TALLINN UNIVERSITY OF TECHNOLOGY
School of Information Technologies

Kalle Hakonen 240905IABB

PRESSURE-TOLERANT ELECTRONICS: THEORY, APPLICATIONS, AND IMPACT

Bachelor's Thesis

Supervisor: Jussi Aaltonen
Doctor of Science (Technology)

Co-supervisor: Gunnar Piho
Doctoral

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Kalle Hakonen 240905IABB

RÕHUKINDLAD ELEKTROONIKASEADMED: TEOORIA, RAKENDUSED, JA MÕJU

Bakalaureusetöö

Juhendaja: Jussi Aaltonen
Doctor of Science (Technology)
Kaasjuhendaja: Gunnar Piho
Doctoral

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Author’s Declaration of Originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

Author: Kalle Hakonen

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Abstract

This thesis presents a novel, low-cost pressure sensor. Firstly, methods for evaluating the pressure resistance of standard electronic components were explored. Following this, a compact and concise summary of basic components and their maximum tested pressures is presented, a collection that, to the best of the author's knowledge, has not been previously compiled in the literature. Then, the sensor was developed based on the knowledge acquired. Development included physical sensors, laboratory verification, software interface, and consideration of economic, environmental, and social impact.

Parts of this thesis, described in chapter 4, have been published by the author on Proc. of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME 2023) 19-20 July 2023, Tenerife, Canary Islands, Spain. [1]

The influence of manufacturing materials on pressure resistance was examined by observing dimensional changes. Traditional stress and elasticity calculation methods were employed, with initial values chosen based on compression and modulus of elasticity due to their availability and the target pressure. This approach allowed certain material pairs that showed significant changes in electrical parameters due to stress to be ruled out.A simple FEM analysis was used to compare the differences between ideal and conventional shapes under pressure. A $4\,\mathrm{mm}^3$ steel-walled container was analyzed to understand the role of shape in the durability of gas-filled objects. It was observed that even minor geometric changes can significantly affect pressure resistance.

Various parameters were examined to study the changes in the electrical properties of materials under pressure. The thermal diffusion coefficient's influence on operation was found to be insignificant. The change in resistance can be calculated for components when the material's gauge factor is known. However, calculations indicate that resistance may change too much for the circuit's operation in more precise measurements. It was found that pressure affects capacitance, but the necessary initial data to calculate the change was not found. Nonetheless, it was observed that capacitance increases while dielectric breakdown resistance decreases under pressure.

It was found that pressure affects the operation of semiconductors, but simple methods for assessing operation were not found. Similarly, the effect on inductance was generally found to be insignificant. An increase in the stiffness of quartz crystal under pressure was observed, increasing its natural resonance frequency. However, insufficient information was found to estimate the magnitude of this phenomenon in practice.

Various publications were searched for mentions of component pressure resistance. While the information was limited, combining different sources helped identify component types that function under pressure. Actual maximum pressures could not be determined, but resistors, coils, and semiconductors were the most pressure-resistant. Among component groups, capacitors and crystals showed the most variation in pressure resistance within their groups, necessitating a more detailed examination of the component under investigation.

A novel pressure sensor, named *Puuhai*, was developed based on the knowledge gathered from the literature. *Puuhai* was found to be low-cost and easy to manufacture industrially and in a simple workshop environment. The concept of an affordable smart sensor is also presented, complete with a sequence diagram and a sample program utilizing the MQTT API.

Results suggest that it is possible to operate even complex electronic devices under pressure, although this may require precision in design. Many standard components were found to be pressure-resistant, and it is possible to manufacture a somewhat pressure-resistant device accidentally, even without specific intent. From an economic perspective, significant cost savings in the production and maintenance of underwater devices and hydraulic systems, as well as in civil engineering applications, could be achieved by using more affordable and readily available components in pressurized environments.

The *Puuhai* sensor represents a thoughtful advancement in pressure sensing technology. Designed with cost-effectiveness in mind, *Puuhai* could potentially offer savings for both industrial and workshop settings. Sustainability was considered in its design and manufacturing process. The affordability and accessibility of the *Puuhai* sensor could make this technology more widely available, opening up new possibilities for a broader range of people.

The thesis is written in English and is 53 pages long, including 7 chapters, 15 figures and 6 tables.

Annotatsioon

Rõhukindlad elektroonikaseadmed: teooria, rakendused, ja Mõju

Käesolevas lõputöös kavandatakse ja hinnatakse uudset, madala maksumusega rõhuandurit. Kõigepealt analüüsitakse standardsete elektroonikakomponentide rõhutaluvuse hindamise meetodeid. Sellele järgneb kompaktne ja lühike kokkuvõte rõhuanduri põhikomponentidest ja nende maksimaalselt testitud rõhkudest, mida autori teadmiste kohaselt ei ole varem kirjanduses publitseeritud. Edasi selgitatakse uudsetel põhimõtetel toimiva rõhuanduri arendamist, läbiviidud laboratoorseid katseid, tarkvaraliidest ning hinnatakse võimalikke majanduslikke, keskkonna ja sotsiaalseid mõjusid.

Osa peatükis 4 kirjeldatud tulemustest, on autor avaldanud rahvusvahelisel konverentsil Proc. of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME 2023) 19.-20. juuli 2023, Tenerife, Kanaari saared, Hispaania [1].

Tootmismaterjalide mõju rõhutaluvusele uuriti mõõtmete muutuste jälgimise teel. Kasutati traditsioonilisi pinge- ja elastsuse arvutusmeetodeid, valides algväärtused kokkusurumise ja elastsuse põhjal vastavalt kättesaadavusele ja sihtsurvele. Selline lähenemine võimaldas välistada teatud materjalipaare, mis näitasid märkimisväärseid elektriliste parameetrite muutusi pingete tõttu. Survetaluvuse erinevusi ideaalsete ja tavapäraste kujude vahel võrreldi lihtsa FEM-analüüsiga. $4\,\mathrm{mm}^3$ terasega vooderdatud konteinerit analüüsiti gaasiga täidetud objektide vastupidavuse mõistmiseks. Täheldati, et isegi väikesed geomeetrilised muutused võivad oluliselt mõjutada survetugevust.

Uuriti erinevaid parameetreid, et mõista materjalide elektriliste omaduste muutusi surve all. Leiti, et termiline difusioonikoefitsient ei oma töö käigule olulist mõju. Takistuse muutust saab komponentide puhul arvutada, kui materjali venitusfaktor on teada. Siiski näitavad arvutused, et takistus võib täpsemates mõõtmistes liiga palju muutuda, mõjutades seeläbi ahela toimimist. Avastati, et surve mõjutab mahtuvust, kuid muutuse arvutamiseks vajalikud algandmed puudusid. Sellele vaatamata täheldati, et mahtuvus suureneb, samal ajal kui dielektrilise läbimurde takistus väheneb surve all.

Leiti, et rõhk mõjutab mahtuvust, kuid vajalikud lähteandmed muutuse arvutamiseks ei leitud. Siiski täheldati, et rõhu all suureneb mahtuvus, samal ajal kui dielektriline läbilöögikindlus väheneb. Leiti, et rõhk mõjutab pooljuhtide töötamist, kuid lihtsaid meetodeid töö hindamiseks ei leitud. Samamoodi leiti, et mõju induktiivsusele on üldiselt ebaoluline. Täheldati ka kvartskristalli jäikuse suurenemist rõhu, mis suurendab loomulikku resonantssagedust. Siiski ei leitud piisavalt teavet selle nähtuse ulatuse praktikas hindamiseks.

Erinevatest allikatest otsiti komponentide rõhutaluvusega seonduvat. Kuigi leitud publikatsioonide arv oli piiratud, aitas erinevate allikate kombinatsioon tuvastada komponentide tüüpe, mis taluvad rõhku. Tegelikke maksimaalseid rõhke määrata siiski ei saanud, kuid kõige rõhutaluvamaks osutusid takistid, mähised ja pooljuhid. Komponentide gruppide seas näitasid mahtuvused ja kristallid oma rühmade sees kõige rohkem varieeruvust rõhutaluvuses, mis nõuab edasist põhjalikumat uurimist. Leiti, et surve mõjutab pooljuhtide tööd, kuid lihtsaid meetodeid selle hindamiseks ei leitud. Samamoodi leiti, et induktiivsusele avaldatav mõju oli üldiselt ebaoluline. Surve all täheldati kvartsikristalli jäikuse suurenemist, mis suurendas selle loomulikku resonantsisagedust. Siiski ei leitud piisavalt infot selle nähtuse praktilise ulatuse hindamiseks.

Kirjandusest kogutud teadmiste põhjal arendati välja uudne surveandur nimega *Puuhai*. *Puuhai* osutus odavaks ja lihtsasti toodetavaks ning valmistatavaks ka lihtsas töökoja keskkonnas. Lisaks esitatakse taskukohase nutika anduri kontseptsioon koos jadagraafiku ja MQTT API-d kasutava näidisprogrammiga. Tulemused viitavad sellele, et isegi keerukate elektroonikaseadmete kasutamine surve all on võimalik, kuigi selleks võib vaja minna eridisaini. Samas osutusid paljud standardkomponendid survekindlaks ning seeläbi võib saavutada suhteliselt survekindla seadme ka juhuslikult, isegi eridisainita.

Majanduslikult võimaldab survetingimustes odavate ja kättesaadavate komponentide kasutamine kokkuhoidu tsiviilehituslike veealuste seadmete ja hüdraulikasüsteemide juures. *Puuhai* anduri näol on tegemist läbimõeldud surveandurite tehnoloogia disainiga, mille kavandamisel arvestati jätkusuutlikkusega, anduri taskukohasuse ning kättesaadavusega et pakkuda potentsiaalset säästu nii tööstus- kui ka töökojakeskkondades tootmisel.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 53 leheküljel, 7 peatükki, 15 joonist, 6 tabelit.

List of Abbreviations and Terms

API	Application Programming Interface
CRM	Critical Raw Material
CRMA	Critical Raw Materials Act
EU	European Union
FEM	Finite Element Method
HPC	High Performance Computing
IoT	Internet of Things
JSON	Javascript Object Notation
M2M	Machine-to-Machine
MQTT	Message Queuing Telemetry Transport
PdM	Predictive Maintenance
SCC	Supply Chain Cost
SMD	Surface-Mount Device
WAN	Wide Area Network
WLAN	Wireless Local Area Network

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1. Introduction

As electronics advance, their applications become increasingly diverse, leading to a growing dependence on them in various processes and hardware, even below the water's surface. From offshore oil drilling [2] to salvaging sunken vessels [3], exploring submerged mines [4], and transporting drinking water through expansive tunnels [5], the need for smarter, smaller, and more cost-effective electronics becomes apparent.

When electronic devices and components require operation under higher pressures, the common practice is to enclose them to ensure the pressure remains manageable. However, as the external pressure increases, for example, to $30\,\mathrm{MPa}$, the required enclosure space grows significantly, necessitating thicker walls and increasing both weight and cost. In addition, it contributes to higher usage of raw materials. Another approach is to use pressure-resistant devices, often housed in lightweight oil-filled enclosures. Despite the availability of suitable dielectric oils, such pressure-resistant systems are considerably more expensive, sometimes costing a hundred times more than their standard counterparts designed for normal pressure.

For instance, while a media converter facilitating the transition of Ethernet traffic from copper wire to fiber optic may cost around 3000€ with a seven-week delivery time, a similar device offering equivalent functionality is available for just 20€ in an Estonian store, with immediate dispatch. This study seeks to develop methods for assessing the pressure resistance of common standard components, recognizing the limited availability of such information and the challenges manufacturers face in assisting with evaluations. The use of components submerged in dielectric oil is a proven method that simplifies the assessment process. This method is particularly effective when the initial focus is on the mechanical properties of manufacturing materials, thereby accelerating the evaluation.

In addition to cost-effectiveness, prioritizing sustainable construction methods for underwater machines is essential. By optimizing material use and minimizing environmental impact, these methods ensure efficient resource utilization while promoting responsible care of underwater ecosystems. This sustainability aspect is vital for the long-term viability of underwater technologies and underscores the importance of environmentally conscious technological advancements.

