. These involve the deposition of QW films in long narrow strips, deposition of thicker films (6 μm) on a Kapton substrate (previously only a few layers were deposited), deposition of films on both sides of the substrate and making of electrical contacts for this configuration. Up to now QW films were made for continuous surfaces, not for the narrow strips shown in Figures 4 and 5. Hi-Z considered that the easiest manufacturing method of fabricating such narrow QW strips is by magnetron sputtering through a shadow mask. A stainless steel shadow mask was fabricated by laser cutting. The Kapton substrate and the mask were placed in the sputtering machine. The resulting film looked good under examination. Only a few 100Å film layers were sputtered on Kapton up to now. This was done by Hi-Z four years ago. The critical part in this procedure is the annealing of the first Si layer deposited on Kapton. This changes the structure of the Si from amorphous to a more ordered structure in preferred orientation, which allows for the successful deposition of the next layers. During this effort, 600 layers were successfully deposited and the film looked good under examination.

During this program the first QW film deposition on both sides of Kapton substrate was successfully performed. A piece of Kapton was sandwiched between two shadow masks, and set on top of a 2-inch diameter silicon substrate. When the deposition on one side was completed, the sandwiched Kapton was removed from the chamber and flipped over, in order to deposit on the reverse side of the Kapton. The resulting film depositions were then examined and they looked good. There was slight warping in Kapton due to heating during the sputtering, and this caused some elements not to be perfectly straight. This problem can be fixed by keeping the Kapton substrate in slight tension during sputtering and a mechanism for this purpose was designed and fabricated.

Several QW modules were fabricated using the Kapton tensioning mechanism developed to prevent warping of Kapton during sputtering. The resulting modules were flat as can be seen in Figure 6, which also shows the module without Kapton tensioning. The new modules were made with the film thicknesses ranging from 1 to 6 μm on each side of the substrate.

With Kapton Tensioning



Without Kapton Tensioning

Fig. 6. Si/SiGe QW Modules on Kapton Substrate, 1-inch OD

Shadow masks were designed and fabricated for the sputtering of gold contacts at the end of each film element. The masks were precision made by laser cutting. These masks had the same eight small holes for the orientation purposes as the masks used in the QW film sputtering. The gold contacts were sputtered on the module, and afterwards the excess Kapton was trimmed off. The detail of the module with gold contacts is shown in Figure 20, with the P-type Si/SiGe elements on this side of the Kapton substrate and the N-type elements visible on the backside of the substrate. As can be seen in this figure, there is good alignment of the elements on both sides of the substrate. The main electrical contacts between hundreds of film layers and between the P & N elements are achieved with the use of Au deposition and silver epoxy paste. These Au deposits vary in their contact resistance. To reduce this problem, sputter cleaning (reversing the sputter deposition process to remove oxides) is needed and is being pursued via equipment modification. An alternate technique is to first deposit Ti or Zr before Au is deposited.

Fig. 7. Detail of Gold Contacts at Ends of QW Film Elements

Testing of Prototype QW Module

The thermoelectric properties, resistivity (ρ), Seebeck coefficient (α) as well as thermal conductivity (κ) of the N and P Si/SiGe materials that comprise the energy-harvesting device shown in Figure 4 are evaluated for every QW TEG module that is fabricated. The Seebeck coefficient of the most recent film is ~820 μV/°C for the P-type and –900 μV/°C for the N-type. These measurements confirm that Quantum Well characteristics have been achieved which lead to a factor of four higher conversion efficiencies than for the bulk materials. All the properties are measured experimentally for both the film and substrate together, and represent an "effective" film-plus-substrate, or composite, with no data correction. Contacts were deposited to measure the resistivity as well as the thermal conductivity. All the properties were measured on the same sample except for the thermal conductivity, which was measured on a different sample but from the same batch, using the 3-omega method. The measurements were performed on samples with near neighbor ordering, which was confirmed with Auger spectroscopy.

