INTEGRATION AND CHARACTERIZATION
OF A P³ MICRO HEAT ENGINE

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The members of the Committee appointed to examine the thesis of MICHAEL REOMA THOMPSON find it satisfactory and recommend that it be accepted.

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INTEGRATION AND CHARACTERIZATION
OF A P³ MICRO HEAT ENGINE

Abstract

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The focus of the research was to design, fabricate, and test a micro heat engine which is a fundamental component comprising a P³ Micro Power System. This external combustion engine converts thermal energy into mechanical energy. The mechanical energy produced is then transformed into electrical energy through the use of a thin-film piezoelectric membrane generator.

The philosophy and procedures used to engineer an operational unit engine are presented in detail. Components for the engine were produced using standard microelectromechanical system (MEMS) fabrication techniques. Clean Room facilities at Washington State University, the Washington Technology Center, and the Army Research Laboratory were used.

To create an individual micro heat engine, a two-phase working fluid, an engine cavity, a thin-film piezoelectric membrane generator, and a heater membrane were integrated. Semiconductor tape was used to separate the two membranes and to define the engine cavity. Fluorinert 5060DL was the two-phase working fluid used for engine
operation. To simulate the periodic heat introduced into the engine, a resistance heater was fabricated on a membrane.

To characterize the micro heat engine’s performance, instrumentation was developed to control the energy supplied into the engine, to monitor the engine’s output voltage and power production, and to record the engine’s internal temperature.
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CHAPTER 1
INTRODUCTION

1.1 MOTIVATION

The United States military currently seeks a power system that is small in size, low mass, and low cost [1]. These power systems are targeted for use in emerging micro air vehicles, distributed sensors, and autonomous robotic systems. A typical infantryman carries over 100 pounds of bundled weight and over 20 pounds of that are batteries alone [2]. The batteries are required to run the soldiers electronics and the amount needed will undoubtedly increase with new power driven technologies for the battlefield. Even consumers can benefit from small, lightweight, and cheap forms of energy to power cellular phones and portable computers [3].

Let us consider the energy density of today’s best lithium ion battery. They approach approximately 1 kJ/g and require an additional power supply for recharging [4]. A hydrocarbon fuel, on the other hand, such as propane, methane, gasoline, and diesel, offer at about 50 times the energy density of this battery [1]. With a modest chemical to electrical energy conversion, a micro power generator can provide an energy density that is five to ten times larger in than a battery. In addition to the energy density shortfalls of a battery, it poises environmental disposal problems, and its available energy degrades with time.

Microelectromechanical systems (MEMS) offer an alternative. Several MEMS teams are now focusing on power generation [5]. The availability of a small and lightweight energy system would fulfill the growing power needs of ever shrinking electronics by harnessing the energy density of hydrocarbons. A MEMS strength is that
fabrication techniques exploit semiconductor industry methods to create incredibly small mechanical devices that are amenable to batch manufacturing for reduced costs.

The work performed in our WSU laboratory offers an alternative and innovative means for MEMS micro power generation. The design is based on a dynamic heat engine that operates on an external heat source [6,7]. The design is scalable, fuel flexible, amenable to batch manufacturing, and modular in architecture.
1.2 $P^3$ CONCEPT

The $P^3$ micro heat engine concept is based on design for micro manufacturing and design for micro operation. Existing micro fabrication techniques drives the engine requirements since these methods are nothing like the macro methods used to manufacture conventional machinery. The macro-scale physics that govern conventional engines are also very different to the micro-scale physics that govern micro engine operation. The engine is designed to take advantage of these phenomena dominating at the micro-scale. The $P^3$ micro heat engine is extraordinarily different to any existing engines in design, fabrication, and operation.

The micro power generation system capitalizes on simple micro fabrication techniques to create single engines that are two-dimensional and modular in architecture. A micro power system consists of individual generic modules or unit engine cells where all functions of an engine are included. Figure 1.1 provides a simplified cross-sectional illustration of a unit engine cell [8]. The unit cell contains a cavity filled with a working fluid. The two-phase working fluid is sealed from the top and bottom by two thin membranes and is saturated throughout the entire engine cycle.

Instead of circulating the working fluid through the engine cavity, heat is alternately conducted into and out of the engine. Heat enters the cavity through the bottom thin membrane through conduction. The introduced heat changes the quality and increases the volume of the saturated mixture. The result causes the top thin piezoelectric membrane to flex outwards. As the expanding working fluid forces the piezoelectric membrane out, the membrane is strained, developing an electrical charge. The charge is drawn off as useful current at the membrane’s peak deflection. Heat rejection
immediately follows. Subsequently the membrane generator flexes back in, compressing
the working fluid. From this stage, the engine cycle repeats.

![Diagram of P³ unit micro heat engine concept]

**Figure 1.1**: P³ unit micro heat engine concept

Depending on the power requirement, a power supply can be constructed with
either a single unit cell engine or an array of several unit cell engines. Each unit cell
engine is expected to produce nearly 1-mW of power operating over a temperature
difference of 10 °C [9].

One advantage of the design concept is that it allows for scalable power. Unit
cells can be arranged in parallel to operate over the same temperature difference.
Configured in series, the unit cell engines forms a cascade, where each unit cell engine
operates at a fraction of the total temperature difference across the complete cascade.
The cascade process is depicted in Figure 1.2 [10].
This flexibility offers power system outputs from the mill-watts to the ten’s of watts. With individual engines the size of a few millimeters across and a few microns in thickness, 1,000 units arranged to produce 1-Watt of power will occupy a 1-cm$^3$, or approximately the volume of a sugar cube [11].

The P$^3$ dynamic engine uses an external heat source for thermal power. Since the P$^3$ is an external combustion engine, additional flexibility in terms of fuel choice is available for the power system. Heat from a variety of sources includes: combustion of liquid hydrocarbons, nuclear, solar, and even waste heat. The heat moved into and out of

**Figure 1.2:** P$^3$ Power System cascade concept.
the engine cavity is performed by conduction. Unlike conventional macro-sized engines that use convection, conduction simplifies the fabrication and operation of the engine on a micro-scale. Conduction eliminates the need for fluid loops and their associated valves and pumps. Temperature loss due conduction is expected to be insignificant compared to the loss due to fluid flow in minuscule conduits.

The conversion of thermal power into mechanical power follows a novel thermodynamic cycle [12]. The ideal working cycle of the micro heat engine consists of four ideal processes: heat addition, expansion, heat rejection, and compression. Figures 1.3 (a) and (b) represents the engine state during each of these processes. During the heat addition process, high temperature heat is transferred to the saturated working fluid, via conduction through the bottom thin membrane. The heat causes the liquid within the cavity to evaporate, in a constant temperature and pressure process. While the liquid evaporates, the enclosed vapor bubble expands, forcing the top and bottom membranes outward. Since the bottom membrane is twice as thick and at least eight times as stiff as the top piezoelectric membrane, it bows only slightly. The more flexible top membrane deflects outward, straining the piezoelectric membrane generator.
The work done to flex the membrane generator outward, by the expanding the working fluid, causes the piezoelectric membrane to store both mechanical (strain) energy and electrical (polarization) energy. Expansion begins as heat addition ends, and the momentum of the membrane generator carries it to a maximum deflection, at which point the electric energy is withdrawn. The heat rejection process begins from the point of the membrane’s peak deformation. Heat is withdrawn from the saturated working fluid.
fluid, again by conduction, through the top membrane generator. The heat removed causes the vapor-phase fluid in the engine cavity to condense at a constant temperature and pressure. With the vapor condensing, the vapor bubble shrinks, and the deflection of the membrane generator decreases. The deflection of the membrane generator continues to decrease past the neutral position, and begins to bow inward, during the compression process. With the membrane generator now flexing in, work is performed on the two-phase working fluid, causing the working fluid temperature and pressure to rise. The mechanical energy stored during the expansion process provides the work of compression. A thermal switch will be used to perform the heat addition and heat rejection processes from high and low temperature sources.

1.3 RESEARCH OBJECTIVES

The objective of this research is to integrate the first prototype $P^3$ micro heat engine and demonstrate its operation to provide proof of the micro engine concept. To meet this objective, four major tasks were performed. They include the: 1) fabrication and evaluation of alternative membrane geometries, 2) development of testing and diagnostic tools, 3) integration and assembly of major engine components, and 4) operation and testing of assembled engines.

The thesis is organized in the following way. First a review of relevant literature is presented in Chapter 2. Fabrication and evaluation of an alternative membrane generator is described in Chapter 3. First membrane generator fabrication at WSU is described. With only wet etch capability at WSU, the membrane generator is limited to square and rectangular shapes. To assess the limitations imposed by this constraint,
membranes of circular geometry were fabricated the Army Research Laboratory (ARL). This fabrication protocol is discussed in detail.

To operate and test the engine, two major tools were developed: resistance heaters and Resistance Temperature Detectors (RTD). The resistance heaters provide a way to introduce a quantifiable and controllable heat pulse to run the prototype engine. The RTD’s provide a measure of the working fluid temperature during engine operation. The development and integration of both resistance heaters and resistance temperature detectors (RTD’s) are discussed in Chapter 4.

To demonstrate and test the engine the integration of the three major components: membrane generator, cavity, and bottom membrane was required. In addition, techniques for filling the engine with working fluid and final assembly were developed. These issues along with results of operating the engine are presented in Chapter 5.

The results and conclusions of this study are presented in Chapter 6.
CHAPTER 2
LITERATURE REVIEW

2.1 MICRO HEAT ENGINE

Micro heat engines are a means to produce miniaturized power sources for MEMS and microelectronics [13]. They offer an attractive option due to the high energy density storage capability of a hydrocarbon fuel [2]. A variety of groups have concentrated on shrinking existing engine designs such as: micro gas turbines (Brayton cycle), micro rotary (Otto cycle) engines, and Otto/Diesel cycle micro heat engines using pulsed combustion driven reciprocating pistons [14,15,16].

A power supply based on the micro gas engine is projected to possess an energy density of at least 10 times greater than the best existing batteries [14]. It is expected to be capable of producing 10-100 watts of electric power, while occupying less than 1 cm³ of space and consuming around 7 grams of jet fuel per hour of operation. The micro rotary engine takes the form of three-sided, eccentrically rotating rotor, covered in a high tolerance casing [15]. The design offers greater simplicity than the micro gas turbine because there are no valves. The pulsed combustion driven reciprocating piston engine consists of a rectangular magnetic piston, a rectangular duct with conducting coil, and two combustion chambers [16]. The combustion chambers, located on either end of the duct periodically pulse, which drives the magnetic pistons back and forth through the coil-embedded duct. This motion induces a current in the coils, which are used for generating electrical power.

These designs are interesting concepts, but suffer from significant difficulties. Fabrication alone is expected to prove a difficult task. The hardware in place for
conventional large-scale engine systems must be redesigned on the micro scale to succeed [7]. The processes used for MEMS fabrication do not readily produce intricate three-dimensional structures [17]. The structural materials used for production, such as silicon carbide and silicon are typically limited to extrusions of two-dimensional shapes. The tolerances required on the micro scale also pose complications for these engine designs. The relative tolerance translated from the macro to micro scale will need to be dealt with to ensure proper sealing and mating parts. All of these dynamic heat engines use internal combustion and have either sliding and or rotating parts. Even though these designs are based on proven thermodynamic cycles, the engines must contend with sealing and friction problems on the micro scale. Viscous forces in the micro scale are extremely high when compared in the macro scale. This distinction severely punishes the efficiency of the micro engine systems with viscous forces.

The real strength in micro manufacturing is in the repeatable production of two-dimensional structures. Thus, an engine design based on a modular two-dimensional architecture, in which a unit engine cell is repeated several times, increases the chances for success. For the macro-scale, convection proves an effective means to move thermal energy through a system. In contrast, conduction is the preferred mode of heat transfer for micro heat engine operation. A micro heat engine should minimize any friction to avoid high efficiency losses.

A key component of the P³ micro heat engine is the application of a piezoelectric material for power production. Previous uses of the material include accelerometers, pumps, and actuators [18]. For micro pumps and actuators, charge is placed across the piezoelectric thin film to induce a strain, which in turn, deflects the film. Efforts are now
conducted into reversing this process for power production [19, 20]. Piezoelectric films of up to 10 µm can be produced using sol-gel process on silicon substrates [21]. These films can then be patterned using standard photolithography and micro machining techniques. Piezoelectric films offer small size and weight. Their energy densities rival electrostatic and electromagnetic devices.