1.1 Research Questions

This leads us to the following research questions:

1. What physical properties of electric components change under varying hydrostatic pressure?
2. What electric properties of electric components change under varying hydrostatic pressure?
3. What are the potential applications of that knowledge?
4. Does any of these potential applications make any economic, environmental, or social impact?

1.2 Methodology

The methodology for this thesis is divided into two main parts: a literature review and lab testing. The combination of literature review and lab testing allows for a thorough and balanced exploration of the pressure tolerance of electric components. The literature review provides the theoretical context and broader implications, while the lab testing provides practical, real-world evidence. This methodology ensures that the findings of this thesis are both theoretically sound and practically relevant and that they consider the broader economic, environmental, and social context.

1.2.1 Literature Review

The first part of the methodology involves conducting a comprehensive literature review, detailed in Chapters 2 and 3. This entails examining and analyzing a wide range of sources related to the pressure tolerance of electric components. The sources include, to name a few, academic articles, technical reports, and industry standards.

The aim of the literature review is not only to gain a deep understanding of the current state of knowledge in the field and identify gaps in the existing research but also to understand the broader implications of current knowledge. This includes a review of the literature on the economic, environmental, and social impacts of making advanced technology more affordable and accessible.

The economic impact analysis will assess the potential cost savings, as well as the potential for job creation and economic growth associated with these technologies. The environmental impact analysis will consider the possible benefits and challenges these technologies pose to sustainable practices and environmental conservation. The social impact analysis will explore how these technologies affect society, with a particular emphasis on developing regions, and it will include aspects such as education and quality of life.

1.2.2 Laboratory Testing

The second part of the methodology involves lab testing. This is the practical component of the research where the theories and concepts identified in the literature review are put to the test. The lab testing involves using specific electronic components and subjecting them to different pressure conditions. The performance and behavior of these components under these conditions are then observed and recorded. The data collected from these tests are analyzed to draw conclusions about the pressure tolerance of the components.

1.3 Structure of the Thesis

This thesis is structured to understand various aspects of the study comprehensively, and each chapter is designed to explore different elements of the research in detail. The thesis is logically divided into three main parts: the first part includes Chapters 2 and 3, presenting the literature review; the second part, encompassing Chapters 4 and 5, focuses on the practical implementation of the research; and the third part, represented by Chapter 6, evaluates the economic, environmental, and social impacts of the proposed technology.

In Chapter 2, we delve into physical properties. This chapter investigates the transformations that physical properties undergo under pressure, providing a foundation for the subsequent chapters.

Chapter 3 presents an in-depth exploration of the behavior of common electric components under pressure. The knowledge shared in this chapter is crucial for understanding the practical applications of these components in real-world scenarios. Chapter 2 as well as Chapter 3 are based on the author's previous work [6].

Moving forward, Chapter 4 presents the innovation based on the knowledge presented in the preceding chapters. This chapter, an extension of a conference publication by the author [1], explores the theoretical and practical implications of the innovation.

Chapter 5 describes an example program for a microcontroller unit and its wireless application programming interface. This chapter bridges the gap between theory, prototype, and practice, enabling the knowledge gained in the previous chapters to be applied.

Chapter 6 assesses low-cost advanced technology's economic, environmental, and social impact. This chapter provides a holistic view of these technologies' implications, considering their cost-effectiveness and impact on society and the environment.

Chapter 7 summarizes the work, encapsulating the key findings and methodologies employed, and presents possible future work.

2. Pressure Resistance

Substances change their properties as pressure varies [7]. In addition to causing deformation, pressure also induces changes in electric properties [8]. Evaluating the effect of pressure on different materials involves considering several variables. This study concentrates on variables that influence both the electric parameters of the component and the properties of existing components. The pressure range studied begins at atmospheric pressure, which is $101\,\mathrm{kPa}$. The chosen target pressure aligns with the deepest point in the oceans, the Challenger Deep, where the pressure at the bottom reaches approximately $110\,\mathrm{MPa}$ [9]. With safety considerations in mind, the upper limit of the pressure range for this study is at $150\,\mathrm{MPa}$.

2.1 Pressure Resistance of Materials

In a fluid, pressure acts uniformly on a submerged object. When the object under inspection is a homogeneous material, the pressure resistance can be evaluated using the material's bulk modulus. The bulk modulus can be calculated using the following formula [7, p. 374-375]:

$$K = \frac{\Delta p}{\Delta V / V_0} \tag{2.1}$$

where Δp is the change in pressure, ΔV is the change in volume, and V_0 is the initial volume. A value of $0.2\,\%$ change in length is common in assessing metals. Corresponding volume change is calculated using that value.

$$\Delta V = -(1 - 0.002)^3 + 1 = 0.006 \tag{2.2}$$

With the initial volume V_0 being 1, the formula is simplified to:

$$\Delta p = 0.006K \tag{2.3}$$

Here, Δp is the maximum useful pressure for the material under investigation. Since bulk modulus are available in tabulated form, the maximum pressure can be calculated within the chosen limits of volume change. Table 1 lists values calculated for some materials.

Table 1. Compressions coefficient [10, p. 365] [11] and calculated maximum pressure.

Material	**Compression coefficient K (GPa)**	**Maximum pressure (MPa)**
Steel	160	960
Copper	140	840
Glass	31	186
Lead	7.7	46.2
Silicon	97.8	586.8
Aluminum	70	420

Using the compression coefficient to assess the suitability of electronic components under pressure is not precisely defined, and therefore, calculating exact values is not meaningful. Additionally, often, only the material's elastic modulus is tabulated. However, the compression coefficient K can often be estimated using the elastic modulus E, such that for metals, ceramics, and glasses,

$$K = E \tag{2.4}$$

for polymers and elastomers [12, p. 8]

$$K = 10E \tag{2.5}$$

Table 2. Young's modulus [10, p. 365] [11] [13, p. 186] and calculated bulk modulus and maximum pressure.

Material	**Young's modulus** E **(GPa)**	**Bulk modulus** $K_{\textbf{estimated}}$ (GPa)	**Maximum pressure (MPa)**
Steel	200	200	1200
Copper	110	110	660
Glass	55	55	330
Lead	15	15	90
Silicon	130	130	780
Aluminum	70	70	420
Epoxy + fiberglass	175	> 175	> 1050

Table 2 shows the results obtained using Cardarelli's compression coefficient estimation. Estimation reveals the most significant error occurring with lead. As a result of the error, lead appears to be suitable at pressures twice as high as estimated with a more precisely defined compression coefficient. However, due to the inherently imprecise nature of the evaluation method, this level of accuracy is still helpful for rapid assessments, especially when the tabulated compression coefficient is unavailable. Using equation 2.5 allows, for example, the estimation of the compression coefficient of FR-4 printed circuit board laminate made of epoxy and glass fiber.

This estimation method does not provide certainty about the suitability of the component at pressures higher than the original target environment. However, it is possible to eliminate materials with substantial volume changes at the target pressure through examination. Notably, the elastic modulus of some synthetic materials changes by several orders of magnitude due to temperature effects in the range of $0\,^{\circ}\mathrm{C}$ to $100\,^{\circ}\mathrm{C}$. It is also advisable to investigate material pairs whose dimensions behave differently further.

The selection of a $0.2\,\%$ change in length as an influence on electric properties is not based on research that was not found but only on established practice in strength calculations. It is possible to find a better reference value related to the electric properties of components. However, it is out of the scope of this study.

2.2 Pressure Resistance of Structures

The shape of components also affects their resistance to pressure. If the object is not made solely of one material and encloses a more compressible material or a gas space, the stress caused by pressure is applied to the inner surface of the outer shell [14].

The effect of shape on the durability of a body containing a gas space was examined using Solidworks Simulation software. For comparison, two models were simulated. For both bodies, the internal volume was defined as $4\,\mathrm{mm}^3$ with a wall thickness of $0.3\,\mathrm{mm}$. EN 1.4404, or stainless steel, was chosen as the material for the analysis.

As expected, according to Figure 1, stresses are evenly distributed on the sphere. With a safety factor of about 2 at its minimum, however, few components are perfect spheres.

The calculation was performed with the body in the following simulation, as shown in Figure 2. In order to achieve a safety factor of approximately 2, the external pressure was reduced from $30.3\,\mathrm{MPa}$ to $20.2\,\mathrm{MPa}$ by trying different values. The cube's edges were rounded heavily to get closer to the real-world situation. Contrary to expectations, not all walls reacted to the pressure in the simulation in the same way. The reason was suspected to be the asymmetry of the element mesh imposed by the simulation software.

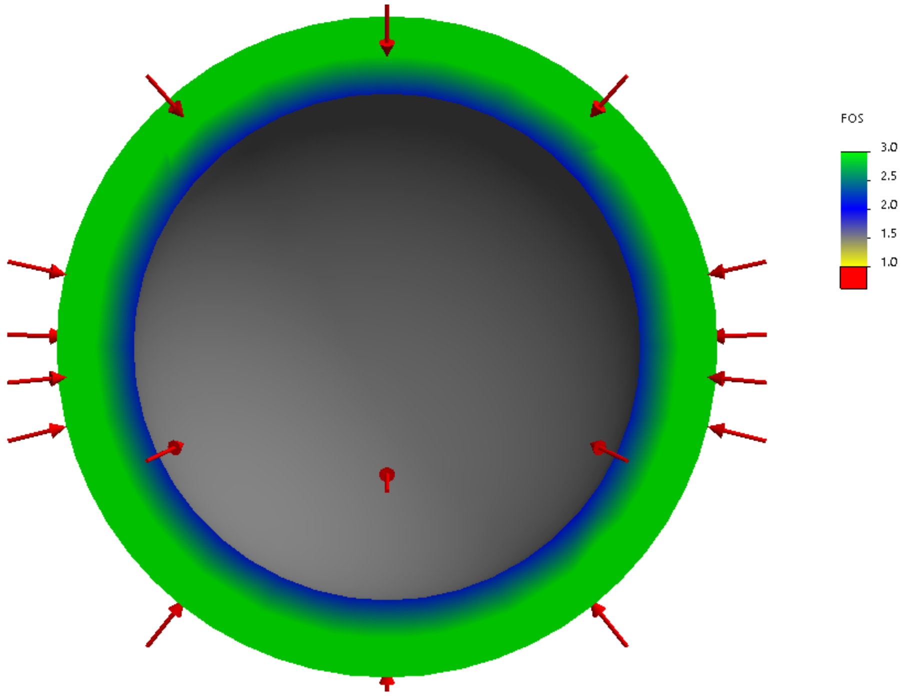

Figure 1. According to the von Mises stresses, the safety factors of the spherical body at 30.03 MPa.

Shape-based assessment can help select more pressure-resistant and electronically equivalent components. However, this is only relevant for components with gas spaces.