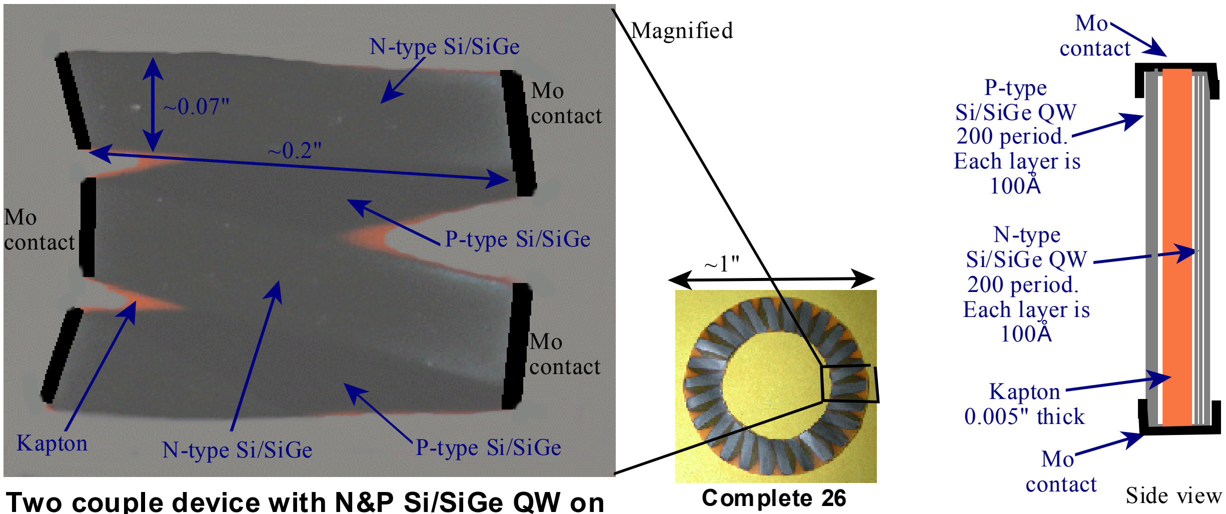
A simple test was performed on the very first QW TEG module that was fabricated in order to determine whether or not it would produce electricity when heat is applied to it. The test setup consisted of a small (0.25-inch diameter) cartridge heater which was enclosed with an aluminum sleeve with a slight taper on the outside surface so that the module inside surface would fit snuggly over it at approximately the mid height of the sleeve. The outside surface of the sleeve was insulated with Kapton tape in order to prevent electrical shorting between the module elements and the sleeve. The temperature of the sleeve was monitored by a thermocouple and controlled by temperature controller. After the output leads were made on the module, the module was placed over the heater sleeve and pressed down until snug fit was achieved. The leads were then connected to a digital voltmeter. Then, the heater was turned on and the module generated electricity as displayed on the voltmeter. **Thus, the test of the first QW TEG module was successful.** This was not a rigorous performance test, but sufficient to demonstrate that the module works. Rigorous performance tests will be done after electrical contacts have been improved and the module packaged with thermal insulation in the housing and heat sink as shown in Figures 4 and 5.

Improved Electrical Contacts with Laser Assisted Sputtering of Molybdenum

Figure 8 shows a recent QW device with two couples of N and P-type Si/SiGe deposited on both side of a Kapton™ substrate. This device was fabricated for milliwatt energy harvesting applications. Only two out of twenty couples of the complete energy-harvesting device were contacted due to limited tooling and fixtures in the high vacuum chamber. An improved sputtering process was successfully developed to deposit the Mo metal contacts that exhibit a negligible contact resistance with both N and P material.

Initial measurements of power output from this Mo contacted device, from T_{cold}= 26°C to T_{hot}= 66°C, indicate it is very stable. The performance of this QW device is shown in Table 1, and the results appear very promising. The output voltage from this device was 225 mVolt, and total power was 0.371 mWatt at a temperature deference of ~40°C. The power and output voltage of this device @ ΔT = 40°C, are very close (<10%) to the calculated values of the N & P materials and they are shown in Table 1.Extrapolating to a full size device would yield total power of ~4.8mWatt at ~2.93Volt for a complete 26 couple energy harvesting device that can power a wireless sensor. We will continue the thermal aging of this device and more devices with metal contacts, such as Mo or other materials, are being fabricated and will be life tested both isothermally and in gradient operation to obtain power as a function of time. Alternate vacuum/coating equipment is being upgraded so we may complete the milliwatt device and fabricate milliwatt modules for the DOE program.

An earlier single couple device was fabricated with N-type Si/SiGe and P-type B4C/B9C is shown in Figure 9. It also has Mo contacts. The substrate with this couple was single crystal Si and alumina was used to electrically insulate N and P legs. It has operated for more than 2500 hours with no degradation (shown in Figure 10). The Si single crystal substrates have a high thermal conductivity and therefore are major heat leak. To reduce this heat loss and increase efficiency, Kapton is being pursued in place of Si since its thermal κ is two orders of magnitude lower than Si. Kapton is