2.2 RESISTANCE HEATERS

To simulate the heat transferred into the prototype engines, micro resistance heaters are fabricated. They are created using standard photolithography and metal etching techniques that are described in detail in proceeding chapters.

Lin et. al. describe a micro bubble powered actuator using a simple micro line resistance heater [22,23]. Spherical vapor bubbles between 2 and 500 µm are created. The device consists of a bubble-generating unit made of two polysilicon pads connected by a micro line polysilicon resistor (2µm by 0.5µm and 60µm long). Its electrical resistance is approximately 950 Ω and deposited using Low Pressure Chemical Vapor Deposition (LPCVD). The other component of the actuator is a polysilicon plate attached to a cantilever beam and the plate is suspended above the heater. This element is also created using polysilicon LPCVD. When a current is applied across the micro line heater, the local temperature of the resistor is sufficient to reach the nucleation temperature of the working fluid and forms a micro bubble. The fluids that have successfully generated thermal bubbles in these studies include Fluorinert liquids, deionized water, and methanol. The research indicates that they have successfully created micro bubble powered actuators that offer low input current, large displacements,
large force, and operation in liquid. Prosperetti et. al. demonstrate similar results in efforts to grow and collapse a vapor bubble under impulsive heating [24]. In these studies, the bubble is created within a channel and used to pump liquid from one reservoir to another. A micro channel connects two reservoirs of fluid and a heater is located off centered within the channel. The bubble periodically grows and collapses which cause a net pumping action in the direction of the reservoir farthest away from the heater. They have found that these bubbles can also serve to push a gate so as to block or open micro channels.

Furjes et al. and Mo et. al. utilize micro heaters for gas sensors [25, 26]. Both designs are of a serpentine line winding across suspended pad. Furjes et al. have shown microfilament heaters that reach a surface temperature of over 600 °C with input power as low as 15-25 mW. Mo et. al. show micro heater temperatures of 400 °C at 9 mW of applied power and thermal response time constant of about 10 ms. The heater device by Furjes et. al. is created from single crystal silicon and attached to a 100µm x 100µm silicon nitride pad. The heaters are suspended across a 60-80µm groove by two platinum wires embedded into silicon nitride.

2.3 \textit{Resistance Thermometers}

To help characterize the temperature within the engine cavity, resistance temperature detectors (RTD) were fabricated. They too, are created using standard photolithography and metal etching techniques that are described in detail in proceeding chapters. One advantageous feature in using these devices is that they can be designed and fabricated using the equipment and facilities at WSU.
The temperature detector utilizes a materials resistance-temperature relationship [27]. Most materials have positive temperature coefficients, or their resistance increases with temperature. Thermistors on the other hand, are characterized with negative temperature coefficient materials. RTD’s provide lower resistance changes with respect to temperature but higher linearity relationships than thermistors. The key feature of RTD’s is that they are easy to integrate on silicon substrates (i.e. in place of the membrane generator) [17]. These devices are highly accurate and thus often used for calibration standards [17]. Kovacs mentions that platinum resistance thermometer detectors are generally expensive but platinum thin films are not [17]. They can be fabricated in standard IC fabrication environments to produce extremely high accuracy and extremely high performance thermometers (resolve 0.01 °C).

Wheeler and Ganji assert that RTD devices are stable, with characteristics that are not likely to change with time due to chemical or other effects [28]. They measure the temperature directly, unlike thermocouples that measure relative temperatures. They come in a variety of designs such as coils and thin films. In RTD design, it is important to minimize strain and self-heating effects. Strain and self-heating contribute to detector uncertainty. Strain across the detector causes resistance changes that are interpreted as a temperature change by associated circuitry. The constant current supplied across the detector and related wiring introduces a self-heating effect that can raise the measured temperature above its true value.

The main disadvantages associated with these temperature measurement devices include self-heating effects and response time. Minimizing the current supplied across the RTD can reduce self-heating effects. The length or size of the RTD dictates the
response time of the device. A larger length detector results in a lower spatial resolution and slower transient response. A three wire lead technique is utilized for the signal conditioning of the RTD detector in a Wheatstone bridge circuit [28]. The resistances of the three leads are matched to one another to eliminate the effects of lead wire resistance changes. The resistances of the leads are matched by using the same material, the same diameter, the same length, and the same routing scheme for all lead wires. If changes in lead wire resistance occur, very little effect on the differential voltage \( V_0 \) will be observed. Figure 2.1 illustrates the three-wire approach. The method provides a higher signal to noise ratio and reduces the error induced by lead resistances [28,29].

![Three wire Wheatstone bridge circuit.](image)

**Figure 2.1:** Three wire Wheatstone bridge circuit.
CHAPTER 3

MEMBRANE GENERATORS

This chapter explores the fabrication and subsequent evaluation of two membrane generator geometries. WSU membrane generators are created using an ethylenediamine, catechol, pyrazine, and water (EDP) solution to wet etch silicon [30]. This anisotropic etch process restricts the membrane geometry to squares and rectangles. ARL membrane generators are created using a Deep Reactive Ion Etcher (DRIE), which allows a higher degree of membrane design freedom. This technology also allows the circular membranes to be fabricated without a silicon substrate, whereas the EDP process leaves a boron-doped silicon layer beneath the generator stack.

3.1 WSU SQUARE MEMBRANE GENERATORS FABRICATION

To fabricate a complete wafer of membrane generators for engine assembly, several detailed procedures are taken [31,32]. Figure 3.1 illustrates a wafer that undergoes these processes. Wafers are first placed into a tube furnace for thermal oxidation. An oxide thickness of about 500 nm develops around the entire wafer. One side of the wafer is protected by tape and then placed into a buffered oxide etch to remove oxide from the unprotected surface of each wafer. Boron is then diffused into this surface using boron nitride disks [32]. The amount of time, boron is allowed to diffuse into the silicon, dictates the thickness of the resulting membranes. A sacrificial low temperature oxide is then grown on the wafers to remove an undesired boron-skin that develops over the boron-doped silicon. This oxide is removed, along with the boron-skin, and another low temperature oxide is grown over the wafers for oxide photolithography and EDP silicon etching.
Figure 3.1: WSU membrane generator fabrication process.
A clear field mask is used for patterning the membranes during oxide photolithography, as shown in Figure 3.2. The dark squares determine the positions of the membranes in relation to each circular wafer and individual dies. Boron-doped silicon membranes are created with an EDP wet etch of the silicon.

![Figure 3.2: Membrane mask for membrane generators](image)

A bottom metal electrode is then deposited on each wafer using a sputtering process [32,33]. The bottom metal electrode consists of approximately 12.5 nm of titanium followed by 175 nm of platinum. The titanium is used to promote adhesion between the silicon oxide and platinum.

A lead zirconate titanate (PZT) solution is then deposited over the platinum using a sol-gel method, which involves several repetitive procedures of spin coating PZT, pyrolysis, and crystallization [21,22].

After this step, the wafer is again placed into the sputtering system. A top electrode consists of 7.5 nm of TiW and 300 nm of Au is sputtered. The thin titanium-tungsten layer promotes adhesion between the PZT and gold. Photolithography and top electrode etching follows to define the top electrode geometry. A final photolithography
process to etch the PZT is required to open access to the bottom electrode and improve membrane failure strength [33]. Figures 3.3 (a) and (b) show a respective top electrode and PZT etching mask designs.

![Figure 3.3: (a) Top Electrode etching mask design (b) PZT etch mask design](image)

A top view of a completed membrane generator die is shown in Figure 3.4.

![Figure 3.4: Membrane Generator Die (Top View)](image)
3.2 ARL CIRCULAR MEMBRANE GENERATOR FABRICATION

Circular membrane generators were created at the Army Research Laboratory, located in Adelphi, Maryland. The laboratory has approximately 10,000 square feet of class-100 clean room space with a variety of process equipment. The key manufacturing tools at the ARL, which allow for dry etching silicon, include: a Plasma Enhanced Chemical Vapor Deposition (PECVD) system and a Deep Reactive Ion Etcher (DRIE). These systems allow the fabrication of circular, silicon free membrane generators with near vertical sidewalls.

The ARL membrane generators are manufactured on 4-inch diameter silicon wafers, which are (100) in crystal orientation, double sided polished, type N, and prime grade. The wafers have two flats in the [110] direction, have 1-20 O-cm resistance, and are 475 ($\pm$ 25) $\mu$m in thickness. Several membrane generator variations are created to provide a wide range of testing and characterization. Circular membranes of one, two, three, and four-millimeter diameters are fabricated with 60, 80, and 110% top electrode coverage. In addition to these combinations, there are various thickness depositions of oxide, bottom metal, and piezoelectric films. Process instructions are included in the appendix. Figure 3.5 illustrates the process protocol that a wafer undergoes to produce an ARL membrane generator.
Figure 3.5: ARL membrane generator fabrication process.
3.2.1 PECVD

The Plasma-Therm 790 is a Plasma Enhanced Chemical Vapor Deposition (PECVD) system, used to create thin film oxides and nitrides on silicon wafers. The PECVD system is entirely computer controlled. Pressure, temperature, chemical flow rates, power settings, and process time are specified in PECVD recipes to determine the thickness achieved of the oxide or oxide-nitride-oxide (ONO) stacks. The oxide provides an etch stop during silicon etching and serves as an adhesion layer for the bottom electrode.

The wafers are first cleaned with a nitrogen air gun located at a nearby chemical station. They are inserted into a PECVD chamber with a standby temperature of 250 °C. The chamber is then sealed shut and pumped down to a base pressure of around 5-mTorr. A process recipe is chosen and the program is run for the desired oxide or ONO thickness. A process time of 27 minutes at 20 watts RF, 900-mTorr, and 70-sccm of silane (SiH₄) has produced a 10,000Å oxide. At the programs end, the chamber is vented and the wafers are extracted. They are allowed to cool on the PECVD shelf surface before being placed into wafer carriers for transport.

3.2.2 Rapid Thermal Annealing

A MAT 610, Rapid Thermal Annealer (RTA), is used to relieve film stresses developed during deposition. Detailed process instructions for the RTA are included in the appendix.

For oxide or ONO film annealing, nitrogen gas is allowed to flow through the machine at 5-sccm. A single wafer is inserted into RTA drawer and securely shut. The
time and temperature are set, at 60 seconds and 700 °C respectively, using a computer keyboard. Once activated, the internal temperature of the RTA can be viewed using a digital display. The RTA ramps up at 30-50 °C per second. The device is allowed to cool to 150 °C or lower before the wafer can be withdrawn from the RTA drawer. The RTA ramps down at 20-30 °C per second. The wafer is cooled using a nearby nitrogen air gun.

3.2.3 Bottom Electrode Deposition

The Varian 3190 is metal sputtering system used to deposit titanium, platinum, and tantalum on wafers. The Varian 3190 uses a load lock and carousel system, which minimizes the time necessary to pump down. A base pressure of 2x10⁻⁷ T is quickly obtained to deposit a metal. All deposition procedures are automated and controlled with a touch screen computer interface. Process instructions for the Varian 3190 are included in the appendix.

Heaters are set to 300 °C for bottom electrode deposition. The wafer is inserted into the load lock and a recipe is chosen on the touch screen control. The wafer compartment is toggled above the desired metal target for deposition. For a bottom electrode thickness of approximately 400 Å titanium and 1,200 Å platinum, recipe #2 is selected. As soon as the recipe starts, all deposition guns operate at 10% for pre-sputtering. The wafer is toggled over the RF gun and etched for 15 seconds at 65% power to clean the wafer surface. Titanium is then deposited for 26 seconds at 14% power. Platinum deposition is for 45 seconds at 17% power. The titanium and platinum
guns have a 3kW max power rating and the process pressures are held at 7.5 mT. All power settings are DC and the RF gun is separate.