2.3 Impact of Pressure on Electric Properties

The impact of pressure on the electric properties of a component is based on both the material properties and changes in structural dimensions. Pressure alters at least the thermal conductivity properties of the material [15, p. 105] as well as the resistivity [16, p. 35]. For copper, the change in thermal diffusivity at the selected pressure of 150 MPa is approximately $1\,\%$. The change is small and positive, so it is unlikely to have significance for the pressure resistance of the component. The change in resistance can be estimated using the change in dimensions and the material's resistivity constant, GF:

$$GF = \frac{\Delta R/R}{\Delta l/l} \tag{2.6}$$

Where R is resistance and l is length [17, p. 284]. The previously chosen $0.2\,\%$ for maximum allowable length change is used as the mechanical durability limit, and assuming GF is known, the formula can be expressed as:

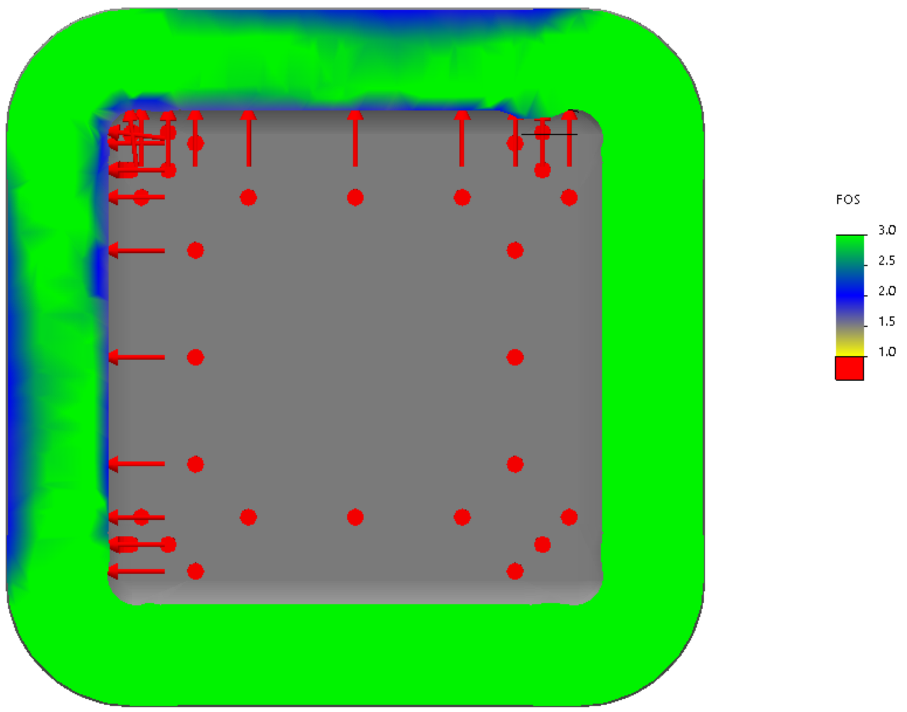

Figure 2. According to the von Mises stresses, the safety factors of the cubic body at 20.2 MPa.

$$\Delta R = \frac{2\,GF\;R}{100} \tag{2.7}$$

This approach allows us to calculate the change in resistance under the pressure limit imposed by mechanical durability. It is also possible to calculate the maximum length change when the maximum allowable resistance change is known:

$$\frac{\Delta l}{l} = \frac{\Delta R/R}{GF} \tag{2.8}$$

Table 3 shows some typical gauge factors for strain gauges. When manufacturing strain gauges, the goal is to linearize the gauge factor over the intended range so they can be considered a safe choice when assessing pressure resistance.

Table 3. Typical gauge factors. [17]

Material	**GF**
Thin film resistor	2-5
Thick film resistor	5-20
Semiconductor	50

The maximum operating pressure can be solved once the maximum allowable resistance change is known. For example, consider the resistance of a copper thick-film resistor. The largest gauge factor value is selected from Table 3 and a resistance change limit of $0.2\,\%$ is chosen. The values are then inserted into 2.8,

$$\frac{\Delta l}{l} = \frac{0.002}{20} = 0.01\% \tag{2.9}$$

It is yielding the length change limited by resistance.

From Table 1, the maximum operating pressure with a $0.2\,\%$ deformation was determined to be $840\,\mathrm{MPa}$. Now we can calculate the operating pressure limited by resistance change:

$$p_{\text{max}} = 840MPa\frac{0.01\%}{0.2\%} = 42MPa \tag{2.10}$$

The surface area of the terminals determines the capacitance of a capacitor, the distance between them, and the dielectric permittivity, as in Equation 2.11 [18, p. 73].

$$C = \frac{\epsilon A}{d} \tag{2.11}$$

As external pressure increases, the terminals move closer to each other. Movement leads to an increase in capacitance and a decrease in voltage endurance. In this case, the insulation properties between the terminals are important. For many materials, the relative permittivity increases as pressure increases, which also increases capacitance. However, this is only the case for some materials [19][20]. Calculating the change requires determining the insulation's compression coefficient and understanding the change in permittivity under pressure. No tabulated data on the change in permittivity for solid materials was found. Therefore, options to determine the capacitance change include either ignoring the change in permittivity or investigating the direction and magnitude of the change.

A coil consists of an electric conductor between two terminals. Pressure affects the resistance of metals slightly and thus influences the operation of the coil. If necessary, the change in inductance can be estimated from the changes in the conductor's dimensions. A pressure of $150\,\mathrm{MPa}$ on copper causes a $0.04\,\%$ change in length, which usually has a negligible effect on inductance. The three-dimensional shape of the coil is also essential in determining inductance. If the conducting material is attached to the component's frame, changes in the frame's dimensions may cause significant variation compared to the nominal value. On the other hand, the change may also be insignificantly small.

For some semiconductors, increasing pressure increases resistivity and decreases permittivity [20]. However, assessing semiconductor physics is too complex for this evaluation. It would also require more precise information about the structures and their doping. In practice, one must rely on measured changes in performance.

Using crystal in electronics is based on the series resonance characteristic frequency, where its impedance approaches zero [18, p. 518-519]. Figure 3 shows the Van Dyke equivalent circuit recommended by standard EN 50324-2 [21].

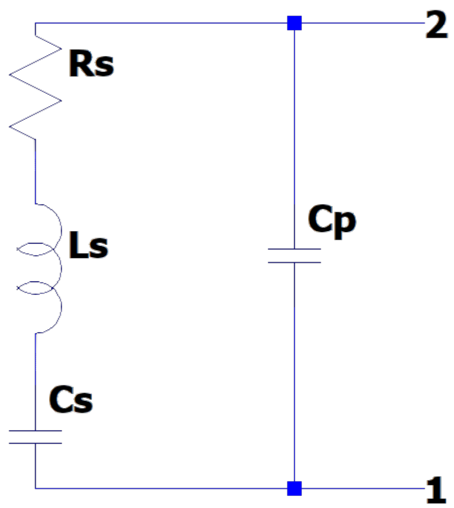

Figure 3. Van Dyke equivalent circuit.

Since resistance decreases under pressure, inductance remains the same, and capacitance increases, we can estimate the direction and magnitude of the change. The series resonance frequency can be calculated using Equation 2.12:

$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}} \tag{2.12}$$

Based on this, the frequency decreases when C_s increases, contrary to experimental measurements [22]. Therefore, the Van Dyke circuit is not applicable for assessing pressure endurance. However, the parameters C_s and L_s in the model are not determined like individual components but based on the physical behavior of the crystal. The stiffness of the crystal increases with pressure, causing C_s to decrease, which does not contradict the measurements [23]. A model that better considers mechanical properties might be useful in assessing crystals [24][25].

3. Pressure Resistance of Basic Electronic Components

Essential components of electronics are resistors, capacitors, and inductors. In 2024, many devices also contain semiconductors, some of which require a clock signal generated often by a crystal oscillator. This section discusses the suitability of these components outside their intended pressure range. The analysis focuses on the most common types of components in use.

3.1 Resistor

The letter R denotes a resistor in circuit diagrams, and while it is not the only one, it is the most common component. There is inconsistency in the literature regarding materials associated with film resistors. Thick film and metal glaze resistors are both film resistors, but the manufacturing method differs. Even manufacturers use terms interchangeably on the same datasheet, so confirming the specific manufacturing method of the component under study may be difficult. Figure 4 shows the structure of a thick film resistor. The resistance of SMD thick film resistors changes less under pressure than through-hole mass resistors [26]. According to Zimmermann and Grumann, the pressure endurance of mass resistors is at least $100\,\mathrm{MPa}$, and that of thick film resistors is $500\,\mathrm{MPa}$.

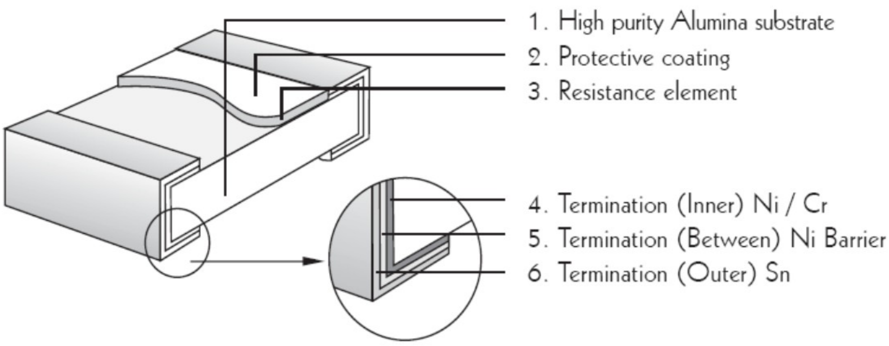

Figure 4. Thick film resistor. [27]

In writings on pressure-resistant electronics, reference is often made to a review published by the US Department of Commerce in 1976. Over the past 50 years, changes in manufacturing techniques for components have occurred, so it is essential to interpret the results presented in the review with caution due to potential inconsistencies. Zimmermann and Grumann suggest that mass resistors react to pressure 25 times more than film resistors. By extrapolating the graph presented in the review, the ratio is approximately 30 when comparing mass resistors to film or wire resistors [28, p. 14-15]. The change in film resistors under $100\,\mathrm{MPa}$ pressure is less than $1\,\%$. The ratios are close to each other, and the values are similar. Based on this, the measurements from the review of resistors are practical for evaluation. Based on previously mentioned sources, film and wire resistors are suitable for use up to $150\,\mathrm{MPa}$ pressure. Mass resistors are also usable if a significant change in resistance does not disturb the device's operation. It is also worth noting that resistance decreases under pressure.

3.2 Capacitor

A capacitor is denoted by the letter C in circuit diagrams. In terms of pressure resistance, capacitors can be divided into three groups. These groups are categorized into dry airless, wet electrolyte, and air-filled capacitors.

Dry airless capacitors are the most pressure-resistant due to their structure. Ceramic capacitors and dry tantalum capacitors are functional up to at least $70\,\mathrm{MPa}$ pressure [28, p. 19]. Pressure resistance exceeds $110\,\mathrm{MPa}$ for these types. Bingham does not provide precise measurements but mentions parts of the Deepsea Challenger in the figure [29]. The Deepsea Challenger dove to a depth of $11\,\mathrm{km}$ [30]. Niobium capacitors have similar structures [31, p. 408]. Injection-molded plastic film capacitors can be airless or air-filled, which directly affects their pressure resistance [29]. Airless ones can withstand pressures of at least $30\,\mathrm{MPa}$ [32]. Capacitors made of ceramic, polystyrene, and polyester have proven usable within pressure ranges of $30\,\mathrm{MPa}$ to $34\,\mathrm{MPa}$ [33, 34].

Electrolytic capacitors are considered to have poor pressure resistance [29, 34]. According to Bingham, a typical aluminum electrolytic capacitor also contains air, significantly weakening its pressure resistance. Barnes and Gennari present the variable reaction of tantalum electrolytic capacitors to pressure. Occasionally, there are even exceedances of up to $20\,\%$ of the measurement range at $70\,\mathrm{MPa}$ pressure. This result is surprising when considering the structure of this capacitor type.

Figure 5 shows no chambers other than solid materials and liquid. If the principal diagram could be enlarged, chambers left in the sintered tantalum core where the electrolyte fluid has not reached would be observed. Newer measurements were not found. These chambers and the electrolyte fluid's properties may explain the measurements. Since the study's publication, manufacturing techniques have also changed, and newer capacitors may allow for pressurized use.

Due to their structure, air-filled capacitors do not withstand high pressures well. However, their use can be considered case-by-case when the surrounding pressure is slightly higher

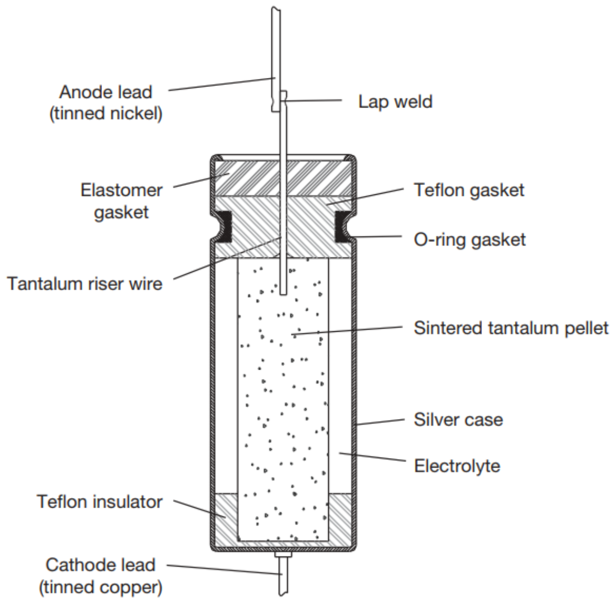

Figure 5. Tantalum electrolytic capacitor. [35, p. 2]

than 101 kPa. Air-filled capacitors include aluminum electrolytic capacitors and some plastic film capacitors. The structure of an aluminum electrolytic capacitor is not gas-tight, but it does not allow unobstructed pressure equalization [31].

