MEM's Optical Pyrometer

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Abstract— **Measuring temperature accurately has been and still is a topic of interest in various professional fields such as Astronomy, Biology, Physics and Medicine. An optical pyrometer has great potential in these fields, because it can optically capture a body's black body radiation and determine a temperature value of the body in question. This technology is well known, yet it is still gaining grounds as new uses are found. In this project a temperature sensor using Mentor Graphics was design, second a four level mask was made into one reticle. Third fabrication of the optical sensor took place using typical process steps in PMOS fabrication. Fourth, a filter out of silica/silicon was made to keep away various wave lengths in the electromagnetic spectrum from the sensor that will just become noise and, fifth testing is in the process of being performed with a known source of black body radiation.**

A thermal couple is a device that can be constructed by micro machining and molding of microstructures to create a optical pyrometer (an optical temperature sensor). The thermal couple is made by the junction of two metals, and a thermopile is various thermal couples in series, the more elements in series the more accurate it becomes. Aluminum – Polysilicon thermal pile of # 16 elements was constructed. In order to minimize alignment error relative large thermal couples in the order of 10μm by 10μm in pixel size. This project used a 4-mask layer process. Having a fabricated 2 by 8 array of sensor, the double sided polished silica filter will be attached to the entire area of the sensors, and voltage meter will then be attached to the leads of the device and testing of various objects will be done.

This type of technology is used today for cost effective way to have temperature sensors in motherboard, temperature sensors, and cheap thermostats. This technology has great potential, especially in areas dealing with CMOS and MEMS.

Index Terms— **Optical Pyromiter, Thermopile, Seebeck coefficient, Thermocouple**

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I. INTRODUCTION

1.1. The necessity for thermopile technology

Thermopile temperature/infrared sensor is used in various applications, such as infrared spectroscopy, radiometry, security systems, and many consumer products. Typically, thermopiles are found in objects ranging from curling irons to satellites in space. A thermopile is defined as device that is very sensitive to changes in infrared radiation or heat as a result of the conductive capabilities of the two joining metals with different conductive capacities that are connected to a sensitive voltage meter.

1.2. The Driving force

Thin film technology/micromachining techniques will be utilized in order to build 2 x 8 thermocouples in series to form the aluminum-polysilicon thermopile. Since signal response is proportional to device size, these devices will be designed as small as possible. These technologies and techniques will allow cheap and reliable sensors, hence becoming appealing to newer applications.

II. THEORY

2. The Thermopile

In simple term; the thermocouple works by absorbing thermal radiation at the "hot junction" (where the two metals meet and radiation is capture) or the "active junction." By setting up a reference junction that is maintained at a constant temperature, the temperature gradient between the hot junction and the reference junction create an electromotive force (a voltage) known as the thermoelectric effect.

Thermopiles are based on theories that deal with thermoelectricity/thermodynamics. There are three theories that are involved with the thermocouple. These are the Seebeck effect, Peltier effect and the Thomson effect. These theories share something in common - they are reversible thermoelectric effects. These follow the concept of conservation of energy. With respect to thermocouple, energy could be absorbed as thermal energy and transformed into electrical energy.

2.1. The Peltier Effect

In 1834, Jean Charles Athanase Peltier, discovered that when an electric current flows between of two conductively different metals, heat will be absorbed or release depending on the direction of the Seebeck current and the electric current. The Peltier effect can be seen in figure 1. (S. Weckmann, **Dynamic Electrothermal Model of a Sputtered Thermopile Thermal Radiation Detector for Earth Radiation Budget Applications, chapter 2**)

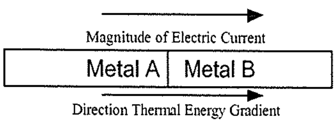

Figure 1: Peltier Effect

2.2. The Thomson Effect

In 1852, Lord Kevin (William Thomson) discovered that a current would be present in a conductor when a temperature gradient is apparent. Absorbed or rejected energy will be dependent on the current of the conductor. The release of thermal energy will imply a current inside the conductor in the same direction as the heat flow; other than this it will be absorbed. The Thomson effect is observed in figure 2. (S. Weckmann)