3.2.4 Bottom Electrode Annealing

For bottom electrode annealing, clean dry air (CDA) is allowed to flow through the RTA at 5-sccm. A single wafer is inserted into the RTA drawer and securely shut. The time and temperature are set, at 60 seconds and 700 °C respectively, using a computer keyboard. Once activated, the internal temperature of the RTA can be viewed using a digital display. To avoid thermal shock, the device is allowed to cool to 150 °C or lower before the wafer can be withdrawn from the RTA drawer. The wafer is cooled further using a nearby nitrogen air gun.

3.2.5 PZT Deposition

The deposition process of PZT at ARL is very similar to process used at WSU [32,33]. A sol-gel technique is used and involves several repetitive processes of spin coating PZT, pyrolysis, and crystallization.

A wafer, with an annealed Ti/Pt bottom metal electrode, is centered on a spin coater. PZT is deposited over the entire wafer using a 0.1 µm PTFE filtered syringe. The spin coater distributes the PZT across the wafer at 2500 rpm for 45 seconds. The wafer is then pyrolyzed on a 350 °C hotplate for 2 minutes. The wafer is then removed and cooled with a nitrogen gun. The process of spin coating PZT and pyrolysis is repeated until four layers are compiled. The wafer must then be crystallized at 700 °C for 30 seconds in the RTA with CDA flowing at 5-sccm. Four additional layers of PZT can be deposited, as instructed above, with a new filter and syringe. This repetition of depositing four layers
before every crystallization step can continue until the desired thickness is achieved. A PZT thickness of 1-2-µm is typically built up.

### 3.2.6 Cluster Tool and Mask Aligner

The Karl Suss ACS 200 Cluster Tool is a fully automated spin coater used to deposit, post bake, and develop either an AZ9245 photoresist or AZ4214 reversible photoresist. The ACS 200 can process a batch of 25 wafers at a time when inserted into a cassette. A cassette with wafers is placed into the left hand side loader. This section is reserved for 4-inch wafers; the right hand side loader is for 3-inch wafers. A recipe is then selected using a nearby computer station. The recipes can be for spin coating, baking, or developing photoresist. Using the same computer terminal, the position of each wafer in the cassette is selected. Once the desired wafers are selected for processing, the program is simply run to completion.

All photoresist deposition processes include automated HMDS vapor prime, a cold plate placement for 30 seconds at 20 °C, photoresist spin coating at a given rate and time, and a hot plate placement for 60 seconds at 110 °C. The AZ9245 deposition recipe requires 25 second spin at 2500rpm while the AZ4512 recipe calls for a 40 second spin at 2000rpm. Only the AZ5412 resist needs the post bake procedure necessary for reverse imaging, which entails the wafer placed on a 110 °C hot plate for 60 seconds. The developing processes for both resists involve an alternating series of developer washes and de-ionized water rinsing. The developer solution reveals the mask pattern by removing unwanted photoresist from the wafer surface.
The MA6/BA6 Mask Aligner performs the necessary patterning on photoresist using UV exposure. The photolithography masks used in the aligner are chrome coatings on 5-inch square soda lime substrates that are 0.090” thick. The chrome coating designs are created on AutoCAD using predetermined alignment marks and saved as DXF files for mask production.

Before any mask alignment and exposure can be performed, the lamp power supply must be activated and warmed up. The lamp must be set to [C-1-1] and its display must change from [Cold] to [900+] for use. The MA6/BA6 Mask Aligner must then be activated and the (Change Mask) button on the aligner console must be pressed. The vacuum to the present mask is disabled so it may be removed and replaced with the desired mask. Instructions on the display appear to secure the mask in place. The (Load) button is then pressed and a wafer inserted into the drawer for patterning. Again, instructions are displayed to proceed. The console arrows are used to move the view of the camera and the micrometers adjust the wafer substrate into alignment positions. The exposure time will depend on the resist and the determined photo detector calibration of the week. The exposure time can be edited by pressing (Edit Parameters). To place the wafer substrate into contact with the mask for UV exposure press (Alignment Check). Once properly aligned, pressing (Expose) and UV light will emit onto the wafer. Directions for unloading the wafer are given on the display after the exposure.

For backside photolithography, backside alignment is necessary for patterning the photoresist. The steps taken are similar to the front side alignment described above. The appropriate mask is inserted into the aligner as previously described. Pressing (BSA microscope) switches the alignment-viewing microscope to the backside. From this
viewpoint the alignment marks on the mask can be acquired by pressing the (Grab Image) button. Acquiring the alignment marks will require the use of the console arrows, toggling to BSA/IR Illumination, and adjusting the Top Substrate Focus knob.

The wafer can now be inserted into the drawer as describe above so the wafer features can be aligned to a superimposed image of the alignment marks. Once alignment is complete, the wafer is exposed as described above.

3.2.7 Backside PZT Etching

PZT usually builds up on the backside of wafers during the PZT deposition process. It is necessary to clean this backside surface for DRIE photolithography and etching. The cleaning procedure is accomplished using the cluster tool and a PZT etch solution.

The wafer is placed into the ACS 200 Cluster Tool for a protective layer of AZ9245 photoresist on the PZT surface. The photoresist is neither patterned nor developed but solely used for PZT coverage. The PZT protected wafer is then placed into a PZT etch solution containing 5 drops HF, 150-mL de-ionized water, and 125-mL of acetic acid. The duration spent in the solution depends on visual inspection of remaining backside PZT. A 1-μm buildup usually takes approximately 10 minutes in the solution to remove. Prolonged submersion will cause unwanted PZT pinholes. The etching solution will penetrate through the photoresist-protected surface given enough time.

After the backside PZT is removed, the wafer is rinse thoroughly with de-ionized water to remove undesired residue. The wafer then placed into a bath of Baker PRS
3000, positive resist stripper, for 10 minutes or until all photoresist is completely removed. The wafer is rinsed with de-ionized water and dried with nitrogen gun.

### 3.2.8 Liftoff

Platinum thin films are difficult to pattern with typical wet or dry methods. Ion milling and the liftoff process are two techniques that allow platinum to be patterned and etched. To pattern the platinum top electrode of the wafer the ACS 200 Cluster Tool is used for reverse image photolithography. Within the ACS 200, a thin coat of approximately 2-µm of AZ5214 photoresist is deposited on the PZT surface. The top electrode is defined using the MA6/BA6 Mask Aligner. An exposure time of 3.5 seconds is used but may vary depending on photo detector calibration. Figure 3.6 shows the Top Electrode design. To complete a successful reverse image process, the wafer must then be baked in the ACS 200 at 110 °C for 60 seconds. The wafer is then UV flood exposed, without the presence of a mask, in the MA6/BA6 Mask Aligner for an equal amount of time used for patterning, which is 3.5 seconds. The wafer is again placed into the ACS 200 for the photoresist developing process.

Before the wafer is placed into the sputtering system for a top electrode, the lead oxide developed on the PZT must be removed. Immersing the wafer into a PZT cleaning solution of 10% acetic acid and 90% de-ionized water for 5 seconds achieves this. The wafer is rinsed with de-ionized water and dried with the nitrogen gun.

Platinum is then sputtered onto the wafer using the Varian 3190 without heat. For the deposition of this top electrode, the system heaters are disabled to prevent the degradation of the photoresist. The wafer is inserted into the load lock and a recipe is
chosen. The wafer compartment is toggled above the platinum metal target for deposition. A top electrode thickness of approximately 1000Å platinum is put down with recipe #3.

To complete the liftoff process, the wafer must be placed into a bath of Baker PRS 3000, positive resist stripper heated to 75 °C, for about 2 hours or until all platinum has lifted off. The stripper removes all photoresist including the platinum deposited on top of it, leaving platinum on directly sputtered PZT surface. Frequent agitation of the wafer in solution and wafer rinsing with de-ionized water speeds the platinum lift off process. Figure 3.7 illustrates the liftoff sequence.

![Figure 3.6: ARL Top Electrode liftoff design](image-url)
Figure 3.7: Liftoff sequence
3.2.9 Top Electrode Annealing

For top electrode annealing, clean dry air (CDA) is allowed to flow through the RTA at 5-sccm. The process time is longer than bottom electrode annealing but the temperature is less. A single wafer is inserted into the RTA drawer and securely shut. The time and temperature are set, at 120 seconds and 350 °C respectively, using a computer keyboard. Once activated, the internal temperature of the RTA can be viewed using a digital display. To avoid thermal shock, the device is allowed to cool to 150 °C or lower before the wafer can be withdrawn from the RTA drawer. The wafer is cooled further using a nearby nitrogen air gun.

3.2.10 PZT Etching

The wafer undergoes another photolithography step for patterning and etching the PZT film. This PZT etch process completes access to the bottom electrode and improves membrane failure strength. PZT etching begins with AZ5214 photoresist deposition onto the top electrode surface using the ACS 200 Cluster Tool. The 2-µm resist is patterned on the MA6/BA6 Mask Aligner using the PZT etch mask design shown in Figure 3.8. Approximately 3.5 seconds is used for the exposure time. The wafer is placed into the ACS 200 for a 60 second 110 °C bake, and then again into the MA6/BA6 Mask Aligner for a 3.5 second UV flood exposure, to perform a negative mask image. The photoresist is developed in the ACS 200 to reveal the PZT etch pattern. The wafer is placed into a PZT etch solution containing 5 drops HF, 150-mL de-ionized water, and 125-mL of acetic acid. The duration in solution determines the amount of PZT etched. A 1-µm buildup of PZT usually takes approximately 10 minutes in the solution to remove. After
the PZT is removed, the wafer is rinsed thoroughly with de-ionized water to remove undesired residue. The wafer is then placed into a bath of Baker PRS 3000, positive resist stripper, for 10 minutes or until all photoresist is completely removed. The wafer is then rinsed with de-ionized water and dried with nitrogen gun.

![Figure 3.8: ARL PZT etch design](image)

3.2.11 DRIE

Deep Reactive Ion Etching (DRIE) provides a method to etch circular membranes onto the processed silicon wafers. This bulk micro machining process produces extremely high aspect ratios of up to ~40:1 (final etch depth divided by minimum feature size of hole at surface) and sidewall angles of 90° ± 2°. Unlike traditional wet silicon etching processes, such as EDP and KOH silicon etching, DRIE is anisotropic and independent of crystal orientation. These features allow a high degree of design freedom.
Sub micron features can be produced. Oxides, like the boron-doped silicon for EDP etching, are used as the silicon etch stop for the DRIE process. The resulting membranes are circular with near vertical silicon sidewalls, and consist of oxide, bottom electrode, PZT, and top electrode stack.

The DRIE process begins with photoresist deposition. AZ9245 photoresist is spin coated on the backside of the PZT etched wafers using the ACS 200 Cluster Tool. The resulting resist is approximately 6-µm in thickness. Backside photolithography is then conducted using the directions previous discussed for the MA6/BA6 Mask Aligner. The DRIE mask shown in Figure 3.9 will be used to pattern the backside photoresist. A UV exposure time of 16 seconds will be necessary to cure the thick AZ9245 photoresist. The patterned wafer is then placed into the ACS 200 for photoresist developing.

A batch of 25 wafers can be inserted into the DRIE for silicon micro machining. The wafers are facing backside up for backside silicon processing. Like ACS 200 Cluster Tool, the Plasma-Therm 770 is fully automated. Wafers are simply inserted into the machine, a program is selected, and the wafers are processed. Within the DRIE, alternating passivation and etch steps occur. This ‘Bosch’ process uses a fluorinated gas (sulphur hexafluoride, SF$_6$) for the silicon etching and a fluorocarbon (octofluorocyclobutane, C$_4$F$_8$) for the passivation layer [34].
A high-density plasma region, above the wafer, is created within the DRIE chamber. The fluorinated gas is pumped into the chamber and broken down by the plasma, to release free radical fluorine that attacks the silicon surface (Figure 3.10) [35]. The fluorinated gas is pumped out and fluorocarbon is pumped in. The fluorocarbon particles are also broken down in the high-density plasma, to produce CF$_2$ and other longer chain radicals. These new particles form Teflon-like polymers that serve as the passivation layer of wafer. The passivation layer deposits on the wafer base and sidewalls (see Figure 3.11). Fluorinated gas is again pumped in and the cycle repeats until the desired silicon etch is obtained. The fluorine radicals drive down vertically towards the wafer and break through the passivation layer. The sidewalls are not bombarded directly, while the base of the patterned hole is, therefore the passivation layer is first removed there and fluorine attacks the silicon.
The Plasma-Therm 770 performs the etching and passivation cycle every 12 seconds. There is a 6 second silicon etch, a 4 second polymer deposition, and a 2 second polymer etch. It takes about 600 cycles, or approximately 2 hours, to etch 435-µm of silicon. The DRIE process is performed with helium cooling until approximately 25-µm of silicon remains. The helium cooling is used to lower the wafer surface.
temperature so that the resist can survive the long etch process. The remaining silicon is machined to the oxide stop without helium cooling to prevent breaking membranes. The helium cooling creates a slight vacuum that may destroy the thin membranes during the DRIE. Figure 3.12 illustrates a wafer processed through DRIE.

