A silicon membrane has been etched, behind which an enclosed volume of gas has been confined. The other side of the membrane contains two diffused resistors, one of which is heated with a pulsating current, which causes thermal expansion. Expansion forces bring the membrane in vibration, which is sensed with the second diffused resistor. The pressure exerted by the gas is proportional to the absolute temperature, and is measured as a change in resonance frequency. The frequency is controlled by a phase locked loop system, which follows the resonance frequency. A high resolution has been achieved.
Graduation report

A RESONANT MEMBRANE ABSOLUTE TEMPERATURE GAS THERMOMETER
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INTRODUCTION

In February 2007 I had a discussion with Prof. J.G. Smits about an existing temperature sensor. This sensor was suitable to measure temperature at a high resolution. The size was to the detriment of this sensor, in which we could do research to make this sensor with Microsystems Technology. We could use the same working principles of this sensor: a resonating membrane with confine gas beneath. The project incorporates: designing a micro sensor, producing a prototype and writing an article about this sensor.

To graduate with this project, it was necessary to involve knowledge out of the major-course Mechatronics and minor-course Microsystems Technology. The project takes place at the Microsystems Technology laboratory at the Hogeschool Zeeland.
With thanks to:

Prof. J.G. Smits

Ir. D.O. Heineke

J. Pleijte
1. PLAN OF APPROACH

1.1 Overview
This project incorporates as final goals: microsensor design, prototype microsensor and an article about the sensor. First is started with the design, hereafter the prototype production an article will follow as a parallel goal.

For the microchip design process it is necessary to make up from an existing design, a micro design. Anticipation on problems in micro scale is needed where applicable.

The microsensor has to measure in high resolution. A sensor which can measure in is resolution, is already available (prototype), but is large in dimensions. It is desirable to scale this sensor into micro scale, which has more benefits for mass production and more reliable measurements.

1.2 Problem definition
There is need of a micro-temperature sensor which can measure temperatures of self-heating processes such as chemical- and biological processes. The requirements of the sensor are:

- Dimensions: ± 1 cm²
- Temperature resolution: 0,1 – 1 mK
- Inexpensive and simple mass fabrication suitable measure device

1.3 Organization and information

Initiator of the project/Supervisor: Dhr P. de Boevere / Prof. J.G. Smits
Examinor: Ir. D.O. Heineke
Laboratory support: Dhr. J.J. Pleijte
Graduation candidate: Dhr. S. Plouvier

Prof. J.G. Smits and Ir. D.O. Heineke will supervise and examine the project, where Prof. Smits will supervise the microchip production and Ir. Heineke supervises the measurement setup. J.J. Pleijte will provide assistance in the laboratory when needed.
1.4 Agreements

As final result a graduation report must be hand in June 2007.

When etching with dangerous chemicals such as hydrogenfluorid (HF) assistance is required. It is prohibited to etch without assistance.

1.5 Phase and planning

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<td>5</td>
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<td>2-5-2007</td>
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<td>Mask production Delta Mask</td>
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<tr>
<td>Prototype production</td>
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<td>20-6-2007</td>
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</tbody>
</table>

**Documents**

| Graduation Report              | 8-3-2007 | 8-6-2007  |
| Article                        | 8-3-2007 | 22-4-2007 |

Contact information:

Prof. J.G. Smits: smits.123@12move.nl
Ir. D.O. Heineke: dheinek@hz.nl
J.J. Pleijte: jpleijt@hz.nl
S. Plouvier: sebastaan@plouvier.nl
2. STRUCTURE OF THE SENSOR

2.1 Silicon wafers

Chips are made on a thin layer of silicon. Thin discs of silicon are called wafers, whereon chips can be produced. Silicon as itself does not conduct electrical energy very well, therefore the generic term semiconductor is used. By applying specific chemical bonds, a well conduction can be achieved. Hence it is possible to make electrical components such as resistors, transistors etc.

Silicon wafers are produced by making a large cylinder of silicon and sawing this into thin slices. Hereafter the discs are polished to give them an equal surface and are ready for production purposes.