3.3 Coil

An inductor is denoted by the letter C and consists of two plates between terminals. There are various ways to encapsulate it. A transformer can also be considered as two or more coils enclosed together. The possible support structures and coil casing may be the only limiting factor. Durability has also been observed practically at 30 MPa pressure [34, 36]. Due to the simplicity of the basic structure, a properly implemented coil will likely function at 150 MPa pressure.

3.4 Semiconductor

Semiconductor resistance is more sensitive to pressure changes compared to conductors [37]. Examining the epoxy housing of a typical semiconductor component suggests that the pressure applied to the semiconductor itself is lower than its surroundings. Observations under pressure 30 MPa revealed no significant changes in the operation of IGBT and diode modules [32]. A complete circuit, consisting of a microcontroller, epoxy-encapsulated diodes, and a motor control circuit, has been repeatedly exposed to 34 MPa pressure successfully [33]. Experiments at 30 MPa pressure were also successful [34]. Forty years ago, an LED component was repeatedly exposed to pressures exceeding 13 MPa without significant changes in operation [38]. The tested LED was housed in a metal casing, the structure of which did not provide sufficient information to assess its impact on the pressure resistance of the semiconductor. Recent experiments at $20\,\mathrm{MPa}$ confirm the LED's pressure resistance [39]. The highest reported pressure is presented in an article where power LEDs manufactured by Cree are reported to operate at $137\,\mathrm{MPa}$ pressure [40]. Generally, pressures up to $98\,\mathrm{MPa}$ cause insignificant changes in semiconductor operation [41].

However, there is generally limited information about the structure of components to assess the disturbances caused by pressure. The varying manufacturing techniques of large circuits also make general assessment difficult [42]. Sometimes, the mechanical structure of a three-dimensional microcircuit used is too complex for simple evaluation [43]. Evaluation is also complicated by differences between manufacturers and product lines, where components of the same type can be manufactured in many different ways [44]. On the other hand, Figure 6 illustrates an example of a SOT-23-packaged transistor with a simple structure. This package type does not contain air space, so that the operation can be assessed based on its electronic properties [44].

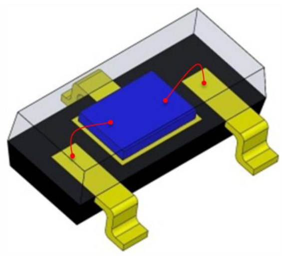

Figure 6. Internal structure of SOT-23 package. [45]

A metallic heat conductor is sometimes installed on the surface of a silicon chip [45]. Implementing the heat conductor can significantly reduce pressure resistance, as shown in Figure 7. The heat conductor is at the top of Figure 7, with the silicon chip in the middle, surrounded by void space.

For manufacturing reasons, some heat conductors are equipped with holes [46]. In this case, the pressure equalizes inside the casing, and the casing does not restrict pressure resistance. The chip and the heat conductor can also be encapsulated so that there is no gas space in the final product [45, p. 94].

Semiconductors are encapsulated in various materials, including plastic, metal, glass, and ceramics [45, p. 133]. In this case, the casing usually contains air space, which inherently weakens the pressure resistance but may not hinder functionality [47]. A standard ceramic IC package has been found unsuitable for pressures of $207\,\mathrm{MPa}$ [48].

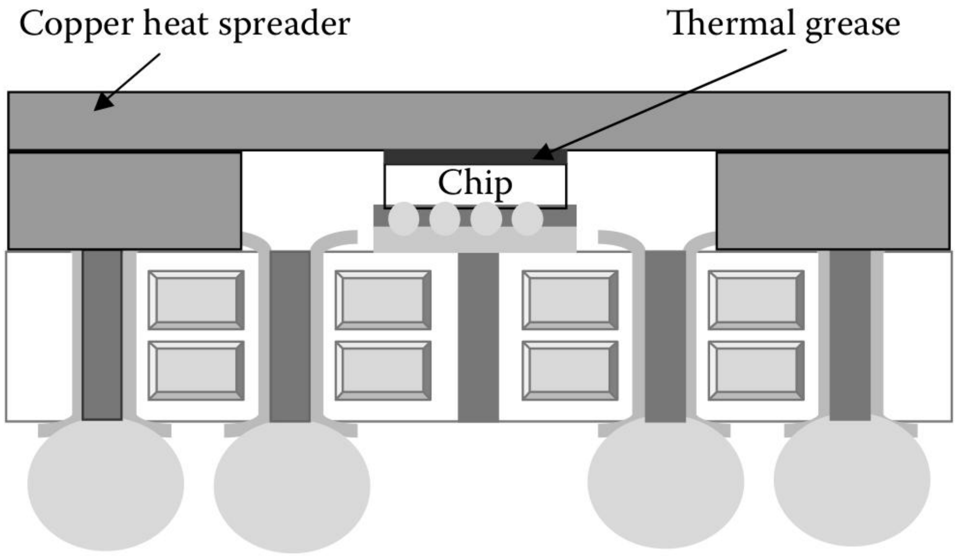

Figure 7. A microchip is enclosed in a BGA package with surrounding gas space. [45, p. 105]

In practice, mechanical encapsulation of the component typically causes semiconductor malfunctions rather than the semiconductor's failure under pressure.

3.5 Oscillator

As the oscillator's oscillator, a piezoelectric crystal can be used [18, p. 518]. The crystal is not always hermetically sealed, which can cause problems in oil [49]. A metal-encased crystal is often excluded from pressure tests based on assumed durability [33]. Figure 8 shows a metal-encased oscillator cut open, revealing ample air space in the casing. However, both metal-cased and metal-lidded crystals have repeatedly functioned at pressures of $2\,\mathrm{MPa}$ [50]. Information about the types of enclosures for the crystals was evaluated based on vague photographs on the manufacturer's website [51]. Oscillators encapsulated in ceramics and metal have been found to function at $60\,\mathrm{MPa}$, where only the signal is attenuated even though the casing lid has collapsed [47]. Attenuated signals prevent the operation of several circuits. The article does not present attenuation as a function of pressure, so there is no way to assess the limiting pressure. Figure 4 illustrates the behavior of several oscillators under pressure.

In the same article, no change in frequency was observed. However, the signal from the Aker oscillator was attenuated by $37\,\%$ when an increase in frequency would have been expected [22, 53]. The frequency change of other oscillators was not presented. Kampmann et al. did not describe the measurement setup. The surprising results regarding the frequency change warrant careful consideration of the measurements. The micro-

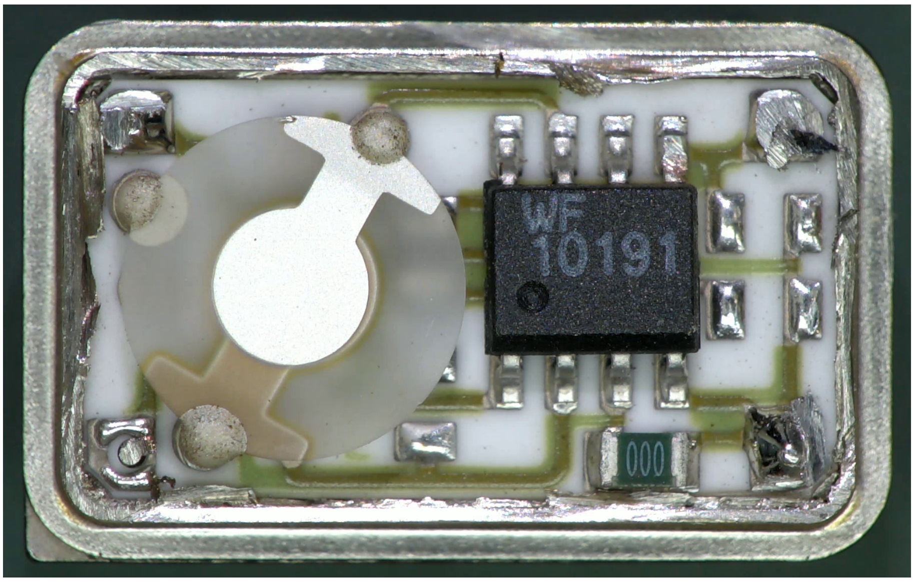

Figure 8. The metal-cased oscillator is displayed with its internal structure exposed, revealing internal voids. [52]

electromechanical resonator and semiconductor oscillator mentioned in the article were attenuated by less than $20\,\%$, indicating they are functional.

The oscillator's oscillator can also be a piezoelectric ceramic resonator. It is solid in structure and operates at least up to $34\,\mathrm{MPa}$ [33]. Like the quartz crystal, its resonance frequency likely reacts to pressure changes as the resonator stiffens, although no test results were found.

Table 4. Signal strength comparison among various oscillators under 60 MPa pressure conditions.[47]

Oscillator	**Frequency [MHz]**	**Type**	**Package Type**	**Remaining signal at** $60\,\mathrm{MPa}$ **[%]**
Epson Toyocom SG-310SCF	20.00	Quartz	Plastic	5
Fox Xpress0	20.00	Quartz	Kovar	30
Aker 23305-20.000-X	20.00	Quartz	Metal and Ceramics	62
Epson Toyocom SG-9001LB	20.00	QMEMS	Plastic	63
SiTime SIT8002AI-13-33E-20.00000T	20.00	MEMS	Plastic	84
Maxim DS1077U-100+	100.00	Solid-State	Plastic	88

Micro-electromechanical oscillators are a new but rapidly growing alternative to more traditional vibrators [54, 55]. The required free space for the vibrator is small, so the stresses on the casing do not transfer to the element as easily as with larger elements. Besides those by Kampmann et al. [47], no pressure resistance measurements were found. Kyocera Tikitin Oy currently manufactures small MEMS resonators, with the maximum length of the resonator element being $300\,\mu m$. One of the company's founders, Aarne Oja, estimates that when manufactured in a suitable casing, pressures of several hundred atmospheres are possible [56].

3.6 Maximum Tested Pressure of Different Components

This section provides a concise and compact summary of basic components and their maximum tested pressures, a collection that, to the best of the author's knowledge, has not been previously compiled in the literature.

Building on this, Table 5 details the measurement results of different component groups analyzed in this study. Components are categorized by group to facilitate evaluation. It is important to acknowledge, however, that within each group, variations in pressure resistance are likely, with some components performing better and others worse.

Table 5. Highest pressures tested under which the components functioned.

Component	Tested pressure (MPa)	Source
Capacitor, Air-free polyester	34	[33]
Capacitor, Air-free polystyrene	30	[34]
Capacitor, Aluminum electrolytic	0.1	[29, 34]
Capacitor, Ceramic	70	[28]
Capacitor, Dry tantalum	70	[28]
Capacitor, Dry tantalum	110	[29]
Capacitor, Wet tantalum	0.1	[28]
Ceramic resonator	34	[33]
Coil	30	[34, 36]
Crystal, Metal-cased	2	[50]
Crystal, Metal-can	2	[50]
Diode	34	[33]
IGBT	30	[32]
Microcontroller	34	[33]
Oscillator, MEMS	60	[47]
Oscillator, Semiconductor	60	[47]
Power LED	137	[40]
Resistor, Film	100	[26]
Resistor, Thick film	500	[26]
Resistor, Wirewound	70	[28]

4. Practical Application

This chapter 4 builds upon the work by the author that has been published on Proc. of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME 2023) 19-20 July 2023, Tenerife, Canary Islands, Spain. [1]

Drawing upon existing literature, a theoretical model was constructed to assess the pressure coefficient of resistance in the context of a thick film resistor. This model served as a fundamental tool in engineering an innovative pressure sensor. Rigorous testing was conducted in both simulated environments and real-world laboratory conditions to ensure the reliability and accuracy of both the model and the newly developed sensor.

The theories and tests described in this chapter formed the basis of our findings, which were subsequently published in a reputable conference. The results from these tests provided strong evidence that the model accurately predicts the pressure coefficient of resistance for the thick film resistor. Furthermore, the pressure sensor, developed based on this model, demonstrated high performance and reliability in detecting and measuring pressure changes.

Therefore, it can be confidently stated that the model and the sensor have met the intended performance expectations. These findings, published in the conference publication, open up new opportunities for advancements in pressure-sensing technology.