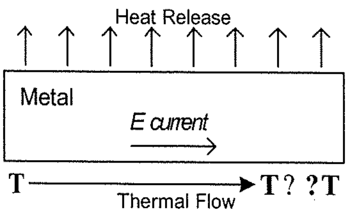

Figure 2: Thomson Effect

2.3. The Seebeck Effect

In 1821, Thomas Johann Seebeck made the discovery that the creation of an electrical voltage was possible by the temperature difference between two metals having different conductive properties at the other end of the two wires. "The Seebeck effect is the result of both the Peltier effect and the Thomson effect" (S. Weckmann). The Seebeck effect is the heart of thermocouples; if two metals having different Seebeck coefficients are jointed together at one end, the presence of a voltage (electromotive force) will be apparent using a voltage meter at the other end. The voltage that is present is due to the temperature gradient, between the two sides. (S. Weckmann). In figure 3, the Seebeck Effect is seen, showing the thermal gradient and the electromotive force to the left at the cold junction (reference junction). The ΔV Coefficient and the Seebeck Coefficient

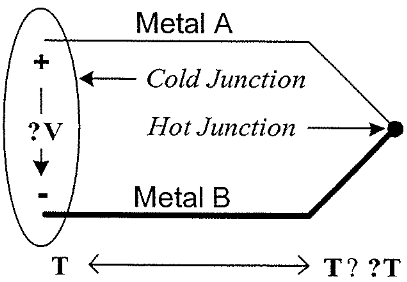

Figure 3: Seebeck Effect

2.4. The ΔV Coefficient and the Seebeck Coefficient

As it was mention earlier, this project will involve the use of two metals for the fabrication of the thermocouple. The two metals will be Polycrystalline Silicon (polysilicon) and Aluminum (Al). Using the three thermoelectric effects with respect to these metals will result in a potential voltage. The main effect that is predominantly applicable is the Seebeck effect, where an electromotive force is formed as a result of the proportionality of the thermal gradient between the hot and cold junctions in the materials. The change in voltage between the two junctions is described by taking an integral over the starting/reference temperature to the final temperature. This is shown by the following equation; $\Delta S = \int_{T0}^{T} S * dT$ which simplifies to $E = S_{A-B} * \Delta T$. Keep in mind that this is true for one thermal couple. S_{A-B} is the Seebeck coefficient difference between the two metals. The Seebeck coefficient is a material property that is temperature dependent, and can be found by $S = dV/dT$. In metals, the Seebeck coefficient is given by the approximation $S \approx (\pi^2 k^2 T / 2qE_{F0})x$ (*Thermoelectric Effects in Metals: Thermocouples © S.O. Kasap 1997-2001, an e-Booklet*). Some of the constants and/or variable that this equation uses include k (which is Boltzmann's constant), Pi, T for temperature in Kelvin, x a numerical consent dependant on charge transport mechanism, q the charge of an electron and E_{F0}, the Fermi energy at 0K.

2.5. Seebeck coefficient calculation for p-type polysilicon and aluminum

In the S. O. Kasap e-Booklet, table 2, lists the coefficient of

Table 1: Poly Silicon Material Properties

TABLE 1. Thermopower (S), resistivity (ρ) and thermal conductivity (λ) of silicon at 300K.

Description	S [$\mu V.K^{-1}$]	ρ [$\mu\Omega.m$]	λ [$W.m^{-1}.K^{-1}$]	Power factor [$W.m^{-1}.K^{-2}$]	ZT
B-doped fine-grained film[a] $p=1.3x10^{20}$ cm^{-3}	281	62	14.2	0.00127	0.027
P-doped fine-grained film[a] $n=6x10^{20}$ cm^{-3}	-120	9.5	14.8	0.00151	0.030
Undoped fine-grained film[a]	-	-	12.8	-	
P-doped CMOS Poly-Si film[b]	-122	8.5	29	0.00175	0.018
As-doped bulk single crystal $n=2.7x10^{19}$ cm^{-3}	-290[c]	25[d]	100[f]	0.00336	0.010
B-doped bulk single crystal $p=5x10^{19}$ cm^{-3}	-	2.63[e]	41[e]	-	-

[a]Present work; [b]Data taken from Ref. 18; [c]Data taken from Ref. 19; [d]Data taken from Ref. 20; [e]Data taken from Ref. 21.