![Silicon Cylinders and Wafers](image1)

After the producing the chip on the silicon wafer it is mostly common to protect it with a cover and make it suitable to connect with other electrical devices (back-end processing). Moldings for the dies are called packages.

![Various Silicon Chips Applied in Packages (Back End)](image2)
2.2 Working principle of the sensor

On a silicon wafer two resistors are placed. One of the resistor is used to heat up the surface of the silicon membrane (heater). The other resistor is used to measure the alteration of the membrane (gauge). Beneath the membrane an enclosed volume of gas is confined. The temperature of this gas depends on the environment in which the sensor exist.

When the heater is activated by use of electrical current, the surface of the membrane heats up in which it will expand. Because of the static place of the membrane, it will deform (see figure 3 and 4). The most deformation will occur when the membrane is resonating in the frequency equal to the natural frequency. This natural frequency is inherent to the temperature of the enclosed gas beneath the membrane.

As the temperature varies, the natural frequency of the membrane will alter. This alteration can be measured by the gauge resistor. (by following the maximal amplitude, caused by the natural frequency)

By a calculation the temperature can be derived from the measured frequency.

![FIGURE 3: SCHEMATIC OVERVIEW (TOPVIEW)](image)

![FIGURE 4: CROSS-SECTION VIEW IN UN- AND HEATED STATE](image)
The gauge resistor will measure a delta in the resistance. When the membrane is heated, the resistor in the first quarter of the membrane, will be compressed. Hence it will compress the resistor on top of the membrane. This results in an alteration in resistance, which is depended of the phase of the pulse.

FIGURE 5: COMPRESSION OF THE RESISTOR ON THE MEMBRANE
2.3 Calculation of temperature

The temperature is a function of the measured frequency and pressure. This can be calculated by using a formula which shows the related pressure dependence of the resonant frequency of the membrane. Exact calculation for a square membrane is not possible, therefore we can use a formula which can calculate exact pressure dependence of resonant frequencies for a circular membrane. This formula is a reliable approach for calculation.

Noticed must be that the resonant frequency of a square membrane is slightly higher than with a circular membrane, though the sensitivity of a square membrane is lower than with a circular membrane.

Circular membrane formula:

\[
f = \frac{10.33h}{2\pi a^2} \sqrt{\frac{E}{\rho} \left(1 + 0.054 \frac{a}{h} \left(\frac{p}{E}\right)^2\right)}
\]

**EQ. 1**

- \(a\) = the radius of the membrane
- \(h\) = the thickness of the membrane
- \(E\) = the Young’s modulus
- \(\rho\) = specific density
- \(p\) = pressure in Torr (mmHg)

The first four variables are expressed in SI units.

**FIGURE 6: PRESSURE DEPENDENCY OF RESONANT FREQCUENY [1]**

\(E\) is in this case the elasticity modulus of silicon.

\[
E_{\text{silicon}} = \frac{1}{7.5 \cdot 10^{-12}} = 1.33 \cdot 10^{11} \, N/m^2
\]

Where \(\rho\) is the specific density of silicon:

\[
\rho_{\text{silicon}} = 2330 \, kg/m^3
\]
Pressure of the gas:

This value is dynamic, because it is related to the temperature. Using the law of Boyle – Gay Lusac, we can calculate the temperature out of the pressure. Though a conversion of Torr to Pascal is needed.

\( R \) is the gas constant

8.314472 m\(^3\) \cdot Pa \cdot K^{-1} \cdot mol^{-1} this is derived from \( n \times k \) [3]

\( V \) is the volume of the gas

The dimensions of the membrane cavity are

\[ a = 0.001 \text{ m} \]
\[ h = 0.00001 \text{ m} \]

Conversions

Boyle – Gay Lusac [3]:

\[ p \cdot V = n \cdot k \cdot T \]

EQ. 2

The values in the formula of figure 6 are expressed in SI, though the value of \( p \) is expressed in mmHg. A conversion to SI unit is needed, so we can replace \( p \) by:

\[ \frac{n \cdot k \cdot T}{V} \]