Two couple device with N&P Si/SiGe QW on Kapton substrate

Complete 26 couple device

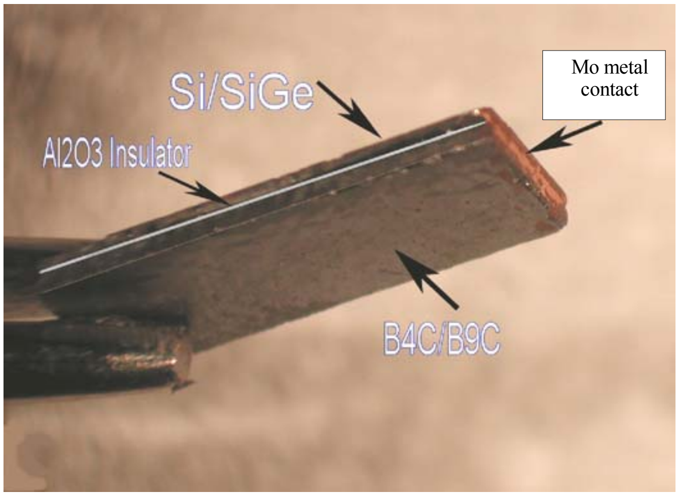
Fig. 8. QW N and P Type Si/SiGe Two-Couple Device on Kapton Substrate. The Molybdenum was Deposited by an Improved Sputtering Process. This is the First Device on Kapton.

also flexible, useful up to ~ 300°C and much lower in cost than 5µm thick Si.

T_{Cold} = 26°C T_{Hot} = 66°C	2 Couples, Measured	26 Couple Device	Calculated, 26 Couple Device
Voltage	0.225 V	2.93 V	3 V
Power	0.371 mW	4.82 mW	5 mW

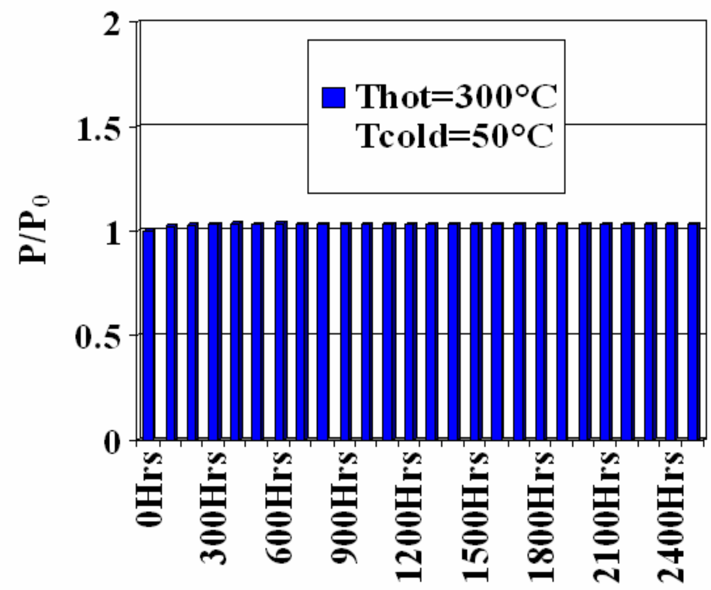
Table 1. Thermoelectric Properties of QW Device on Kapton Substrate with Molybdenum Contacts Compared to Calculated Values. The N and P Elements are 200 Periods (400 Layers) of Si/SiGe, and Each Layer is 100 ÅThick. The Elements are 0.07"x0.2". The Kapton is 0.005" Thick.

Fig. 9. QW Si/SiGe-B_4C/B_9C couple for thermal stability test. The Mo was deposited by an improved sputtering process.



This is the first couple where an Al_2O_3 insulator was used. Other oxides, such as stabilized ZrO_2, with much lower thermal conductivities will be incorporated in future couples.

Fig. 10. Power ratio life test data



This latest achievement in fabricating a two-couple module was in the following:

(1) The N and P elements are both Si/SiGe QW layers.
(2) The couple represents the same materials and processes as proposed for the Navy mW sensor power supply and the DOE waste heat recovery from vehicles programs.

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CONCLUSIONS

The novel manufacturing techniques needed for this QW thermoelectric power supply have been developed and successfully demonstrated. The first QW module was fabricated and tested and it produced electricity when heat was applied to it. It remains to complete the molybdenum electrical contacts on the entire module, and to perform the conventional tasks of packaging the module in the housing with thermal insulation and the heat sink, and conducting the performance test for the entire device.

The thermoelectric generator developed under this program was sized to provide adequate power for a wireless sensor/transmitter used in the health monitoring of the Navy machinery. This power supply can also be used to power wireless sensor/transmitters for health monitoring of the equipment on aircraft, aerospace, power plant and process plant industries. The COTS wireless sensors/transmitters require power in the milliwatt range. However, this technology can also be used on a much larger scale in, for example, recovering the waste heat from the exhaust of the truck and automobile engines, where the generated electricity can be used to eliminate the alternator and thus reduce the load on the engine, improve overall efficiency and reduce fuel consumption. Another application is for auxiliary power units. A thermoelectric module can act as a cooler if electricity is applied to it, and in this application with QW technology it can reach a higher coefficient of performance (COP) than the SOTA vapor-compression refrigeration systems and with the distinct advantage of having no compressor, moving parts, or fluids.

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