4.1 Introduction to Practical Problem

Pressure sensors in hydraulic and sub-sea systems often present as hefty and intricate electromechanical structures. This chapter outlines some of the existing solutions to this challenge. Drawing from the literature, a model was developed to calculate the pressure coefficient for thin and thick film resistors. This newly proposed formula has been successfully tested with readily available commercial components within a pressure chamber. Finally, this chapter introduces a novel, cost-efficient design for an absolute pressure sensor.

4.2 Current Pressure Sensing Solutions

Pressure sensors, also known as pressure transducers, pressure transmitters, or pressure indicators, are integral components in a wide range of applications, including hydraulic systems and sub-sea installations. These devices operate by quantifying the force exerted per unit area by gases or liquids, subsequently producing an output signal that can be harnessed for monitoring and control purposes.

The majority of contemporary pressure sensor components are architected around the concept of mechanical deformations. This could involve a moving diaphragm, a distorted Bourdon tube, or a bending optical fiber, which are generally regarded as conventional pressure-sensing solutions. The manufacturing of these devices necessitates specialized facilities, such as clean rooms, to uphold accuracy and prevent contamination.

This is achievable for sensors that utilize an absolute reference when a known pressure reference is integrated into the structure. The reference force can be incorporated into the sensor using a vacuum chamber, while a gas-filled chamber or a mechanical spring can provide the required known constant pressure. A generic example of this structure is illustrated in Fig. 9.

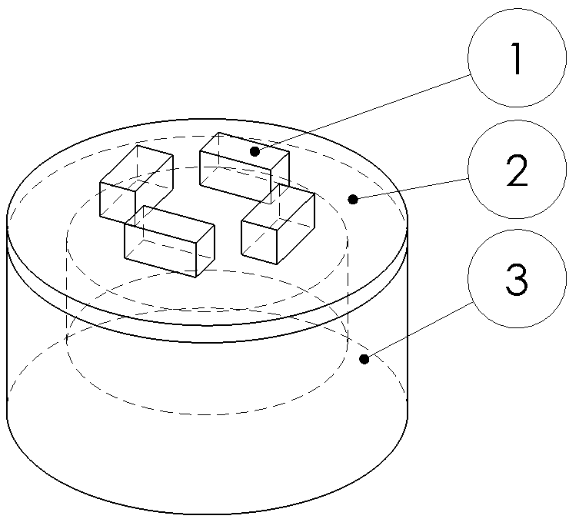

Figure 9. Typical pressure sensor construction. 1: Sensing components, 2: Diaphragm, 3: Pressure reference chamber.

Moreover, conventional devices often employ strain gauges that are resistors affixed to the diaphragm surface. The deformation of the diaphragm surface causes these strain gauge resistors to stretch and compress, subsequently altering the resistance that can be detected. Resistors can also be directly fabricated on the membrane surface as a thin or thick film layer. Semiconductor-based solutions leverage the piezoresistive effect, which manifests as a change in resistance. Piezo elements can also be utilized in pressure measurement through their distinct vibration frequency, which alters as a function of the pressure.

In addition, capacitors, which consist of two moving plates separated by a dielectric medium, can also be used in pressure measurement. The capacitance changes as a function of the applied pressure: the distance between the plates reduces due to increased pressure. This capacitance change can be utilized in a resonator circuit, so the change in pressure corresponds to the change in frequency. These changes alter the capacitor's impedance, and thus, it can be used as a resistor when excitation is performed with an alternating current.

It is crucial to distinguish between pressure gauges and pressure sensors. Pressure gauges offer an immediate reading of a specific pressure value, known as gauge pressure. On the other hand, pressure sensors produce a signal output that is proportional to the pressure measurement. This signal must initially undergo conditioning and processing to transform the signal output level into a calibrated pressure reading.

4.3 Recent Advances in Pressure Sensing Methods

Many studies centered on pressure measurement can be found in the literature. These studies introduce innovative methods and diverse sensor technologies, including piezoresistivity, carbon nanotubes, and optical fiber. Piezoresistive sensors are popular because they are relatively easy to manufacture and integrate with other systems. The piezoresistive effect, a long-established phenomenon, is harnessed in developing manufacturing and application technologies for new application areas. These practical applications demonstrate the versatile potential of the piezoresistive effect across a broad pressure spectrum. Fiber optic solutions, while more complex to interface, are ideal for challenging environments due to the simplicity of constructing the fiber itself. The applications of this technology are numerous, including the sensing element's resistance to electrical interference and its suitability for chemically challenging applications. Research has also shown that Inkjet printing technology can be used to make resistive flexible sensors. As wearable electronics continue to increase, the demand for flexible sensors is expected to rise. With its scalable nature, Inkjet printing technology facilitates the transition of sensor manufacturing from small experimental batches to large-scale production, which is encouraging for its future use. [57, 58, 59, 60]

4.4 Physical Properties of a Common Resistor

Modern pressure sensors function on the concept of mechanical deformations. These deformations happen in various structures, such as pipes and chamber walls. It is widely recognized that the electrical characteristics of components subjected to pressure alter under the influence of pressure [28, 61]. In particular, the resistance of a resistor alters as a function of pressure [26]. Nevertheless, few studies focusing on hydrostatic pressure-induced changes are typically aimed at specific applications.

The change in resistance under pressure is predominantly due to the deformation of the resistive layer. In Surface-Mount Device (SMD) resistors, a resistive layer is established on the ceramic insulator. The structure of this resistor is illustrated in Fig. 10.

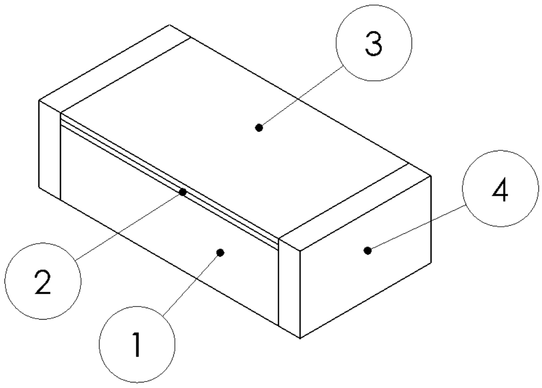

Figure 10. Surface mount film resistor construction. 1: Alumina substrate, 2: Resistive layer, 3: Protective coating, 4: Metal contact.

The thickness of the resistive layer varies from $0.1\,\mu m$ for a thin film to $100\,\mu m$ for a thick film. Earlier research indicates that thin and thick film resistors exhibit different responses to pressure. The manufacturing processes for these types of resistors also differ. The thin film is sputtered onto the surface of the alumina substrate, while the thick film is spread onto the surface as a paste through a mechanical process.

The deposited layer is uniformly metallic, and resistance changes are typically estimated based on the conductive area and the length of the conductor. Under hydrostatic pressure, deformation is three-dimensional and can be estimated using equation 4.1 for bulk modulus.

$$K = -V\frac{dP}{dV} \tag{4.1}$$

where K represents the bulk modulus, V is the volume at the reference pressure, dP is the change in pressure, and dV is the change in volume under pressure.

Previous studies have reported that the resistance of a thin film resistor decreases by $0.8\,\%$ for every $100\,\mathrm{MPa}$ [26]. Concurrently, the thick film layer comprises metallic particles in glass. The change in resistance for metal remains the same as in the case of a thin film layer, but the bulk modulus of glass is different. Under pressure, the glass volume decreases while the metal volume reacts less. This results in a decrease in resistance under hydrostatic pressure. The bulk modulus of nickel, a commonly used metal, is $180\,\mathrm{GPa}$. The bulk modulus for glass is $35\,\mathrm{GPa}$. It is important to note that these values may not be precisely accurate for the mentioned resistor types but are selected to represent a reasonable range of potential values.

4.5 Novel Method for Pressure Sensing - Theory

Prior research has shown that the resistance of both thin and thick film resistors is subject to a pressure coefficient of varying degrees. Assume a scenario where the resistance values are gauged under pressure and compared with the baseline value at atmospheric pressure. If the coefficient of the resistors is known, it becomes possible to ascertain the pressure. Unfortunately, such data is not presently accessible. Concerning thick film resistors, conductive particles are fused within the glass. Despite the non-resistive glass, it governs the degree of contact between the metal particles, thereby affecting the resistance. The resistance is presumed to hinge largely on the bulk modulus of the glass. By employing the previously stated values of $35\,\mathrm{GPa}$ and $180\,\mathrm{GPa}$, it can be deduced that the resistance shift of a thick film resistor is 5.14 times that of a thin film resistor.

4.6 Novel Method for Pressure Sensing - Implementation

A Wheatstone bridge was fabricated in a simulator, incorporating three thin film resistors and one thick film resistor. The model was devised using the LTspice software. A schematic illustration is presented in Fig. 11.

The bridge is energized with an ideal voltage source, delivering a voltage of $15\,\mathrm{Vdc}$. All four resistors are ideal resistors with a resistance of $10\,\mathrm{k\Omega}$, except for the pressure coefficient. The resistance under pressure was computed using equation 4.2,

$$R_{pr} = R + \frac{P}{100\,\mathrm{MPa}} C_{pr} R \tag{4.2}$$

where R represents the resistance at the initial pressure, P denotes the pressure, and C_{pr} signifies the resistance coefficient. The C_{pr} for the thin film is -0.008, as per previous

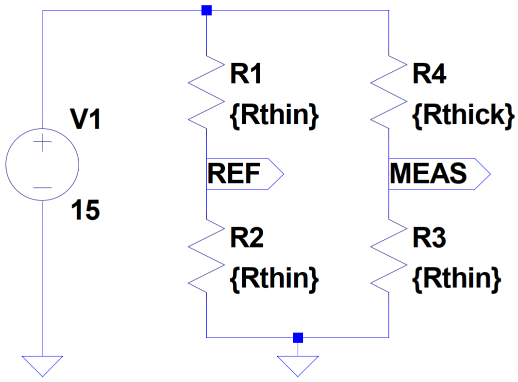

Figure 11. The sensor model block diagram. R1, R2, and R3 are thin film resistors. R4 is a thick film resistor.

research, and for the thick film, it is -0.04, as per the theory described. Given that the proposed model is linear and solely depends on pressure and coefficient, it will primarily serve as a reference for physical implementation, negating the need for more complex simulations at this stage. The simulation results and the functional test results are presented in Table 6.

4.7 Verification - Functional test

A proof-of-concept test was designed with a minimalistic setup. The Wheatstone bridge was assembled for the prototype circuit board, which was then immersed in dielectric oil and pressurized. Fig. 12 depicts the pressure side of the sensing element.

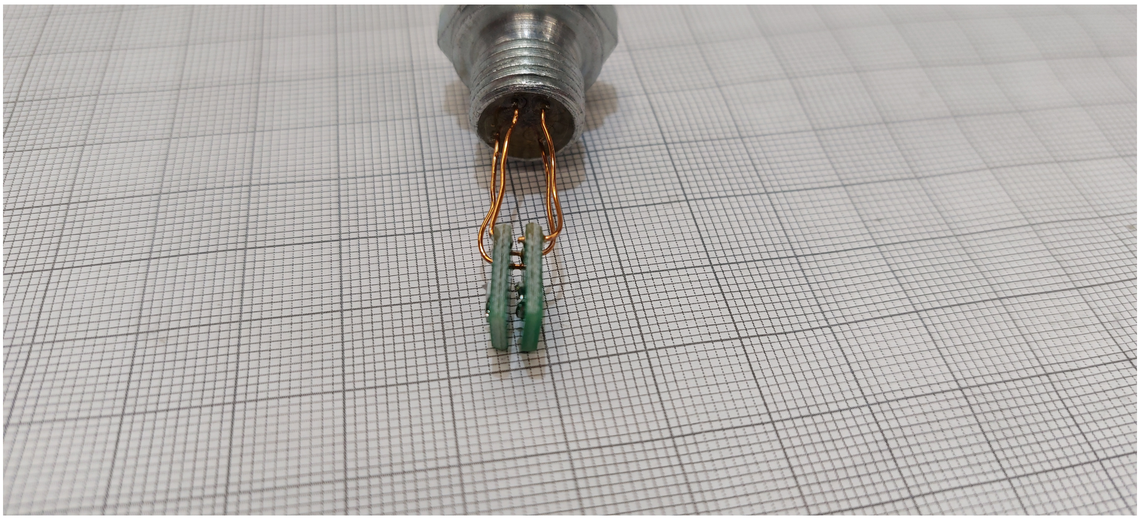

Figure 12. The prototype of the pressure sensing element.