EQ. 3

1 mm Hg = 101.325/760 Pa ≈ 133,322 Pa [2]
To convert the \( p \) from Torr to Pa, we have to multiply \( p \) with:

\[
\frac{1}{133}
\]

\text{EQ. 4}

A conversion factor is also needed for the Boyle – Gay Lusac formula (eq. 2) Under normal temperature and pressure the number of particles in the cavity is:

\[ n = 5 \times 10^{16} \]

With the given volume and the number of particles we can convert equation 2 into:

\[ p = 460T \]

\text{EQ. 5}

Using the known material constants and dimension, we can substitute the equations 4 and 5 in equation 1 to obtain:

\[ f = 124160\sqrt{1 + 3.475 \times 10^{-7}T^2} \]

\text{EQ. 6}

This equation (eq. 6) represents the start frequency with its alteration related to the temperature. Also see attachment: “Derivation formula”
Simulation with a temperature range from 0 to 373 Kelvin gives the theoretical frequencies related to the temperature:

\[ f = 124160 \left( 1 + 3.475 \times 10^{-7} T^2 \right) \]

**FIGURE 7: NATURAL RESONATING FREQUENCY RELATED TO TEMPERATURE**
2.4 Measurement setup

For measurement, a phase locked loop system is chosen. A PLL is a closed-loop feedback control system that generates and outputs a signal in relation to the frequency and phase of an input signal. In this case the measurement of the gauge resistor is used for the input signal. The output signal will follow the reference signal, whereby the resonance frequency of the membrane will be followed constantly. An interface will measure the frequency of the membrane through the gauge resistor. An EX-OR port will compare the measured frequency, phase and the control frequency to the membrane. The difference between those frequencies is constantly adjusted so that it always will follow the frequency that causes the most amplitude alteration (= resonance frequency). Translating the measured frequency at that time with the formula will result in temperature value at that time.

![PLL Diagram](image1)

![Gauge Frequency in Relation to Heater Pulse](image2)
The PLL is made with the Philips HEF4046B. This chip contains all the necessary elements to set up the PLL we want to use.

![Diagram of HEF4046B PLL](image)

**FIGURE 10: HEF4046B [5]**

Minimal requirements for the PLL are predefined:

- Detection range: 110kHz – 140kHz
- Bandwidth: 100Hz
- Center frequency: 125kHz

Consulting the datasheet of the HEF4046 we find the following values for C1, R1 and R2 of the VCO (see HEF4046 datasheet attachment):

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1.5nF</td>
</tr>
<tr>
<td>R1</td>
<td>10kΩ</td>
</tr>
<tr>
<td>R2</td>
<td>12kΩ</td>
</tr>
</tbody>
</table>

Then we have to calculate the resistor and capacitor values for the low-pass filter to determine the minimal and maximal frequency where the frequency can be followed and locked.

\[
k_o = \frac{2\pi \cdot (140-110)}{10} = 18.9\]

\[
k_d = \frac{10}{\pi} = 3.18\]

\[
f_c = 2 \cdot 30 \cdot 10^3 = 6 \cdot 10^4\]
B = 200Hz and $\xi = 0.7$

\[ \omega_n = 2\pi \cdot 200 = 1256.62 \]

\[
\tau_c = \frac{1}{f_c} = \frac{1}{6 \cdot 10^5} = 1.67 \cdot 10^{-5} = 16.7\mu s
\]

\[
\tau_2 = \frac{2\xi - \tau_c}{\omega_n} = \frac{2 \cdot 0.7 - 16.7\mu s}{1256.62} = 1.1ms
\]

\[
\tau_3 = \frac{1}{\omega_n^2 \cdot \tau_c} = \frac{6 \cdot 10^4}{1256.62^2} = 38ms
\]

\[
\tau_1 = \tau_3 - \tau_2 = 37ms
\]

If we choose for $C_{1_{lpf}} = 1\mu F$ then for $R_{1_{lpf}}$ and $R_{2_{lpf}}$ of the low-pass filter we get:

\[
R_{1_{lpf}} = \frac{37}{1} = 37k\Omega = 39k\Omega
\]

\[
R_{2_{lpf}} = \frac{1.1}{1} = 1.1k\Omega = 1k\Omega
\]

After setting up the phase-locked-loop, the minimal and maximal detection region were not satisfactory.