Figure 3.12: ARL Wafer through DRIE

### 3.2.12 Asher

The photoresist used to pattern the backside of the wafer for DRIE is hardened and must removed using a Metroline M4L Asher. This de-scum procedure is also completely computer controlled and automated. The asher is pumped to ~20,000-mTorr before being opened. Within the asher are three trays; so several wafers can be processed at a time. The wafers are inserted into the trays, with the photoresist facing up. The asher is shut and a recipe is chosen using the a mounted touch screen. For AZ9245 resist, a recipe with 500-sccm of O₂, at 1000-mTorr, at 600-W, a 35 minute de-scum, and 24-42 °C chamber temperature, is set. The [Run] command is pressed on the touch screen and the wafers are finished approximately 40 minutes afterwards. A completed ARL membrane generator is shown in Figure 3.13.
ARL membrane generators were designed and fabricated for characterization and comparison to WSU membrane generators. To optimize the manufactured yield, 52 membrane generators of various sizes and various top electrode areas, were patterned on 4-inch wafers as described in section 2.2. The tests used to assess performance are free oscillation ring outs, power production, static, and dynamic membrane operation.

The bulge tester is the primary instrument used to perform the discussed experiments [36]. The apparatus consist of fluid filled chamber bounded by a stainless steel diaphragm and an acrylic wafer carrier with the membrane generator of interest. Figure 3.14 provides a cutaway view of the bulge testing system [adapted from 31]. An acrylic wafer carrier, specifically designed for the ARL membrane generator wafer, is placed on the bulge tester and the individual membrane of concern is centered over the system orifice. A clamping bar is used to fasten the wafer carrier to the bulge tester. Water fills the bulge tester cavity and is pressurized either statically or dynamically. Static forces are applied to the system using a micrometer positioned below the

**Figure 3.13:** ARL membrane generator (Top View)
diaphragm. Dynamic forces are applied with the aid of an actuator placed in contact with the diaphragm. A generated waveform feeds into an amplifier, which relays the driving frequency and amplitude force to the actuator. A pressure transducer, located on the sidewall of the bulge tester, measures the developed internal pressures. Membrane generator response is observed by connecting oscilloscope leads to the top and bottom electrode of the membrane generator of interest.

Membrane ring out plots are constructed using the bulge tester and help determine the damped natural frequency and dampening of the devices. The actuator receives a step input from the function generator and the oscilloscope captures a decaying membrane generator response or ring out.
The damped natural frequency of the device is computed as one divided by the time differential between peaks [37]. To measure the power production of ARL membrane generators its output is coupled in parallel to a decade resistance box. The setup is depicted in Figure 3.15 [adapted from 33]. The resistance of the decade box is gradually increased from zero Ohms and the proportional output voltage is recorded. Power is determined as the amount of energy dissipated across the resistor. In this case, the power is computed as Equation 3.1 shows [38].

\[ P = \frac{V^2}{R} \]  

where, \( P \) is the power production, \( V \) is the output voltage monitored by the oscilloscope, and \( R \) is the resistance of the decade box.

**Figure 3.15**: Power-Impedance Schematic for ARL Membranes [adapted from 31]

An impedance curve is created (Power vs. Load Resistance) and the optimum resistance, for power transfer, is determined from the peak power production. The peak power production indicates the matched impedance of the engine system.

Static bulge testing is used to compute the membrane generator stiffness. The bulge testing system is combined with a laser interferometer and a camera system as
Figure 3.16 shows, adapted figure [adapted from 33]. A timing circuit is not necessary to take static deflection images.

A static force is applied to the membrane using a micrometer positioned below the bulge tester diaphragm. This force causes the internal pressure to rise and the membrane to deflect. The internal pressure transducer records the applied pressure. The deflection is captured using the camera that is mounted to the long distance working microscope. The image appears as a fringe pattern, due to the constructive and destructive light fusion detected with laser interferometer. The distance between two dark fringe lines is $\lambda = 532$ nm. With pressure and deflection measurements, a pressure vs. deflection plot can be created to determine the membrane stiffness.

Dynamic bulge testing is performed to characterize the membrane generator output with respect to deflection. System details are shown in Figure 3.17 [adapted from 31]. The image capturing system is integrated with the bulge tester. The function generator is used to synchronize the image acquisition with the actuator of the bulge
tester. The system initiates off the rising edge of a generated square waveform. The timing circuit synchronizes laser and frame grabbing software. The timing circuit generates two delay times, one to trigger the laser, one trigger the camera. The two delay times fix the sampling interval in relation to the square waveform produced by the function generator. Thus the deflection can be captured for any position in the dynamic cycle. An oscilloscope monitors the membrane generator output.

![Dynamic Testing Setup](adapted from 31)

**Figure 3.17: Dynamic Testing Setup [adapted from 31]**

### 3.4 ARL Membrane Generator Results

The testing equipment, discussed in the previous section was used to characterize circular, silicon-free membrane generators. Various 1, 2, and 4-mm diameter membrane generators with 110% top electrode coverage were tested on wafer #611. These devices contained 1/2 μm of oxide, 1μm of PZT film, a 1,600Å thick titanium-platinum bottom electrode, and a 1000Å platinum top electrode.
The ring out results for these ARL membrane generators yielded damped resonance frequencies of \( \sim 15,625 \) Hz for 1-mm, \( \sim 4,000 \) Hz for 2-mm, and \( \sim 1,200 \) Hz for a 4-mm diameter membrane generator. Increasing the peak-peak pressure oscillations for the driving step impulse produce a relatively consistent damped natural frequency. Figure 3.18 displays the ring out results for a 4-mm diameter ARL membrane generator at various peak-peak pressure oscillations (i.e. 1.25 peak-peak psi).

Figure 3.18: Ring out for 4-mm ARL Membrane Generator

Power production experiments indicate that the matched impedance for a 1-mm diameter membrane is 4,500Ω, which Figure 3.19 shows. A 4-mm diameter membrane generator has about a 2,900Ω matched impedance.
Static bulge testing data for these circular membrane generators demonstrate near linear pressure-deflection relationships at deflections less than 40µm. Figure 3.20 presents this relationship for two 4-mm, one 2-mm, and one 1-mm ARL membrane generator on wafer #611.

A resulting force-deflection plot, created by converting the pressure applied to each membrane into a force using Equation 3.2 below, can be evaluated to acquire the membrane stiffness coefficient [39].

\[ F = \frac{P}{A} \]  

The force \( F \) in the equation is calculated using the pressure \( P \) and the membrane area \( A \). The membrane area for 4-mm, 2-mm, and 1-mm diameter ARL membrane generator is 12.566 mm\(^2\), 3.14 mm\(^2\), and 0.785 mm\(^2\) respectively. The plot in Figure 3.21 shows the
Force vs. Deflection relationship for the membranes on wafer #611 with 110% top electrode coverage.

**Figure 3.20:** Pressure vs. Deflection plot for Wafer 611 110%TE

**Figure 3.21:** Force vs. Deflection plot for Wafer 611 110% TE
The slope of a trend line, through all these points, represents the stiffness coefficient for these membranes. The stiffness for these membrane generators with 110% top electrode coverage is approximately 4,400 N/m.

A PZT Output vs. Deflection plot for various size membrane generators is shown in Figure 3.22. The plot shows that larger diameter membranes provide larger deflections at a given PZT output. Testing conditions are at frequencies below resonance and pressure waves in phase with the membrane deflection. Further analysis of the information helps characterize the membrane generator.

![PZT Output vs. Deflection plot for Wafer 611 110%TE](image)

**Figure 3.22:** PZT Output vs. Deflection plot for Wafer 611 110%TE

The strain at the center of a circular membrane during deflection can be calculated using Equation 3.3 [40]:

\[
S = c \cdot \frac{h^2}{a^2}
\]  

(3.3)
where $S$ is the strain, $h$ is the amount of deflection and $a$, is the membrane radius. For ARL circular membranes the constant $c = 2/3$ (for square membranes the $c = 0.5698$ and the radius = $\frac{1}{2}$ the side length). Figure 3.23 indicates a linear relationship for the PZT output with respect to the percent strain at the center of the membrane. From this plot a Volt per %strain*PZT thickness value, or specific voltage can be obtained for each membrane size. For these samples, with 1$\mu$m of PZT, values of $8.77 \text{ V/(%strain*}\mu\text{m})$ for a 4-mm diameter, $6.69 \text{ V/(%strain*}\mu\text{m})$ for a 2-mm diameter, and $2.69 \text{ V/(%strain*}\mu\text{m})$ for a 1-mm diameter membrane generator are found.

![Figure 3.23: Output vs. %Strain*PZT thickness plot for Wafer 611 110%TE](image)

The data set can be normalized by defining a PZT membrane generator specific output voltage per amount of total top electrode (TTE) area which includes the contact lead and pad. The %strain is multiplied by an area (membrane area/total top electrode area) ratio to define a new normalized specific PZT output response for all membrane generator sizes. Figure 3.24 reveals how all data points collapse to form a PZT output
response trend line, independent of membrane size. A PZT voltage response of 10.4V/[%Strain*(Membrane Area/Total Top Electrode Area)] is demonstrated for these membrane generators.

**Figure 3.24:** Output vs. %Strain*(Membrane Area/Total Top Electrode Area) plot

The total top electrode area is calculated considering the contact pad and connection. Figure 3.25 illustrates the dimensions of the total top electrode area. To calculate the total top electrode area, the Equation 3.4 is used where $A$ denotes the top electrode area, and the $d$ indicates the diameter of the membrane coverage.

**Figure 3.25:** Total Top Electrode Dimensions
Additional membrane generator with 80% and 60% top electrode coverage from wafer #611 have provided the following results. Figure 3.26 shows the specific voltage of all 80% and 60% top electrode covered membrane generator. The 110% and 60% top electrode covered membrane generators of identical size show similar specific voltages. The 80% top electrode covered membrane generators do not behave like the others, in that, the larger the membrane the larger the specific voltage.