[f]We did not found the thermal conductivity of arsenic-doped silicon. We used the thermal conductivity of phosphorus-doped silicon at the same carrier concentration taken from Ref. 21.

selected metals. Here the aluminum Seebeck coefficient is shown as

It needs to be noted that a positive sign on the Seebeck coefficient indicates that electrons are migrating from the cold junction to the hot junction. The Seebeck coefficient for Al was calculated at room temperature (300K) using $S \approx (\pi^2 k^2 T / 2qE_{F0})x$ to be $-1.75645\frac{\mu V}{K}$. Polysilicon's Seebeck coefficient, on the other hand is not as simple as Al's. In a document online at http://www-ee.uta.edu/Online/cbutler/MEMSWebpage/pdfs/EE5349chapter5.pdf it was shown that the Seebeck coefficient for n-type polysilicon and p-type polysilicon where;

$$S_{n-poly} = -\frac{k}{q}\{[\ln(N_C / n) + \frac{5}{2}] + (1 + Sn) + \Phi_n\}$$

$$S_{p-poly} = \frac{k}{q}\{[\ln(N_V / p) + \frac{5}{2}] + (1 + Sp) + \Phi_p\}$$

Where N_V is the effective density of states in the valance band, Φn & Φp are the excitations of molecules as a result of the thermal gradient. In the same document an approximation for n-type polysilicon and p-type polysilicon is shown as $S_{p-polysilicon} = \frac{2.6k}{q} Ln(\frac{\rho}{\rho_o})$ where ? is receptivity and $?_0$ is $5x10^6$ O-cm. For accuracy, the results of a paper by A. Jacquot named "FIGURE-OF-MERIT AND EMISSIVITY MASUREMENT OF FINE GRAIN POLYCRYSTALLINE SILICON THIN FILM" shown in table 1. By using a p-type phosphorous doping at a concentration of n=6E20 [m^{-3}] and a Seebeck coefficient of about -122 µV/K at room temperature for the polysilicon, the resulting S_{AB} for the Al-Polysilicon becomes $-1.78\frac{\mu V}{K} - (-)122\frac{\mu V}{K} = 123.78\frac{\mu V}{K}$. For the thermocouple calculation of the thermal gradient induce voltage then becomes $\Delta V = 123.78 * \Delta T$.

2.6. The Model Equation for a thermal system.

In Weckmann's paper, she establishes a model for a thermocouple and thermopile system represented by the differential equation $C\frac{d\Delta T}{dt} + K\Delta T = P_e$. By keeping the absorption at a constant rate a solution to the differential equation can be made, represented by $\Delta T = \frac{P_e}{\sigma_H}(1 - e^{(-\sigma_H / C_p)t})$.

Where

ΔT is the temperature in [K]

P_e is the radian energy in [W]

C_p is the heat capacity in [J/K]

→ { $Cp = mc_p$ }

m is the mass [kg]

c_p Is the specific heat [J/kg*K]

σ_H is the thermal conductance [J/K]

→ { $\sigma_H = \frac{Area * \sigma_k}{length}$ }

σ_k is the thermal conductivity [W/m*K]

A is the area in [m^2]

l is the length in [m]

Therefore ΔT equation becomes:

$$\Delta T = \frac{P_e}{(\frac{A*\sigma_h}{l})}[1 - e^{\frac{-(\frac{A*\sigma_h}{l})}{m*c_p}*t}]$$

Now the electromotive force equation makes logical sense with respect to volume $\Delta V = S_{AB} * \Delta T$ for a thermocouple and $\Delta V = n * S_{AB} * \Delta T$ for a thermopile, with elements in series. Weckmann also showed another important equation - the equation to have a measure for the thermocouple's sensitivity where it is the ratio of output voltage over input power. Shown by: $Sensitivity = \frac{\Delta V}{P_e}$.

Table 2: Seebeck Coefficient for Al

Metal	S@ 0°C [uV/K]	S@ 27°C [uV/K]	Ez [eV]	x
Al	-1.6	-1.8	11.6	2.78

2.7. Specifications/Dimensions

What amount of energy is this device going to absorb? To answer this question some limitations and assumptions need to be made. For example let's limit the device by assuming that the dimension length*width* height of aluminum are approximated to the dimensions of Poly-silicon. Then let's assume that heat conduction is dependent upon the smallest conductivity and the smallest heat capacity of the two materials. Let us also assume that the time needed for any given measurement is about 1 second. Then let's assume that the device will be able to measure a heat flux in the order of 1nW. Having a small specification for heat flux absorption lets the device be capable of measuring very small changers in temperature. This project will use relative large structures in comparison to what is used today in the smallest critical dimension. This is going to be done to prove the concept of making a thermopile/thermocouple. As a result, it was decided to use a width of 2 micro meters, a height of 1 micro meter, and a length of 10 micro meters. This will give a volume of about 2E-17 m^3. In table 3, some important values for the design of the structure are shown. Given the values in table 3 and $\Delta T = \frac{P_e}{\sigma_H}(1 - e^{(-\sigma_H / C_P)t})$, ?T becomes 30.0483851637 [K]. Now that this is known then the value for the approximated voltage can be found from $\Delta V = n * S_{AB} * \Delta T$, given that the previous value for S_{AB} was 123.78 [μV/K], and having one thermopile or a thermocouple, results in a value for ?V being 3.5530413 [mV]. (As it can be seen the value for heat flux is too big, but it can be changed)