Looking at the equation of the bandwidth (eq. 6), we find that we have to narrow the bandwidth by changing the value for R2.

\[
(A\omega_b) = \frac{1}{\tau_c} \sqrt{2\pi \cdot m \cdot (F_o = 1)}
\]

**EQ. 7 [6]**
By doubling the value of \( R_2 \) \((2k2\Omega)\), we measured the following properties for the PLL.

Detection range: \(94,4 - 177,4\)kHz

Lock range: \(118,7 - 151,9\)kHz

The transfer function of the low-pass filter is:

\[
F_s = \frac{u_c}{u_d} = \frac{R_2 + \frac{1}{sC_i}}{R_1 + R_2 + \frac{1}{sC_i}} = \frac{1 + sR_2C_1}{1 + s(R_1 + R_2)C_1} = \frac{1 + s\tau_2}{1 + s\tau_3}
\]

EQ. 8

The transfer function for the PLL in general is:

\[
H_s = \frac{F_s}{F_s + s \cdot \tau_c}
\]

EQ. 9

Combining those equations (eq. 8 and 9) we get the overall transfer function:

\[
H_s = \frac{1 + s\tau_2}{1 + s\tau_3 + s\tau_c} = \frac{1 + s\tau_2}{1 + s\tau_2 + (1 + s\tau_3)s\tau_c} = \frac{1 + s\tau_2}{\tau_c\tau_3s^2 + (\tau_c + \tau_2)s + 1}
\]

EQ. 10

Because the value for \( R_2 \) is changed, \( \xi \) and bandwidth are also changed. \( T_2 \) gets a new value: \( C_1 \) is still \( 1\)mF so then \( T_2 = 2,2\)msec.

This range is more than enough to follow the altering resonance frequency of the membrane. The following figures illustrates the detection range and the detection of the start frequency of the membrane. At this frequency \((124\)kHz\)) the phase difference is about \(85\) degrees, which is almost around the centre frequency of the PLL. The lock range of this PLL system is \((152-119)\) \(33\)kHz, this is enough to follow the \(3500\)Hz difference between 0 to 373 Kelvin.
FIGURE 12: MAX FREQUENCY DETECTION RANGE - 172KHZ

FIGURE 13: MIN FREQUENCY DETECTION RANGE - 94KHZ

FIGURE 14: ABOUT 90 DEGREES OUT OF PHASE AT STARTFREQUENCY OF MEMBRANE
If we measure the control voltage of the VCO, a linear function can be found. From 1.30V at 94kHZ to 8.35V at 172kHz.

![FIGURE 15: VOLTAGE OF VCO CONTROL FOR 94 TO 172KHZ](image)

For start frequency of the membrane, the VCO is controlled with a voltage of about 4.20 volts.

The properties of the PLL are measured and verified with the pre-calculated values:

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection range</td>
<td>110 – 140kHz</td>
<td>94 – 177kHz</td>
</tr>
<tr>
<td>Lock range</td>
<td>-</td>
<td>119 – 152kHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>200</td>
<td>84kHz</td>
</tr>
<tr>
<td>Center frequency</td>
<td>125kHz</td>
<td>133kHz</td>
</tr>
</tbody>
</table>

*To measure the frequency of the membrane, an interface should be designed. By lack of time, this is not done yet. Though at chapter “Recommendations” a suggestion is done.
3. MAKING THE DESIGN OF THE CHIP

3.1 Requirements

The design has to include the following requirements:

- Heater resistor
- Gauge resistor
- Membrane
- Bonds for resistors
- Bonds for connection to the silicon itself
- Testing resistor

The dimension of the membrane should be 2x2 millimeters and 10 microns thick. The heater and gauge should be placed on top of the membrane, whilst the bonding pads for the backend are located outside the membrane to let it resonate freely.