An excitation voltage of 15 V was produced using a laboratory power supply, and measurements were taken. Three measurements were conducted and are displayed in Table 6, alongside the results from the simulation. The reference sensor used was Trafag DPS25.0PAP1.

Table 6. Proof of concept simulation and test.

Pressure (kPa)	Simulation Voltage (mV)	Simulation Change (mV)	Test Voltage (mV)	Test Change (mV)
0	0		182,86	
1013	1,22	1,22	183,93	1,07
2026	2,43	2,43	185,10	2,24

Unlike the test performed with actual components, DC bias is absent in the simulation. The crucial value is the change, which signifies the voltage shift relative to the initial value. Two test points exhibited a discrepancy of $14\,\%$ and $8\,\%$ when compared with the simulated results. The outcomes validate the hypothesis that standard resistors can function as pressure sensors. The result is encouraging, mainly since the bulk modulus values used to formulate the coefficient are approximations and have not been verified to align with the components used.

4.8 Verification - Durability

A sensor-specific circuit board was designed, and the new sensor was affixed to the hydraulic pipe and linked to the pressure cycling test bench. The new sensor is depicted in Fig. 13.

Figure 13. Pipe with the epoxied new sensor.

The test bench facilitated the alternation between two pressure levels multiple times. The pressure chamber was equipped with pressure line and tank connections controlled by individual valves. The new sensor, hereafter referred to as *Puuhai*, and the reference sensor was concurrently connected to the chamber. The reference sensor employed was Kulite ETM375M-350. The cycle comprised one second of high pressure followed by one second of low-pressure period. The total cycle count was 5000. Fig. 14 presents the values from both sensors.

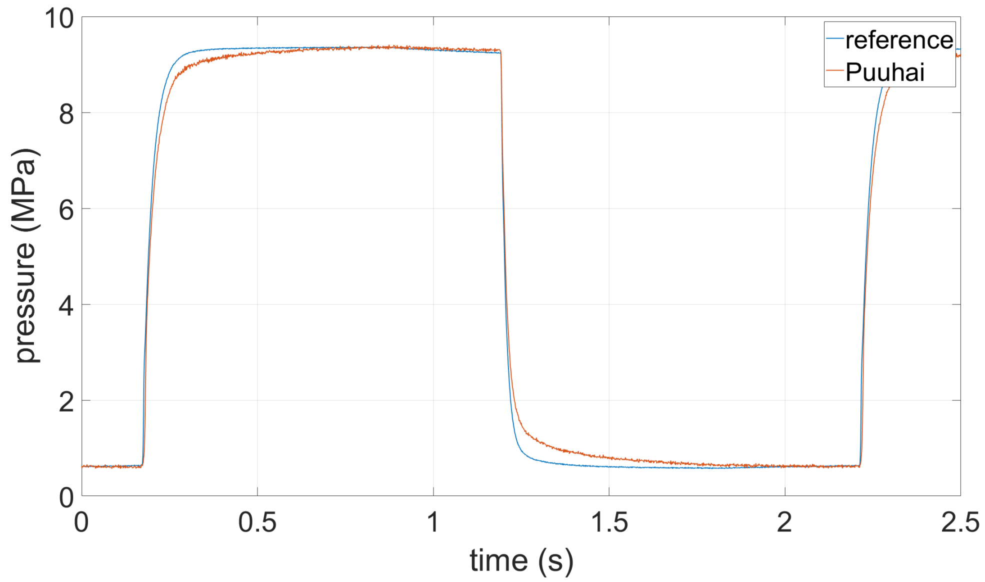

Figure 14. Single cycle from the test. Pressure cycle number 150. The signal from the *Puuhai* has DC bias removed, and the maximum value is matched with the reference sensor.

The number of successful pressure cycles also provides a measure of reliability. However, further research is required involving cycling multiple sensors until failure. The temperature coefficient of thick and thin film resistors varies by a factor of five. The thin film used in this study had a temperature coefficient of resistance of $10 \times 10^{-6}\,\mathrm{K}^{-1}$, while the thick film had $50 \times 10^{-6}\,\mathrm{K}^{-1}$. When incorporated into a hydraulic system with a temperature swing of $50\,\mathrm{K}$, the error from temperature is well within the $0.5\,\%$ tolerance of the resistor. The precision of the resistors used is not pertinent to the measurement. However, an initial value mismatch induces a DC bias to the bridge, potentially posing challenges for amplifier design.

4.9 Manufacturability and unit price

At the time of this writing, thick-film resistors boasting a precision of $0.5\,\%$ are priced at 0.004 €. In comparison, thin-film resistors with a precision of $0.1\,\%$ are priced at 0.02 €. Consequently, the combined cost of the sensor element and the reference falls under 0.10 €. The manufacturing process for thick film resistors is straightforward and uncomplicated. It does not require the use of diverse technologies or methods. Standard circuit board construction techniques are sufficient and need no alterations. When in contact with the dielectric—a non-aggressive medium—the sensor does not necessitate a diaphragm or any other protective measures, thereby simplifying the construction process even further.

4.10 Discussion

The findings from this study are encouraging. The pressure dependency of thin and thick film resistors can be simplified to a coefficient for readily available commercial parts. Moreover, it is feasible to incorporate a pressure sensor into the pressure-tolerant circuit for self-awareness, as the entire sensor can be integrated into the circuit board. This study, however, only investigated pressure dependence. The coefficient for the resistor types used was derived from existing literature, and determining precise values necessitates further work. Real-world components possess additional properties, such as temperature coefficient and capacitance. The impact of these properties on the sensor's functionality requires more detailed research. The temperature coefficient of resistance for thick and thin film resistors differs by a factor of five. The thin film used in this study had a temperature coefficient of resistance of $10 \times 10^{-6}\,\mathrm{K}^{-1}$, while the thick film had $50 \times 10^{-6}\,\mathrm{K}^{-1}$. When used in a hydraulic system with a temperature variation of $50\,\mathrm{K}$, the temperature-induced error is well within the $0.5\,\%$ tolerance of the thick film resistor. Functional testing indicated the presence of hysteresis at low pressures. However, the measurement setup did not allow for a more in-depth examination of this phenomenon. Long-term reliability necessitates careful analysis. However, cycling the pressure 5000 times did not expose any significant defects. This technology's potential applications and impact are discussed in detail in Chapter 6. Some scenarios where compact and cost-effective pressure sensing could be beneficial include pressure switches and sensors in household and industrial appliances, condition monitoring in hydraulic systems, and submerged data centers. While current and new pressure measurement solutions are effective in terms of accuracy and other attributes, the pressure coefficient formula of thin and thick film resistors presented in this study, along with the pressure sensor based on it, allows for the manufacture of more straightforward and more affordable sensors as components of more complex systems.

5. Implementing Smart Sensor System

A sensor marketed as low-cost may ultimately prove expensive if it requires a costly interface and complex infrastructure. In addition to measurement, connectivity is essential for the modern application of basic sensors. Even though sensors and indications of the measured value are useful in many applications, a network of sensors and data consumers will show their true potential.

This chapter introduces a potential software solution, depicted through a sequence diagram presented in Fig. 15 and an example program 5.1. The example program is written with MicroPython for Raspberry Pico W. MicroPython is reasonably easy to work with limited education and has good community support in case problems arise during the development work. The target microcontroller unit (MCU) is Raspberry Pico W due to its affordability and Wireless Local Area Network (WLAN) connectivity. A charitable organization developed this device to promote education [62], which could further advance the reach of accessible technologies. The cost-effectiveness of the device was a key consideration, as it allows for the integration of low-cost sensors in a modern context without necessitating significant infrastructure or financial investment. The application programming interface (API) is MQTT. MQTT is well suited for sensor data in local and Wide Area Networks (WAN). The interface is also computationally light and can be implemented in reasonably low-end systems.

5.1 Sensor to User Interactions

The presented program will calibrate zero pressure when powered up. After calibration, it will connect to the network and MQTT broker. It will report new pressure values every second and overall status every minute. The status report is more significant in terms of required memory than the pressure value alone, and this way, the smart sensor does not require as much bandwidth. The latest values are readable from the MQTT broker, where those are potentially displayed by the user through the smart display or computer program.

5.2 Example Program

The provided code, written in Python, is designed with simplicity in mind. The complete code is included in Appendix 2 at page 64. It uses a sensor to measure pressure, updates

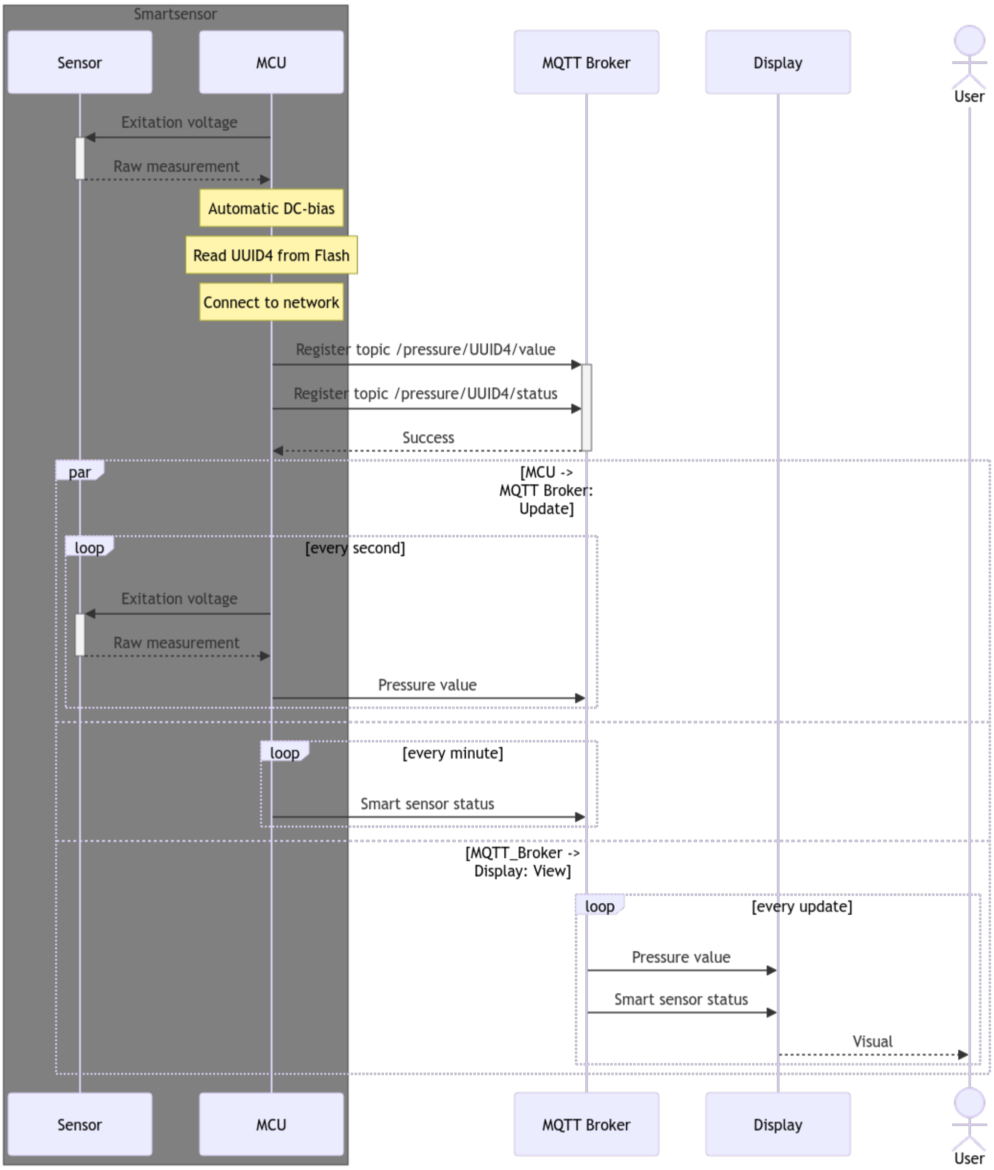

Figure 15. Sequence diagram of the sensor-to-user interactions.

the measurement to a local database, and then publishes the updated pressure value to a specific topic on an MQTT broker.