Data from Figure 3.26 normalized to illustrate relationships for all various top electrode coverage’s are shown in Figure 3.27. The PZT voltage response for the various total top electrode coverage’s do not collapse onto a single line.
Figures 3.28, 3.29, and 3.30 show data collected from additional ARL wafers. They vary in membrane thickness, composition, and behavior from the results obtained on wafer #611. Table 3.2 displays complete ARL wafer composition.
Figure 3.29: Pressure vs. Deflection plot for Wafer 613

Figure 3.30: Output vs. Deflection plot for Wafer 613
3.5 Membrane Generator Comparison

With the results obtained from testing various 1, 2, and 4-mm diameter ARL membrane generators with 110%, 80%, and 60% top electrode coverage, and results for WSU membranes are taken from references [30,41], several comparisons can be noted. The ARL membrane generator exhibit near linear pressure vs. deflection curves at defections less than 40 µm as opposed to WSU membrane generators that exhibit a cubic trend. The damped resonant frequency of a 3 mm side length WSU membrane generator is most similar to a 4 mm diameter ARL membrane generator at 1900 Hz and 1200 Hz, respectively. These damped resonant frequencies are determined without the bottom wafer carrier during ring out experiments. The stiffness for these membranes is approximately 4,400 N/m. The specific voltage of these two different geometries differ significantly. The WSU membrane generator, with similar PZT thickness and composition, yields a specific voltage of 10.2 V/(%strain*um) while the ARL membrane generator yields only 8.77 V/(%strain*um). Table 3.1 illustrates the differences between WSU and ARL membrane generators. Table 3.2 displays fabricated ARL wafers and their composition. The stress measurement after each deposition denotes the stress state (+ tension / –compressive) for that individual layer. The PZT formula signifies the batch number of 52:48 (Zr:Ti) PZT composition.
Table 3.1: WSU and ARL comparison

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<th>Wafer</th>
<th>Top Electrode Coverage (%)</th>
<th>Silicon Thickness (mm)</th>
<th>PZT Thickness (µm)</th>
<th>PZT Etch</th>
<th>Resonant Frequency (Hz)</th>
<th>Stiffness (N/m)</th>
<th>Specific Output (V/%strain*mm)</th>
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| 1.00               |       | 611                         | 80%                    | 0                  | 1.042    | yes                     |                |                                | 3.22 |
| 1.00               |       | 611                         | 60%                    | 0                  | 1.042    | yes                     |                |                                | 2.91 |
| 2.00               |       | 611                         | 110%                   | 0                  | 1.042    | no                      | *4000          | 4,400                          | 6.69 |
| 2.00               |       | 611                         | 80%                    | 0                  | 1.042    | yes                     |                |                                | 2.07 |
| 2.00               |       | 613                         | 80%                    | 0                  | 0.99494  | yes                     | 8,100           |                                | 3.95 |
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*W/O bottom wafer holder
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CHAPTER 4

RESISTANCE HEATERS & TEMPERATURE DETECTORS

Micro resistance ring heaters are used to simulate the heat transferred into the prototype engines. They provide a quantifiable and controllable heat pulse into engine cavity. The resistance temperature detectors (RTD) provide a non-intrusive means to measure the working fluid temperature of the P³ micro heat engine during operation. They are easily fabricated with equipment and facilities at WSU. Both devices are integrated on silicon substrates using metal deposition and metal etching techniques.

4.1 RESISTANCE HEATERS

The resistance heater serves as a controllable and quantifiable heat source for running the engine. They have approximately 2.3 µm thick silicon membranes and are typically 1-2 Ω in resistance.

The fabrication of resistance heaters and square membrane generators are similar. All processes leading to the production of thin membranes via ethylenediamine, catechol, pyrazine, and water (EDP) solution are identical. The only exception is that a membrane mask for heaters is used during the oxide photolithography and silicon etching process.
Once membranes are created with EDP, the wafers are sputtered with approximately 12.5 nm TiW and 300 nm Au. The metal on these wafers is then patterned, similar to top electrode patterning of square membrane generators. The ring heater mask shown in Figure 4.2, designed by Scott A. Whalen, is used to define pattern on the sputtered metals.

Figure 4.1: Membrane mask for resistance heaters

Figure 4.2: Ring Heater mask pattern
The large square pads connecting to the ring heater are used for contacts. The ring heater itself is patterned above a 2-mm square membrane. Two larger membranes on either sides of the ring heater are created for throughway contact during engine assembly. Figure 4.3 illustrates a completed resistance heater die.

![Figure 4.3: Resistance Heater Die (Top View)](image)

### 4.2 HEATER INSTRUMENTATION

The Transistor-Transistor-Logic (TTL) Pulse circuit board helps regulate the power introduced into the P³ micro heat engine [42]. The TTL Pulse circuit diagram is shown in Figure 4.4 below. The circuit allows a quantifiable and controllable heat pulse into engine via resistance heater. Current and voltage are regulated by a DC power supply. A function generator controls the frequency and duty cycle.
4.3 **RESISTANCE THERMOMETER DETECTORS**

To measure the internal cavity temperature of the P³ micro heat engine, a Resistance Temperature Detector (RTD) was designed, fabricated, and calibrated for testing. The concept is to replace the membrane generator in an assembled engine with a RTD. The RTD is patterned onto a thin membrane identical to the membrane generator. The metal used for the RTD has an electrical resistance that is a function of the metal temperature. During engine operation, the resistance of the RTD will change as internal cavity temperature cycles. A Wheatstone bridge circuit is used to measure the resistance change of the RTD. These measurements are then correlated to a temperature.

Figure 4.4: TTL Pulse circuit diagram
4.3.1 RTD Design

Gold is the material used for the RTD since it is readily available for sputtering and easily patterned using available photolithography techniques and a gold etching solution. The resistance of a bulk material is given by:

\[ R = \frac{\rho \cdot L}{A} \]

where \( \rho \) represents the material resistivity in \( \Omega \cdot m \). Gold has a resistivity of \( 2.35 \times 10^{-8} \, \Omega \cdot m \) at room temperature. The projected RTD temperature range of operation is moderate (between 0 and \( 100^\circ C \)) so the corresponding temperature-resistance relationship is given by:

\[ R = R_o (1 + \alpha [T - T_o]) \]

where \( R_o \) represents the initial material resistance at initial temperature \( T_o \) and \( \alpha \) is the coefficient of resistance, for gold it is \( 0.0034 \)-parts/\( ^\circ C \). As the equation describes, the resistance \( R \), changes with the temperature \( T \), of the material and the expected relationship is plotted in Figure 4.5.
The RTD configuration resembles a serpentine line that covers an 800x800-µm square area and is located at the center of a thin square membrane. This region effectively covers the vapor bubble of the two-phase working fluid, used in the micro heat engine. Strain, caused by thermal expansion or membrane expansion, also causes resistance changes. Figure 4.6 illustrates a detailed view of an RTD design. The length $L$ of the RTD serpentine line is $14950 \times 10^{-6}$ m and the cross-sectional area $A$ is $6 \times 10^{-12}$ m$^2$ using a line width of 20-µm and a gold deposition height of 300 nm.
4.3.2 RTD Fabrication

RTD fabrication is comparable to that of the resistance heaters. Membranes are fabricated with the methods previously discussed in section 3.1 using the same membrane design developed for membrane generators. Gold deposition and patterning follow the methods of gold deposition and patterning used for resistance heaters. Sputtering is used to cover the boron-doped wafer surface with approximately 12.5 nm of TiW and 300 nm of gold. The gold is then patterned using the photolithography, using the etching procedures previously described for the top electrodes of square membrane generators and resistance heaters. The clear field mask design illustrated in Figure 4.7, is used to pattern the RTD’s during the photolithography step.

The fabrication process at WSU allows sixteen RTD’s to be manufactured on one 3-inch diameter wafer. The resistances of each of these devices vary widely due to...
processing differences. RTD resistance is sensitive to the amount of UV exposure time, the mask quality, and the gold etching. Consequently, each RTD must be calibrated for use. This process is described in section 4.3.5.

4.3.3 RTD Circuitry

The RTD circuit allows the resistance changes of the RTD device to be monitored and recorded. A RTD circuit diagram is shown in Figure 4.8. This Wheatstone bridge incorporates several fixed and variable resistors, in addition to the RTD. The resistors at $R_1$ and $R_4$ are fixed at 150 $\Omega$ while the resistor at $R_2$ is variable. The variable resistor is used to match the initial resistance of the RTD.

Figure 4.7: RTD Gold Etch Mask Design with RTD Close-up
The resistance matching allows the Wheatstone bridge to operate in a balanced mode. The resistances of leads A, B, and C are matched to one another to eliminate the effects of lead wire resistance changes. The resistances of the leads are matched by using the same material, the same diameter, the same length, and the same routing scheme for all lead wires. The differential voltage recorded by the RTD circuit is amplified using a gain [43]:

Figure 4.8: RTD circuit diagram with an amplifier chip
\[ G = 1 + \frac{49.4k\Omega}{R_g} \]

The gain, \( G \), is approximately 101 when using a gain resistance \( R_g \) of 497 \( \Omega \) across pins 1 and 8 on a Burr-Brown® INA 128 amplifier. A multi-channel power supply is used to provide the RTD circuit excitation voltage \(+V_s\) and ground, as well as, the amplification voltage \(+V_a\) and \(-V_a\). The excitation voltage at node A is held at +1 V, with a current limitation of 0.1 A. The ground wire connects to node C. The amplification voltages of +9 V and –9 V, with a current limitation of 0.1 A, are connected across pins 7 and 4, respectively, on the amplifier. The RTD completes the Wheatstone bridge and connects to \( R_2 \) and \( R_4 \) via lead resistances \( R_A \) and \( R_B \). Lead resistance \( R_C \) connects from node D and feeds to the amplifier. As the RTD resistance changes, the differential voltage across nodes B and D will be registered on the oscilloscope as \( V_0 \) and \( RREF \).

### 4.3.4 RTD Connections

The RTD system allows direct internal temperature measurements of the engine cavity. It consists of the RTD circuit, the RTD, a multi-channel power supply, and an oscilloscope. Recall that the RTD device replaces the membrane generator in an assembled engine. The RTD system schematic is illustrated in Figure 4.9 [adapted from 8]. A Hewlett Packard 6629A, four-channel DC power supply, is used to power the RTD system. Channel 1 & 4 provide the amplification voltages, while Channel 2 supplies the input excitation voltage across the Wheatstone Bridge.
The negative lead of Channel 1 and the positive lead of Channel 4 are tied together and grounded with the negative lead of Channel 2. This enables a positive +9 V at Channel 1 and –9 V at Channel 4. These amplification voltages are connected to the appropriate pins on the amplifier of the RTD circuit. The excitation voltage +V_s and ground are tied to the appropriate nodes of the Wheatstone bridge (see Section 4.3.3). The RTD has two pad contacts on opposite sides of the RTD pattern. These contacts are connected to the Wheatstone Bridge at nodes C and D. As the resistance of the RTD changes, according to temperature, a corresponding voltage differential, across nodes B and D can be measured. Leads from these nodes connect to the amplifier in the RTD circuit. The amplified signal is measured with an oscilloscope at V_0 and the reference voltage RREF.

Figure 4.9: RTD system schematic [adapted from 8]
4.3.5 RTD Calibration

To calibrate a RTD, an individual device is secured in a wafer carrier and placed into a bath of water at room temperature (~22 °C). The appropriate wires are connected to the RTD and RTD circuitry. A hotplate is placed below the water bath and thermocouple is fixed near the RTD. The bath temperature is allowed to increase to 50 °C. Voltage differential readings are recorded every ~2 °C of registered thermocouple change. Figure 4.10 shows a RTD calibration plot. A typical calibration plot of about 0.03 V/°C is obtained. As shown, the RTD provides a stable linear output response. The calculated self-heating effects are negligible at low circuit power supply voltages, ~1 V.

The effects of strain on error is also found to be minor at deflections less than 50-μm. Figure 4.11 illustrates the output response induced by strain during deflection. The data are obtained using a bulge tester and laser interferometer. A static pressure is applied to the RTD with the bulge tester, the response output is recorded, and the deflection is measured with the laser interferometer. The effects of strain are less than 0.03 V for the first 50-μm of deflection, which imply ~1 °C bias in this range.
Figure 4.10: RTD Calibration Plot (RTD output vs. Temperature)

Figure 4.11: Strain effects on RTD output (RTD output vs. Deflection)
CHAPTER 5

P³ MICRO HEAT ENGINE

The assembly of a prototype P³ micro heat engine involves the integration of the resistance heater, an engine cavity, and a membrane generator. A heater wafer is diced into individual resistance heater dies. A heater die is attached to one half of an acrylic test cell holder. An engine cavity is defined and using semiconductor tape. The working fluid is injected into the cavity and a membrane generator die is placed across to trap the working fluid. A bubble is nucleated and the membrane generator is position directly above the heater membrane for alignment. An o-ring is placed above the membrane generator and the assembly is fastened together with a mating acrylic holder.

5.1 ENGINE ASSEMBLY

5.1.1 Test Cell Holder

An acrylic test cell holder provides the necessary pressure to seal the working fluid, in the engine cavity, between the heater and generator chips. The acrylic holder consists of two 4” x 4” square, ¼” thick acrylic pieces that fasten together with four screws at each corner. A ½” diameter circle is drilled through the center of each square piece so the top and bottom membranes can freely flex outward. Two smaller holes, for device electrical contact, are placed on opposite sides of the center hole. Figure 5.1 shows this test cell holder with an appropriately placed heater chip.
5.1.2 Engine Cavity Assembly

Assembly of an engine is begun by centering a resistance heater chip, ring heater up, on the bottom half of an acrylic test cell holder. The resistance heater is fastened to the acrylic using Scotch tape, without obstructing the access holes on the bottom half of the acrylic. These openings connect to the contacts of the membrane generator chip.