3.2 The design

The design is made out of five different layers. Each layer has its specific function in the production process. A distinction is made of:

- Front-To-Back alignment (yellow)
- Diffusion (for heater and gauge resistor) (red)
- Metal (blue)
- Via windows (for interconnection between the diffusion and metal) (green)
- Membrane etch (cyan)

These layers are printed separately onto a plate of glass. This is called a mask, which is the inverted print of the layer in monochrome.

![Diagram of the complete design](image)

**FIGURE 16: OVERVIEW COMPLETE DESIGN**
3.3 Front to Back Alignment

While we have different layers, we have to align them compared to each other. The initial layer will be used to align the subsequent layers. (diffusion, metal and via windows) The layer is placed on the top of the wafer. A mirrored copy will be used on the other side of the wafer, to align the membrane etch layer.

FIGURE 17: FRONT TO BACK LAYER (TOP PLACEMENT)

FIGURE 18: FRONT TO BACK LAYER (FLIPPED / BOTTOM PLACEMENT)
3.4 Diffusion layer

The diffusion layer is constructed to apply the heater and the gauge resistor onto the silicon wafer. The diffusion layer is aligned against the front-to-back layer. Both resistors will have the same inductance, while the heater is placed towards the first quarter of the membrane and the gauge on the last quarter. Noticed that when the resistor is spread on the half membrane’s surface, less alteration can be detected. While we have a compression on the resistor in the quarter, we will have an expansion in the second quarter, which together nullify the alteration. So therefore the resistor is placed only in a quarter of the membrane in the beginning of the edge.

FIGURE 19: DIFFUSION ALIGNED ONTO FRONT-TO-BACK LAYER
3.5 Via windows layer

For conduction between the metal layer and the diffusion layer, via windows are made. Without via windows, the conductivity between the aluminum and resistors would be too low.

FIGURE 20: VIA WINDOWS (GREEN)
3.6 Metal layer

To connect wiring onto the silicon, metal bonding pads must be placed. The metal connect with the via windows with the diffusion in which electrical conduction will be achieved. The bonding places are for attachment of the wiring because directly wiring to the resistor is not possible.

FIGURE 21: METAL LAYER (BLUE)
3.7 Membrane etching layer

For construction of the membrane out of the thicker silicon wafer, silicon has to be removed to obtain a thin membrane. This is achieved by etching silicon via the surface at the downside of the wafer. This process is called: Backside etch.

![Removal of partial silicon constructs membrane](image1)

**FIGURE 22: REMOVAL OF PARTIAL SILICON (ORANGE) CONSTRUCTS MEMBRANE**

![Membrane layer aligned onto front-to-back](image2)

**FIGURE 23: MEMBRANE LAYER ALIGNED ONTO FRONT-TO-BACK (FLIPPED)**
4. PROTOTYPE PRODUCTION

4.1 Application of the Front-To-Back layer

We use a double polished wafer, which has on both sides an equal surface. To etch the Front-to-back alignment, we need a layer of silicon oxide. The wafer is placed into a special oven which heats the wafer up to 1050˚C. A mixture of oxygen gas and water vapor is blown into the oven. The silicon wafer reacts with the oxygen to silicon oxide:

Endothermic reaction: \( \text{Si} + \text{O}_2 \rightarrow \text{SiO}_2 \)

After several hours there is about 0,40 microns of silicon oxide on the silicon wafer.

Then photoresist is applied onto the wafer’s surface. First the wafer is placed into an oven with an temperature of 200˚C for about 30 minutes, to remove moisture. Hereafter the wafer is placed into a spinner, which rotates with 5000rpm for 30 seconds. First a primer is applied, then the photoresist. By spinning the thickness of the photoresist layer is set. The wafer is placed into an oven at 105˚C for 15 minutes. This is intent to dry the photoresist. Then the other side of the wafer is applied with photoresist and placed in the oven to dry. Now the wafer is equipped with photoresist on both sides.