Table 3: Material Properties

	σ_H [J/K]	σ_B [W/m*K]	Cp [J/K]	cp [J/kg*K]	*Mass [kg]*	*Density [kg/m³]*	*Volume [m³]*
Al	1.28E-11	237	4.86E-11	900	5.4E-14	2700	2E-17
P-polySi	1.35E-12	29	3.26E-11	700 (Si)	4.66E-14	2330	2E-17

III. EXPERIMENT

3.1. Process Flow

- Scribe, , RCA Clean
- Nitride1 is flexible with thickness via ASM LPCVD
- LTO via ASM LPCVD
- Lithography Level1 is Active, via GCA Stepper and SVG88 coating and developing track.
- Resist Strip, RCA Clean
- Poly Deposition via ASM LPCVD
- Spin-on-glass
- Sinter - 20 min. 425°C in H_2/N_2
- Etch Spin-on-glass in – 25 min in BOE
- Measure Resistance via ResMap
- Lithography level 2 poly, via GCA Stepper
- Dry plasma etching of Nitride and Poly
- Resist Strip, RCA Clean
- 2nd Nitride via ASM LPCVD
- Lithography Level 3 Poly Contact, via GCA Stepper
- Resist Strip, RCA Clean
- Deposit Aluminum via CVC thermal evaporation
- Lithography level 4 aluminum, via GCA Stepper
- Etch aluminum via hot aluminum etch

3.2. Testing

An appropriate test setup was developed in order to test the chips. It consisted of a voltage meter, a microscope, and a

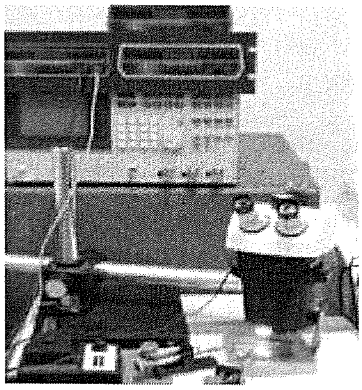

Figure 4: Test Setup

heater lab. It is seen in figure 4.

IV. RESULTS

Electrical Test Results concluded that the pyrometer works seen in table 4. , yet more testing should be done to see the correlation to temperature change. Having built this device, looking back there are many things that can be done to improve how the device works. Some of these things include the design, the fabrication and the testing.

Table 4: Results

1st Light source		
Intensity [mW/cm^2]	*Voltage [V]*	*Temp [C]*
0	0.044	23
0.01	0.119	23
0.5	0.162	24
2	0.205	24

2nd Light source		
Intensity [mW/cm^2]	*Voltage [V]*	*Temp [C]*
0	0.044	23
0.01	0.142	23
0.5	0.170	24
2	0.200	24

V. CONCLUSION

The goal was to build a simple 2 × 8 thermopile consisting of 4 lithography levels. This was accomplished using a phosphorous doped poly and aluminum combination thermocouple in a 16 pixel array. The test chip can is shown in figure 5. It is seen that the aluminum etch ways completely in the require places. Yet, in figure 5 it is also observe the alignment error. The test chip showed preliminary results. Various elements can be improved to make a better overall design, ranging from the design to testing.

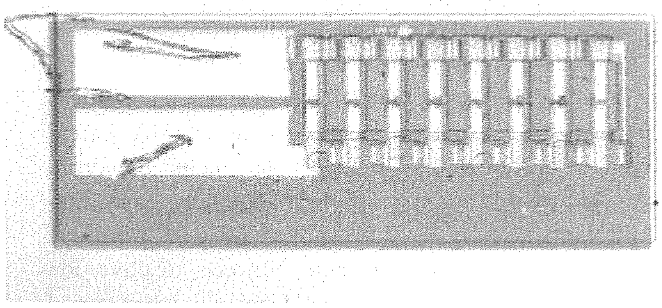

Figure 5: Working Pyrometer

There were certain things that were left un-resolved and should be studied further. The first thing is a complete understanding of the phenomenon in the bi-metallic junction. The second thing is the development of an exact approach to optimize the sensitivity of the sensor in accordance to a particular range of emitted energy. And finally the third thing is the creation of an appropriate filter for the energy range and packaging.

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VII. REFERENCES

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[3] (A, Jacquot , Figure-Of-Merit And Emissivity Measurement OF Fine Grain Polycrystalline Silicon Thin Film.)