An engine cavity is fashioned out of semiconductor tape. The semiconductor tape serves as a spacer between the top piezoelectric membrane generator and the bottom membrane resistance heater. The depth of the cavity is equal to the nominal tape thickness, approximately 60 µm. The shape cut into the semiconductor tape dictates the planar dimensions of the cavity. Since square membrane generators and square membrane resistance heaters are used, four-millimeter square engine cavities are created for engine use.

To construct an engine cavity, a four-millimeter square is cut into a ten-millimeter square piece of semiconductor tape. This leaves a three-millimeter border surrounding the cavity, which is used to contain the working fluid with the top and bottom membrane
chips. A razor blade or exacto knife effectively cuts the tape. Figure 5.2 shows a prepared engine cavity.

![Figure 5.2: Engine cavity using semiconductor tape](image)

The tape is centered and affixed over the heater ring of the resistance heater device as shown in Figure 5.3.

![Figure 5.3: Heater with Engine Cavity](image)

### 5.1.3 Vapor Bubble Nucleation

For nucleation, the TTL Pulse circuit is set to a frequency of 10Hz at 50% duty cycle. The DC power supply is set to approximately 2.2V DC. Fluorinert PF-5060-DL is squirted into the engine cavity using a syringe. The liquid quickly evaporates, so ample
fluid must be used to fill and flood the cavity. Care is necessary to avoid rupturing the heater membrane with the syringe tip during the working fluid addition.

A membrane generator chip is placed, face down and perpendicular to the heater chip as shown in Figure 5.4. The membrane generator used for the engine test cell is poled at 20 V DC for 5 minutes. This process improves the piezoelectric response in the thin film membrane generator [44]. The poling process involves applying a high electric field across the piezoelectric membrane stack, by placing a direct current voltage across the top and bottom electrode of the membrane generator chip. The generator chip is placed in such a way that the generator membrane does not lie over the cavity. This orientation is necessary to avoid the rupture of either heater membrane or generator membrane during nucleation. The membrane generator chip is then moved across the semiconductor tape to completely cover the cavity filled engine.

**Figure 5.4: Membrane Generator Chip over Fluid Filled Engine Cavity**
Vapor bubble nucleation takes place by applying the positive lead of the DC power supply to one end of the resistance heater and the Resistance Heater lead from the TTL Pulse circuit to the other end. The TTL Pulse circuit settings will pulse the resistance heater and nucleate a vapor bubble in the engine cavity.

A low audible, ‘pop’, signifies the formation of the bubble. Figure 5.5 depicts a vapor bubble and the bottom ring heater as seen through a top transparent membrane [45]. If nucleation does not take place, the process can be repeated with a small increase in the DC power supply voltage ~ +0.05 V DC.

![Vapor Bubble over Ring Heater](image)

**Figure 5.5:** Top view of Vapor Bubble over Ring Heater [45]

Once the bubble is created, the membrane generator is slid across semiconductor tape and fluid until the generator membrane is directly by above the engine cavity. An o-ring is positioned above the generator membrane pit to help sandwich the engine components with the acrylic test cell holder as shown in Figure 5.6. The two-phase working now fills the engine cavity and is sandwiched between the bottom heater membrane and top generator membrane.
5.1.4 Finished Assembly

The top half of the acrylic holder is placed over the engine stack and fastened to the bottom acrylic holder with four screws. This acrylic holder provides the necessary compression to seal the working fluid between the top and bottom membrane chips. With proper alignment, the electrical connections to both the resistance heater and membrane generator contacts are available via the access holes located on both halves of the acrylic test cell holder.

If the top membrane generator deflects outward excessively, away from the engine cavity, following the final assembly of the top acrylic holder, the process must be repeated. Testing has shown that a membrane generator that is in the neutral or slightly bowed out position provide the best results. Membrane generator deflection can be controlled after nucleation by waiting a short period of time before fastening. Figure 5.7 portrays a top and side view of an assembled engine [adapted from 8].

Figure 5.6: Generator Membrane over Engine Cavity and Heater Membrane
ENGINE CHARACTERIZATION

The operation of the P³ micro heat engine can be characterized in several ways. An oscilloscope may be used to capture the electrical output of a membrane generator. A RTD may be used for temperature measurements. Engine deflection data may be obtained using either a laser interferometer setup or the laser deflection & positioning system. Power production may be assessed with the use of a decade box, as a variable load resistance.

5.2.1 Engine Output

The frequency and duty cycle to the micro heat engine can be controlled by manipulating the voltage input to the resistance heaters from the TTL Pulse circuit. The output from the TTL Pulse circuit may be monitored via oscilloscope. The open circuit voltage output of the piezoelectric membrane generator may also be monitored via an
A signal is sent from the function generator into the TTL Pulse circuit. This signal determines the frequency and the duty cycle or the amount of energy delivered per cycle to the engine. For lower frequencies, simple function generators perform the task adequately. At higher frequencies, a function generator that can specify a duty cycle below 10% is necessary. A Tektronix AWFG 310, arbitrary waveform generator, can produce such waveforms. Accompanying software, Wave Writer v4.01e, allows a waveform of desired frequency and duty cycle to be created. The waveform is downloaded to the AWFG 310 using a National Instrument GPIB-USBA cable. The waveform is saved in the AWFG310 as USER1, USER2, USER3 or USER4 preset.
The negative lead of the DC power supply connects to the TTL Pulse circuit and provides the regulated power of the engine. The TTL Pulse circuit consumes an additional 0.707 V from the DC power supply. This voltage drop is displayed in the oscilloscope. The positive lead of the DC power supply connects directly to one contact of the resistance heater. The other contact of the resistance heater connects to the TTL Pulse circuit.

### 5.2.2 Deflection Output

The deflection of a membrane on an engine can also be measured and recorded with a laser positioning and detector system. It employs a laser, a laser-positioning detector, supports, an adjustable stage, and Labview software for data acquisition. The laser beam shines onto one surface of the membrane and reflects into a laser-positioning detector. As the membrane flexes in or outward, the angle of incidence changes, along with the position of the laser on the detector. Rigid mounts and supports are used to fix the engine, laser, and detector into position. The detector connects to the Labview software, for data acquisition and analysis, via A/D converter and PC. A schematic of the testing system is shown in Figure 5.9 [adapted from 8].
The system requires an initial calibration with the laser interferometer setup. Calibration is accomplished by placing an assembled engine into the laser interferometer system. Voltage from the DC Power source is connected straight into the resistance heater. The voltage does not flow into the TTL Pulse circuit since heat will not be pulsed into the engine. A constant voltage is applied to the heater to provide a constant amount of heat flux into the engine cavity. When the engine reaches equilibrium, the top membrane generator will have flexed out some distance. This deflection, along with the applied voltage, is recorded for comparison. The voltage is increased and the engine is again allowed to reach steady state before the deflection is measured. This process continues until about 50-µm of deflection is achieved. A deflection vs. DC input voltage plot is obtained.

The engine is removed from the laser interferometer setup and placed in the laser positioning and detector system. The engine is allowed to cool to ambient. The voltage

Figure 5.9: Laser Positioning & Detector Output Schematic [adapted from 8]
from the DC Power source is connected into the resistance heater. The same DC input voltages are applied as before. Once the engine has reached equilibrium, as before, a detector reading is recorded. A detector output vs. DC input voltage plot is obtained.

Since the same constant voltage applied to the engine is expected to result in the same amount of deflection, the data from both experiments allows the creation of a deflection vs. detector output plot.

5.3 ENGINE RESULTS

5.3.1 Engine Base Tests

After an engine is assembled, a preliminary baseline test is conducted to assess the relative performance of the engine test cell. The TTL Pulse circuit is configured to provide pulse inputs to the resistance heater as described in Section 4.2. The membrane generator contacts are connected to the oscilloscope to monitor the engine voltage output.

The engine is operated at a frequency of 10Hz, 50% duty cycle, and at a DC Power supply voltage of 1.5 V DC. The peak-peak voltage output of the engine is recorded. The voltage is gradually increased every 0.25 V DC and the resulting peak-peak output voltage is recorded. The voltage increase is restricted to 2.5 V DC. Further voltage was found to rupture the thin membranes or break the engine cavity seal. Other problems with sealing included pinholes in the thin membranes, an acrylic test cell holder not adequately fastened together, and debris on the semiconductor tape preventing sealing.

Multiple configurations were assembled to identify superior engine components. Engines were assembled using various heater resistances, various membrane thicknesses
and sizes, and various membrane generator designs. For example, heaters with resistances between 1.2 – 2.1Ω were used in the assembled engines. The thickness of membrane generators and heaters were either 1.1 µm or 2.3 µm thick. The heater membranes had membrane side lengths of either 2mm or 3mm. PZT etched and un-etched membrane generators were tested in the engine cells.

In general, the best engine configuration consisted of a 2.3 µm thick heater membrane with a 2mm side length. Membrane generators with PZT etch, about 1 µm of PZT, a 3mm side length, and with silicon membrane thickness of 1.1 µm provided the best results in engine performance. An engine, with the components described above, generated a peak-peak output voltage of 760 mV at a standard operating frequency of 10Hz, 50% duty cycle, and 2.5 V DC input voltage. A sample waveform of the engine’s output voltage is shown in Figure 5.10 [45].

![Figure 5.10: Engine Output Voltage [45]](image-url)
5.3.2 Power Production

Power production by the prototype $P^3$ micro heat engine can be demonstrated by dissipating the electrical output of a generator through a known resistance. The micro engine, at standard settings 10Hz and 50% duty cycle, produces voltage output in the hundreds of peak-peak milli volts. The membrane generator output can be dissipated through a decade box to assess maximum power transfer by matching the load impedance to the source impedance of the generator. Figure 5.11 illustrates the engine and power-impedance setup [adapted from 8].

To maximize power the resistance of the decade box is gradually increased from zero Ohms as the output voltage drop is recorded [41]. Power is determined as the amount of voltage drop across the resistor squared over the resistor’s resistance.

![Figure 5.11: Power-Impedance Schematic [adapted from 8]](image)

Peak power production occurs at the impedance match of the engine’s generator and the load resistor. The experiment produced a Power vs. Load Resistance plot displayed below in Figure 5.12 [45]. The figure reveals a peak power production of 1.5 $\mu$W at a load resistance of 180-kOhm.
5.3.3 Combined Engines

A number of tests were conducted to test whether the output of several P³ micro heat engines could be combined together. Two to six engines were operated together. In the first attempts, the resistance heaters were operated in parallel using one DC power supply and TTL Pulse circuit. With one DC power supply, insufficient current was distributed to the heaters. The current limiting setup prevented higher engine output and performance.

In the second set of attempts the resistance heaters were arranged in parallel. This arrangement resolved the current limitations but resulted in random heater failures. The failures developed as a heater shorts or as thin membrane ruptures, due to varied ring resistances among the heaters of each engine. Each ring heater can handle a certain amount of current and voltage. To maintain the same amount of power input to each
resistance heater, the voltage increased proportionally to the amount of combined
engines; assuming the resistances of each heater is equal. With multiple ring heaters in
series, heater failure occurred when the DC power supply increased because each
engine’s heater resistance is not matched perfectly with the other engine’s heaters.

Currently, combined engine operation utilizes multiple power supplies and
multiple TTL Pulse circuit signals. One TTL Pulse circuit can operate the combined
engines but the signal must be branched with the appropriate number of TIP 120
transistors. The diagram in Figure 5.13 illustrates the TTL Pulse circuit modification and
Figure 5.14 shows the combine engine output setup [adapted from 8]. Multiple power
supplies allows increased flexibility in controlling individual engines. A unit engine
output can be manipulated independently of accompanying engines. The Hewlett
Packard 6629A DC power supply allows up to four engines to function in unison and
permits control of voltage input and current.

With multiple engines in operation, the engine output can be monitored
individually or in combination. To monitor engine output individually, the leads from the
oscilloscope are attached to the top and bottom electrode of the single engine, as
previously described. To monitor the output of combined engines, the output of each
engine is connected in series. The top electrode of one engine connects to the bottom
electrode of another. This sequence repeats for all engines until one top electrode and
one bottom electrode from discrete engines are connected to the oscilloscope.
Figure 5.13: TTL Pulse Circuit Modification

Figure 5.14: Combined Engine Output Schematic [adapted from 8]
Figure 5.15 illustrates the combined engine voltage output of two engines running in unison. The resulting combined voltage output is nearly the sum of each individual engines output.