When the photoresist is brought in contact to UV radiation, places that are contacted will dissolve in the developer. If the wafer is exposed to UV radiation via the front-to-back mask, the wafer contains areas of photoresist that will and not will dissolve into the developer solution. Exposure of UV radiation is made by the mask-aligner.

After the exposure of the bottom and top side with UV via the front-to-back masks, the wafer will be developed. This process takes up to one minute in developer and three minutes rinsing in demi-water. Hereafter the wafer will be checked on quality under a microscope. The wafer the can be etched if the photoresist that was intended to dissolve, is dissolved far enough.

The remaining photoresist protects the wafer against the strong acid HF, where the wafer is etched in. Depending on the thickness of the layer silicon oxide, the wafer is etched for one to two minutes in HF. What remain is the wafer with silicon oxide (which was protected against HF) and silicon (which was not protected). The print of the front-to-back is viewable as silicon and the surroundings as silicon oxide.
4.2 Application of the diffusion layer

After the etching of the front-to-back print, the wafers are oxidized again in the oven. The wafer is held for one hour at 1050°C with a mixture of oxygen and water vapor. The wafer is surrounded with SiO₂ but with a difference in thickness between the front-to-back etch and the rest of the wafer.

With the mask-aligner the wafer is exposed to UV radiation through the resistor mask. After developing we have a print with resistors which are not protected against HF. The surroundings though, are protected by not dissolved photoresist.

Etching for 2 minutes in HF, gives a clean silicon surface in the resistor print. After cleaning the photoresist with acetone, alcohol and demi-water, the wafer is placed to dry in the desorb oven at 200°C. Hereafter Boron-mixture is applied on the wafer in the spinner, and spinned at 5000rpm for 30 seconds.

Then the wafer is placed in the oxidation oven to dry the boron film for 10 minutes at 300°C. Hereafter at 1050°C the wafer is baked with a lot of nitrogen gas for 1 hour and afterwards 2-3 hours with a mixture of water vapor and oxygen. After this process the boron is bonded with silicon to electrical conductive resistors. On top a thick layer of silicon oxide is grown, to protect the wafer and resistors.

![FIGURE 24: WAFER WITH RESISTORS](image-url)
4.3 Application of the etch mask

Both sides of the wafer are applied with photoresist. The etch mask is applied to the backside of the wafer. The membranes are visible as gray blocks of silicon. The thickness of silicon is now about 360 microns. The thickness of the membrane must be 10 microns in the end. To reduce the thickness of the membrane, 350 microns of silicon have to be etched away.

![Diagram of silicon and silicon oxide](image)

**FIGURE 25: SILICON AREA (PINK COLORED) HAS TO BE ETCHED TO GET A THICKNESS OF 10 MICRONS**

Etching will be done, using a solution of TMAH (Tetramethylammonium hydroxide). TMAH is a strong base that is commonly used for silicon etching. Silicon oxide is here a protective layer against the TMAH, while the bare silicon will be etched. The etching process is very slow at low temperatures. To speed up the etch rate, the temperature of the solution has to be around 60 to 90 degrees Celsius. It takes almost a day to etch the membranes.

After etching the wafers a very fragile, which is a difficulty for the further processing steps. We choose to split up the etching process into two steps. In the first step, the wafer will be etched to a depth of 150 microns. Afterwards the wafer will be applied with via windows and metal pads. At last the remaining depth is etched.

![Wafer with etched cavities](image)

**FIGURE 26: BOTTOM SIDE WAFER WITH ETCHED CAVITIES**
4.4 Application of the via windows and metal pads

On the resistor side of the wafer, a layer of silicon oxide covers up the resistors. Tiny holes have to be made through the silicon oxide, to reach the resistors contact points. The wafer will be spun again with photoresist and aligned with the via windows mask. Etching in HF will result in tiny holes at the contact points.

Then in a vacuum-chamber aluminum is brought on to the wafer. Photoresist is brought on again and exposed to UV radiation via the metal-layer mask. Etching in a sulfide, results in a wafer with paths of aluminum from the wirebond path to the resistor.