The program begins by checking if there is a bias value in the database. If there is no defined value for DC bias, it will set the bias for the pressure sensor, a constant error value that must be subtracted from all measurements to get accurate results.

Next, the program establishes a connection to a WLAN. Connection is necessary for the device to communicate with other devices on the network. The program proceeds once the connection is established.

Following the WLAN connection, the program connects to an MQTT broker.MQTT stands as a streamlined messaging protocol designed for machine-to-machine (M2M) interaction and Internet of Things (IoT) implementations. The broker functions as a server, accepting all client messages and directing them to the suitable recipient clients. The MQTT topic to which the pressure values will be published is defined as "/pressure/[sensor-ID-code]/value".

The program then enters an infinite loop. Inside this loop, it first updates the pressure measurement by calling the update_pressure() function. This function takes a new pressure reading from the sensor and updates the pressure value in the database.

The updated pressure value is then published to the previously defined MQTT topic. Value is the updated pressure value converted to bytes, since MQTT can only transmit binary data. Finally, the function pauses for one second before repeating the loop, which, in practice, means that a new pressure value is published to the MQTT broker nearly every second. For simplicity, the code does not implement a status update.

The database uses Python data structure *dictionary*. Utilizing a standard Python structure allows for varying storage and interaction methods. In the example, sending the whole database, excluding secrets, would be straightforward as a status message to the MQTT broker. Initializing the database can be done in two ways, either directly from a JSON file, or using the hardcoded default values. Code listing 5.1 shows both methods for initializing the database at the program's start.

In conclusion, this program is a good example of how a simple IoT device can measure, process, and transmit sensor data using modern communication protocols like MQTT. Using a database for storing sensor data and device information also adds flexibility and scalability to the system. The code is good starting point for smart sensor development.

Code Listing 5.1. Alternative ways to initialize database.

```
try:  # Open JSON file and load settings database
    with open('database.json', 'r') as f:
        database = ujson.load(f)
except:  # Data read failed, fallback to hardcoded defaults
    database = {
        "UUID4": "d180006c-9fd4-4401-830b-2708e2f443fe",
        "status": "Setup failed",  # Using fallback defaults
        "SSID": "thesis",  # WLAN SSID
        "PWD": "thesis",  # WLAN Password
        "MQTT_BROKER": "10.0.0.1",  # Default MQTT broker
        "bias": False,  # DC bias not set
        "factor": 1,  # Factor from raw value to bars
        "pressure": -1  # Latest pressure reading in bars
    }
```

6. Economic, Environmental and Social Impact

The innovative pressure sensor design brings various potential benefits across economic, environmental, and social aspects. This section aims to explore these impacts in-depth, highlighting how advancements in sensor technology can lead to transformative changes beyond traditional industrial applications.

Economically, the *Puuhai* sensor not only decreases the direct costs associated with production and operation but also enhances the competitiveness of businesses by enabling the creation of more reliable and efficient products. Furthermore, it makes advanced sensor technology accessible to smaller businesses and startups, potentially catalyzing innovation and competitive differentiation. Examples from industries such as healthcare and manufacturing will illustrate how sensor technology is being integrated into various sectors to drive economic growth, including applications in predictive monitoring that anticipate maintenance needs and operational efficiencies.

Environmentally, the *Puuhai* sensor promotes energy efficiency and resource conservation, contributing to reducing carbon footprints and advancing green technologies. In the environmental sphere, examples from industries like renewable energy and waste management will be discussed, showcasing how the sensor technology contributes to sustainable practices and operations.

Socially, it improves safety standards, enhances public health, and makes advanced technology more accessible, particularly in developing regions. Also, the impact of this technology on strengthening public safety and healthcare outcomes through improved monitoring and control systems is discussed.

The following sections will detail how each of these impacts is interrelated and integral to driving a sustainable future, with specific attention given to how different industries leverage this technology to address unique challenges and opportunities.

6.1 Economic Impact

6.1.1 Reducing Supply Chain Cost

Organizations focus on measuring Supply Chain Cost (SCC) in order to enhance their net income and decrease costs [63]. Studies highlight that reducing SCC enhances net income and serves as a competitive lever, contributing to increased market value and shareholder earnings [64, 65].

Measurement items for supply chain costs encompass a variety of categories, including the total cost of resources, distribution costs, manufacturing costs, inventory costs, and return on investment [66]. The total cost of resources reflects the entirety of resources allocated within supply chain activities [67, 68, 69]. Distribution costs include expenses related to both inbound and outbound transportation, along with the administration of these processes within the supply chain [63, 70]. Manufacturing costs entail expenses associated with the use of equipment, materials, and processes, and may also include costs for rework, labor, and maintenance [63, 71, 72, 73, 74]. Inventory costs are composed of fixed and unit variable ordering costs, unit holding costs, and penalty costs [75, 63, 76]. Return on investment is typically calculated as the net profit generated by the investment [73, 77, 78].

Thus, reducing manufacturing costs would benefit the reduction of total SCC, leading to an increase in net income. The proposed *Puuhai* pressure sensor design is characterized by its simplicity and cost-efficiency, and it has the potential to significantly mitigate the expenses associated with the manufacturing of pressure sensing systems. This is primarily because the *Puuhai* sensor design allows for a more streamlined manufacturing process, reducing the need for complex machinery and specialized labor. This reduction in complexity not only simplifies the manufacturing process but also reduces the associated costs, making the production of these sensors more cost-effective.

Industries heavily dependent on such sensors, encompassing the automotive, aerospace, and industrial manufacturing sectors, stand to gain from decreased costs. The reduced costs of manufacturing and operating these sensors could substantially increase their profit margins. This increased profitability could make companies utilizing new technology more competitive, potentially expanding their market share.

Moreover, the cost savings could be passed on to the consumers. The reduced cost of the sensors could make them more affordable for a broader range of consumers, leading to an increase in demand for their products and services. This increased demand could stimulate growth in these industries, further contributing to their economic success.

In addition, the increased affordability of these sensors could also make them more accessible to smaller businesses and startups. This could stimulate innovation and competition in the market, leading to the development of new applications and technologies.

In conclusion, the innovative pressure sensor design has significant economic implications. Reducing manufacturing and operational costs could stimulate economic growth and innovation in industries that rely on pressure-sensing systems. Furthermore, making these sensors more affordable and accessible could lead to increased demand and competition in the market, further contributing to economic development.

6.1.2 Enhancing Predictive Maintenance

Predictive maintenance (PdM), utilizing sophisticated sensors, analytics, and machine learning, has become a norm in asset management. It enables the proactive detection of potential equipment failures. Machine malfunctions during production may result in negative impacts on the production timeline, delays in delivery, or the need for employees to work overtime to make up for the downtime. The predictive approach has been employed across various sectors, including the Internet of Things (IoT), high-performance computing (HPC), data centers, smart factories, and Industry 4.0. [79, 80, 81, 82]

HPC clusters, necessary for complex tasks such as scientific simulations and financial modeling, and data centers, the basis of modern IT infrastructure, benefit significantly from PdM. PdM guarantees the uninterrupted operation of servers, storage, and networking components. Administrators can foresee hardware failures by analyzing various metrics, temperature changes, and workload patterns. However, the evolution of HPC systems, including new techniques like immersion cooling, brings new challenges [83]. Furthermore, the increasing use of IoT devices has changed how we interact with the physical world. Keeping these devices in good shape involves using PdM, which monitors sensor data, network connections, and device behavior to catch problems early.

PdM is more than a cost-saving strategy; it is necessary for IT operations. As the component count in IT installations continues to grow, the reliability of each component is becoming one of the major issues in designing these systems [84]. It boosts efficiency and reliability by preventing unexpected downtime, optimizing maintenance schedules, and prolonging equipment lifespan. PdM will remain a fundamental aspect of effective asset management as technology advances.

The enhanced performance and dependability of the novel *Puuhai* sensor could significantly augment the efficacy of the PdM. This augmentation is primarily because the sensor enables advanced condition monitoring, which ensures that the systems function optimally at all times. The sensor's high accuracy means it can provide precise measurements, enabling the systems to operate within their optimal parameters. This reduces the likelihood of system failures, which can be costly and disruptive.

As a result, products that incorporate this sensor are likely to have extended life cycles. The extended life cycles directly result from the sensor's reliability and the resulting reduction in system failures. For example, we can look at a computer motherboard exposed to multiple pressure cycles in a wave power generation facility. This motherboard could effectively employ the newly developed on-board sensor. A counter in the permanent memory increments each time a pressure cycle occurs. This count, accessible through an API, serves as a valuable indicator of the motherboard's lifespan, similar to how the number of startups is used to estimate the lifespan of hard drives [85]. This reduces the frequency of product replacements, which can be costly and time-consuming, and also leads to significant savings in maintenance expenditures. These savings can substantially impact the bottom line, making the products more cost-effective over their lifetime.

Furthermore, the improved system reliability facilitated by the *Puuhai* sensor could increase customer satisfaction. This is because the products are less likely to malfunction or require frequent unexpected repairs, which can be frustrating and inconvenient for the customers. High customer satisfaction is crucial for the success of any product, as satisfied customers are more likely to become repeat customers and recommend the product to others [86].

This increased customer satisfaction could, in turn, enhance the reputation of the manufacturers. A strong reputation can be a decisive competitive advantage, helping to differentiate the manufacturers in a crowded market. This could lead to increased market share and profitability, further enhancing the economic viability of the manufacturers.

In conclusion, with its enhanced performance and dependability, the *Puuhai* sensor could significantly augment the efficacy of PdM systems. This could lead to extended product life cycles, reduced maintenance expenditures, increased customer satisfaction, and enhanced manufacturer reputation. These benefits could have far-reaching economic implications, underscoring the value of the novel sensor.

6.2 Environmental Impact

6.2.1 Improving Energy Efficiency

Energy efficiency is crucial not only for its potential to lower energy costs and reduce environmental impacts but also for its role in enhancing energy security and promoting sustainable development. In response to these needs, the European Union (EU) has updated the Energy Efficiency Directive, and committed to a significant reduction in energy consumption, setting an ambitious target to decrease final energy consumption by at least $11.7\,\%$ by 2030 [87].

The introduction of a more reliable pressure sensor could lead to a significant reduction in energy consumption across various applications. The reduction in energy consumption is primarily because a more efficient control system, enabled by reliable pressure sensing, can optimize energy use. This optimization means that systems can operate at their most efficient point, thereby lowering carbon emissions. Lower carbon emissions are crucial in the fight against climate change, making the role of reliable pressure sensing in energy efficiency even more important.

Building on the principles of PdM discussed in 6.1.2, which lead to substantial economic benefits, enhanced condition monitoring plays a crucial role. As a key component of PdM, reliable condition monitoring facilitated by accurate pressure sensing significantly contributes to energy conservation. By timely detecting system faults or inefficiencies, condition monitoring ensures that such issues are promptly addressed, preventing unnecessary energy consumption. This reduces operational costs and minimizes carbon emissions, supporting the broader goal of environmental sustainability by optimizing the use of resources.

6.2.2 Enhancing Resource efficiency

The European Union's Critical Raw Materials Act (CRMA), adopted in March 2024, addresses the growing demand for critical raw materials (CRMs) essential for various industries and aims to reduce the EU's dependency on a limited number of suppliers [88]. In this context, the simplified design of the novel pressure sensor complements the goals of the CRMA by reducing the raw materials required for production. This streamlined design minimizes the use of resource-intensive components, supporting the EU's effort to strengthen circularity and resource efficiency.

The simplified design of the *Puuhai* sensor decreases the amount of raw materials required for production while reducing the need for complex and resource-intensive manufacturing processes. This efficient use of materials could significantly reduce the environmental footprint of the sensor's production, contributing to resource conservation.

In addition to the benefits of reduced raw material and energy consumption, the *Puuhai* pressure sensor's simplified design could also contribute to waste reduction. With fewer components and a simpler assembly process, there is less potential for waste generation during manufacturing. This waste reduction could further enhance the environmental sustainability of the sensor's production.

These factors - reduced raw material use, lower energy consumption, and minimized waste - contribute to resource conservation and waste reduction, which are crucial for sustainable development and environmental protection. Therefore, the novel pressure sensor represents a significant advancement not only in terms of technological innovation but also in terms of environmental sustainability. It is an example of how technological progress can go hand in hand with environmental governance, leading to a more sustainable future.