![Combine Engine Output plot](image)

**Figure 5.15:** Combine Engine Output plot

### 5.3.4 High Frequency Operation (100Hz +)

For higher frequency P³ micro heat engine operation, a function generator capable of generating duty cycles of less than 10% is required. Increased operating speeds result in excess energy into the engine system, decreasing the engine performance. At these frequencies, the duty cycle is varied to evaluate the optimum energy transfer rate. Figure 5.16 shows the mean deflection of the membrane generator versus energy added in one engine cycle. The figure demonstrates the mean deflection of the top membrane generator increases as energy per cycle increases. Surplus heat energy is stored in the engine system raising the mean deflection of the top membrane generator. By raising the
mean deflection, the membrane generator cannot oscillate over the largest possible
distance, reducing the engine performance. This plot also indicates the need for active
engine cooling at these higher operating frequencies. The deflection measurements were
obtained using the laser positioning and deflection system described in Section 5.2.2

![Figure 5.16: Mean Deflection vs. Input Energy](image)

**Figure 5.16: Mean Deflection vs. Input Energy**

**5.3.5 Engine Temperature Measurements**

To conduct engine temperature measurements, the RTD device and RTD circuit
must be applied. The integration of the RTD device in an engine follows the integration
of membrane generator as described in Section 5.1. Instead of assembling an engine with
a membrane generator, the RTD device is used for the top membrane. An integrated
RTD Engine is illustrated in Figure 5.17 below [46]. The wiring description in Section
4.3.3 and 4.3.4 show the proper connections.
RTD temperature measurements seen in Figure 5.18 indicate that a P3 micro heat engine operates over about an 8 °C temperature differential [46].

Figure 5.17: RTD in Engine Test Cell [46]

Figure 5.18: Engine Temperature with RTD [46]
CHAPTER 6
CONCLUSIONS & RECOMMENDATIONS

6.1 CONCLUSIONS

The integration of a top thin film piezoelectric membrane generator, a middle spacer to define a fluid filled cavity, and a bottom membrane with a resistance heater, has successfully been accomplished to create a prototype P³ micro heat engine. This engine has been characterized in terms of output voltage, varied operating frequencies, power production, and internal temperature operation over a range of operating frequencies.

To accomplish this task, resistance heaters were fabricated to run the engine. RTD’s were design, fabricated, and calibrated to measure the internal engine cavity temperature during engine operation.

An engine is capable of providing a peak-peak output voltage of 760 mV at a standard operating frequency of 10Hz, 50% duty cycle, and 2.5 V DC input voltage. The output voltage of several engines has been combined to demonstrate power addition, which is also essential to the P³ micro power concept. Engine performance increases with increased operating frequencies. Excess engine heating can be controlled by varying the duty cycle, or pulse width, at higher frequencies. A peak power production of 1.5 µW at an optimum resistance of 180-kO has been attained from a single engine running at 10 Hz. Using the RTD device to acquire temperature measurements, the engine cycle has been shown to operate over an 8 °C temperature differential.

ARL membrane generators with 110% top electrode coverage show 4-mm, 2-mm, and 1-mm diameter membrane generators with a damped resonant frequency of 1,200 Hz, 4,000 Hz, and 15,625 Hz, respectively. These membrane generators have a stiffness of
approximately 4,400 N/m and a specific voltage as high as 8.7 V/(%strain*um) for the 4mm diameter membrane generator.

6.2 RECOMMENDATIONS

To reach expected power outputs in the 0.1-1 mW range, any of the following three aspects may be addressed: Further optimization of the PZT membrane generator characteristics, an incorporated thermal switch to effectively transfer heat into an out of the engine system, and increased engine operational speed.

Engine test cells may offer improved repeatability results with heaters having equal resistances. The resistance variations seem to cause variation in nucleation voltages and output response for set frequencies, duty cycles, and voltage inputs. The technique used to nucleate and seal a vapor bubble can also be enhanced. Current methods produce varying loading conditions. The top membrane generator, capping the working fluid, has either a neutral, compressive, or expanded state. These loading conditions also affect the engine test cell performance.

Engine operation at resonant frequencies can aid in obtaining lower optimum load resistances and higher power production. Resonant operation also increases the strain energy developed in the deflected membrane. This energy can be exploited in the compression phase of the engine cycle, since at resonance a maximum output deflection is attained for a given input force.

The integration of a circular, silicon-free membrane generator, in an engine test cell assembly may prove advantageous. Plenty of energy is fed into the engine cavity through the resistance heater, but additional cooling or heat rejection is necessary to
operate the engine at higher speeds. The equipment at ARL has the capability to fabricate membrane generators of any geometry and with the absence of silicon. A membrane generator without silicon offers less thermal resistance, which increases heat rejection.
REFERENCES

1. Internet source: http://www.darpa.mil/mto/mems/vision/index.html and

2. Bill Andre, personal communication.

3. P. Sharke, Pocket-sized PEMs, Mechanical Engineering, February 2000, 122 (2)

   Soldier Systems Center, Natick, MA (2000).

5. E. W. Pfeiffer, Richard Muller A Founding Father of MEMS, Small Times,
   July/August 2002 Vol. 2, No. 4


   Engine”, ASME MEMS, 2000, 2.

   Head Workshop (2002).


12. Y. A. Cengel, and M.A. Boles, Thermodynamics: An Engineering Approach, 3rd

14. I. Waitz, G. Gauba, and Y. Tzeng, Combustors for Micro-Gas Turbine Engines,


30. B. Olson, MS Thesis, Washington State University, 2002

31. K. Bruce, MS Thesis, Washington State University, 2001


34. Internet Source: http://www.memsnet.org/mems/beginner/etch.html


42. Norman E. Apperson, personal communication.
43. Internet Source: Burr-Brown INA 128 Product Data Sheet: 
APPENDIX
(ARL) OXIDATION

Plasma-Therm 790 – PECVD

1. From [Utilities] drop down menu, select [Set Standby Temperature] and set to 250°C.
2. From [Utilities] drop down menu, select [Vent] to open PECVD chamber.
3. With chamber open, place wafer(s) into the chamber.
4. From [Utilities] drop down menu, select [Pump Chamber] and press down on chamber cover to seal the chamber.
5. From [Process] drop down menu, select [Edit].
6. Select appropriate recipe (oxide or nitride) and change Process deposition time and gas flow rates for desired thickness.
7. Example Oxide Deposition Process: OXIDE.PRC
   i. Initial
   ii. Ignition
   iii. Process Time
   iv. N₂ Purge
      
      Change item iii. Process Time for desired oxide thickness. See sample recipes below.
10. When process complete, retrieve wafer(s) by repeating step [2].
    
    Clean wafer using nitrogen before inserting into PECVD.
- Cool wafer on PECVD shelf surface after extraction before placing into wafer carrier.

~10,000Å OXIDE RECIPE:

<table>
<thead>
<tr>
<th>Process Pressure (mT)</th>
<th>Time (min)</th>
<th>SiH₄ (sccm)</th>
<th>NH₃ (sccm)</th>
<th>He (sccm)</th>
<th>N₂O (sccm)</th>
<th>N₂ (sccm)</th>
<th>RF (W)</th>
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<tr>
<td>Film 900</td>
<td>27</td>
<td>70</td>
<td>0</td>
<td>93</td>
<td>390</td>
<td>0</td>
<td>20</td>
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</tbody>
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~5,000Å/500Å/5,000Å OXIDE/NITRIDE/OXIDE RECIPE:

<table>
<thead>
<tr>
<th>Process Pressure (mT)</th>
<th>Time (min)</th>
<th>SiH₄ (sccm)</th>
<th>NH₃ (sccm)</th>
<th>He (sccm)</th>
<th>N₂O (sccm)</th>
<th>N₂ (sccm)</th>
<th>RF (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film 900</td>
<td>13</td>
<td>70</td>
<td>0</td>
<td>93</td>
<td>390</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Film 900</td>
<td>6</td>
<td>90</td>
<td>3</td>
<td>488</td>
<td>0</td>
<td>160</td>
<td>45</td>
</tr>
<tr>
<td>Film 900</td>
<td>13</td>
<td>70</td>
<td>0</td>
<td>93</td>
<td>390</td>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>
(ARL) ANNEALING

Mat 610 – RTA ANNEALER

1. Switch Power Breaker (Tool #92) to ON position.
2. Toggle switch to ON position on keyboard computer.
3. Toggle switch to ON position on RTA drawer.
4. Toggle switch on Neslab Cool flow Liquid/Liquid Re-circulating Chiller.
5. OPEN both SUPPLY and RETURN process cooling valves behind Chiller.
6. OPEN either Nitrogen or CDA gas valves behind mass flow measurement controller. Gas type depends on annealing Bottom Metal, PZT, or Tope Metal. Should read approximately 5 sccm.
7. Insert wafer into RTA drawer. Note glass wafer tab placement for appropriate wafer size.
8. From keyboard set time and temperature by pressing:
   - Time: Press [S]
     Press [A] and enter time (sec)
     Press [Enter]
   - Temperature: Press [S]
     Press [T] and enter temperature (°C)
     Press [Enter]
9. Execute RTA by pressing [A]
10. Extract wafer when RTA digital display temperature read out drops below 30.0 (corresponds to 300°C).
11. Shut RTA drawer.

12. Cool wafer with nearby nitrogen gas.

NOTE: Chiller and Process Cooling Valves can only be shut off with a RTA digital display temperature of 15.0 (150°C) or lower.
(ARL) METAL DEPOSITION

Varian 3190 – SPUTTERER

1. Toggle ON STATIONS 4, 3, & 1 for heater power supplies in back service chase.
2. Toggle ON RF switch on Control Box in back service chase.
3. Set heater temperature (not for top electrode w/pzt) to ~300ºC and press [Enable Heaters] on the touch screen display.
4. Press [Select Recipe], depositions posted, and choose 1-10.
5. Position wafer chamber in Ti station press [Change Clip] to open Load Lock in position A.
6. Load wafer into Load Lock with carousel position at A.
7. Press [Rotate] once to revolve carousel to the RF station and then press [Start Process]. Choose station number 2. See chart below for proper station numbers.
8. When the process is complete press [Rotate] the correct number of times to position the wafer over the correct metal. When the wafer positioned over the metal of choice, press [Start Process] and choose the correct station number.
9. When complete with metalization, return the wafer to the Ti station for extraction with the [Rotate] button. Press [Change Clip] to open the Load Lock.

-As soon as the recipe starts, all deposition guns operate at 10% for pre-sputtering
-The titanium and platinum guns have a 3kW DC max power rating
-The tantalum gun has a 12kW DC max power rating
-Base pressure at 2x10⁻⁷ T and process pressures are held at 7.5 mT
Varian Station Positions

[Diagram showing Varian Station Positions]

**Varian Recipes:**

### #2

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<thead>
<tr>
<th></th>
<th>Pt</th>
<th>RF</th>
<th>Ta</th>
<th>Ti</th>
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<td>Deposition/Etch Time (sec)</td>
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<td>Power (%)</td>
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1600Å Ti/Pt (~400Å Ta ~1200Å Pt) or 1600Å Ta/Pt (~400Å Ti ~1200Å Pt)

### #6

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<th>Ti</th>
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</thead>
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<td>15</td>
<td>6</td>
<td>13</td>
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<tr>
<td>Power (%)</td>
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<td>65</td>
<td>14</td>
<td>14</td>
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</table>

800Å Ti/Pt (~200Å Ta ~600Å Pt) or 800Å Ta/Pt (~200Å Ti ~600Å Pt)

### #11

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<thead>
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<th></th>
<th>Pt</th>
<th>RF</th>
<th>Ta</th>
<th>Ti</th>
</tr>
</thead>
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<td>Deposition/Etch Time (sec)</td>
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<td>15</td>
<td>12</td>
<td>26</td>
</tr>
<tr>
<td>Power (%)</td>
<td>17</td>
<td>65</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

3000Å Ti/Pt (~400Å Ta ~2400Å Pt) or 3000Å Ta/Pt (~400Å Ti ~2400Å Pt)
(ARL) PHOTORESIST SPIN COATER/BAKER/DEVELOPER

Karl Suss ACS 200 – CLUSTER TOOL

1. Change photo resist pump settings on Cybor Control Module
   i. Press [Enter] until ACTV option appears
   ii. Press [Disp/Actv] to open ACTV recipe mode
   iii. Enter program number followed by [Enter]
   iv. Repeat step iii. for each pump

<table>
<thead>
<tr>
<th>ACTV RECIPE MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1=</td>
</tr>
<tr>
<td>2=</td>
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<tr>
<td>3=</td>
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<tr>
<td>4=</td>
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</table>

<table>
<thead>
<tr>
<th>AZ5214 Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ9245 Pump</td>
</tr>
</tbody>
</table>

*Set pumps to 3 for 3” wafers and 4 for 4” wafers

2. Insert appropriate loaded carrier in to cluster tool. Left boat holds 4” wafers and the right boat holds 3” wafers.


4. Select wafer positions to be processed. Wafer position increases from bottom to top of wafer carrier.

5. Select Run.
1. Turn lamp power supply ON. Set the lamp to [C-1-1] and wait for the display to read from [Cold] to [900+]

2. Press the (Change Mask) button on the aligner console to release the mask vacuum and place the desired mask into mask holder. Follow display instructions to secure mask into place.