The chips are now electronically functional when connected to a pulsating voltage source.

![Figure 27: Wafer with Resistors and Metal Paths](image)
4.5 Bonding glass plate and wafer

To enclose the gas under the membrane, the wafer is placed on a soda-lime glass plate. The wafer and the glass plate have to bond very tight to ensure that there are no gas leaks. Epoxy or other adhesives are not recommended. It makes that there is more space between the wafer and glass plate, which results in an increase of volume of gas under the membrane. A better solution to bond is by anodic bonding [4].

![FIGURE 28: SETUP FOR ANODIC BONDING](image)

The silicon wafer and the glass plate are placed onto each other. They are surrounded by two chucks of brass alloy. All is placed onto a hotplate to heat up to about 400 degrees Celsius. When the temperature is reached, an high electrical voltage is applied. The voltage is about 300 volts. The combination of heat and electrical energy results in a bonding between the silicon wafer and the glass plate. This bond is strong enough to maintain the pressure of the gas under the membrane. The pressure under the membrane will increase when the gas is heated and oppositely.
4.6 Wire bonding and packaging

The wafer has reached its completion stadium. Now the bare dies have to be separated from each other before they can be placed in a package.

A machine can cut the wafer into pieces where after the dies can be placed into a package. In this project a package is not yet developed. A concept design is done though.

When the die is placed into the package, connection from the die to the terminal are needed. These are done by wire bonding with aluminum or gold wire. On a small piece of PCB the die is placed and wired to in- and output pins.

![Figure 29: Package with pins and wire bonds](image)

<table>
<thead>
<tr>
<th>Pin</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pulse +</td>
</tr>
<tr>
<td>2</td>
<td>GND</td>
</tr>
<tr>
<td>3</td>
<td>Gauge</td>
</tr>
<tr>
<td></td>
<td>GND</td>
</tr>
<tr>
<td>4</td>
<td>Gauge</td>
</tr>
<tr>
<td></td>
<td>Input (DC)</td>
</tr>
</tbody>
</table>
The design for the package is conceptual, only to get an idea how the chip could be placed into a package while not losing its functionality.

The chip will be placed into a plastic molding. An opening for the membrane is made, so that the membrane can resonance freely. Wire bonds and pins are protected by the plastic against chemicals, mechanical damage and moisture. Because of the depth of the resonating membrane, it is more protected against mechanical damage, than if the membrane was placed equal to the surface of the package.

Completely covering of the membrane is not recommended. The membrane would have on both sides pressures by confined gasses. This would lead to another characteristic than where the sensor is designed for.

FIGURE 30: THERMOSENSOR PACKAGE CONCEPT
5. CONCLUSIONS

The sensor is not fully developed, as it is only in prototype function. The timeline to develop the entire sensor, was too short. I reached the stadium that the bare die is developed. Measuring and calibrating as one of the prominent things, are not fully deployed as a lack of time.

The masks we made at the laboratory were not satisfactory because of the precision between the mutual masks. Therefore the masks were made externally with computer aided systems and laser printing. At a project which contains only one mask, the “self-made” masks are good, but when several masks are needed you have to make them with professional equipment.

The measurement setup is also not fully deployed. Connecting the gauge resistor directly to the HEF4046 controller cannot be done. An interface which translates the alternating resistance of the gauge resistor to a frequency must also be designed and implemented.

The resolution of the thermosensor is dependent of the resolution where the frequency is measured with. The higher the resolution of the frequency measurement, the higher resolution of the temperature calculation.

There still several other problems I had to deal with in the laboratory. Such as the fragility of the wafers while etching, dust particles that damage the photoresist as a protective film against HF etc. The yield would be much higher if the prototype is made with automated machinery, but this would be too expensive for a project like this.

The Phase-Locked-Loop design was successful, the controller follows the resonance frequency as it should. The pre-calculated values differ from the measured values because of the narrow detection area we wanted, nevertheless the PLL is completely usable.