6.2.3 Advancing Green Technologies

Green technologies are essential for sustainable development. The EU has recognized this by adopting the European Green Deal [89]. This comprehensive strategy targets a net emissions cut of at least 55% by 2030 and aims to achieve climate neutrality by 2050 by integrating initiatives across energy, transport, industry, and agriculture. By promoting green technologies, the Green Deal facilitates a coordinated approach to reduce environmental impacts and advance the EU towards a sustainable and competitive economy.

The *Puuhai* pressure sensor could play an important role in promoting the adoption of green technologies. This is because the sensor, with its advanced capabilities, enables more efficient control and monitoring in systems like renewable energy installations and electric vehicles - key components in the shift towards a more sustainable and eco-friendly society.

The improved efficiency of these systems could lead to their broader adoption. As these green technologies become more efficient and reliable, they become more viable alternatives to traditional technologies that are often harmful to the environment. This could result in a significant shift in societal attitudes and practices, accelerating the transition towards sustainability.

Furthermore, the *Puuhai* pressure sensor could stimulate innovation in the field of green technologies. This is because the improved performance and reliability of the sensor could inspire researchers and engineers to develop new green technologies or improve upon existing ones. With its innovative design, the sensor represents a technological advance and could accelerate further innovation in the field.

6.3 Social Impact

6.3.1 Increasing Accessibility and Affordability in Developing Regions

In recent years, the impact of technology on the labor market has garnered significant attention from academics and policymakers. Key studies, including the European Parliament's [90] titled "The impact of new technologies on the labour market and the social economy," the World Trade Organization's [91] "Impact of technology on labour market outcomes", and research from Moscow Engineering Physics Institute [92] titled "Development of Russian labor market in the context of informatization and computerization of the economy" collectively highlight this recent focus worldwide.

A common conclusion across these reports is that technological progress has increased the demand for skilled workers, driving positive changes in wage structures and employment opportunities. Moreover, the studies note that the proportion of jobs at risk due to automation is higher in developing countries, where a larger segment of the workforce is engaged in routine tasks susceptible to technological displacement. To mitigate this risk, enhancing technological literacy in these regions is crucial. Promoting access to advanced, low-cost technologies, such as the proposed *Puuhai* pressure sensor, can directly support the development of skills and infrastructure needed to adapt to these changes.

By democratizing access to sophisticated technology, such innovations can help equip workers with the skills necessary to thrive in a rapidly evolving labor market, particularly in developing regions. This democratization is primarily due to the sensor's affordability, making it a viable option for a wide range of users. For instance, small-scale farmers could leverage this technology to create homemade pressure switches for irrigation systems, a critical component of their agricultural practices. The efficient use of water is crucial for agricultural productivity and sustainability, especially in regions where water resources are scarce or inconsistently available. By enabling more precise control of irrigation systems, the *Puuhai* pressure sensor could lead to more efficient water use, enhancing agricultural productivity and contributing to food security in these regions.

Furthermore, the accessibility of this advanced technology could empower entrepreneurs and create new startups in these regions. This comes from the ability to incorporate advanced pressure sensing into their products or services, which could otherwise be prohibitive due to cost or complexity. These startups could bring fresh perspectives and novel solutions that address local challenges and needs, driving further innovation and growth. They could also create new job opportunities, contributing to employment growth and economic development.

Educational institutions in developing regions could also benefit significantly from this technology. Access to such advanced yet low-cost technology could provide students hands-on experience working with state-of-the-art sensor technology, a valuable skill in today's high-tech world. This practical experience could enhance their learning outcomes, making their education more relevant and engaging.

Moreover, this exposure to advanced technology could prepare students for careers in the high-tech industry, equipping them with the skills and knowledge needed to succeed in such careers. This could lead to better student job prospects, contributing to these regions' workforce development and economic advancement. In addition to benefiting individuals, this could also contribute to social mobility. The skills and knowledge acquired through training could make students more competitive in the job market, enhancing their career prospects and supporting social mobility.

In conclusion, the novel pressure sensor's low cost and simplicity can potentially democratize access to advanced pressure sensing technology in developing regions, benefiting various sectors of society, from agriculture and entrepreneurship to education and workforce development.

6.3.2 Improving Safety and Public Health

As discussed in the section 6.1, the context of reliability is important in terms of cost savings, which in turn have a broad economic impact. Besides the economic impact, reliability also impacts the health and safety sectors.

Pressure sensors play an important role in enhancing the safety and reliability of a wide array of equipment across various industries. Enhanced pressure-sensing capabilities contribute to more accurate control and monitoring of devices and machinery, ensuring that they operate within their intended parameters. This precision is crucial in mitigating the risk of malfunctions that could lead to hazardous situations and accidents, thereby enhancing overall safety.

Moreover, the improved accuracy provided by advanced pressure sensors leads to increased equipment reliability. Reliable devices and machinery are less prone to unexpected breakdowns, resulting in more consistent performance and reduced downtime. This reliability is especially critical in sectors where equipment failures, such as healthcare and manufacturing, can have severe consequences.

Such accidents not only pose a risk to the machinery operators but can also have implications on public health, especially in the case of medical devices. Therefore, by potentially reducing accidents caused by equipment malfunction, enhanced pressure sensing plays a vital role in improving workplace safety and reducing public health risks.

Furthermore, enhanced pressure sensors could significantly improve the reliability of these devices and machinery. Reliable equipment is less likely to break down unexpectedly, leading to more consistent performance and less downtime. This reliability is critical in sectors such as healthcare and manufacturing, where equipment failure can have serious consequences, ranging from disruption of patient care to significant financial losses.

An additional impact of advanced pressure sensing is the improved availability of medical supplies, particularly in developing regions. The affordability of new, low-cost sensors opens up access to essential medical equipment in areas where more expensive sensors are prohibitive. Even minor cost reductions can make a significant difference in these settings, enabling healthcare facilities to acquire the necessary supplies for patient care.

Overall, these advancements in pressure-sensing technology offer tangible benefits, including safer equipment operations, increased reliability, and broader access to medical supplies in regions where cost is a significant barrier. These improvements are vital for supporting safety, efficiency, and healthcare access on a global scale.

7. Conclusions

This thesis explores the development of a novel, low-cost pressure sensor named *Puuhai*, offering a comprehensive examination of the pressure tolerance of standard electronic components and their applications under high-pressure environments. The study begins with an in-depth literature review that establishes the theoretical groundwork for assessing the physical and electrical properties of electronic components under varying hydrostatic pressures. Subsequent laboratory tests validate the theoretical concepts by subjecting components to different pressure conditions and monitoring their performance.

The thesis then transitions into practical applications, detailing the development of the *Puuhai* sensor, which leverages findings from both the literature review and laboratory experiments. The sensor's development is highlighted by its cost-effectiveness and ease of manufacture, making it accessible for industrial production and workshop settings. The design of *Puuhai* considers economic, environmental, and social impacts, emphasizing sustainability and affordability, which could lead to widespread adoption and significant cost savings in industries reliant on pressure-resistant technologies.

This thesis presents research into the pressure resistance of electronic components, leading to the development of the novel *Puuhai* sensor. Development included physical sensors, laboratory verification, software interface, and consideration of economic, environmental, and social impact. Parts of this thesis, described in chapter 4, have been published by the author on Proc. Of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME 2023) 19-20 July 2023, Tenerife, Canary Islands, Spain. [1].

Recognizing the critical need for robust, cost-effective electronics that can operate under significant hydrostatic pressures, the research began with a methodical evaluation of the pressure resistance capabilities of standard electronic components. Initially, the thesis presented a systematic approach to evaluating these components, followed by compiling the maximum tested pressures for basic components. This compilation, unprecedented in existing literature, served as a foundational element for the subsequent development of the *Puuhai* sensor.

Key findings demonstrate that while standard components like electrolytic capacitors exhibit limited pressure tolerance, altering physical configurations, such as the distance between capacitor plates, can enhance their functionality under pressure. Also, components like oscillators might continue to operate effectively despite partial structural compromises, provided these do not alter the stiffness crucial for their operation. A considerable portion of the study was devoted to evaluating the performance of electronic components under pressures reaching up to $150\,\mathrm{MPa}$. Despite the limited number of direct tests available in the literature, indirect evidence from various studies suggested that many components might possess inherent pressure-resistant properties previously undocumented. This insight is important for industries like deep-sea exploration, mining, and oil and gas, where equipment operates under high pressures and the economic stakes of equipment failure are high. The thesis underscores the potential for substantial cost reductions in designing and maintaining underwater machinery and other pressure-sensitive systems by selecting inherently pressure-resistant components, thus avoiding the need for costly specialized enclosures. The development of the *Puuhai* sensor encapsulates the practical application of these findings. The affordability and straightforward manufacturing process make the *Puuhai* sensor an accessible technology, potentially broadening its use across various sectors. The concept of an affordable smart sensor based on the *Puuhai* sensor is also presented, incorporating a sequence diagram and a sample program utilizing the MQTT API. This integration highlights the sensor's ability to function within smart systems, enhancing its applicability in IoT environments and enabling real-time data communication and control. The MQTT API component emphasizes the sensor's adaptability and ease of integration into existing technological frameworks, broadening its potential impact and making high-tech education more accessible, thereby benefiting society and promoting technological advancement in related industries.

For future research, several avenues could further enhance the *Puuhai* sensor's capabilities and integration into more complex systems. Investigating the sensor's long-term stability and accuracy under varying environmental conditions could validate its reliability for critical applications. Additionally, exploring alternative materials and design adjustments might offer improvements in pressure tolerance and sensor performance at even higher pressures. Research could also investigate the long-term reliability and durability of these components in extreme conditions, including varying temperatures and corrosive environments, which are common in deep-sea applications. Enhancing the sensor's integration capabilities with other IoT platforms beyond MQTT could also be considered to broaden its application range. Another promising direction is the development of machine learning algorithms to predict component failure under pressure based on real-time sensor data, potentially leading to predictive maintenance models for industrial applications. These future studies would contribute to the advancement of pressure-sensing technologies, making them more versatile and practical in high-pressure environments.

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Appendix 2 - Smart Sensor Example Program

```
from machine import ADC
from time import sleep
from network import WLAN
from umqtt.simple import MQTTClient
from ujson import load

#Create sensor object and connect it to pin 28 with ADC
sensor = ADC(28)

try:  # Open JSON file and load settings database
    with open(’database.json’, ’r’) as f:
        database = ujson.load(f)
except:  # Data read failed, fallback to hardcoded defaults
    database = {
        "UUID4": "d180006c-9fd4-4401-830b-2708e2f443fe",
        "status": "Setup failed",  # Using fallback defaults
        "SSID": "thesis",  # WLAN SSID
        "PWD": "thesis",  # WLAN Password
        "MQTT_BROKER": "10.0.0.1",  # Default MQTT broker
        "bias": False,  # DC bias not set
        "factor": 1,  # Factor from raw value to bars
        "pressure": -1  # Latest pressure reading in bars
    }

def update_bias():
    sensor_raw = sensor.read_u16()  # Read analog input
    database[’bias’] = sensor_raw  # Update DC bias to current value

def update_pressure():
    sensor_raw = sensor.read_u16()  # Read analog input
    # Convert raw value to bars
    database[’pressure’] = (sensor_raw - database[’bias’]) \\
                                     * database[’factor’]

def connect_wlan():
    nic = network.WLAN(network.STA_IF)  # Use client-mode
    nic.active(True)  # Power up network interface
    nic.connect(database[’SSID’], database[’PWD’])
    while not nic.isconnected():  # Wait to be connected forever
        time.sleep(2)
```

```python

def connect_mqtt():
    mqtt_client = MQTTClient(database['UUID4'],
                             database['MQTT_BROKER'])
    mqtt_client.connect()

def main():
    if not database['bias']:
        update_bias()
    connect_wlan()  # Connect to WLAN
    connect_mqtt()  # Connect to MQTT broker
    mqtt_topic = "/pressure/" + database['UUID4'] + "value"
    while True:
        update_pressure()
        mqtt_client.publish(mqtt_topic, database['pressure'].encode())
        time.sleep(1)

if __name__ == "__main__":
    main()
```