3. Press the (Load) button and insert the wafer for patterning into the system drawer. Follow display instructions for appropriate sequence to secure mask is system.

4. To align wafer with mask design, use console arrows to move the viewing camera and the micrometers to adjust the wafer substrate. Place wafer features in position with wafer alignment marks.

5. Press (Edit Parameters) to adjust exposure time. Use console arrows to toggle the duration.

6. Press (Alignment Check) to place wafer substrate in contact with mask.

7. Press (Expose) for UV exposure and shield eyes from harmful UV light.

8. Directions for unloading the wafer are shown on the display.

FOR UV FLOOD EXPOSURE:

1. Place clear glass plate into mask holder.

2. Place wafer above mask and continue from step 5 above.
(ARL) PZT BACKSIDE ETCHING

1. Place wafers into ACS 200 and run 9245ES51.PATH to deposit 9245 resist on the PZT surface.

2. Place into premixed PZT etch solution of: 5 drops HF, 150 ml de-ionized water, 125 ml acetic acid. The solution is located under the wet process bench across from the Plasma-Therm 790 PECVD. (Remember to use the plastic beaker).

3. Let wafer set in solution until all PZT removed from backside surface. Important to clean backside for DRIE. For 1 um PZT, approximately 10 minutes.

4. Place wafers into resist stripper (BAKER PRS 300) until photoresist is removed, approximately 10 minutes.

(ARL) PZT CLEANING BEFORE TOP ELECTRODE DEPOSITION

PERFORM BEFORE TOP ELECTRODE DEPOSITION OF LIFTOFF PROCESS

1. Place wafer into a PZT clean solution of: 10% acetic acid 90% de-ionized water for 5 seconds. Cleans lead oxide formed on PZT.
(ARL) LIFTOFF

1. Run 5214ES51.PATH on the ACS 200 for the desired wafers. AZ5214 reversible photoresist will be coating the wafers.

2. Pattern the wafers with the top electrode using the MA6/BA6. (exposed for 3.5 seconds)

3. Run 5214EB51.PATH on the ACS 200 to post bake photo resist on a hot plate at 110ºC for 60 seconds.

4. Flood expose the wafers on the MA6/BA6. (exposed for 3.5 seconds)

5. Run 5214ED51.PATH on the ACS 200 to develop the photo resist.

6. Deposit the desired metals onto the wafers using the Varian 3190. (do not use heat for top electrode deposition)

7. Place wafers into heated positive resist stripper (BAKER PRS 300) until all desired metals have lifted off. (approximately 2 hours)
1. Push PWR on Metroline Asher.

2. Press [Vent] to pump machine to atmosphere ~20000mT

3. Place wafers into Metroline.


   For post DRIE 6µm photoresist choose 9245 6 µm strip.

   SETTINGS: 500sccm O₂ flow rate, 1000mT pressure, 600W power,

   35min process time, 24-54°C chamber temperature.

5. Press [Run] and enter operator name and wafer numbers.
1. Press PWR on mechanical power supply (RL400).

2. Press PWR on lamp power supply and then press IGNITION.

3. Open VASE MANAGER on computer desktop.


5. Select the PROJECT file to save data (i.e. Micro power).

6. Select the RECIPE to be used to measure the thin film (i.e. PZT).

7. Select the SCAN PATTERN to be used to sample the wafer (CROSS).

8. Select the DATA ANALYSIS STRATEGY to be used (i.e. PZT 1-2µm).

9. Enter sample DESCRIPTION to identify the measurement. Usually the wafer number (and layers of PZT if being measured).

10. Press [Measure] and [Ok].

11. Align crosshairs into the box using ellipsometer platform knobs.

12. Ensure Black Spot centered in White Circle of left gun. Adjustment made with micrometer.

13. Press [Continue].

14. To return to main menu press [Enter].
1. Press PWR on computer.
2. OPEN both SUPPLY and RETURN process cooling valves behind Tencor.
3. Press PWR on Tencor.
4. Open Tencor cover and place appropriate wafer guides inside.
5. Place wafer into Tencor with process side up and flat towards and against the back of the Tencor. (Double Sided Polished only)
6. Open WINFLX program in PROGRAM MANAGER window.
7. Select 2002 Login.
8. From [Edit] drop down menu, select [Process Program] and choose appropriate wafer specifications (i.e. 4” DSP 475µm thick choose 100dsp475.prc).
9. From [Measure] drop down menu, select [First (no film)] and enter wafer data.
10. Press [Measure] tab for 0°, 45°, 90°, and 135° orientations. Initial wafer orientation at 0° with flat faced away and rotate clockwise.
11. For film stress: From [Measure] drop down, select [Single] and enter film data (i.e. Wafer#, A, 0°, Film, NEGATIVE Film Thickness).
7. Press [Vent] to pump machine to atmosphere ~20000mT
8. Place wafers into Meteroline.
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<th>Heater Thickness (um)</th>
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RTD Math Model

Resistance Thermometer Detector (RTD) with Strain Effects

\[ T_0 = 20 \quad \text{Room temperature (} ^\circ\text{C)} \]

\[ \rho = 2.35 \times 10^{-8} \quad \text{Gold resistivity at } 20 \; ^\circ\text{C (} \Omega \text{m)} \]

\[ L = 15147 \times 10^{-6} \quad \text{Length of RTD (m)} \]

\[ w = 20 \times 10^{-6} \quad \text{Width of RTD (m)} \]

\[ h = 100 \times 10^{-9} \quad \text{Height of RTD (m)} \]

Resistivity Equation for Bulk Material (Kovacs 2.51)

\[ R_0 = \frac{\rho \cdot L}{w \cdot h} \quad \text{Resistance of RTD at } T_0 (\Omega) \]

\[ R_0 = 177.977 \]

Electrical Resistance Equation (Kovacs 2.5.2)

\[ \alpha = 0.0083 \quad \text{Gold Temperature Coefficient of Resistance (parts/} ^\circ\text{C)} \]

\[ T(R_{td}) = T_0 + \left( \frac{R_{td}}{R_0} - 1 \right) \quad \text{Approximate Temperature of the Resistance Thermometer (} ^\circ\text{C)} \]

Temperature vs. Thermometer Resistance

\[ T(R_{td}) = T_0 + \left( \frac{R_{td}}{R_0} - 1 \right) \]

Resistance of Thermometer

\[ R_{td} \]

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RTD Circuit (Wheeler & Ganji 9.13)

Lead resistances assumed equal (same material, diameter, and length)
With balanced mode, \( R_1 = R_4 \) and thus \( R_2 = \text{Rtd for } V_0 = 0 \)

\[ R_1 := 150 \quad R_4 := 150 \quad \text{Reference resistors on bridge circuit (} \Omega \text{)} \]

\[ R_2 := R_0 \quad R_2 = 177.977 \quad \text{Adjustable resistor used to zero the bridge circuit (} \Omega \text{)} \]

\[ V_s := 1 \quad \text{Supply voltage to bridge circuit (} V \text{)} \]

\[ R_{\text{td}}(V_0) := R_2 \frac{V_s - 2 \cdot V_0}{V_s + 2 \cdot V_0} \quad \text{Equation for Resistance Thermometer (} \Omega \text{)} \]

where \( V_0 \) is the voltage difference across the resistors (V)

Voltage vs. Thermometer Resistance

Voltage Difference Between Resistors
Thermometer resistance \( (R_{td}) \) increases as temperature increases. A voltage difference \( (V_0) \) can be measured and correlated to a temperature using the Temperature vs. Thermometer Resistance graph.

\[
R_{td}(T) := R_0 \left[ 1 + \alpha \cdot (T - T_0) \right]
\]

Rearranged Electrical Resistance Equation \((\Omega)\)

\[
R_{td}(21) = 179.454
\]

Thermometer resistance associated for a 1°C temperature rise

\[
rtd := R_{td}(21) \quad rtd = 179.454
\]

Rearranged Resistance Thermometer Equation \((V/°C)\)

\[
V_0(R_{td}) := \frac{V_s}{2} \left( \frac{R_2 - R_{td}}{R_2 + R_{td}} \right)
\]

\[
V_0(rtd) = -2.066 \times 10^{-3}
\]

This is the change in voltage associated with a 1°C increase in temperature for the Resistance Thermometer.

Self Heating Effect of RTD

\[
R_{total} := \frac{2 \cdot R_1 \cdot (R_2 + R_{td}(20))}{R_2 + R_{td}(20) + 2 \cdot R_1}
\]

Total Min Resistance in the RTD circuit \((\Omega)\)

\[
R_{total} = 162.795
\]

\[
I := \frac{V_s}{R_{total}} \quad I = 6.143 \times 10^{-3}
\]

Total Max Current in the RTD circuit \((C)\)

\[
P := V_s \cdot I \quad P = 6.143 \times 10^{-3}
\]

Total Power Generated in RTD circuit \((W)\)

\[
i_1 := \frac{V_s}{2 \cdot R_1} \quad i_1 = 3.333 \times 10^{-3}
\]

Resistance in R1 Resistor\((C)\)

\[
i_{2\text{max}} := \frac{V_s}{(R_2 + R_{td}(20))}
\]

Max Current through Rtd Resistor \((C)\)

\[
i_{2\text{max}} = 2.809 \times 10^{-3}
\]

\[
P_{\text{max}} := i_{2\text{max}}^2 \cdot R_{td}(20)
\]

Max Power Consumption for Rtd Resistor \((W)\)

\[
P_{\text{max}} = 1.405 \times 10^{-3}
\]
\[ i_{2\text{min}} := \frac{V_s}{(R_2 + R_{td}(70))} \]

\[ i_{2\text{min}} = 2.327 \times 10^{-3} \]

\[ P_{\text{min}} := i_{2\text{min}}^2 R_{td}(70) \]

\[ P_{\text{min}} = 1.363 \times 10^{-3} \]

**RTD Resolution**

\[ V_{0\text{min}} := V_0(R_{td}(20)) = (0) \]

\[ V_{0\text{max}} := V_0(R_{td}(70)) = (-0.086) \]

An A/D card has 16 bit converter, thus it has \(2^{16}=65536\) steps. The range goes from \(-.625\text{V}\) to \(.625\text{V}\). Must use an Amplifier to take advantage of the full range and resolution.

\[ b := 16 \]

**Bits per conversion**

\[ \text{steps} := 2^b \]

\[ \text{steps} = 6.554 \times 10^4 \]

**Step per Voltage Range**

\[ V_{\text{range}} := 1.25 \]

**Voltage Range of A/D card (V)**

\[ \text{Volstep} := \frac{V_{\text{range}}}{\text{steps}} \]

\[ \text{Volstep} = 1.907 \times 10^{-5} \]

\[ \text{Resolution} := \frac{\text{Volstep}}{|V_0(\text{rtd})|} \]

**Temperature resolution \(\text{oC/step}\)\)

\[ \text{Resolution} = 9.23 \times 10^{-3} \]