To get the sensor fully working, still a package and an interface are required.
6. RECOMMENDATIONS

For further developments for the thermosensor I would make some recommendations:

Wafer:

- Make sure that you make enough wafers, because of the very low yield.
- The last step before bonding the wafer on glass, is etching. Etching makes the wafer very fragile that it may break in the succeeding steps.
- Etching the wafer with aluminum pads can only be done if you protect the side with the aluminum. Placing the wafer on a protective glass plate with silicone rubber is not recommended. When you want to separate the wafer again the wafer will break when you cut it loose. Covering the wafer with “flintwax” is more advisable. You can remove the flintwax using acetone, which will require less force than cutting it loose out of silicone rubber.
- When you have etched the wafer it may not stick (enough) to the spinner. You can place the wafer on plastic film. Cut the remaining foil away and place the wafer on a small plastic dish with small cavities at the edge (they are available at the laboratory). The dish will stick to the spinner when opening the vacuum valve. Make sure that the acceleration of the spinner is not too high. About 1000rpm/s².
- Etching in TMAH with a high temperature (>60 degrees Celsius) gives a uneven surface on the membrane. Etch longer with a lower temperature but also make sure that the stirrer is stirring fast enough.
- Always use fresh photo-developer. When the developer is more than one day old, it will lose its effect.
- The mask for aluminum metal pads, is wrong for its purpose. For all the masks it is needed to make a copy of the original before you can use it. (the original masks are the inverse of what you need. While copying you get a functional mask). Use the original mask for the aluminum in mirror image. Otherwise you will etch the aluminum away, that just had to be the remaining aluminum.

Control System:

- For interfacing the alternating resistance of the gauge: the output signal of the resistor will not be a clean sinus signal. Probably it will look more like and e-power equation (see fig. 9) as it is not yet proven. A monostable multivibrator could convert the measured wave to a new pulsating signal which could be interpret by the EX-OR port of the HEF4046.
- An interface made with software like Simulink, could translate the measured frequency of the monostable multivibrator to temperature values.
7. EVALUATION OF THE PROJECT

I think this was one of the most complex and time consuming projects I ever did at Hogeschool Zeeland, though it was very interesting and instructive. I have learned a lot more about physics and control systems.

The production of the prototype was very time consuming, but I knew that before. There are many steps to follow before you have a prototype. When one step fails, you may have to start all over. It has overcome me a few times. It is not good for your moral, but I just continued because I wanted to get it finished.

The prototype is not finished, but I ended up with it very far. If I had more time (about a month or 3) than it maybe was fully finished and working with the controlling system attached to it.

I also learned a new concept in controlling systems: a phase locked loops. I never had classes about this subject, but I think it can be very useful for different applications. It was great that Mr. Heineke spent some of his time to learn me the principles of a PLL system.

I think that working on this project with more students would be more recommendable because sometimes you can do it all alone. Etching with HF also requires that there is minimal 1 person to help, but also for other purposes it is more handy to be with more persons than yourself.

In overall it was a very good experience to learn to plan and work on a difficult project, learning how to divide your time on parts of the project and their respective priorities.

It was pleasant to bring up solutions to common problems, like etching, spinning and alignment problems. Also when Mr Smits, Heineke and I were calculating at the formula for the resonance of the membrane, it was nice to see that three persons were desperate to get the formula right. Eventually we came out of it and it was nice to remark that many persons are interested in this project and wanted to help me.

It was too bad that I didn’t had more time to write more for the article, but I think that is just one of the consequences of this project when working alone and in just 4,5 months. Though I think that without making a prototype first, you cannot defend your article fully. You discover a lot of new things when making the prototype and sometimes you have to adjust certain statements. You cannot do that afterwards if you want to publish your article.

Overall it was a pleasant project and have learned a lot. I am very grateful for the help of Mr Smits, Mr. Pleijte and Mr. Heineke, without them I came not as far as I did now.
8. REFERENCES


9. ATTACHMENTS:

- Production guideline for a thermosensor
- HEF4046B Datasheet
- Derivation formula “Frequency Dependence on Temperature Of A Resonating Gas Thermometer”
- Logbook